Localization and Tracking 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 techniques to estimate the assignment of radioactive detections to person tracks. These techniques provide a measure for each person that reflects the probability that the person is a radioactive source carrier. The problem of source localization is thus reduced to a matching problem between person tracks and sequences of count rates.

I. 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 with the ability to continuously observe an area by distributed sensor systems. Ideally, these systems call the security guards only in case of detection and finally give a hint to those persons who can be assumed to carry the detected source. These persons can then be separated for further investigation.

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, or radiological dispersion devices (RDD) like dirty bombs [3]. 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 incidents 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 counters 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. Tracking sensors in contrast enable a precise localization of all persons but have no detection abilities. A combination of these complementary types of sensors reduce the search space to a countable set of potential source positions. The problem of source localization thus becomes a matching problem between the person tracks and the sequences of count rates. A security assistance system combining sensors for chemical substances with tracking data has first been proposed by Wieneke and Koch [1]. Within this sensor system localization means the calculation of assignment probabilities between a series concentration measurements and each person track. The decision whether a person is a source carrier or not can thus be interpreted as a task of classifying the persons. This paper is dedicated to the localization of radioactive source carriers. We propose two techniques to estimate the assignment between a series of radiation counts and person tracks and evaluate their capability of finding the source carrier. The evaluation is carried out on the basis of real and experimental data.

II. MEASUREMENT PROCESS AND SENSOR MODEL

The radiation strength of a radioactive source is called the activity [2]. The activity $A$ of a source is defined as the
expected number of radioactive decays per second. 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 second. The actual number of decays 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

\[ P_A(X = a_k) = \frac{\exp(-A)A^{a_k}}{a_k!} \quad (1) \]

to numbers \(a_k \in \mathbb{N}_0\). Gamma radiation is electromagnetic radiation of high frequency. A gamma scintillation detector counts the number of emitted gamma rays that hit the detector surface. The expected number of gamma rays per decay, denoted \(G\), is given by the decay scheme of the radiator. For example, the decay of Co-60 causes two gamma rays with a probability of 99.88% and one gamma ray with probability 0.12%. In the following, the expected number of gamma rays per second is called the source intensity. It is designated by \(\alpha\), with \(\alpha = G \cdot A\). The unit of \(\alpha\) is counts per second (CPS). The number of gamma rays registered at 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 rays are equally distributed on the surface of a sphere with radius \(d_r\). The area \(D_r\) of the absorbing part of the detector marks a section of this surface. Further influences due to the intrinsic detector efficiency are comprised by factor \(E_r\). Besides the source rays, the detector registers gamma rays of the background radiation with count rate \(\beta^r\) in CPS.

For a stationary source the relation between the measured counts \(c^r\) at detector \(r\) and the source intensity is hence given by Eq. (2), where \(\theta = [x, y, \alpha]^T\) is the source parameter vector with position \([x, y]^T\) and source intensity \(\alpha\). Of course, in case of a moving source, the distance \(d_r\) and the count rate \(c_r\) are time dependent.

\[ P_{\lambda(\theta)}(X = c^r) \quad \text{with} \quad \lambda(\theta) = \beta^r + \alpha \cdot \frac{E_r D_r}{4\pi d_r^2} \quad (2) \]

Recall that both the actual gamma ray emission and the actual background radiation result from a Poisson distributed process. The decision whether a measured count rate is greater than the background \(\beta^r\), i.e. whether a real source is present or not, is a problem of statistical testing. A decision threshold with type I error 0.05 for a measuring time \(\tau_0\) is given by Eq. (3).

\[ q^r = \frac{1}{2\tau_0} \kappa^2 \left( 1 + \sqrt{1 + \frac{4\beta^r \tau_0}{\kappa^2}} \left( 1 + \frac{\tau_0}{\tau_{\beta^r}} \right) \right) \quad \text{with} \quad \kappa = 1.645 \quad (3) \]

where \(\kappa\) is the quantile of the normal distribution for type I error. The background rate \(\beta^r\) is determined in advance by a long-term measurement with measuring time \(\tau_{\beta^r}\).

\(^1\)SI – International System of Units
section is dedicated to the derivation of a Poisson filter for simultaneous tracking and intensity estimation of a moving radioactive source. This is a preparation of Section V, where the Poisson filter is exploited within the PMHT-C framework for classification of persons into carriers and non-carriers.

