Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Analysis of the impact of positioning uncertainty on dose estimation

Janghee Lee[a], Minjae Lee[b], Woosung Cho[a], Song Hyun Kim[b,*]
[a]*Division of Advanced Nuclear Engineering, Pohang University of Science and Technology, 77, Cheongam-ro, Nam-Gu, Pohang-si, Gyeoungsangbukdo 37673, Republic of Korea*
[b]*SierraBASE Co. Ltd., 77 Cheongam-Ro, Nam-Gu, Pohang, 37673, Republic of Korea*
[*]*Corresponding Author: shkim@sierrabase.co.kr*

****Keywords:*** Dose Monitoring, Radiation Worker, Positioning Technology, Positional Uncertainty, Computational Dosimetry

1. Introduction

In radiation-related facilities, the radiation exposure of the workers has been frequently reported. The use of personal dosimeters is widely recommended for preventing over-exposure. However, in situations where dosimeters are lost or damaged, there currently exists no alternative method to monitor personal radiation dose. Consequently, it is essential for developing an independent dose monitoring method.

Recently, several research has been proposed for a dose monitoring method that automatically calculates radiation distribution and locations of workers by using positioning sensors [1, 2]. However, given the limited performance of current positioning technologies, estimating position of the workers within radiation distribution remains challenging, which makes it difficult to estimate the exposure dose of workers. In this study, we provide an overview of recent positioning systems, discussion of their representative error types, and analysis of their uncertainties of dose estimation for worker monitoring.

2. Overview of Positioning Technology

This section describes representative positioning technologies, such as signal-based and vision-based positioning system, and their associated limitations.

2.1 Signal-based

Each signal-based technology, such as Wireless Local Area Network (WLAN), Radio-Frequency IDentification (RFID), and Ultra-WideBand (UWB), estimates the location by using own method; Time of Arrival (TOA) and Received Signal Strength (RSS) between tag devices and anchors. Several weaknesses such as signal propagation, diffraction, and signal interference among tag devices are remained as challenges. The positioning accuracy depends on the type of signal-based technologies, which varies from a few tens of centimeters to a few meters [3].

2.2 Vision-based

Vision-based systems provides the most precise spatial information without carrying tag devices. However, a lack of direct depth information makes it difficult to estimate accurate position. The accuracy of vision-based positioning system depends on a region of interests for workers with differences ranging from a few centimeters to a few tens of centimeters [4].

3. Errors on Dose Estimation

3.1 Measurement Error

All sensors used in positioning technology are subject to noise factors such as time latency and interruption by occlusions. These factors are the main causes to increase positioning errors when optimally estimating distance between the sensor and the target. Therefore, a true position X_{true}^{i} can be estimated by combining a measured position $X_{measure}^{i}$ from the sensor and its noise δ_{noise}^{i} at a given time i as depicted in Eq (1).

(1) $X_{true}^{i} = X_{measure}^{i} + \delta_{noise}^{i}$

3.2 Inconsistency Error

The accurate dose estimation could not be performed without simultaneously combination of radiation distribution and positioning system. This error for dose monitoring results from an inconsistency in the coordinate system between radiation distribution $[X]_{rad}^{i}$ and the worker positioning system $[X]_{pos}^{i}$. The types of inconsistency are typically denoted by translation vector, t, and rotation matrix, R. The coordinates of two systems are matched by rigid body transformation as illustrated in Eq (2).

(2) $[X]_{rad}^{i} = R[X]_{pos}^{i} + t$

4. Experiment and Result Analysis

4.1 Experiment Methods

An experiment environment with reference to the Sellafield Ltd nuclear facility was modeled by using GAZEBO simulator [5]. In the simulation, the exposure dose was estimated by an ionizing radiation detector and 4 radio-active sources which have relative activity values (intensity) of 5000, 900, 500, and 200, respectively. The dose rates were measured by radiation detector carried by a walking worker in the nuclear facility.

