Radiation Source Localization via a Mobile Robot by Integration of Filtered Back-projection

Yutaro Fujino[1], Shinsuke Nakashima[1], Ren Komatsu[1], Hanwool Woo[2], Hajime Asama[1], and Atsushi Yamashita[3]

***Abstract*—Localization of radiation sources via a mobile robot is a necessary technique. Direct inverse methods are often used to estimate the directions of radiation sources due to their time efficiency. However, there has been no method to estimate source locations using filtered back-projections, one of the direct inverse methods. This work proposes a new method to estimate source locations by integrating the filtered back-projection results.**

***Index Terms*—Compton camera, mobile robot, SLAM, filtered back-projection**

I. Introduction

Radiation is indispensable to the modern world and applied in various fields, while it is harmful to the human body. When radioactive substances are scattered, they must be shielded with lead for safety. In order to estimate the location of the radiation sources, mobile robots play important roles because they can enter such a dangerous environment.

Techniques for radiation source localization using mobile robots and radiation sensors have been studied. Radiation source localization generally consists of two steps: observation of radiation at several points and integration of the observation results. Kim et al. proposed the scheme for the 3D reconstruction of radiation source locations using Simultaneous Localization and Mapping (SLAM) [1].

Two main methods are commonly used for radiation source localization: direct inverse methods and iterative methods. Direct inverse methods are based on back-projection and time-efficient. On the other hand, iterative methods provide higher accuracy but are time-consuming because of their optimization for many iterations.

Robots can be broken if they are put in a high-dose environment for a long time. Therefore, we adopt direct inverse methods to quickly search for radiation sources. However, there has been no method to estimate 3D source locations using the filtered back-projection, which is one of the direct inverse methods. In this work, we propose a novel method of estimating the 3D location of radiation sources using the filtered back-projection.

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[1]Department of Precision Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan. {fujino, nakashima, komatsu, asama} @robot.t.u-tokyo.ac.jp

[2]Department of Mechanical Systems Engineering, Kogakuin University, 2665-1 Nakanomachi, Hachioji 192-0015, Japan. woo@cc.kogakuin.ac.jp

[3]Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan. yamashita@robot.t.u-tokyo.ac.jp

II. Methodology

A robot equipped with a radiation sensor moves around and stops at some points to observe radiation. The method to estimate radiation source locations using the observation results is proposed here.

A. Gamma Ray Measurement

Gamma rays are emitted from radiation sources. Compton cameras were developed in order to detect gamma rays.

Gamma rays are detected at a scatterer and an absorber of a Compton camera. For each set of these two events, the scattering angle β can be calculated as follows,

$$\cos\beta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right), \tag{1}$$

where $m_e c^2$ is the rest mass energy of an electron. E_1 and E_2 are the energies detected in the scatterer and the absorber. The source location from which a gamma ray is emitted can be restricted on a cone surface with the half-angle β, which is called a Compton cone.

B. Back-projections of Compton Cones

After many Compton cones are collected, we can detect the direction of radiation sources by using direct inverse methods.

Simple back-projection (SBP) is a method to project all the Compton cones to image space. In this work, the image space

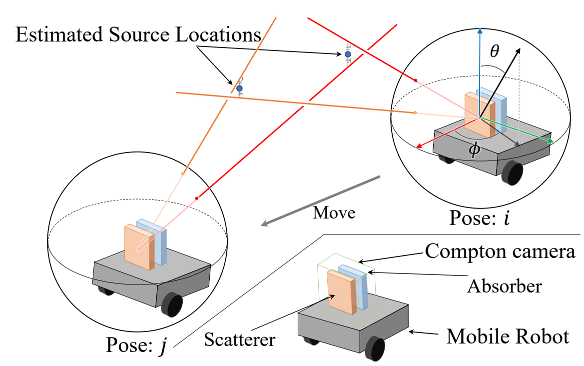
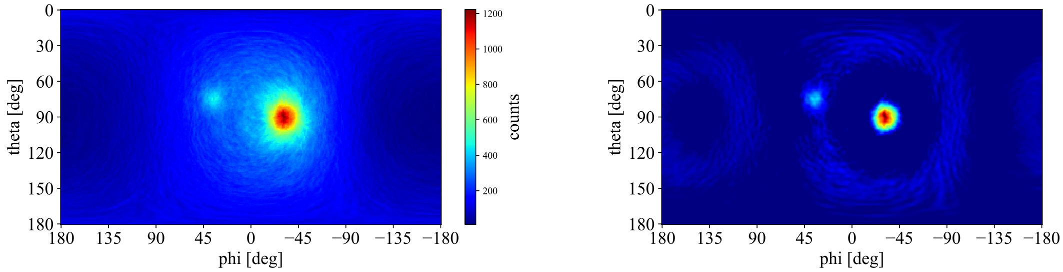


Fig. 1: Concept of the proposed method. The mobile robot stops at poses i and j. Radiation source locations are estimated as the closest points from both red and orange lines.