Let \( Z^k \) be the series of all measurements recorded up to scan \( k \), including the position measurements of the tracking sensors. We assume that person \( m \) is inside detection area \( r \) and want to calculate the joint density \( p(x_k^m, \alpha^m | Z^k) = p(\alpha^m | x_k^m, Z^k) p(x_k^m | Z^k) \) for person \( m \). The second factor is calculated by the tracker. Since the conjugate prior of the Poisson distribution is the Gamma distribution, the first factor can be transformed to Eq. (8) \((m \text{ is omitted in the following})\).

\[
p(\alpha | x_k, Z^k) = p(\alpha | x_k^m, c_k^r, Z^{k-1})
\]

\[
\propto \mathcal{P}(c_k^r | x_k, \alpha) \quad \mathcal{G}(\alpha; \mu_{k|k-1}, \nu_{k|k-1})
\]

\[
\propto \frac{\alpha^\nu \exp(-\alpha)}{n_k!} \times \frac{\nu_{k|k-1}^\mu}{\Gamma(\mu_{k|k-1})} \alpha^{\mu_{k|k-1}-1} \exp(-\nu_{k|k-1} \alpha) \tag{7}
\]

\[
\propto \alpha^{\mu_{k|k-1}-1+n_k} \exp(-(\nu_{k|k-1} + 1)\alpha) \tag{8}
\]

where \( n_k \) is the number of gamma emissions that is required at the person’s position to cause the count rate measurement \( c_k^r \) at the detector. Note that the source is moving and that a person may move a lot during the detector interval of 1 second. Gamma scintillation counters typically work at rate of 1 Hz. Therefore, an integration is required to get the number \( n_k \). For a source moving in parallel to the x-axis, this can be carried out analytically. The relation between the measured count \( c_k^r \) and the emitted number of gamma rays \( n_k \) is then given by Eq. (12), in which \( p_c^r \) is the x-position of detector \( r \), \( v_{k|}\Delta \) is the person’s velocity at time \( k\Delta \), and \( h_r \) designates the shortest distance between person and detector. \( \Delta = 1 \) s is the detector interval. \( b_k^r \) is the number of background counts during \( \Delta \).

\[
c_k^r = b_k^r + \int_{(k-1)\Delta}^{k\Delta} \frac{n_k E_r D_r}{4\pi a_r^2} \, dt
\]

\[
= b_k^r + \int_{(k-1)\Delta}^{k\Delta} \frac{n_k E_r D_r}{4\pi (h_r^2 + (x_t - p_c^r)^2)} \, dt
\]

\[
= b_k^r + \int_{0}^{\Delta} \frac{n_k E_r D_r}{4\pi h_r^2 + (x_{(k-1)\Delta} + v_{(k-1)\Delta} t - p_c^r)^2} \, dt
\]

\[
= b_k^r + \frac{n_k E_r D_r}{4\pi h_r^2} \left[ \tan^{-1} \frac{x_{(k\Delta)} - p_c^r}{h_r} \right]
\]

\[
- \frac{n_k E_r D_r}{4\pi v_{(k\Delta)} h_r} \left[ \tan^{-1} \frac{x_{(k\Delta)} - p_c^r}{h_r} \right] \tag{12}
\]

Clearly, the integration formula in Eq. (12) is applicable for arbitrary path segments as well, after the segment has been brought into the described parallel position via rotation. Solving Eq. (12) for \( n_k \) yields the required number of gamma emissions during a path segment. Note that tracking sensors typically work at much higher rates than gamma scintillation counters. For example, if the tracking sensor works at a rate of 5 Hz, then five path segments per detector interval are provided by the tracker. In this case, the \( n_k \)-values of the segments are simply added up. Since \( b_k^r \) is not known, it is replaced by \( b^r \), which is determined in advance by a long-term measurement.

Since we now have the formula to calculate \( n_k \), the focus is again on the filtering problem in Eq. (8). Obviously, Eq. (8) is a Gamma density with parameters \( \mu_{k|k-1} + n_k \) and \( \nu_{k|k-1} + 1 \). The expected value of this Gamma distribution is \((\mu_{k|k-1} + n_k) / (\nu_{k|k-1} + 1)\), which leads to the following update formulæ:

\[
\mu_{k|k} = \mu_{k|k-1} + n_k \tag{13}
\]

\[
\nu_{k|k} = \nu_{k|k-1} + 1 \tag{14}
\]

The estimated source intensity is thus the mean over all numbers of person-related gamma emissions \( n_k \). Note that only the true source carrier is able to produce a sequence of source intensity estimates that converges quickly to its expected value. Only the movement profile of the true source carrier “matches” the sequences of count rates measured at the detectors. Therefore, the average deviation of \( n_k \) from the expected value is inversely proportional to the probability of being the carrier. The greater the deviation the less suspicious is the person. This is shown in a simulated example.

