Localization of Radioactive Source Carriers in Person Streams

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Abstract: The localization and tracking of radioactive sources in public facilities like airports or stations is a problem of highest security relevance. The accumulation and the severity of terrorist attacks during the past decade give reason to the assumption that future attacks could also involve radioactive material packaged with conventional explosives. The only way to avoid such kind of attacks is to localize and arrest the person carrying the material to its destination. But since radiation is not perceivable by human beings, the security guards are largely dependent on technical decision support to perform this task. We consider a security assistance system comprising three gamma scintillation detectors that are distributed along a corridor wall to check passing people for radioactive material. Furthermore, the system consists of a set of tracking sensors simultaneously providing the positions of all persons during their walk through the corridor. In this paper we propose and evaluate techniques to estimate the assignment of radioactive detections to person tracks. These techniques provide a measure for each person reflecting the probability that the person is a radioactive source carrier.

1 Introduction

In the context of intelligent surveillance of public places, the observation and analysis of persons by distributed sensor systems increasingly gains in importance. The detection of hazardous material in busy areas as well as its assignment to a person is a challenging task that cannot be performed without technical decision support. However, the application of conventional technologies and the corresponding courses of action lead to long waiting times and pressure of work for the security personnel. This situation can be extremely relieved by security assistance systems that continuously observe an area by distributed sensor systems, that call the security guards only in case of a detection and that finally give a hint to those persons who can be assumed to carry the detected source.

In this work we concern ourselves with the localization of radioactive source carriers in person streams. The discussions about potential substances used for terrorist attacks are not only coined by the already applied improvised explosive devices (IED) but also by the fear of improvised nuclear devices, better known as dirty bomb or radioactive dispersion device (RDD). An RDD consists of a conventional explosive wrapped up with radioactive material. The conventional explosive conduces to disperse the radioactive material in the environment. Although this type of threat has not been put into practice so far, of growing concern are numerous accidents involving a loss or theft of radioactive sources that could possibly be used for a dirty bomb. Hence, there is an increasing need for security assistance systems that are able to localize such material either on the way to the creation place of the bomb or already packaged on the way to its detonation place.

In this work we consider the transportation of radioactive material by a person walking through a public facility. In such a scenario a security assistance system for source carrier localization is ideally equipped with multiple sensors of complementary type. We propose a combination of scintillation detectors for radiation detection with tracking sensors for determining the positions of the persons. While the strength of radiation detectors lies in their detection capability, their substantial weakness is given by a limited spatio-temporal resolution capability. Hence, a single detector is not able to reliably localize the source and to assign it to a person, whereas tracking sensors enable a precise localization of all persons and thus reduce the search space to a countable set of potential source positions. A security assistance system combining sensors for hazardous substances with tracking data has been first proposed by Wieneke and Koch [WK09]. Within such a kind of sensor system localization means the calculation of an assignment probability between a series of radiation detections and each person track. The decision whether a person is a source carrier or not can thus be interpreted as a classification task.

We will propose three techniques to estimate the assignment between a detection series and a person track and evaluate their capability of finding the source carrier. For this first analysis we completely exclude potential position uncertainties in the tracking data and assume the positions of the persons inside the surveillance area to be exactly known. Persons are considered as point objects.

2 Measurement Process and Sensor Model

The radiation strength of a radioactive source is called activity [VS07]. The activity α of a source is defined as the number of radioactive decays per time unit. The SI unit[1] of activity is Becquerel (Bq). One Bq corresponds to one decay per second. From a statistical point of view the activity is the expected value of the number of decays per time unit. The actual number of decays in a certain time interval randomly deviates from the expected value. The frequency of the numbers follows a Poisson distribution. Let a_k be the number of decays during the current time interval k. The Poisson distribution is a discrete probability distribution that assigns probabilities $\mathcal{P}_\alpha(X = a_k) = \exp(-\alpha)\alpha^{a_k}/a_k!$ to numbers $a_k \in \mathbb{N}_0$.

There are three main types of radiation: alpha, beta and gamma radiation, listed by their increasing capability of penetrating matter. Gamma rays can cause serious damage when absorbed by living tissue, and are thus a health hazard. A gamma scintillation detector counts the number of emitted gamma particles that hit the detector surface. The number of emitted gamma particles per decay is given by the decay scheme of the radiator. For the sake of simplicity, we assume a material with one gamma emission per decay.

[1] SI – International System of Units

The strength of radioactive radiation at a detector r is inversely proportional to the square of the distance d_r from the detector to the source (inverse square law). In other words, the emitted particles are equally distributed on the surface of a sphere with radius d_r and the area A_r of the absorbing part of the detector marks a section of this surface. Besides the source particles, the detector counts particles of the background radiation with rate α_B.

