CURRENT STATUS OF A JAEA DEVELOPMENT PROGRAM ON NUCLEAR AND RADIOACTIVE MATERIALS DETECTION TECHNIQUES IN MAJOR PUBLIC EVENTS

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ABSTRACT

To prevent nuclear terrorism in major public events, the JAEA is developing radiation detector systems, which survey nuclear and radioactive materials left in a public space. The system is various combinations of a radiation detector, a camera, localization devices for in-and-outdoor survey, and an unmanned vehicle. A network device, Wi-SUN FAN, is being tested to perform efficient survey with several devices. In addition, an artificial intelligent program is being developed to diagnose an observed gamma-ray spectrum to identify U-235 and to eliminate false alert. A fast neutron detection system with a PSD plastic scintillator is also being developed for neutron emitter survey. Although the detector is sensitive to both fast neutrons and gamma rays, fast neutron events can be chosen by using a pulse shape evaluation technique. Taking the advantage of angular dependence of a detector, a detector system consisting of two rod-shaped detectors was numerically studied. The system can find the direction of a radioactive source. This report overviews the development project.

INTRODUCTION

Nuclear security is a matter of international concern. Prevention of theft and pilfer of nuclear and radioactive (N&R) materials is a point for improvement of nuclear security. Detection of transportation of N&R materials out of the regulatory control is the other. In addition, advancement of the ability of watching nuclear explosive devices or radiological dispersal devices (so-called dirty bomb) in a public space would minimize the risk of nuclear terrorism. The Integrated Support Center for Nuclear Security and Non-proliferation (ISCN) of the Japan Atomic Energy Agency (JAEA) started the development of broad-area covering rapid N&R material detection technologies as a four-year project (2020-2023 Japanese Fiscal Year). The project includes development of radiation detector systems, and application of peripheral technologies such as localization, networking, and remote controlling technologies as well as artificial intelligent programs [1,2]. This paper overview the project and briefly presents the progress.

DEVLEOPMENT OF A BROAD-AREA SURVEY SYSTEM

The procedure of broad-area surveillance is probably as follows: (1) find the increase of radiation field, (2) figure out the source position, and then (3) identify the radioisotopes.

Information to the authorities should include the nuclear species and strength, as well as the location for the next action. Figure 1 shows technologies to be developed for the rapid and broad-area monitoring system. Those technologies will be combined together to improve deterrent capabilities against nuclear terrorism.

A dose rate mapping technique using a radiation detector and a device of Global Positioning System (GPS) would be helpful for finding N&R materials. However, this cannot apply to inspection inside stadiums and buildings, where GPS signals cannot reach. Therefore, requirement is a system incorporated with a Simultaneously Localization and Mapping (SLAM) system using, for example, Light Detection And Ranging (LiDAR). Figure 2 shows an unmanned vehicle with a radiation detector, a GPS, a LiDAR, and a camera we are testing. Such a system would be useful to find a N&R material location from the measured dose rate map. Video devices should be required to record surrounding views. In addition to the system. A compact Compton camera with GAGG crystals is being developed to visualize the source position.

In order to survey a broad area efficiently, several detectors are used simultaneously. Integration of each measured data is required to avoid skip and duplicate measurements. Such a system employs a network system. Mobile network, such as telecommunication network, is an alternative that can connect devices with high-speed covering a broad area. Nevertheless, there still exists a requirement of a localized network from a security reason. Wi-Fi network is also commonly used in various places.

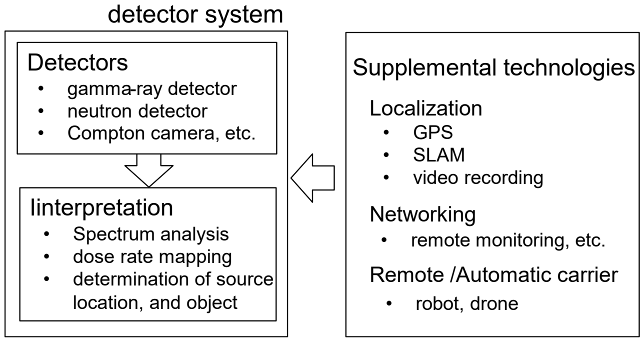

Fig. 1. Image of technological developments of a system incorporating with various technologies.

