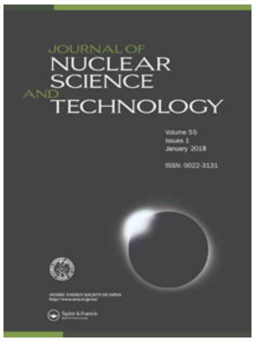

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ARTICLE

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ABSTRACT
A remote radiation imaging system comprising a lightweight Compton camera and a multicopter drone was developed to remotely and quickly measure radioactive contamination inside the buildings of the Fukushima Daiichi Nuclear Power Station (FDNPS). The drone system is used for measuring detailed radiation distributions in narrow areas, which have been difficult to gauge with conventional aircraft monitoring using helicopters. A measurement of radiation distributions in outdoor environments in the coastal areas of Fukushima, Japan, was performed. The drone system with the Compton camera succeeded in remote observations of dense hotspots from the sky over a contaminated area near the FDNPS. The time required for image reconstruction is approximately 550 s in the case of a 9-m flight altitude for the hotspots with a surface dose rate of several tens of μSv/h. This drone system will be used inside the buildings of the FDNPS for remote measurement of radioactive contamination.

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1. Introduction

The Fukushima Daiichi Nuclear Power Station (FDNPS), operated by Tokyo Electric Power Company Holdings, Inc. (TEPCO), went into meltdown after a large tsunami erupted due to the Great East Japan Earthquake on 11 March 2011. Large amounts of radionuclides were released from the damaged plant. Radiation distribution measurements inside the buildings of the FDNPS are indispensable to execute the decommission tasks in the reactor buildings. The main radioactive contamination inside the buildings is radioactive cesium, and a handheld survey meter has been used for the gamma survey. However, the radiation exposure to the workers inside the buildings during the survey is a critical issue. In addition, contamination level measurements for a wide area using survey meters is time consuming, and locally existing hotspots are overlooked. Therefore, there is a distinct need for a device that can automatically measure the radioactive contamination for a wide area quickly and easily. The combination of a gamma-ray detector and remote equipment is a useful way to remotely measure the radioactive contamination under high-dose-rate environments.

The remote radiation monitoring using a radiation detector and remote equipment was performed on the outdoor environment affected by these diffused radioactive substances. Aerial monitoring by helicopters and unmanned helicopters equipped with NaI(Tl) and $LaBr_3$:Ce scintillation detectors was performed by Japan Atomic Energy Agency (JAEA) [1,2]. As an example, the measurement of the distribution of air dose rate and the distribution of radioactive cesium (^{134}Cs and ^{137}Cs) deposition on the ground within a radius of approximately 5 km from FDNPS was performed using an unmanned helicopter equipped with the $LaBr_3$:Ce scintillation detector. In addition, the footprint of the radioactive plumes that extended from FDNPS has been illustrated [2].

Conversely, remote radiation monitoring inside the buildings of the FDNPS is performed with difficulties, different from those encountered in the outdoor environment. It is presumed that the radioactive contamination has spread to the ceiling, walls, and many building structures as well as to the ground surface. Thus, directional radiation detectors are necessary to accurately reconstruct the radiation distribution map inside the buildings. The NaI(Tl) and the $LaBr_3$:Ce detectors used in the helicopter systems are omni-directional in terms of sensitivity to radiation.

For this reason, a gamma-ray imager is considered as a directional radiation detector. Gamma-ray imagers are powerful devices for measuring the distribution of radioactive contamination inside the field of view (FOV) and are generally classified into two types: pinhole camera and Compton camera [3–5]. The pinhole camera needs a collimator that allows gamma rays to pass through only toward the gamma-ray sensor installed inside the gamma-ray shield, thereby avoiding

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the contribution by gamma rays originating outside the FOV of the gamma-ray sensor. This sensor is heavy, weighing more than several tens of kilograms because the pinhole collimator is made of lead (Pb) or tungsten (W). Moreover, the detection efficiency of the sensor is limited by the geometrical area of the pinhole, which must be as small as possible to achieve a good angular resolution. The second type of gamma-ray imager is the Compton camera. A Compton camera comprises two gamma-ray sensors: a scatterer and an absorber. This gamma-ray imager uses the kinematics of Compton scattering to estimate the direction of the gamma rays that are incident on the sensor without using pinhole collimators. Because heavy collimators are not used, the size and weight of this sensor are lower than those of pinhole camera imagers.

