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SNM-DAT: simulation of a heterogeneous network for nuclear border security

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Abstract

We approach the problem of detecting Special Nuclear Material (SNM) smuggling across open borders by modeling a heterogeneous sensor network using an agent-based simulation. Our simulation (SNM-DAT) combines fixed seismic, metal, and radiation detectors with a mobile gamma spectrometer. Decision-making within the simulation determines threat levels by combined signatures. The spectrometer is a limited-availability asset, and is only deployed for substantial threats. "Crossers" can be benign or carrying shielded SNM. Signatures and sensors are physics-based, allowing us to model realistic sensor networks. The heterogeneous network provides great gains in detection efficiency compared to a radiation-only system. We can improve the simulation through better sensor and terrain models, additional signatures, and crossers that mimic actual trans-border traffic. We expect further gains in our ability to design sensor networks as we learn the emergent properties of heterogeneous detection, and potential adversary responses.

Keywords: Nuclear; Security; DSN; Border; Radiation; Sensor Network

1. Introduction

We hypothesize that domestic nuclear security of remote border regions will require a layered, defense-in-depth approach. The first layer of a decision hierarchy will distinguish between different types of potential targets using inexpensive, complementary sensor nodes using in-situ, real-time distributed processing when possible. Subsequent layers will exploit such analysis to allocate scarcer, more expensive resources, such as spectroscopic radiation detectors, sensors placed on small UAVs (Unmanned Aerial Vehicles) or other emergent concepts. We expect that terrorists will attempt to conceal materials by hiding obvious signatures or take advantage of weaknesses inherent in any fixed detection scheme. Not all signatures can be easily maintained within "normal" ranges while transporting significant SNM.

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We anticipate that heterogeneous sensor networks will be more difficult to defeat as they force opponents to trade between abnormal radioactive signatures on the one hand and abnormal movement patterns, electromagnetic emissions, or other suspicious signals on the other. Heterogeneous networks pose challenges for system integration, but can also provide much greater detection capability if they improve the utilization of expensive, scarce, or intrusive detection assets. To investigate interdiction strategies based on heterogeneous networks combined with hierarchical decision trees, we are developing an agent-based sensor network model incorporating realistic depictions of sources, sensors, and response strategies.

2. SNM-DAT

The SNM Data Analysis Tool (SNM-DAT), based on an open source software package (REPAST), used for customizing agent-based system simulations. In an agent-based framework, each individual entity (a sensor, source, or innocent bystander, perhaps), is an independent agent, operating by its own rules in response to external stimuli. An overarching "border space" agent receives input from all of the agents, and provides information as appropriate (for example, as a source updates its position, the border space provides updated signal strengths to nearby sensors). Since each agent functions independently, realistic characteristics, such as failure modes, can be built into the system model. The agent-based modeling framework provides tools to construct a standard graphical user interface, including control buttons for performing tasks such as starting, stopping, stepping and resetting the simulation and a window for modifying parameters specific to the SNM-DAT application. Besides the visual display of a heterogeneous detection network in action, SNM-DAT can generate plots of sensor activity as well, either as individual detectors, or as statistical measures computed across all sensors of a given type.

Our prototype system model involves three types of fixed detectors (seismic, metal, and radiation) and one mobile detector (a gamma spectrometer). The fixed sensors are simple and inexpensive enough to be ubiquitous across the border region, while the mobile detector is considered to be costly and have a limited range- making it a scarce resource that can only be deployed against highly significant targets. All of the detector types are modeled in a physically-realistic fashion, as are source terms, signal propagation, and analysis. We assume that detection information is relayed wirelessly to a sensor node with sufficient computational power to make decisions based on sensed information.

2.1. Seismic detectors

The seismic detection scheme is based on field results reported by Houston and McGaffigan [1]. That work used GS-11 geophones and a spectral analysis technique to detect foot traffic. Our seismic model reproduces their detection technique; a "crosser" (an individual walking through the border area) generates individual footstep signals that are propagated with attenuation to the seismic sensors. The SNR of the seismic model was chosen to mimic the detection efficiency of Houston and McGaffigan.

2.2. Scintillators

The scintillators are modeled as linear detectors, each 3m in length and 75cm diameter. Essentially plastic pipes filled with doped mineral oil, they provide large area detection for SNM and radiological dispersal device materials at very low cost (the tubes could be as much as 10m long in a deployed system). The modeled scintillators are sensitive to gammas and charged particles, but could also be made sensitive to neutrons. We do not model discrimination capabilities; in practice, discrimination against airshower muons and radon would be advantageous. The model includes a background term based on the expected terrestrial radiation flux, and incorporates standard counting statistics.

2.3. Metal detectors

A model of the pulse induction metal detector, used by Das et al. [2], was created using the sensitivity map technique described by Silvester and Omeragić [3]. Static sensitivity is defined, by Silvester and Omeragić, as the ratio of open-circuit output voltage change to input voltage. Our model generates a spatial sensitivity map based on a specified coil geometry (The coil geometry is arbitrary). The modeled SNR accounts for the coil geometry and electronics used by Das et al.

2.4. Mobile Spectrometer

The spectrometer is envisioned as a small device tethered beneath a UAV. The UAV is capable of hovering, thereby maintaining the spectrometer at a distance of ~1m from a source of interest. The UAV can acquire and track a source if it is within 10 m of the source; initial position information is derived from the seismic track information. The spectrometer itself is modeled as having a $20cm^2$ detection area and an energy resolution of 3% at 662 keV.