(a) simple back-projection (SBP)

(b) filtered back-projection (FBP)

Fig. 2: The equirectangular images obtained in simple back-projection (a) and filtered back-projection (b). Points with more counts are more likely to be the source directions.

is set to a sphere whose center is the scatterer of the Compton camera (Fig. 1). SBP image $g_{\mathrm{sbp}}(\vec{\Omega})$ for N Compton cones can be obtained as follows,

$$g_{\mathrm{sbp}}(\vec{\Omega}) = \sum_{i=1}^{N} \delta \left(\cos^{-1} \left(\frac{\vec{m} \cdot \vec{v}}{|\vec{m}||\vec{v}|} \right) - \theta_i \right), \tag{2}$$

where $\vec{\Omega} = (\theta, \phi)$, $\vec{m}$ is the direction$(\vec{\Omega})$ and $\vec{v}$ is the vector through scattered and absorbed points.

Generally, an SBP image is blurred due to the summation of Compton cones in Eq. (2). The filtered back-projection (FBP) method was proposed to obtain the image with higher resolution [2]. Here, SBP is considered to be the convolution of the ground truth $g(\vec{\Omega})$ and the point spread function $h(\cos\omega)$.

We can get FBP image $g_{\mathrm{fbp}}(\vec{\Omega})$ by using the spherical convolution theorem,

$$G_{\mathrm{fbp}}{}_l^m = \frac{(2l+1)\ G_{\mathrm{sbp}}{}_l^m}{4\pi H_l}, \tag{3}$$

where $G_{\mathrm{fbp}}{}_l^m, G_{\mathrm{sbp}}{}'^m_l$ and H_l are the spherical harmonics transformations of $g_{\mathrm{fbp}}(\vec{\Omega})$, $g_{\mathrm{sbp}}(\vec{\Omega})$ and $h(\cos\omega)$.

C. *Integration of Back-projection Results*

With the FBP image from a robot pose, one can detect the directions of radiation sources. Now, integration of results from several robot poses is necessary.

We assumed that there are only point-like sources in the environment and each location can be expressed as (x, y, z).

The concept of the proposed method was shown in Fig. 1. As shown in Fig. 2, an FBP image becomes a distribution that has some peak points. Firstly, the peak points are detected by finding local maximums. Here, in this work, we assumed that the number of sources is known. Then, the lines through the Compton camera center and each peak point are obtained.

Each source location can be estimated as the closest point from the corresponding two lines (Fig. 1). We assumed that the translation and rotation vectors between two robot poses are not large, therefore corresponding two lines can be decided as closer ones in both FBP images.

III. Simulation Experiment

This work conducted a simulation experiment to validate that the radiation source locations can be estimated with the proposed method.

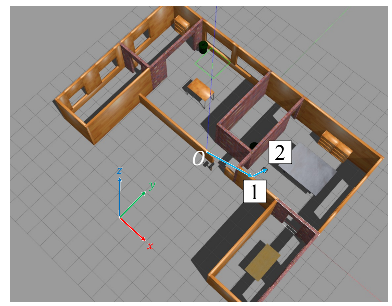


Fig. 3: House used in the simulation. 1 and 2 are key points.

A. *Experimental Settings*

A house was created in a simulated environment, Gazebo [3], shown in Fig. 3. A mobile robot with a LiDAR moved in xy space and HDL graph SLAM [4] was performed to create the environment map and localize the robot poses at key points. Simulation of radiations was conducted with Geant4 [5] and attenuation of radiation was neglected for simplicity.

Two radiation sources (Cs137) were put in the house and the robot stopped at two key points.

B. *Result*

Two key points where the robot stopped are shown in Table I and the result of radiation sources localization is shown in Table II. The ground truth and the estimated location of two radiation sources and the robot path are visualized in Fig. 4.

The locations of two radiation sources were estimated with 456.9 mm and 34.0 mm errors, respectively. The error of the source colored red in Fig. 4 was larger. Therefore, the error can be larger when the radiation source is put farther from the key points where the robot stops.

TABLE I: Robot poses: $[x, y]$

key points	ground truth [m]	estimated poses [m]	error [m]
1	[2.648, 0.603]	[2.641, 0.586]	0.0184
2	[3.565, 1.739]	[3.566, 1.709]	0.0300

TABLE II: Radiation localization result

source	ground truth [m]	prposed method [m]	error [m]
1 (Green)	[4.000, 0.000, 0.000]	[4.015, 0.028, 0.012]	0.0340
2 (Red)	[5.000, 3.000, 1.000]	[4.832, 2.619, 0.812]	0.4569

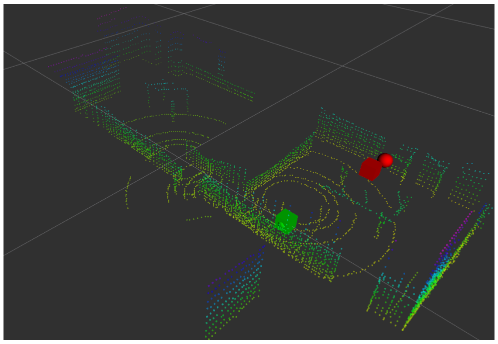


Fig. 4: SLAM and visualization of source locations. Spheres and cubes are ground truths and estimated locations by the proposed method, respectively.

IV. CONCLUSION

In this work, the method of radiation source localization by integrating FBP results was proposed. The source locations were estimated with less than 500 mm errors. This method can be applied to online searches for radiation sources because it does not use conventional iterative methods.

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