Previously, Jiang et al. [6] performed experiments using a Compton camera mounted on an unmanned helicopter outdoors in the Hamadori region (coastal areas) of Fukushima, Japan. The radiation distribution map of several hotspots that have a dose rate of ten and several μSv/h exited on the ground were obtained from a 10-m flight altitude. However, the helicopters have difficulty in navigating within the FDNPS, in particular, inside the reactor buildings, due to numerous structures and narrow pathways.

Recently, small unmanned helicopters with multiple rotors known as drones or multicopters have been attracting attention worldwide. Owing to the development of automatic control technology, it is possible to control drone flights relatively easily. In addition, drones are compact and inexpensive compared to the aforementioned helicopters. A drone system with directional radiation detectors can be used to measure detailed radiation distributions in narrow areas, which have been difficult to measure with conventional aircraft monitoring.

In the present work, a remote radiation imaging system was developed using a lightweight compact Compton camera mounted on a multicopter drone to remotely measure radiation distributions inside the buildings of the FDNPS. The areas were previously not surveyed because workers are not allowed to enter the space due to high radioactive fields. In this paper, a system integration of the drone system with the Compton camera is introduced, and the results of the performance evaluation test for remote radiation imaging are shown. The usability of the drone system for measurement of the radiation distribution inside the buildings of the FDNPS is also discussed.

2. Compact Compton camera and drone system

2.1. Compact Compton camera

A photograph of the compact Compton camera installed on the drone is shown in Figure 1(a). The

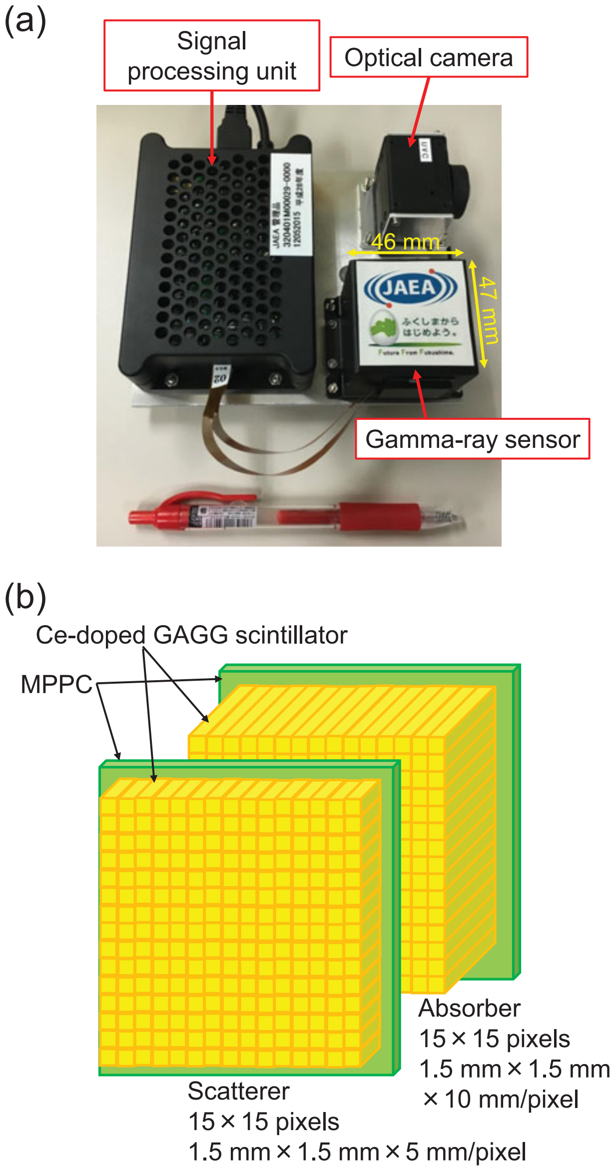

Figure 1. (a) Photograph of the Compton camera and (b) schematic of gamma-ray sensor.