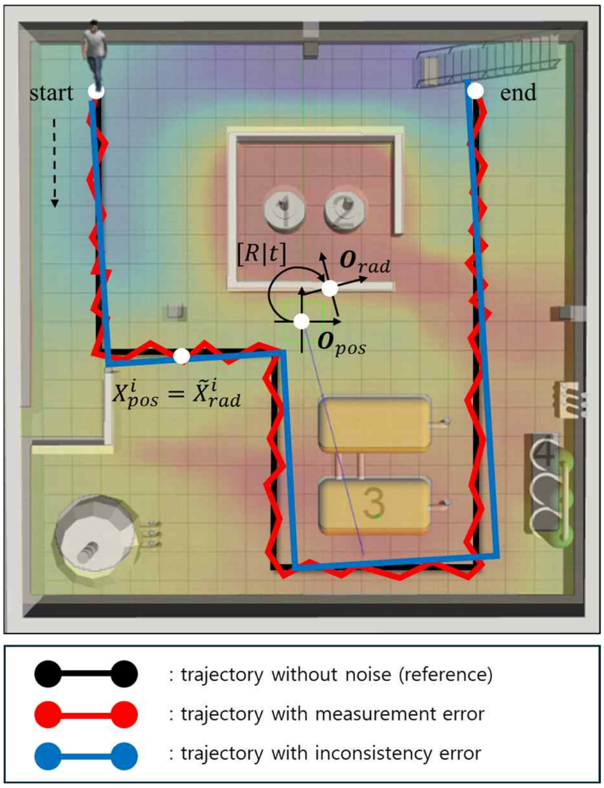

Fig. 1. Overview of the simulation of radiation workers' walking paths, reconstructed by radiation field and positioning system in the GAZEBO simulator.

To estimate uncertainty of dose monitoring system, 360 trajectory samples of radiation worker in a two-dimensional reactor room were tested, including 300 scenarios with measurement error or inconsistency error as shown in Fig. 1. The sensor measurement error was assumed to have a gaussian noise with a mean and standard deviation 10 cm in distance. The inconsistency error, with gaussian noise for translation and orientation errors, is summarized as shown table 2.

Table I: Summary of the Experimental Parameters Used in the GAZEBO Simulation

Experimental Parameters	Specification
The Number of Scenario	300 (#)
The Number of Trajectory Sample	360 (#)
Walking Range	44 (m)
Dose Sampling Rate	10 (Hz)
Average Velocity	1.25 (m/s)
Measurement Error	E_m~N(0.1,0.1^2) (m)
Inconsistency Error (translation)	E_t~N(0.05,0.05^2) (m)
Inconsistency Error (rotation)	E_R ~N(0, 2^2) (deg)

4.2 Results and Discussion

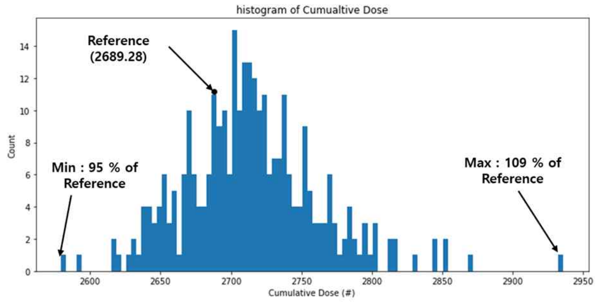

Fig. 2. Histogram of cumulative dose based on monitoring result of radiation worker's trajectory.

From the monitoring observations, the histogram of the cumulative exposure dose for 300 scenarios was as described in Fig. 2. This result shows the error from 95% to 109% when compared to the reference model. Especially, the higher error was observed in occluded regions near the source as depicted in Fig. 3. The main cause of the error stem from the sensitivity to positional estimation errors. Surprisingly, even an error as small as a positional discrepancy of 10cm could lead to a dose evaluation error up to 101.6 times. On the other hand, inconsistency errors within 2 degrees led to an additional average positional estimation error of 20 cm. Consequently, the uncertainty of dose monitoring system is proportional to radiation dose, which implying the necessity for a new method that can minimize the noise from measurement and inconsistency.