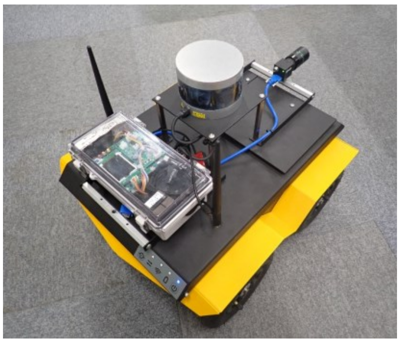

Fig.2. An unmanned ground vehicle (Jackal, Clearpath robotics) equipped with a CsI scintillation detector, a GPS, a LiDAR, and a camera.

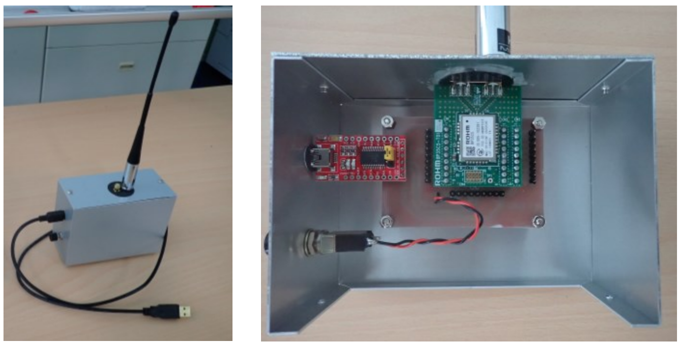

Fig. 3. A network test device equipped with a Wi-SUN FAN network board.

Table 1 Results of a performance test for artificial isotope identification using various methods.

Detector	Method	Precision	Recall	F-score
HPGe	FC-ANN	1.000	0.880	93.62
HPGe	CNN-19	1.000	1.000	100.0
HPGe	Conventional (3σ)	0.735	1.000	84.75
CsI(Tl)	FC-ANN	0.722	0.520	60.47
CsI(Tl)	CNN-19	0.958	0.920	93.88
CsI(Tl)	Conventional (3σ)	0.822	0.600	71.43
CsI(Tl)	Conventional (2σ)	0.667	0.800	72.73

Examined methods are as follows: FC-ANN (fully-connected artificial neural network program), CNN-19 (convolutional neural network program with 19 layers [4,5]) and Conventional (threshold for peak detections in conventional method [7,8]). The resultant values are defined by Precision, $p = TP/(TP + FP)$, Recall, $r = TP/(TP + FN)$, and F-score $F = 200 \times p \times r/(p + r)$, where TP is the fraction of true positive, FP is the false positive, and FN is the false negative, respectively. The brackets in the conventional method refer to the threshold for peak detections.

However, the range is not sufficiently long to cover a broad area. Therefore, we started testing a secure low-power wide-area network (LPWAN) system, Wireless Smart Utility Network for Field Area Network profile (Wi-SUN FAN) [3]. The system can provide two-way IP communication with many devices. They connect devices with a distance of 1 km maximum and with a speed of 300 kbps at maximum (to be upgraded to 2.4 Mbps). The Sub-GHz band of Wi-SUN FAN has better wraparound characteristics than those used for Wi-Fi and Bluetooth. It improves the connectivity of single Wi-SUN FAN device. By using muti-hop communication (24 hop maximum), ideally, the system could connect devices 25-km apart. Figure 3 shows a test device equipped with a Wi-SUN FAN network board (Rohm). Connection between computers was succeeded. The data transfer rate using the UDP connection was approximately 50 kbps with a side-by-side device setup, where the effective transfer rate of Wi-SUN FAN in Japan is limited to be 60 kbps maximum because of the limitation of connection time stipulated by the Radio Act of Japan.

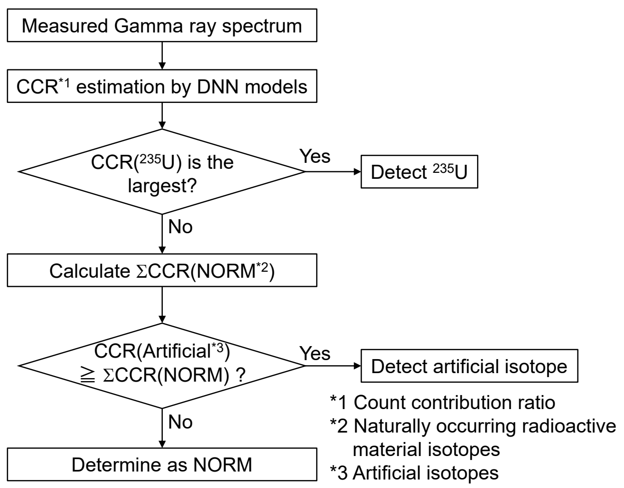

Fig 4 Radioisotope identification algorithm, where CCR is count contribution ratio of each nuclide on the measured gamma-ray spectrum [4,5].