2.5. Border Space

Our current code models a square area 100m on a side. Seismic sensors (50 total) are distributed randomly on both sides of a literal border line composed of metal detectors and linear scintillators (30 each). The linear and radiation sensors form a continuous line of detection. Crosser agents (both single and multiple crossers can be modeled) can be benign or malicious. Malicious Crosser agents can be carrying an arbitrary amount of SNM or radiological material. We employ the 413 keV line for Pu detection, and the 186keV and 1001 keV lines for U or HEU. The sources are assumed to be spherical, and can be shielded by an arbitrary amount of iron. Self-shielding in the radioactive source is included.

A “Decision Agent” aggregates the seismic data, and forms a track, estimating the location and path of the crosser(s) by calculating a “center of mass” based on the seismic signal amplitude. A crosser’s position is thus known when it crosses the detection line. The radiation and metal signatures are passed to the decision agent; if it determines a sufficiently threatening anomaly (a combination of positive metal signature and/or high radiation) exists, it launches the UAV from its station in the lower right corner of the space. Using the estimated path of the intruder, the UAV locates the suspicious crosser, lowers a sensitive gamma spectrometer via a tether in the immediate vicinity of the suspected terrorist, and begins recording. After sufficient integration time, if SNM is indicated, the highest level of response (interdiction by a government authority) is triggered.

3. Preliminary results

We now present an example of sensor network system studies that can be performed by use of SNM-DAT. In Figure 1, we show a calculated Receiver Operation Curve (ROC) for the sensor network described above. This allows us to determine whether heterogeneous sensor networks permit increased effectiveness at detecting SNM crossing remote border regions. The first scenario assumes a single opponent carrying 1Kg of Pu^{239} shielded in 10Kg of iron. Results were based on 1000 runs divided between five different sensor thresholds (={9,6,4.5,3,1}σ above background). Using the full capabilities of the heterogeneous network (solid line), the clustered points in the upper left of the ROC curve show that it is possible to achieve a high rate of interdiction (>~90%) over a 3-fold range of sensor thresholds while maintaining the false alarm rate less than a few percent (computing the exact false alarm rate would require orders of magnitude more runs). The inflection in the ROC curve illustrates the effects of system complexity: as detection thresholds are decreased, the UAV spends more time chasing false alarms, thereby lowering the overall detection rate. Running the same scenario after disabling all but the scintillators (dashed blue line) shows that a detection strategy based on radiological monitoring would lead to severely reduced detection rates and an unacceptable number of false alarms. The reason for highly favorable ROCs achieved by the heterogeneous network is obvious: since seismic and metal detection discriminates against radiation that is not related to a crosser, the many false positives associated with low detection thresholds can be eliminated by the decision agent. The primary failure mode occurs when a scintillator has a random excursion above threshold nearly coincident in time and space with the arrival of the Crosser. This can cause the UAV’s initial aimpoint to be incorrect, so that it never closes within 10m of the Crosser.

The second scenario of Fig. 1 simulates a Crosser carrying 5 kg of U^{238} in 10 kg shielding. In this case, the ROC results are poor for both heterogeneous (dotted) and radiation-only networks (blue dot-dash). This is because we still define a positive detection by a radiation signature: virtually nonexistent for shielded U^{238}. If we changed the rules of the scenario, declaring a positive result to be the detection of >10kg of metal (arguably an unusual condition in a remote area), the ROC would again be favorable.

These results imply that a significant decrease in sensor density would be possible without significantly degrading system performance. We are currently examining this possibility, and determining detection limits based on both radiological and metal detection.

4. Conclusions

The interplay between radiation detection and metal detection illustrates the trade off between anomalous sensor readings that heterogeneous sensor networks can exploit. Substantial shielding could reduce the signal detected by the nearest gamma scintillator to near background levels but would necessarily increase the electromagnetic signature to highly suspicious values, thus a heterogeneous sensing network confronts nuclear terrorists with a much more difficult logistical problem than if only radiological signals were monitored.

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The mature SNM-DAT will predict the behavior of large, heterogeneous detection networks incorporating a hierarchically organized defense-in-depth. SNM-DAT is a simulation “sand-box” in which to explore the collective information conveyed by different types of radiological sensors, along with multiple non-radiological sensors (seismic, IR, electromagnetic, etc.). Realistic terrain features and crosser behaviors can also be incorporated.

The SNM-DAT model incorporates several unique and interesting features:

-SNM-DAT is designed around a preexisting object-oriented, agent-based framework.

-SNM-DAT is based on high fidelity, physics-based models of radiation sources combined with similarly accurate models of both radiological and non-radiological detectors that may help to “fill in” the picture of human traffic crossing our nation’s remote, unattended borders.

-SNM-DAT can exploit the knowledge of experts in various fields, including seismic, electromagnetic, and infrared sensors, advanced radiological detection technologies, network communication protocols and state-of-the-art signal analysis.

-SNM-DAT is platform and vendor independent. The agent based framework lends itself naturally to multi-processor use without requiring modifications of the underlying software.

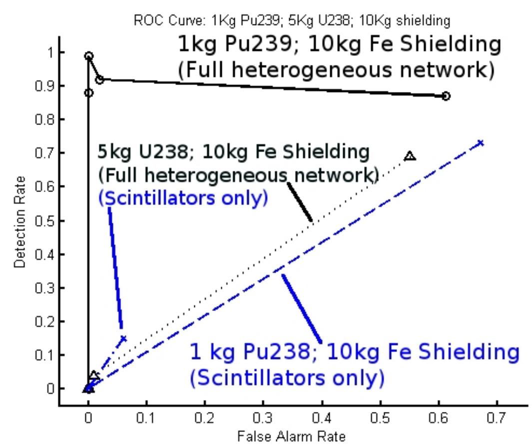

Fig. 1. Receiver Operation Characteristic Curves for various scenarios, demonstrating the benefits of the heterogeneous network.