1. ABSTRACT:
Physical Sciences Inc. (PSI), in collaboration with its partners, Raytheon Integrated Defense Systems (RTN-IDS) and Los Alamos National Laboratory (LANL) have developed a simulation environment which successfully demonstrates the effectiveness of a network of non-directed radiation sensors deployed for the detection and localization of radiological threats in urban environments. The simulation environment has been developed using Mak Technologies' VR-Forces tool kit, a well known software for simulating battlefield scenarios. At the core of the simulation are algorithms applicable to sensor networks that improve overall system performance through integration and analysis of all available sensor data and responses. The VR-Forces simulation environment has re-created Downtown Philadelphia as the test bed scenario and makes use of a network of radiological sensors (PVT, NaI) connected via wireless protocol to a C2 post. These sensors are deployed on fixed (e.g. buses) and random (e.g. taxis) route vehicles navigating in radiological backgrounds synthesized based on empirically collected urban data. We show that a network of 13 non-directed PVT sensors (8 buses, 5 taxis) achieves a $P_d \approx 91\%$ against a 1 mCi $^{137}$Cs source released to 1500 possible random locations within a $\sim 1.3 \text{ km} \times 1 \text{ km}$ area centered around Philadelphia City Hall. The sensor network is able to localize more than 80% of all possible source locations to within 15 m accuracy. 45% of all possible source locations are found to within 7 m and $\sim 70\%$ of threats are detected within 10 minutes of insertion in the environment.

2. INTRODUCTION:
An integrated and intelligent data fusion sensor network architecture allows cooperative sensor behavior and improves the probability of localization, detection and identification of threats (radiological, chemical, biological), while at the same time significantly reducing the false alarm rates, search time, and overall system cost. Such an open and modular architecture facilitates the use of any currently available sensor technology, as well as instrumentation under future development efforts. A comprehensive, real-time data fusion approach enhances confidence levels associated with lower cost, less sensitive detectors through determination of a fused network probability of detection resulting from an intelligent aggregation and usage of all sensor data. The technical objective behind this initial effort was to demonstrate the feasibility and quantitatively assess the performance of collaborative sensor networks (sensors mounted on vehicles) in detecting and localizing radiological dirty bombs in complex urban environments. Future efforts will focus on adding the capability for identification of threat isotopes with high probability of correct discrimination between NORM (Naturally Occurring Radioactive Materials) and non-NORM sources, as well as the propagation of higher level system noise (e.g. positioning errors, random shielding, etc). Figure 1 illustrates the concept of a sensor network deployed in an urban environment for the detection of radiological threats.
3. DESCRIPTION of TECHNOLOGY and DEMONSTRATED CAPABILITY:
The simulation environment developed under this effort enables high level feasibility assessment of sensor network performance under realistic urban conditions, as well as the testing and validation of data fusion algorithms for detection, localization and identification of radiological threats. The simulation platform has been developed using Mak Technologies’ VR-Forces tool kit, a well known software for simulating battlefield scenarios. The simulation environment consists of two primary modules: 1) The Virtual World (VW), and 2) The Analysis and Control (AC) module. The Virtual World unit incorporates the relevant aspects of the geographical and urban layout coupled to vehicle behavior and navigation, radiation propagation and sensor properties to create a realistic representation of the mission environment. The Analysis and Control unit consists of algorithms for processing the signals generated by the VW unit. The AC may also generate commands for controllable sensors (i.e. police units) depending on the mission objectives and response protocol. The simulation architecture is shown in Figure 2.

![Simulation Architecture Diagram](image)

**Figure 2.** The architecture of the simulation showing the relationship between vehicle dynamics, detector response and urban characteristics.

3.1 Virtual World
The simulation environment is set up as a 2-D grid and is a close representation of a 1.3 km x 0.9 km area of downtown Philadelphia (1 m spatial resolution). Grid elements may contain buildings, which can obscure line-of-sight from source to sensor, or may be open. Total radiation counts detected at the sensors are a contribution from both background and source radiation. The source radiation propagates through the environment and is detected via a high fidelity model that accounts for each detector characteristics. The background radiation is a spatially varying radiological map which was constructed as follows: 1) Made use of 16 field measurements and interpolated for points in between, 2) Re-scaled/compressed to fit within downtown Philadelphia region of interest (ROI), and 3) Added artificial variability on a finer spatial scale (1 m).

Currently, two types of detectors are modeled: NaI (medium energy resolution, medium cost) and PVT (low energy resolution, low cost). Each detector is mounted on a vehicle platform and its motion can be described by any of the following cases: 1) Fixed path (e.g. bus mounted), 2) Fully random (e.g. Taxi mounted), and 3) Initially random, but controllable (e.g. Police Car mounted, and primarily used for quickly converging on suspected source locations). The fixed paths (bus routes) were acquired by analysis of the Philadelphia Transit Schedule/Map and utilizing the data based on ~8:00 AM rush hour statistics. In the future, we will increase the fidelity of the bus navigation model by importing entire schedule columns to account for changing bus frequency as a function of time of day. The random motion vehicles (e.g. taxis) need to move to and from various points in the environment or be commanded to move to an identified high probability threat ROI. These random motion vehicles need to determine the shortest, most optimum travel distance from their current location to spatial points on the edge of the ROI or destination point. We utilize Dijkstra's shortest path algorithm for calculating the shortest distance of travel within the environment.
3.2. Analysis Module

