Information Systems 57 (2016) 195–206

Contents lists available at ScienceDirect

Information Systems

journal homepage: www.elsevier.com/locate/infosys

Detection of radioactive sources in urban scenes using Bayesian Aggregation of data from mobile spectrometers

Prateek Tandon [a,*], Peter Huggins [a], Rob Maclachlan [a], Artur Dubrawski [a], Karl Nelson [b], Simon Labov [b]

[a] Carnegie Mellon University Pittsburgh, PA 15213, United States
[b] Lawrence Livermore National Lab Livermore, CA 94550, United States

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
7 October 2015
Accepted 16 October 2015
Available online 10 November 2015

Keywords:
Machine learning
Data fusion
Bayesian methods

ABSTRACT

Mobile radiation detector systems aim to help identify dangerous sources of radiation while minimizing frequency of false alarms caused by non-threatening nuisance sources prevalent in cluttered urban scenes. We develop methods for spatially aggregating evidence from multiple spectral observations to simultaneously detect and infer properties of threatening radiation sources.

Our Bayesian Aggregation (BA) framework allows sensor fusion across multiple measurements to boost detection capability of a radioactive point source, providing several key innovations previously unexplored in the literature. Our method learns the expected Signal-to-Noise Ratio (SNR) trend as a function of source exposure using Bayesian non-parametrics to enable robust detection. The method scales well in spatial search by leveraging conditional independence and locality in Bayesian updates. The framework also allows modeling of source parameters such as intensity or type to enable property characterization of detected sources. Approaches for incorporating modeling information into BA are compared and benchmarked with respect to other data fusion techniques.

1. Introduction

From preventing the proliferation of nuclear weapons to assessing radiation health risks from a collapsed power plant, a nation's capability to effectively monitor radiation sources in its cities is increasingly crucial to its safety. Dirty bombs built from radioactive material or radioactive emanation from stolen medical or industrial-use isotopes are frightening but very real threat scenarios. Mobile radiation detection systems provide promise for effective nuclear search and broad area monitoring for threats in urban scenes. They aim to help law enforcement officers detect and localize sources of radiation in complex urban environments that have frequently changing radiation landscapes.

Advances in hardware design have allowed for the ability to collect significant amounts of radiation spectrum data. One of the fundamental challenges is to automate the mining and analysis of the large amounts of sensor data that can be collected in real time to provide sensitive detection capabilities but maintain low false detection rates. Naturally occurring variability in the background radiation photon count rates as well as possible nuisance sources in an environment can cause false alarms for mobile radiation detector systems. The remedy is to account for the expectable variation in background and common potential nuisances via computational models, so a system can tell a truly threatening radioactive source of

---

[*] Corresponding author.
E-mail address: prateekt@andrew.cmu.edu (P. Tandon).

http://dx.doi.org/10.1016/j.is.2015.10.006
0306-4379/© 2015 Elsevier Ltd. All rights reserved.

interest from a benign one. For appropriate response by authorities, a significant useful capability of algorithms is to infer properties of a detected radiation source such as its intensity or isotope type.

1.1. Related work

The problem of detecting a radioactive point source from observations of radiation spectra has been previously studied by many efforts.

A well-known early study in radiation source detection looked at the case of detecting a fully isotropic source using a mobile spectrometer [1]. Since background photon count rates are typically unknown, the study identified that characterizing and suppressing the background is an important challenge in finding the source. Interestingly, the mathematical model they used found that background and source photon counts both scale proportionally with the surface area of the sensor, making it difficult to gain from a larger detector.

To improve robustness and performance on actual collected sensor data, algorithms in the literature leveraged statistical models that could capture variability and imperfections in data in an attempt to improve detection of radioactive sources in real world settings. These formulations were based both on frequentist and Bayesian approaches and resulted in better signal separation models for signal and noise components on actual collected sensor data.

One of the popular approaches is K-Sigma, which models collected photon counts under a Poisson likelihood model that takes into account the distribution of total gross photon counts in collected radiation spectra [2]. The K specifies a detection parameter such that a spectrum is flagged as containing a source if the total counts in the spectrum is larger than K standard deviations away from the total counts in a mean background spectrum.

Building upon the anomaly detection theme, the Spectral Anomaly Detector algorithm [3] employs Principal Component Analysis (PCA) to capture major directions of background fluctuation and variation. The Spectral Anomaly Detector algorithm can be used to capture the key principal linear directions of variance in background spectra containing multiple energy bins. Projecting a new radiation observation onto a learned basis for background (and subtracting out projections in these directions) results in a spectral anomaly score, which can be used to decide whether the observation exhibits source-like behavior or is more background-like.

Both vanilla K-Sigma and the Spectral Anomaly Detector score individual sensor spectrum observations. Using Bayesian techniques, algorithms could be extended to account for fluctuations in signal and noise across multiple correlated sensor observations via Bayesian data fusion [4–6]. For instance, particle filters [7–9] are a popular approach to aggregating multiple observations to detect a target in a Bayesian framework.

Aside from the Bayesian data fusion approach, the Weighted Combining (WC) method [10] has been popular for fusing evidence from multiple observations to detect sources. The WC method uses $1/r^2$ distance weighting on measurements to flag a source location. The method is presumed to be very powerful for flagging the locations in the environment that maximize the estimated SNR at the locations, given the source is isotropic. The algorithm maintains a geographic background "map" and a geographic source "map" which are iteratively updated. Given a new measurement, WC estimates the signal and noise components of the measurement and adds these estimates to its running estimates of signal and noise at geographic locations in its maps. The geographic location with the highest SNR score, after aggregation, is predicted to be the source location.

1.2. Innovations of Bayesian aggregation

Our Bayesian Aggregation (BA) approach builds upon many of the existing works but provides many improvements not previously explored in the literature.

First, BA provides key innovation on the radiation source/background signal separation problem. It is one of the premier Bayesian methods to fully utilize spectral information in empirical modeling of data likelihoods from real-world background data instead of just total photon counts in a spectrum. Using nonparametric density estimation techniques and appropriate measurement scoring schemes, BA can effectively suppress background radiation and non-threatening radiation emanated by nuisance sources without making *a priori* parametric assumptions about the distribution of local background and nuisances. These capabilities help provide robust signal separation when compared to other methods of aggregating evidence.

Second, our framework enables not only source localization from multiple spatially-correlated observations but inference of characteristics of the source such as the source intensity multiplier or source type. The inferential capabilities of BA allow simultaneous tracking of multiple, multi-modal hypotheses about the source parameters in a joint space while detecting the source. Modeling of source intensity and source type information in a Bayesian framework enables this previously unexplored capability.

BA resembles the framework underlying particle filtering [11,18] and sequential importance sampling [12] and, given sufficiently extensive posterior sampling, offers equivalent theoretical detection performance as particle filters [13]. However, BA is designed to be substantially more computationally scalable by using fast data structures and a manageably complex space of source parameter hypotheses. By using data structures such as kd-trees to speed up computation of hypotheses, BA can enable rapid evaluation of many real world scenarios.

2. Methods

2.1. Data

In this study, we focus on gamma-ray spectrometry measurements, where each measured photon has an associated scalar energy estimate. A single gamma-ray spectrometry measurement (after calibration) is a 128-dimensional numeric vector that histograms the energies