Compton camera comprises three parts: (1) a gamma-ray sensor (47 mm × 46 mm × 44 mm), (2) a signal processing unit (77 mm × 113 mm × 30 mm), and (3) an optical camera (39 mm × 37 mm × 30 mm). The weight of the entire unit is less than 1 kg. The gamma-ray sensor has two stages – scatterer and absorber. Each stage comprises a Ce-doped GAGG ($Gd_3Al_2Ga_3O_{12}$) scintillator coupled with a multipixel photon counter (MPPC) (Hamamatsu Photonics K.K.), as shown in Figure 1 (b) [7–9]. The distance between the two gamma-ray sensors is 23.5 mm. The incident angles of gamma rays on the scatterer are estimated using the kinematics of Compton scattering. The operating principle of the Compton camera is described in [4] and [5].

The gamma-ray sensor is connected to a signal processing unit that records and processes information about the position of gamma-ray interaction and the energy deposition values in the scatterer and the absorber. The processed signals are sent to a PC via a

USB 3.0 port. The sum of power consumption of the signal processing unit and the gamma-ray sensor is less than 5 W. Electric power is supplied via a USB bus. Optical images captured using an optical camera (OPT Corporation: NM33-F) are sent to the PC via a USB 2.0 port. The power consumption of the optical camera is less than 2.5 W. Image reconstruction for visualization of the radioactive substances is performed on the PC. The radiation images are reconstructed by a back-projection method by using the data measured with the gamma-ray sensor and are superimposed on the optical images for visualization of radioactive substances.

An operation test of radiation imaging using the Compton camera was performed outdoors in the Hamadori region of Fukushima, Japan. The main radioactive contamination deposited in the fields is radioactive cesium due to the FDNPS nuclear disaster. The fabricated compact Compton camera could clearly visualize hotspots on withered grass, with a contamination level greater than 60 μSv/h (at a height of 1 cm above the ground surface), as shown in Figure 2. The distance between the hotspot and the Compton camera was approximately 2.2 m. The measurement time was 180 s. In the measurement, the event data used for an image reconstruction were selected to observe the contamination due to ^{137}Cs that emits 662-keV gamma rays. The energy spectrum of a sum of energy depositions in the scatterer and absorber shows the 662-keV photopeak, and these photopeak events were used for the image reconstruction. The selected energies are set to 625 keV $\leq E_s + E_a \leq$ 725 and 10 keV $\leq E_s \leq$ 165 keV, where E_s and E_a are the energy depositions in the scatterer and absorber, respectively.

In contrast, radiation images were not observed on the road surface (photo right of Figure 2(c)), which has low contamination levels at 1.5–4.0 μSv/h (at a height of 1 cm above the ground surface) compared with the visualized hotspot.

