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Estimation of Radiation Distribution Using Shielding Attenuation by a Mobile Robot Equipped with Non-Directional Detectors and Lightweight Shielding

Eiji Morita
The University of Tokyo
Tokyo, Japan

Shinsuke Nakashima
The University of Tokyo
Tokyo, Japan

Ren Komatsu
The University of Tokyo
Tokyo, Japan

Qi An
The University of Tokyo
Tokyo, Japan

Atsushi Yamashita
The University of Tokyo
Tokyo, Japan

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ABSTRACT

This study proposes an estimation method of radiation source distribution in high-dose environments using a mobile robot equipped with a non-directional detector and lightweight shielding, exploiting shielding attenuation. One challenge with radiation source distribution estimation using non-directional detectors is the decreased accuracy when measurement points are unevenly distributed. By leveraging the rotational motion of lightweight shielding and capitalizing on shielding attenuation, we propose a method to enable the non-directional detector to acquire directional information. The obtained radiation measurement results were used to explore the most likely radiation source distribution through maximum likelihood estimation. Through simulation experiments, the effectiveness of the proposed method was confirmed, demonstrating an improvement in the accuracy of radiation source distribution estimation.

1. INTRODUCTION

The Fukushima Daiichi disaster was triggered by an earthquake and subsequent tsunami, leading to core meltdowns and the release of large amounts of radioactive materials into the environment.

To reduce the spatial radiation dose in such contaminated environments, it is necessary to shield or decontaminate the dispersed radiation sources using materials like lead that are less permeable to radiation. This requires estimating the distribution of radiation in the environment.

For radiation distribution estimation, two main types of radiation detectors are used: directional detectors and non-directional detectors. Directional detectors, such as Compton cameras and gamma cameras, provide information on both the direction and count of radiation. In contrast, non-directional detectors, like survey meters, only measure the count of incoming radiation, necessitating more observation time and locations.

Compton cameras, being lightweight, are primarily used in mobile robots but face issues in high-dose environments where they fail to detect direction. Gamma cameras can be used in high-dose environments but utilize heavy collimators, which can exceed the maximum load capacity of mobile robots. Additionally, prolonged use of cameras in high-dose environments may lead to malfunctions.

There exists a study that performed three-dimensional visualization of contamination distribution (JAEA 2021, Morelande et al. 2007). In this study, an integrated radiation imaging system combining a 3D laser scanner, Compton camera, and survey meter was constructed. A limitation of these studies is that the method cannot be used if there is no low-dose environment around the contaminated area to be measured.

A method for estimating radiation distribution using a non-directional detector is proposed (Minamoto et al. 2014). Under the assumptions that radiation attenuates according to the inverse square law and that the radiation count follows a Poisson distribution, they measured radiation levels three-dimensionally and estimated the position and intensity of the point sources using the Maximum Likelihood Estimation (MLE) method. The limitation of this study is that accurate estimation cannot be achieved if the measurement points are not evenly distributed on the grid.

Various methods and studies on radiation source estimation and radiation mapping exist, however they often face issues such as the potential for misestimation and the assumption of low-dose environments where humans can operate.

Therefore, this study aims to propose a method for estimating radiation distribution with high accuracy even at non-uniformly spaced measurement points in high-dose environments where directional detectors cannot be used. To eliminate the need for human intervention, this method utilizes a mobile robot equipped with non-directional detectors and lightweight shielding, leveraging shielding attenuation.

2. APPROACH

This chapter explains the proposed method, which aims to improve estimation accuracy by utilizing shielding attenuation. By comparing cases with and without a lightweight shield and shielding attenuation, the proposed method increases the amount of information obtained from the same measurement points.

2.1. Problem Setting

In this study, a ground-based mobile robot is utilized. As shown in Figure 1, a non-directional detector is mounted at the rotation center of the robot, and a lightweight shield is placed around it.

2.2. Mathematical Model of Radiation Measurement

The measured radiation dose follows the inverse square law with respect to the distance between the point source and the detector. The radiation dose measured at the 3D coordinate $\boldsymbol{m}^{pos} = [x_i, y_i, z_i]^T$ from a point source of intensity q_j located at $[x_j, y_j, z_j]^T$ is given by $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$ and

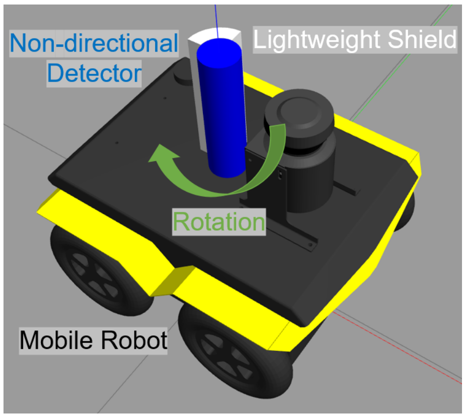


Fig. 1 The Configuration of the Robot

$$I(\boldsymbol{m}^{pos}) = \frac{Sq_j}{4\pi d_{ij}^2} e^{-\mu_{air} d_{ij}}. \tag{1}$$

In Equation (1), S represents the area of the detector, and μ_{air} is the linear attenuation coefficient of air. The linear attenuation coefficient of Cesium-137 in air, which is the radiation source considered in this study, is $9.700\,25 \times 10^{-3}$ at an ambient temperature of 20 degrees Celsius. In this study, measurements are taken at relatively close distances to the radiation source; thus, we assume $e^{-\mu d_{obs}} \approx 1$.