For a stationary source the relation between the measured counts c_r at detector r and the source activity is hence given by Eq. (1), where $\theta = [x, y, \alpha]^\mathsf{T}$ is the source parameter vector with position $[x, y]^\mathsf{T}$ and activity α.

$$\mathcal{P}_{\lambda(\theta)}(X = c^r) \qquad \text{with} \qquad \lambda(\theta) = \alpha_B + \alpha \cdot \frac{A_r}{4\pi d_r^2} \tag{1}$$

Recall that the actual particle emission a_k and the actual background radiation a_B are both random variables. The decision whether a measured countrate is greater than the background a_B, i.e. whether a real source is present, is a problem of statistical testing. A decision threshold with type I error 0.05 and type II error 0.05 is given by Eq. (2) [VS07]

$$\tau = 1.65\sqrt{a_B/\Delta}\,, \tag{2}$$

where Δ is the detector interval. The background rate a_B is determined in advance by a long-term measurement.

3 Accumulation of Counts

A first simple approach to the problem of source carrier localization is the accumulation of counts. Let C_r^m be the accumulation variable of person m with respect to detector r that is gradually increased as follows: 1.) $C_r^m := 0\ \forall r$. The procedure starts when person m enters the detection area of detector r. 2.) As long as the person is inside the detection area all measured counts c_k^r are compared with the decision threshold τ. If $c_k^r - a_B > \tau$ we accept the hypothesis that a source is present and add the measured counts to the accumulation variable: $C_r^m = C_r^m + (c_k^r - a_B)$. If $c_k^r - a_B \leq \tau$ we continue. 3.) When the person leaves the detection area the accumulated counts are divided by the retention time of the person: $C_r^m = C_r^m / T_r^m$. 4.) Steps 1.) up to 3.) are processed for all passed detectors. Hence, each person m collects a personal countrate C_r^m for each detector r. When person m leaves the surveillance area the variables $C_r^m, r = 1, \ldots, R$ of all R detectors are summed up to C^m. The greater C^m the more suspicious is the person. Thus, in this first approach the detector counts are either fully included into the accumulation process (if person is inside the detection area) or completely ignored (if person is outside).

A second approach for source carrier localization can be derived by introducing count weights. With these weights w_k^{rm} the counts during the detection phase of a person are no longer fully included but partially corresponding to the relation of the person's path segment to the detector position $\mathbf{p}^r$, as shown in Eq. (3), where $\mathcal{N}()$ denotes a gaussian.

$$w_k^{rm} = \frac{\int_{(k-1)\Delta}^{k\Delta} \mathcal{N}([x_t^m, y_t^m]^\mathsf{T}; \mathbf{p}^r, \mathbf{\Sigma}^2)\; dt}{\sum_{m=1}^{M} \int_{(k-1)\Delta}^{k\Delta} \mathcal{N}([x_t^m, y_t^m]^\mathsf{T}; \mathbf{p}^r, \mathbf{\Sigma}^2)\; dt} \tag{3}$$

4 Activity as Additional State Estimate

In this section we present a novel approach to source carrier localization based on the treatment of activity as an additional state estimate. Let $\mathcal{Z}^k$ the series of all measurements up to scan k including the position measurements of the tracking sensors. We want to calculate the joint density $p(\mathbf{x}_k^m, \alpha^m|\mathcal{Z}^k) = p(\alpha^m|\mathbf{x}_k^m, \mathcal{Z}^k)p(\mathbf{x}_k^m|\mathcal{Z}^k)$ for person m. The second factor is calculated by the tracker. We assume that person m is inside detection area r. Because the conjugate prior of the Poisson distribution is the Gamma distribution, the first factor can be transformed to Eq. (6) (m is omitted in the following)

$$p(\alpha|\mathbf{x}_k, \mathcal{Z}^k) = p(\alpha|\mathbf{x}_k, c_k^r, \mathcal{Z}^{k-1}) \propto \underbrace{\mathcal{P}(c_k^r|\mathbf{x}_k, \alpha)}_{\text{Poisson}} \times \underbrace{\mathcal{G}(\alpha; \mu_{k|k-1}, \nu_{k|k-1})}_{\text{Gamma}} \tag{4}$$

$$\propto \frac{\alpha^{a_k} \exp(-\alpha)}{a_k!} \times \frac{\nu_{k|k-1}^{\mu_{k|k-1}}}{\Gamma(\mu_{k|k-1})} \alpha^{\mu_{k|k-1}-1} \exp(-\nu_{k|k-1}\alpha) \tag{5}$$

$$\propto \alpha^{\mu_{k|k-1}-1+a_k} \exp(-(\nu_{k|k-1}+1)\alpha)\,, \tag{6}$$

where a_k is the measured count at the person's position calculated by solving Eq. (9) for $\alpha =: a_k$. For a source moving parallel to the x-axis, the relation between the measured count c_k^r and the activity α is given by Eq. (9) (applicable also for arbitrary path segments).