In this example, a fictitious surveillance corridor of length 20 m was simulated with three gamma scintillation counters, equally distributed at distances of 5 m on one side of the corridor. Two persons traversed the corridor from the left to the right, walking one after the other at a constant distance of 0.8 m between the persons. The movement corresponded to a straight horizontal line. The distance from the movement line to the detector wall was 0.8 m as well. The persons walked at a velocity of 1 m/s. One of them carried a gamma source of intensity \( \alpha = 250 \) kilo-CPS. The detection radius of each scintillation counter was assumed 2 m. The detectors worked synchronously at a rate of 1 Hz. The background radiations \( \beta^r \) were set to 10 CPS. The count rate data of each detector was simulated according to the inverse-square law in combination with Eq. (12). Tracking data was not simulated. The true positions and velocities were used within the Poisson filter. Fig. 1 visualizes the output of the filter in case the source was carried by the leading person (upper plot) and by the following person (lower plot). The circles represent the current \( n_k \)-values. The solid line is the final estimated source intensity. The \( n_k \)-values of the non-carrier have a large deviation from the intensity estimate. This is because the movement of the non-carrier does not obey the radioactive dispersion model.

V. PMHT\(^2\) with Classification Measurements

The original motivation for the development of the PMHT with classification measurements (PMHT-C) [4] was to exploit available classification data for improved tracking and data association. Basically, the algorithm processes pairs of position measurements and classification data and derives estimates for both the kinematical state and the class of each target. This enables to exploit the “attached” classification data as an additional assignment measure, besides the usual position

\(^2\)Probabilistic Multi-Hypothesis Tracking
In the assignment phase, the standard processing of PMHT-C works as follows: In measurement (as mentioned above). With this interpretation, rate measurement as a pair of position and classification interpret each pair of detector location and quantized count interpreted to make the PMHT-C applicable in this way [1]. Koch showed how the source localization scenario has to be like a tracking-aided classification approach. Wieneke and this sense, the source localization problem requires something space to a countable number of possible source positions. In

With regard to radiation detection, the basic idea is to interpret each pair of detector location and quantized count rate measurement as a pair of position and classification measurement (as mentioned above). With this interpretation, the standard processing of PMHT-C works as follows: In the assignment phase the algorithm calculates assignment probabilities between each detector and each person at each scan. In the standard version, these probabilities are governed by the position likelihood evaluating the distance between detector and person. In the PMHT-C version proposed in this paper, the assignment probabilities are additionally controlled by a velocity likelihood and a source intensity likelihood. The velocity likelihood compares the slope of the count rate sequence (increasing or decreasing) with the detector-related velocity of the person (approaching or moving apart). The source intensity likelihood evaluates the deviations of the person-related counts from the current source intensity estimate as described in the previous section. In the optimization phase all estimates are refined. The confusion matrix estimates are refined by using the probabilities of the assignment phase. Note that each assignment probability reflects how relevant the corresponding class measurement (i.e. the quantized count rate) is for the classification of the person. Let $w_{t}^{m}$ be the assignment probability of detector $r$ and person $m$ at scan $t$. Then each entry in the confusion matrix $C$ is updated by

$$C(j, m) = \sum_{t=1}^{T} \sum_{r=1}^{R} \delta(z_{t}^{r} - j)w_{t}^{rm} \quad \text{with } z_{t}^{r} := \left\lfloor \frac{e_{t}^{r} - \beta^{r}}{\hbar} \right\rfloor,$$

where $\delta$ is the Kronecker delta and $z_{t}^{r}$ is the classification measurement, i.e. the background-reduced, quantized count rate output, which can also be interpreted as an alert level. Actually, PMHT-C works iteratively. However, in the following evaluation only a single iteration is carried out on a growing data window.

VI. EXPERIMENTAL RESULTS

The Accum-C approach and the PMHT-C approach are now compared on the basis of real and simulated data. The measure of performance is the ability of each approach to discriminate the carrier person from the non-carrier person. The greater the difference between the carrier probability of the true carrier and the carrier probabilities of the non-carriers, the better is the discrimination ability and thus the performance of the considered approach. The carrier probabilities are normalized with respect to the persons.