The radiation count b_{ij} obtained from a radiation source of intensity q_j at position $[x_i, y_i, z_i]^T$is given by Equation (1), where the constant part is denoted by Γ:

$$b_{ij} = \frac{Sq_j}{4\pi {d_{ij}}^2} = \frac{\Gamma q_j}{{d_{ij}}^2}. \tag{2}$$

At this point, the total count $b_i(\boldsymbol{q})$ obtained at position $[x_i, y_i, z_i]^T$ from M radiation sources is:

$$b_i(\boldsymbol{q}) = \sum_{j=1}^{M} \frac{\Gamma q_j}{{d_{ij}}^2}. \tag{3}$$

Here, by defining $A_{ij} = \frac{\Gamma}{d_{ij}^2}$, we set $\boldsymbol{A}$ as follows:

$$\boldsymbol{A} = [A_{ij}]. \tag{4}$$

The measurement $\boldsymbol{b}(\boldsymbol{q})$ obtained from a non-directional detector due to the radiation distribution $\boldsymbol{q}$ is:

$$\boldsymbol{b}(\boldsymbol{q}) = \boldsymbol{A}\boldsymbol{q}. \tag{5}$$

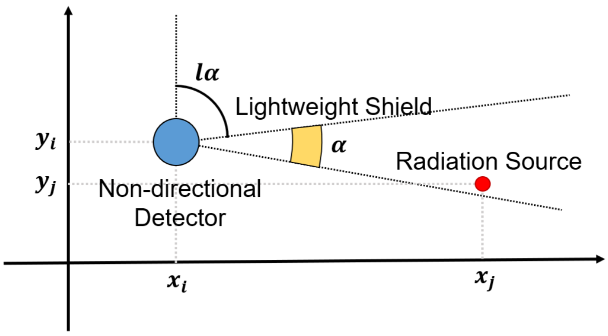


Fig. 2 State After the l-th Rotation

2.3. Utilization of Shielding Attenuation

The proposed method involves the utilization of shielding attenuation. When a non-directional detector is placed at the center of the robot, radiation counts remain unchanged when the robot rotates. The count decreases only if a lightweight shield, as shown in Figure 2, is positioned between the non-directional detector and the radiation source. This approach effectively imparts directionality to the non-directional detector, enabling the estimation of radiation distribution with fewer measurement points.

Let the number of rotations s at each measurement point be $s = \frac{2\pi}{\alpha}$. In Figure 2, at position $[x_i, y_i, z_i]^T$, during the l-th measurement (where $l = 1, \cdots, s$) after rotating the lightweight shield, if the shield is positioned between the non-directional detector and the radiation source located at $[x_j, y_j, z_j]$, then:

$$A_{((i-1)s+l)j} = \frac{\Gamma}{{d_{ij}}^2} \cdot e^{-\mu x}. \tag{6}$$

In Equation (6), μ represents the linear attenuation coefficient, and x denotes the thickness of the lightweight shield.

The count $b_{(i-1)s+l}(\boldsymbol{q})$ at the $(i-1)s+l$-th position is,

$$b_{(i-1)s+l}(\boldsymbol{q}) = \boldsymbol{A}_{((i-1)s+l)}\boldsymbol{q}. \tag{7}$$

In equation (7), $\boldsymbol{A}_{((i-1)s+l)}$ is the $(i-1)s+l$-th row of the $N' \times M$ matrix $\boldsymbol{A}$.

2.4. MLE and Optimization

Based on Equation(5), the problem of estimating the radiation distribution is formulated as an inverse problem, where the radiation distribution $\boldsymbol{q}$ is estimated from the measured count $\boldsymbol{b}(\boldsymbol{q})$. Let $\bar{\boldsymbol{q}}$ be the radiation distribution $\boldsymbol{q}$ that maximizes the posterior probability $p(\boldsymbol{q}|\tilde{\boldsymbol{b}})$. The estimation of the radiation distribution is performed by finding $\bar{\boldsymbol{q}}$ using the maximum likelihood estimation method.

$$g(\boldsymbol{q}) = \sum_{i=1}^{N} \tilde{b}_i \log b_i(\boldsymbol{q}) - \sum_{i=1}^{N} b_i(\boldsymbol{q}). \tag{8}$$

The radiation distribution can be estimated by finding $\bar{\boldsymbol{q}}$ that maximizes Equation (8). Adam optimization is used as the optimization method to search for $\bar{\boldsymbol{q}}$ (Kingma et al. 2015).

