Intelligent Sensor Management in Nuclear Searches and Radiological Surveys

A.V. Klimenko[1], W.C. Priedhorsky[1], H. Tanner[2], K.N. Borozdin[1], N. Hengartner[1]

[1] *Los Alamos National Laboratory, Los Alamos, NM 87545 klimenko@lanl.gov*
[2] *University of New Mexico, Albuquerque, NM 87103 tanner@unm.edu*

INTRODUCTION

Special nuclear materials (SNMs) are weak emitters of radiation and are difficult to detect, especially in the presence of natural backgrounds. Success in this difficult task of detection depends largely on the proximity of the sensor to the source of radiation and the time allowed for the measurement. We have developed intelligent sensor management strategies for nuclear search and radiological surveys and demonstrate these strategies in experiments and simulation. Our model-driven algorithms promise to reduce search times by order of magnitude, with increased reliability of detection and reduced number of false positives.

RADIATION FIELD MODEL

The present approach to the radiological survey and nuclear search is to expose the area uniformly and identify the strongest hot spots. The reliability and speed of the search can be improved by using an adaptive approach, where the data are assimilated into a global model of the radiation field that, in turn, controls the next measurement. Smart search algorithms that we have developed are based on the Classical Sequential Testing theory [1] and the Bayesian rule.

In [2] we have demonstrated the upper theoretical limit of nuclear search performance with smart algorithms. Infinitely fast sensor mobility was assumed. We looked for known source within fixed, known background. In [3] we have developed and simulated a control algorithm using our sequential search method. Here we present the formalism for sensor management in scenarios where backgrounds can vary and it takes time for sensor to get from point A to point B.

The natural gamma ray background in the environment is a function of various factors. Gamma ray background has a cosmic ray component and a component from naturally occurring radioactive isotopes. The count rate in a small detector (one cubic inch La_2Br scintillator) is low and the probability of observing k counts, given mean expected count rate is well described by the Poisson distribution:

$$P(X = k \mid \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Since natural gamma ray background varies from one location to the other, our model of radiation field has to account for that. Gamma distribution is a good choice for the initial guess of the expected mean count rate:

$$\pi(\lambda) = \beta^\gamma \lambda^{\gamma-1} e^{-\beta\lambda} \times \frac{1}{\Gamma(\gamma)}$$

where γ is the shape parameter, β is scale parameter and $\Gamma(\gamma)$ is the gamma function defined as:

$$\Gamma(\gamma) = \int_0^\infty t^{\gamma-1} e^{-t} dt$$

As the new measurements are collected, the probability distribution of λ is updated using the following recursive formula:

$$\pi(\lambda|X) = \frac{P(X = k|\lambda)\pi(\lambda)}{\int P(X = j|\lambda)\pi(\lambda) d\lambda}$$

Our model of the radiation field is discrete, with pixel size comparable to the size of the radiation sensor. Each pixel is characterized by a λ and β parameter.

MODEL-DRIVEN SENSOR MANAGEMENT

We plan and coordinate sensor management by developing new search and sensor deployment algorithms based on a formal method for robot motion planning. The method is used to steer a robot from any initial configuration to its goal by generating an artificial vector field over the area of interest and aligning the system's velocity with the vector field. If this vector field is produced as the gradient of an appropriately constructed scalar function (called a navigation function), then the field will not exhibit attractive singular points and the system is guaranteed to move from *any* point to its goal.

This method has been very successful for robot motion planning, but has never been used for search and mapping. Our main idea is that since the level sets of a navigation function provably contain the goal point, we can "slide" along their boundary and scan an area completely and efficiently, without passing over the same point twice. Our motion planning algorithm drives the sensor toward high navigation function values first, and updates dynamically the values at points already visited.

Using a navigation function-based sensor management we address a variety of problems, including:

- mapping of the area by achieving the minimum variance on the knowledge of the mean count rate in each location;

- localization and characterization of all the hot spots in the area

To achieve both of these goals we construct a navigation function, based on the probability of that the given location i has radiation level above the threshold L:

$$P_i(X > L) = \int_L^\infty \pi(\lambda|X)$$

and using the variance of the probability distribution:

$$V(\Gamma) = \frac{\gamma}{\beta^2}.$$

The resulting navigation function has a form:

$$U_i = P_i(X > L)^\alpha V(\Gamma)^\phi$$

, where α and ϕ are the optimization parameters. At the value of α=0, the algorithms is in the mapping mode, while when α>0 and ϕ>0, the sensor is biased towards locations that have higher probability to contain the source.

In a discretized area grid, the sensor moves to the neighboring cell with highest U_i, reduces the value of U at the cell it is currently located by a certain percentage, and regulates its speed so that it is inversely proportional to U_i. In this way, regions of high U_i values are given priority and longer detector exposure times. With time, the "landscape" changes as visited regions appear as valleys and points of interest show as hills to a sensor driven to higher elevation.

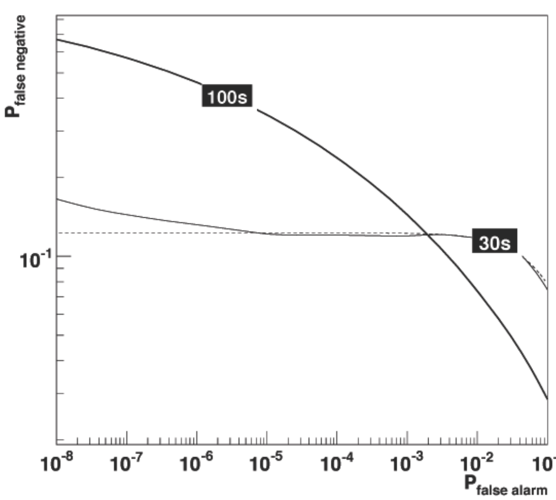

Fig. 1. Simulated model-driven nuclear search. 10 cts/s source was hidden within one of 100 locations with 1 cts/s background. Performance of uniform search (think solid line) is compared to the sequential (dashed line) and Bayesian nuclear search methods.

RESULTS AND CONCLUSION

We have developed intelligent sensor management algorithms that can be applied to either manually operated or automated radiation sensors. We have developed smart sensor management techniques for realistic nuclear searches. Our new simulations and experiments show significant improvement in the performance of the nuclear search and radiological survey (both in terms of speed and reliability) (see Fig. 1).

In our experiments the mobility is provided by miniature commercially available Khepera[4] robot while gamma-ray radiation is detected by small CsI(Tl) sensor installed on the robot (Fig.2). Both sensor and robot are powered from rechargeable batteries and can either work autonomously, or be controlled wirelessly from the laptop computer.

Our strategies can be applied to various nuclear search scenarios, for both mobile and stationary detectors, hand-held detectors and sensors on robotic platforms. Our methods can be used against nuclear smugglers and terrorists, for safeguards and non-proliferation treaty monitoring, as well as in other situations where radioactive sources need to be found.

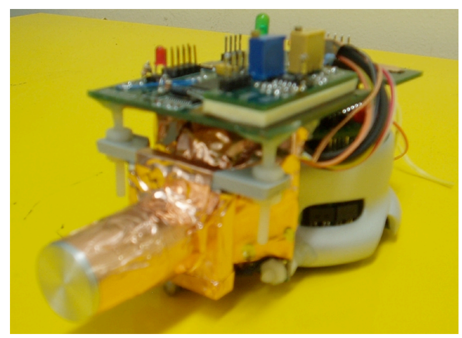

Figure 2: A miniature Khepera robot, equipped with our gamma-sensor and data acquisition electronics. We use this robot/sensor combination in our demonstration experiments

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4. The product of K-Team Inc.