A. Experiments with Real Data

The experiments with real radioactive sources of Cobalt 60 (0.22 MBq) and Caesium 137 (0.25 MBq) were carried out in the experimental environment of the Fraunhofer INT institute. Fig. 2(d) shows a screen shot of the evaluation software. The environment consists of a corridor of length 18 m and width 1.5 m in the basement of the institute. The person tracking component was realized by a standard PMHT working on the basis of laser measurements. The laser measurements were produced by two SICK laser range scanners [5] at a rate of 5 Hz and with an angular resolution of 0.5°. One of the scanners is shown in Fig. 2(b). The positions of the scanners are marked by black crosses underlayed with a gray rectangle.
Three gamma scintillation counters were distributed along the right corridor wall. The distance between two neighboring detection systems is 5 m. An example of the used devices is shown in Fig. 2(c). The system is called Stride™ detection unit [6]. The positions of the scintillation counters are marked by black crosses underlayed with a yellow rectangle. The screen shows intermediate tracking and classification results of a scenario with three persons. The middle person is the source carrier, which is correctly determined by the PMHT-C already during the walk through the second detection area. The detection areas are rectangular and visualized by the light yellow areas in the screen shot. Systematic experiments were carried out with two persons. The source was carried in the right hand, except for the last experiment. The persons walked from the left to the right. The red rectangle on the left is the track extraction area. Fig. 2(a) shows the empty test corridor.

Tab. I comprises the final carrier probability of the true carrier calculated by each of the two approaches. The experiments can be divided into four groups. The first group consists of distance experiments with two persons walking in line, having a distance of 3.0 m, 2.0 m and 1.0 m between each other. The source was Cobalt 60 (Co-60). The second group consists of overtaking experiments, in which the carrier is overtaken

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Accum-C</th>
<th>PMHT-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 persons, distance 3.0 m, Co-60 in the front</td>
<td>0.995</td>
<td>0.985</td>
</tr>
<tr>
<td>2 persons, distance 3.0 m, Co-60 in the back</td>
<td>0.989</td>
<td>0.985</td>
</tr>
<tr>
<td>2 persons, distance 2.0 m, Co-60 in the front</td>
<td>0.770</td>
<td>0.978</td>
</tr>
<tr>
<td>2 persons, distance 2.0 m, Co-60 in the back</td>
<td>0.824</td>
<td>0.997</td>
</tr>
<tr>
<td>2 persons, distance 1.0 m, Co-60 in the front</td>
<td>0.526</td>
<td>0.937</td>
</tr>
<tr>
<td>2 persons, distance 1.0 m, Co-60 in the back</td>
<td>0.570</td>
<td>0.894</td>
</tr>
<tr>
<td>2 persons, Co-60 is overtaken on the left</td>
<td>0.618</td>
<td>0.989</td>
</tr>
<tr>
<td>2 persons, Co-60 is overtaking on the left</td>
<td>0.680</td>
<td>0.646</td>
</tr>
<tr>
<td>2 persons, Co-60 is overtaking on the right</td>
<td>0.668</td>
<td>0.767</td>
</tr>
<tr>
<td>2 persons, Co-60 is overtaken on the right</td>
<td>0.540</td>
<td>0.732</td>
</tr>
<tr>
<td>2 persons, distance 3.0 m, Cs-137 in the front</td>
<td>0.936</td>
<td>0.854</td>
</tr>
<tr>
<td>2 persons, distance 3.0 m, Cs-137 in the back</td>
<td>0.998</td>
<td>0.991</td>
</tr>
<tr>
<td>2 persons, distance 1.0 m, Cs-137 in the front</td>
<td>0.608</td>
<td>0.976</td>
</tr>
<tr>
<td>2 persons, distance 1.0 m, Cs-137 in the back</td>
<td>0.582</td>
<td>0.863</td>
</tr>
<tr>
<td>2 persons in parallel, Co-60 on the right</td>
<td>0.502</td>
<td>0.986</td>
</tr>
<tr>
<td>2 persons in parallel, Co-60 on the left</td>
<td>0.500</td>
<td>0.929</td>
</tr>
<tr>
<td>Average</td>
<td>0.707</td>
<td>0.907</td>
</tr>
</tbody>
</table>
by the non-carrier and vice-versa. The third group comprises distance experiments with Caesium 137 (Cs-137). Finally, in the fourth group of experiments two persons passed the detector array in parallel. In this case the second detector was placed on the left wall of the corridor at position \([9.0, 2.5]\) m. The photos in Fig. 3(a) and Fig. 3(b) show examples of a distance experiment and an experiment with overtaking source.