$$c_k^r = \alpha_B\Delta + \int_{(k-1)\Delta}^{k\Delta} \frac{\alpha A_r}{4\pi d_{rt}^2}\, dt = \alpha_B\Delta + \int_{(k-1)\Delta}^{k\Delta} \frac{\alpha A_r}{4\pi(h_r^2 + (x_t - p_\mathrm{x}^r)^2)}\, dt \tag{7}$$

$$= \alpha_B\Delta + \int_0^{\Delta} \frac{\alpha A_r}{4\pi(h_r^2 + (x_{(k-1)\Delta} + v_{(k-1)\Delta}t - p_\mathrm{x}^r)^2)} \tag{8}$$

$$= \alpha_B\Delta + \frac{\alpha A_r}{4\pi v_{k\Delta} h_r}\left[\tan^{-1}\frac{x_{k\Delta} - p_\mathrm{x}^r}{h_r}\right] - \frac{\alpha A_r}{4\pi v_{(k-1)\Delta} h_r}\left[\tan^{-1}\frac{x_{(k-1)\Delta} - p_\mathrm{x}^r}{h_r}\right], \tag{9}$$

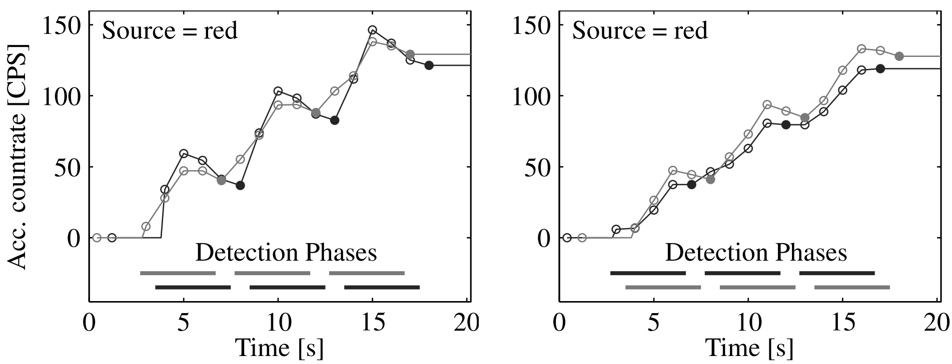
where p_x^r is the x-position of detector r, $v_{k\Delta}$ is the person's velocity at time $k\Delta$, h_r is the shortest distance between person and detector. Eq. (6) is a Gamma density with parameters $\mu_{k|k-1}+a_k$ and $\nu_{k|k-1}+1$. The expected value of α is $(\mu_{k|k-1}+a_k)/(\nu_{k|k-1}+1)$ leading to the update formulae $\mu_{k|k} = \mu_{k|k-1} + a_k$ and $\nu_{k|k} = \nu_{k|k-1} + 1$. The average deviation of the expected value is inversely proportional to the probability of being the source carrier. The greater the deviation the less suspicious is the person.

5 Experimental Results

The surveillance area consists of a corridor with three gamma scintillation detectors that are equally distributed at distances of 5 m along a single side of the corridor. Two persons traverse the corridor from the left to the right, walking on after the other at a constant distance. Their velocity is 1 m/s. The source activity is 250 kBq. Hence, from the decision threshold in Eq. (2) a detection radius of 2 m can be derived for the scintillation detectors

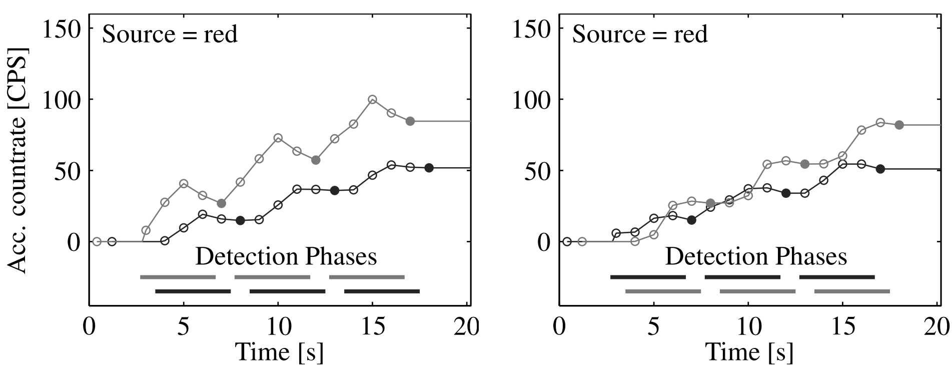
$r = 1, 2, 3$. The detectors synchronously work at a detection interval Δ of 1 s. The background radiation a_B under the photo peak is 10 counts per second [CPS].