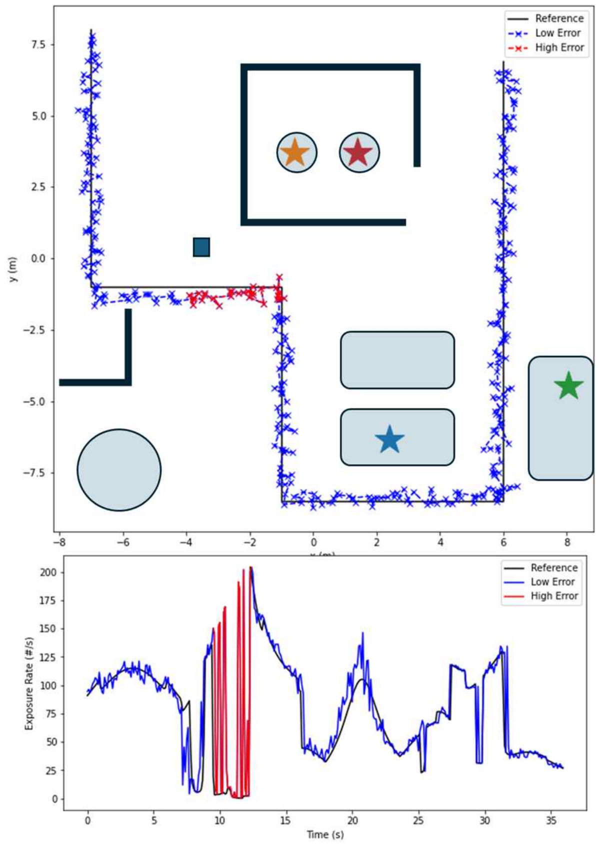

Fig. 3. Time-dependent trajectories and exposure dose rates during the highest error scenario compared to reference model

5. Conclusion

In this study, the influence of measurement and inconsistency error on dose estimation was analyzed by comparing the exposure doses for 360 trajectories. This result shows a positional error as small as 10 cm can lead to a dose error of 100 times, emphasizing the importance of reducing positional uncertainty through the minimization of inconsistency and measurement noise. Therefore, the development of position estimation system will be performed in the future by using vision-based approach, which has an advantage of a high precision. Also, the proposed dose monitoring algorithm will be verified by comparing results of test-bed and simulation. Through precise positional estimation system, it is anticipated in an enhancement in the accuracy and precision of dose estimation. Furthermore, we expect this method to apply in a variety of fields such as interventional radiology, serving as a viable alternative of standard dosimeters to face challenges in taking measurements.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) with the funding of the government (Ministry of Science and ICT) (No. 2021M2D2A20184452161082139290201); by the funding of Ministry of Trade, Industry and Energy [Development of Automatic Safety Inspection and Management System Based on Autonomous Driving Drone / Project Number: P0025720]; by the Institute of Civil Military Technology Cooperation funded by the Defense Acquisition Program Administration and the Ministry of Trade, Industry and Energy (Grant No. UD10044TU); and financially supported by the Robot Industry Technology Development Project, funded by the Korea Evaluation Institute of Industrial Technology under the Ministry of Trade, Industry and Energy (Grant Nos. RS-2024-00423589, RS-2024-00422721).

REFERENCES

[1] A. Badal, F. Zafar, H. Dong, and A. Badano, A real-time radiation dose monitoring system for patients and staff during interventional fluoroscopy using a GPU-accelerated Monte Carlo simulator and an automatic 3D localization system based on a depth camera, In *Medical Imaging 2013: Physics of Medical Imaging,* Vol. 8668, pp. 600-610, 2013.

[2] M. Abdelrahman, P. Lombardo, F. Vanhavere, A. Seret, C. Phillips, and P. Covens, First steps towards online personal dosimetry using computational methods in interventional radiology: Operator's position tracking and simulation input generation. *Radiation Physics and Chemistry*, Vol. 171, 108702, 2020.

[3] B. Silva, Z. Pang, J. Åkerberg, J. Neander, and G. Hancke, Experimental study of UWB-based high precision localization for industrial applications, IEEE International Conference on Ultra-WideBand (ICUWB), pp. 280-285, 2014.

[4] M. Tölgyessy, M. Dekan, and Ľ. Chovanec, Skeleton tracking accuracy and precision evaluation of Kinect V1, Kinect V2, and the azure kinect. *Applied Sciences*, Vol. 11, No. 12, 5756. 2021.

[5] T. Wright, A. West, M. Licata, N. Hawes, and B. Lennox, Simulating ionising radiation in gazebo for robotic nuclear inspection challenges, Robotics, Vol. 10, No. 3, 86, 2021.