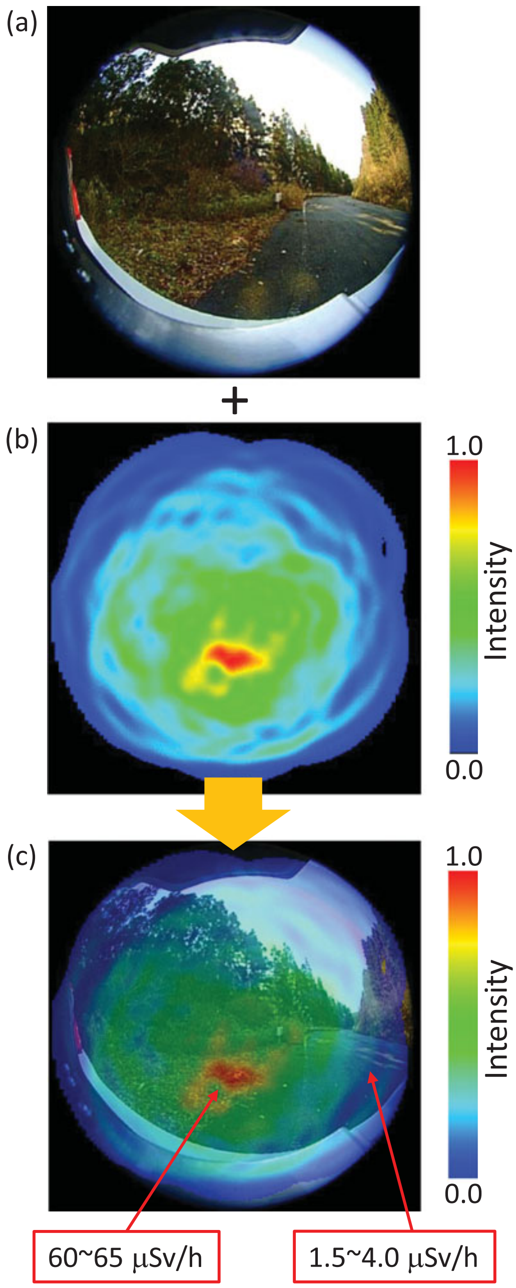

Figure 2. (a) Optical image and (b) reconstructed radiation image measured with an optical camera and Compton camera, respectively. These images are superimposed for visualizing radioactive substances, as shown in panel (c). The reconstructed hotspot has a dose rate higher than 60 μSv/h at 1 cm above the ground surface. Incidentally, the dose rate on the road surface (photo right) is 1.5–4.0 μSv/h. The measurement time is 180 s.

2.2. System integration

We developed a remote radiation imaging system comprising a drone (DJI: Matrice 600) and a compact Compton camera, as shown in Figure 3. The size of the drone system is 1668 mm × 1518 mm × 759 mm. The Compton camera is mounted on a gimbal (DJI: RONIN-MX) installed on the drone to maintain FOV angle as the drone sways. In addition, we installed a stick PC (Thirdwave Diginnos Co., Ltd.: DG-STK4S Pro) on the drone, and this PC is connected to the signal processing unit and the optical camera of the Compton camera. Electric power for the stick PC and the Compton camera is supplied by a portable USB battery (SONY: CP-S15B 15,000 mAh). Image reconstruction for the visualization of radioactive substances is performed on the stick PC. The reconstructed radiation image is transferred wirelessly (via Wi-Fi) to a base station PC after the end of measurement. The range of wireless communication was validated up to 60 m, and the operable flight time of the drone system is approximately 16 min. The drone system hovers above the objective point, and the Compton camera visualizes radiation distribution in the measurement area.