Identification of radioactive isotopes is required to evaluate the threat and to decide the next action. Naturally occurring radioactive material (NORM), medical, and industrial radioisotopes are potentially the source of the alarm. A software for rapid diagnose of the alarming spectrum would be helpful for the person who is not trained nor having knowledge. An algorithm using deep artificial neural network (DNN) developed by Kimura [4,5] is being tested for our system. The algorithm utilizes convolution neural network (CNN) model developed by Visual Geometry Group for ImageNet Large scale Visual Recognition Challenge (VGG-ILSVRC) [6].

The performance of the proposed CNN model for radioisotope identification was evaluated. Table 1 shows resultant values achieved using various methods. F-scores of CNN-19 shows quite good agreement, proving its applicability not only for a high resolution HPGe detector but also for a scintillation detector.

Figure 4 describes the algorism that follows the evaluation of CNN program. The algorism developed by Kimura [4,5] judges whether the alarm is caused by U-235, or artificial isotopes, or NORM.

DEVELOPMENT OF A FAST NEUTRON DETECTOR SYSTEM USING PLASTIC SCINTILLATORS

(a)

(b)

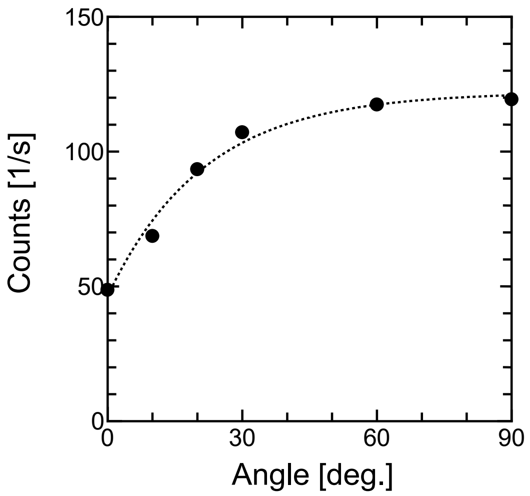

Fig. 5 (a) Photograph of a rod-shape plastic scintillator (EJ-299-33M, Eljen). Two photomultipliers ware attached at the both ends. (b) Experimentally achieved angular dependent neutron count rates. Each measurement was performed for 600 s. The statistic errors are within the size of the marks. The dashed line is a result of a fitting that reproduce the data, where a function, $g(x) = a_0 + a_1 \times (1 - exp(-x/a_2))$, was chosen.

Neutron detection would be useful to find out nuclear materials and neutron sources shielded by heavy-element materials because its penetration power is larger than that of gamma rays. Plastic scintillator was chosen as a detector material, which is low-cost, sensitive to fast neutrons, easy to handle, and thus easy to be deployed. Gamma-ray background can be reduced by employing a Pulse Shape Discrimination (PSD) technique, enhancing the sensitivity to fast neutrons. Developments of systems using PSD plastic scintillators are in progress [2,9].

Figure 5 (a) shows a rod-shaped plastic scintillation detector. The scintillator (EJ-299-33M, Eljen: 25×25×250 mm) was covered with Teflon tape reflector and aluminum light shield case. Two photomultiplier tube (Hamamatsu H11934-100-010) were placed on each side of the scintillator. Output signals were measured by a digitizer (CAEN V1730SB). List data of incident time, integrated digitized values in a different gate, i.e., Q_{long_gate} and Q_{short_gate} was recorded. Neutron and gamma-ray event was discriminated by the pulse shape parameter $PSD = Q_{long\_gate} / (Q_{long\_gate} + Q_{short\_gate})$, where the Q_{long_gate} and

Q_{short_gate} is the sum of the two detector outputs. The neutron and gamma-ray separation achieved from the PSD spectrum was approximately $FOM = 0.7$, where $FOM = S / (\delta\gamma + \delta n)$, S is the distance between the gamma ray and neutron peaks, and $\delta\gamma$ and δn are the full width at half maximum (FWHM) values of the each peak, determined by a double gaussian fitting [10]. Figure 5 (b) shows experimentally measured neutron counts where a PuBe (α, n) source (1.4×10^6 n/s) [11] was placed at 1-m apart from the center of the detector. The counting rate increased as the increase of the angle, where the axis of the detector aligned with the source at 0 deg. The change of count rate is mainly from the solid angle of the detector from the neutron source.