For each experiment, the better performance result is highlighted by a yellow cell color in the table. The results confirm, what was already expected in Section IV: The closer the persons walk, the worse is the discrimination ability of the Accum-C approach. For the 1.0 m distance experiments the carrier probability is rather close to 50%, which means almost no discrimination. The PMHT-C approach in contrast results in a source carrier probability of about 90% in these cases and has thus a much better performance than the Accum-C. Fig. 4(a) and 4(b) provide examples of the classification results of the PMHT-C. The red and blue bars mark the time range, during which a person was inside the respective detection area. Analogous plots are presented in Fig. 5(a) and 5(b) for the Accum-C. The performance difference is clearly visible.

Fig. 6(a) and 6(b) show the source intensities of the persons estimated by the Poisson filter of the PMHT-C approach. Here, the results are shown for the 1.0 m distance experiment with the Co-60 source in the front. The estimates of the source carrier form an almost horizontal line.

The estimates of the non-carrier person, in contrast, have small variabilities and usually converge later to the expected value. However, the essential feature for the discrimination is given by the deviations of the person-related numbers of Gamma counts (the \(n_k\)-values, as discussed in Section IV) from the estimated source intensity. The \(n_k\)-values are plotted as black circles connected by black lines. The values of the non-carrier show large deviations from the estimated source intensity, while the values of the source carrier are constantly close to the mean.

Fig. 7(a) and 7(b) refer to the same experiment and show
the distribution of the class probabilities in the confusion matrix, which is estimated by the PMHT-C. Considering the probability distribution of the true carrier, most of the count rate classes referring to the presence of a source have a peak in the plot. Computing the weighted sum of classes thus leads to the large values in Fig. 4(a). The non-carrier person, in contrast, has a high peak for the zero class indicating that there is no detection caused by this person.

Looking back at Tab. I, some more conclusions can be drawn. In the second group of experiments, a decreasing performance of the PMHT-C can be observed. These are the experiments with overtaking. Naturally, in such situations the detection results are influenced by shielding, because there may be another person between the source carrier and the detector. But also the other case, in which the source carrier shields the non-carrier, may cause falsifications in the estimates. In both cases, the person-related gamma count \( n_k \) will get to small, if shielding is not taken into account. However, shielding effects are out of the scope of this paper. The performance of the PMHT-C in the overtake scenarios is still better than that of the Accum-C, even without the modeling of shielding effects. Let us finally consider the group of parallel person movements (last group in the table). Here, the PMHT-C fully proves its superiority. The Accum-C is not able to distinguish between the persons anymore, since both persons enter and leave the detection areas at the same time. However, the detector placement has to be adjusted, so that during the walk the property of being closest to the detector changes from one person to the other. The table entries show the results after the persons have passed the first two detectors. An extension of this 2-detector array would require another two detectors, one on each side. Computing the average over all experiments, leads to the final conclusion that the PMHT-C is significantly better than the Accum-C approach.

**B. Simulation Study**

In addition to the real experiments, a simulation study for scenarios with two persons walking in line was carried out.
The assumed surveillance area and the detector placement was identical to Fig. 2(d). The background rate $\beta'$ was set to 230 CPS for each detector, which corresponds approximately to the values in the real experiments. The source intensity was set to $\alpha = 220$ kilo-CPS. In this analysis potential position uncertainties in the tracking data are completely excluded. We assume that the positions of the persons inside the surveillance area are known exactly. The persons are considered as point objects. 200 runs for each distance between the persons were simulated. Fig. 8 shows the average carrier probability of the true carrier for each distance. The two plots verify what could be expected by considering Tab. I. The performance of the Accum-C approach decreases significantly when the distance between the two persons gets smaller. The PMHT-C approach in contrast, is able to discriminate fairly well.

VII. CONCLUSION

In this work we presented two approaches to localize a radioactive source carrier in a person stream. The PMHT-C with additional source intensity estimates could be proven to be the best in terms of source carrier discrimination. The source intensity estimation is realized by a recursive Bayesian filter using Gamma densities. The methodical future activities will consider persons as extended objects and shielding effects.

REFERENCES