In the following we will evaluate all three approaches for source carrier localization: the accumulation of countrates (ACR), of weighted countrates (AwCR) and the deviation of the estimated activity (αDev). Fig. 1 – Fig. 3 show the approaches for an exemplary data set. The distance between the persons is 0.8 m. $h_r = 0.8\,\text{m}\ \forall r$. The simple ACR approach in Fig. 1 obviously has the worst discrimination capability. The weights in AwCR lead to an improvement. The best approach is αDev. For ACR and AwCR the carrier probabilities



(a) Source carrier in the front (b) Source carrier in the back

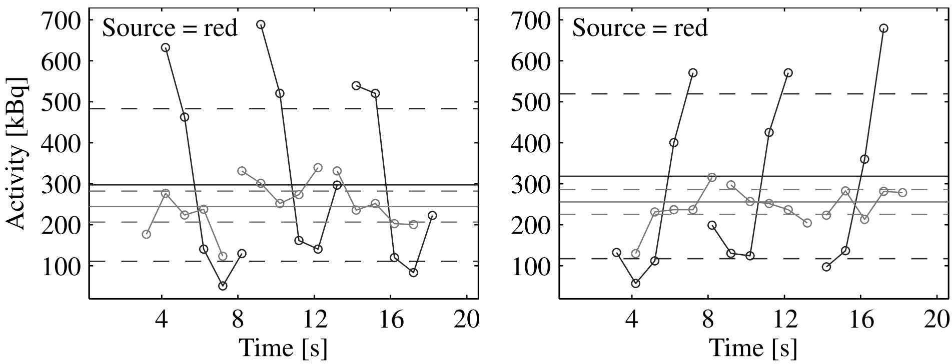
Figure 1: Accumulated counts as carrier criterion (example). Red lines correspond to the true carrier. The filled circles show the accumulated countrate after the person has left a detection area. Carrier probabilities: $P_C = 0.515$ in Fig. 1(a) and $P_C = 0.518$ in Fig. 1(b).



(a) Source carrier in the front (b) Source carrier in the back

Figure 2: Accumulated weighted counts as carrier criterion (example). For further description see Fig. 1. Carrier probabilities: $P_C = 0.620$ in Fig. 2(a) and $P_C = 0.616$ in Fig. 2(b).

are calculated as $P_C(m) = C^m/(C^1 + C^2)$. In the αDev approach the carrier probability is evaluated as $P_C(m) = 1 - \text{dev}(\alpha)^m/(\text{dev}(\alpha)^1 + \text{dev}(\alpha)^2)$. The results in Tab. 1 confirm the evaluation based on Fig. 1 – Fig. 3. Besides the worse discrimination capability, ACR also makes wrong decisions when the persons are close to each other.



(a) Source in the front (b) Source in the back

Figure 3: Deviations from estimated activity as carrier criterion (example). The red lines correspond to the source carrier. The solid lines show the estimated activity. The dashed lines represent the average deviation. Carrier probabilities: $P_C = 0.832$ in Fig. 3(a) and $P_C = 0.869$ in Fig. 3(b).

Distance Carrier	1.0 m front	0.8 m front	0.6 m front	0.4 m front	1.0 m back	0.8 m back	0.6 m back	0.4 m back
ACR	0.523 –	0.516 –	0.509 1% F	0.501 30% F	0.526 –	0.515 –	0.508 –	0.506 –
AwCR	0.655	0.617	0.574	0.536	0.654	0.613	0.573	0.540
αDev	0.864	0.827	0.760	0.683	0.845	0.810	0.764	0.712

Table 1: Average over the carrier probabilities P_C of the true carrier. 100 simulations per walking distance and carrier (front/back). ACR involves false decisions ($P_C < 0.5$).

6 Summary and Future Work

In this work we presented three approaches to the problem of source carrier localization in person streams. The novel αDev approach based on activity deviations could be proven to be the best in terms of discrimination. The activity estimation in αDev is realized by a recursive Bayesian filter using Gamma densities. Future evaluation will also include asynchronous detectors, position uncertainty, real data and various source strengths. The methodical future activities will consider persons as extended objects and shielding effects.

References

[VS07] Hans-Gerrit Vogt and Heinrich Schultz. *Grundzüge des Praktischen Strahlenschutzes (German).* Hanser Fachbuchverlag, 3 edition, 2007.

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