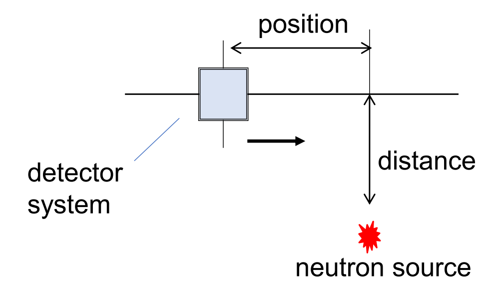

Fig. 6. A schematic drawing of a survey system passing near a neutron source.

This directional efficiency distribution of the detector would be useful for finding a neutron source. Figure 6 shows a detector system moving straight measuring radiation field, which shows a peak at the nearest point to the neutron source. To determine the direction of the source location, two paired-detector system were proposed and numerically studied. The rod-shaped detectors were arranged + and x shape to the moving direction. The left panels of Fig. 7 show the detector arrangement. The calculated count

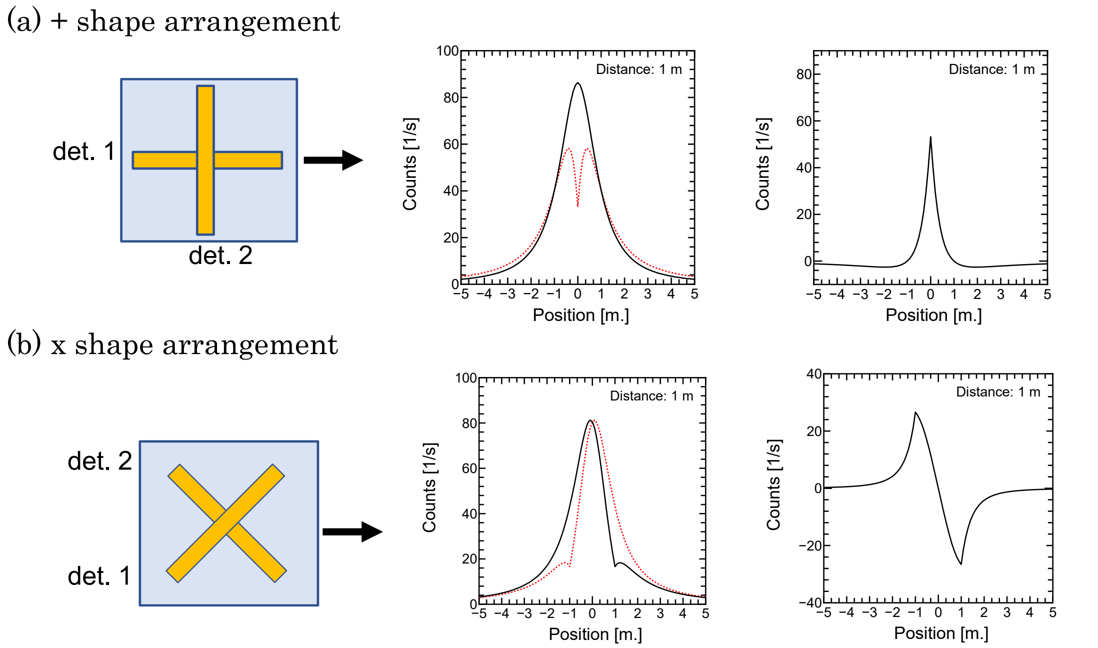

Fig. 7 Estimated counting rate of paired-detector systems passing at distance of 1 m. Two different detector arrangement are presented: (a) + shape arrangement (b) x shape arrangement. The left panels show the arrangement of the detectors. The center panels show the calculated count rates, where the black solid line and the red dashed lines indicate detector 1 and 2 of the left panels, respectively. The right panels show the count rate difference. The source intensity is assumed 10^6 n/s.

rate using $Y\,[1/s] = \frac{g(\theta)}{N \times r^2}$ are given in the center panels of Fig. 7, where $g(\theta)$ is a function that reproduced the count rate angular correlation given in Fig. 5(b). N is the normalization factor for the neutron emission rate of 10^6 n/s. r is the distance between the source and the detector system. The right panels of Fig. 7 show the count difference between the two detectors.