3. EXPERIMENTS

3.1. Simulation Setting

Since it is challenging to replicate high-dose environments in real-world settings, we constructed a simulation environment. Based on the EEE Manchester library, we built this simulation environment using ROS and Gazebo[1]. The simulated environment covers an area of 10 $\times$ 10 m, with source strengths ranging from 30 to 100 Sv/h. The grid is divided into 40 $\times$ 40 cells, and the non-directional detector is covered by a lightweight shield at an angle of $\alpha = \frac{\pi}{2}$ [rad]. Experiments were conducted using the source parameters listed in Table 1. The radiation source to be estimated is Cesium-137, which emits gamma rays. All sources are point-shaped gamma sources.

3.2. Evaluation Metrics

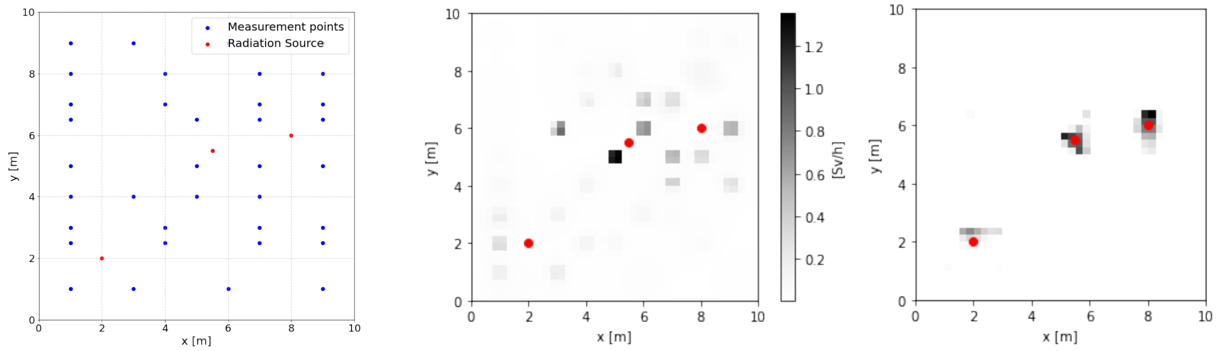
To verify the effectiveness of the proposed method, a comparison with previous method is conducted. As the previous method, we adopt the approach described in the previous research (Minamoto et al. 2014). For the evaluation of this experiment, the L1 norm is used as the metric to compare the previous method and the proposed method.

The L1 norm, given the ground truth of the radiation sources $\boldsymbol{t} = [t_1, t_2, \ldots, t_M]$ and the

[1] https://github.com/EEEManchester/gazebo_radiation_plugin

Table 1 Experiment Setting

Position(x, y, z)[m]	Intensity [Sv/h]
(2.0, 2.0, 0.1)	50
(5.5, 5.5, 0.1)	80
(8.0, 6.0, 0.1)	90



(a) Measurement Points **(b) Previous Method** **(c) Proposed Method**

Fig. 3 Experiment Setting and Results

estimated intensities of the radiation sources $\boldsymbol{q} = [q_1, q_2, \ldots, q_M]$, is defined as

$$\sum_{i=1}^{M} |t_i - q_i|. \qquad (9)$$

The smaller the value of equation (9), the more accurately the intensity of the radiation source is estimated.

3.3. Result

In Figure 3(a), the red points indicate the positions of the radiation sources, while the blue points represent the locations where radiation measurements were taken. The measurement points were randomly selected from the candidate points, totaling 36 points. Total intensity means the total intensity of estimated radiation distribution result.

The radiation distribution estimation results using the previous method are shown in Figure 3(b), and the results using the proposed method are shown in Figure 3(c). The radiation distribution estimation results are presented in grayscale, with red dots indicating the positions of the radiation sources.

In Table 2, total intensity means the total intensity of estimated radiation distribution result. Table 2 shows that the proposed method improves estimation accuracy, even in scenarios with multiple sources.

Table 2 Comparison of estimation accuracy

Methiod	L1 Norm [Sv/h]	Total Intensity [Sv/h]
Previous	271.2	55.4
Proposed	270.0	198.7

4. CONCLUSION

In this study, we propose a method for estimating radiation distribution in high-dose environments by using
a robot equipped with a non-directional detector and lightweight shielding, leveraging shielding attenuation. Through simulation experiments, we confirmed the effectiveness of the proposed method by estimating the radiation distribution of multiple sources in the environment. Future prospects include extending the method to three-dimensional estimation and further improving its accuracy and applicability.

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