The Analysis Module processes the information collected by the vehicles/detectors as they navigate through the environment (location – x,y; time; count measurement). The task of detection and localization of a radiological source is approached as a statistical inference problem. The threat is modeled as a point gamma source parameterized by location \( r = (x, y) \) and activity \( I \):

\[
\rho = (x, y, I) = (x, y, I)
\]  

(1)

Using a Bayesian framework, we estimate the distribution \( p(\rho | k') \) given the vector of count values, \( k' \), acquired by the detectors. Using Bayes’ formula we have:

\[
p(\rho | k') = \frac{p(k' | \rho) p(\rho)}{\sum_{\rho} p(k' | \rho) p(\rho)}
\]

(2)

The distribution \( p(k' | \rho) \) encompasses the stochastic nature of the radioactive decay, the physics-based model of gamma-particle propagation, and the response function of the detectors. The prior probability distribution, \( P(\rho) \) is assumed to be uniform over the range of mission-relevant activity values and locations (a non-trivial prior may be used to account for high-value target areas based on a priori intelligence information). Threat location and activity are estimated as the expectation value of source parameters,

\[
\tilde{\rho} = \langle \rho | k' \rangle = \sum_{\rho} \rho p(\rho | k')
\]

(3)

The global decision related to the threat presence (i.e. positive detection) is made by comparing the ratio of “threat present” \( (I > 0) \) probability and “threat absent” \( (I < 0) \) probability to a threshold \( T \), empirically selected based on the desired false alarm rate \( T \) is determined by observing the ratio of probabilities in a source-free environment).

\[
p(I > 0 | k') = \sum_{x,y,I>0} p(k' | x,y,I) P(x,y,I)
\]

\[
p(I = 0 | k') = \sum_{x,y,I=0} p(k' | x,y,I) P(x,y,I)
\]

\[
\begin{cases} \frac{p(I > 0 | k')}{p(I = 0 | k')} > T & \text{threat} \\ < T & \text{no threat} \end{cases}
\]

(4)

3.3. Quantitative Assessment of System performance

In order to assess the performance of a network of sensors deployed in downtown Philadelphia for the quick detection and accurate localization of radiological dirty bombs, we conducted a systematic analysis of key performance parameters (KPP). We define the primary KPPs as: 1) Probability of detection \( (P_d) \), 2) Probability of localization within an acceptable localization error \( (P_L) \), 3) TTD – time to detect, and 4) TTL – time to localize within an acceptable localization error. Several factors impact the system parameters. These factors can be deterministic (algorithms used, environment characteristics, resources – i.e. number and type of sensors, and source locations) or random (stochastic count values, initial sensor locations, randomness of the taxi motion, etc.). A full system analysis requires a complex multi-dimensional analysis approach. However, in this effort we focused on the evaluation of the KPPs as a function of possible source locations, with all other system parameters fixed. The source location represents a key aspect in an urban environment where a successful mission is defined by the ability of the sensor network to quickly detect and localize potential threats.

Below we present an example of a set of simulation runs that demonstrates the performance of the system. The KPPs were evaluated against a possible 1500 source locations (randomly selected within the environment and excluded from building locations). The fixed simulation parameters were: 1) 1364 x 951 m² area in Downtown Philadelphia, 2) Threat isotope: Cs137, 3) Threat activity: 1 mCi, 4) PVT
detectors at 1 second integration time, 5) 8 fixed-route vehicles (PVT detectors mounted on buses) and 6) 5 random vehicles (PVT detectors mounted on taxis). The vehicle motion was pre-recorded and used for each of the 1500 simulation runs (i.e. source locations) in order to evaluate the effectiveness of the system only with respect to source position. Figure 3 shows a 2-D representation of the environment illustrating positive source detections (green dots represent source locations detected in less than 91 seconds, and blue dots are source locations detected in longer than 91 seconds; the median TTD is 91 seconds). The system achieves a $P_d$ of 91.5% (1372 out 1500 sources are positively detected). The system achieves a $P_d$ of 72% within 10 min of source insertion in the environment, and reaches the $\sim$92% asymptote within 90 min. Figure 3 also illustrates that sources located near the city center are typically detected faster due to more frequent detector sampling as a result of key bus lines passing through the area. It is important to note that low activity sources located away from main vehicle routes (i.e. secondary streets and alley ways) are still detected as long as there is a direct line of sight to a detector which may be as far as 60 m away. At these ranges, the SNR is as low as $\sim$ 2, yet low activity sources are still detected as a result of the intelligent data fusion approach utilized for processing the signals from multiple detectors. Figure 4 shows the probability of localization (to within 7 m or 15 m error) as a function of time after source insertion. 42% of source positions are localized to within 7 m, while 80% of all sources are localized to better than 15 m in less than 10 min after source insertion in the environment. It is important to note that a network of higher resolution NaI detectors achieves even better performance with a $P_d$ of 99% ($P_d$ of 90% reached in under 30 min).

4. **CONCLUSIONS:**
The results presented in this paper demonstrate that intelligent data fusion algorithms can be effectively utilized in a network of radiological sensors tasked with detecting and localizing low activity threat sources in cluttered urban environments.

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![Figure 3. 2-D spatial distribution of positive source detections. Green = source locations detected in under 91s, Blue = source locations detected in longer than 91s, Red = locations not detected.](image)

![Figure 4. Probability of localization as a function of time after source insertion (blue – within 15 m error, green – within 7 m).](image)