The system (a) of Fig. 7 shows a sharp count rate decline, indicating precise angle of the source. However, the system could not deduce the source direction (left or right) because of the detector system is placed symmetrically along the moving direction. The system (b) of Fig. 7 can, on the other hand, identify the source direction. Statistical uncertainty reduces the precision of the source angle. Experimental study will be performed soon. A drawback of the rod-shaped detector is that decline of the function when the source is not appears on the detector axis. In order to overcome the drawback, we are planning to develop a plate type detector.

SUMMARY

To prevent nuclear terrorism in major public events, the JAEA is developing radiation detector systems, which survey N&R materials in a broad area. The system should be a combination of a radiation detector, a camera, and localization devices for in-and-outdoor survey. Wi-SUN FAN is being tested for efficient implementation of N&R material surveillance connecting securely the control center and surveying detectors. In addition to the surveying system, an artificial intelligent program is being developed to detect U-235 and to eliminate false alert. Fast neutron detection system with a rod-shape PSD plastic scintillator was being developed. Although the detector is sensitive to both fast neutrons and gamma rays, fast neutron events can be selected by using PSD method. Taking the advantage of the angular dependence of the detection efficiency, a portable paired-detector system was being developed. The system can figure out the place of a radioactive source in a public space.

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REFERENCES

[1] T. Takahashi, M. Koizumi, T. Mochimaru, K. Hironaka, Y. Sato, Y. Terasaka, H. Yamanishi, G. Wakabayashi, “Development of Detection Techniques of Nuclear and Radioactive Materials for Major Public Events”, Proc. the INMM & ESARDA Joint Virtual Annual Meeting, 2021.

[2] T. Takahashi, M. Koizumi, T. Mochimaru, K. Hironaka, H. Yamanishi, G. Wakabayashi, “Development of Detection and Direction Estimation Techniques of Neutron Sources”, Proceedings of the INMM 63rd Annual Meeting, 2022.

[3] Rei Hirakawa et al., "A Novel Routing Method with Load-Balancing in Wi-SUN FAN Network", 2021 IEEE 7th World Forum on Internet of Things (WF-IoT) p. 362.
[4] Y. Kimura and T. Yamaguchi, "Mobile Radiation Measurement System by Multiple Small Gamma-ray Detectors for Radioisotope Detection and Identification Supporting Responders in the Field of Nuclear Detection and Nuclear Security", International Symposium on Zero-Carbon Energy Systems, Organizing Committee of IZES, Tokyo, Japan (2023).
[5] Y.Kimura, and K. Tsuchiya, to be published in Radioisotopes.
[6] K. Simonyan, and A. Zisserman, "Very Deep Convolutional Networks for Large-scale Image Recognition", Conference paper at ICLR 2015, May 7-9, San Diego, 1360 US (2015).
[7] Gamma-ray spectrometry using germanium detector (4th edition) [in Japanese], Radioactivity measurement method series, no. 7, Nuclear Regulation Authority, Tokyo, Japan (2020).
[8] Instrumental analysis using NaI (Tl) scintillation spectrometer [in Japanese], Radioactivity measure ment method series, no. 6, Nuclear Regulation Authority, Tokyo, Japan (1974)
[9] M. Koizumi et al., Nucl. Inst. and Meth. in Phys. Res. A 1042 (2022) 167424.
[10] A. Lintereur, J. Ely, J. Stave, B. Mcdonald, Neutron and Gamma Ray Pulse Shape Discrimination with Polyvinyltoluene, PNNL-21609, 2012.
[11] G. Wakabayashi, T. Itoh, K. Hashimoto, S. Ito, H. Yamanishi, W. Sugiyama, T. Horiguchi, S. Hohara, History and present situation of kinki university reactor, in: Proceedings of Int. Meeting on Reduced Enrichment for Research and Test Reactors, 2012.