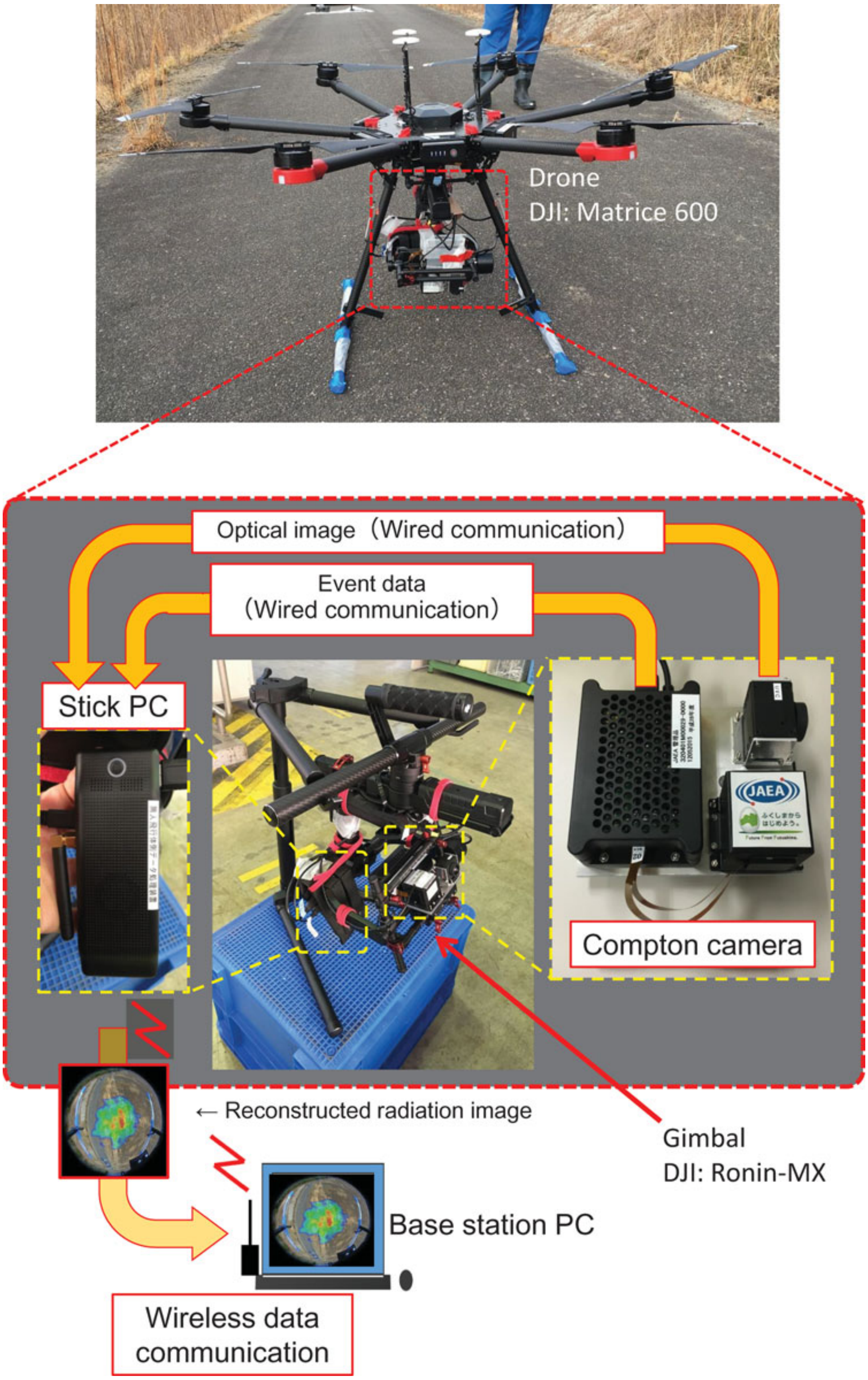

Figure 3. Photograph of the remote radiation imaging system comprising a drone and a compact Compton camera.

3. Performance evaluation test of the remote radiation imaging system

An attempt was made to detect a ^{137}Cs-radioactive source by using the fabricated drone system. This was a foundational experiment to confirm that image reconstruction is possible for a point-like radioactive source. Figure 4(a) shows the experimental conditions inside the test building. Figure 4(b) shows an optical image measured with the optical camera when the drone was hovering in the air at approximately 1.5 m above the ground level. It was observed that the ^{137}Cs-radioactive source (0.96 MBq) was located in right under the flying drone. The radiation image was observed on the position of the ^{137}Cs-radioactive source, as shown in Figure 4(c). A measurement time of 10 min was necessary for the image reconstruction in this experiment.

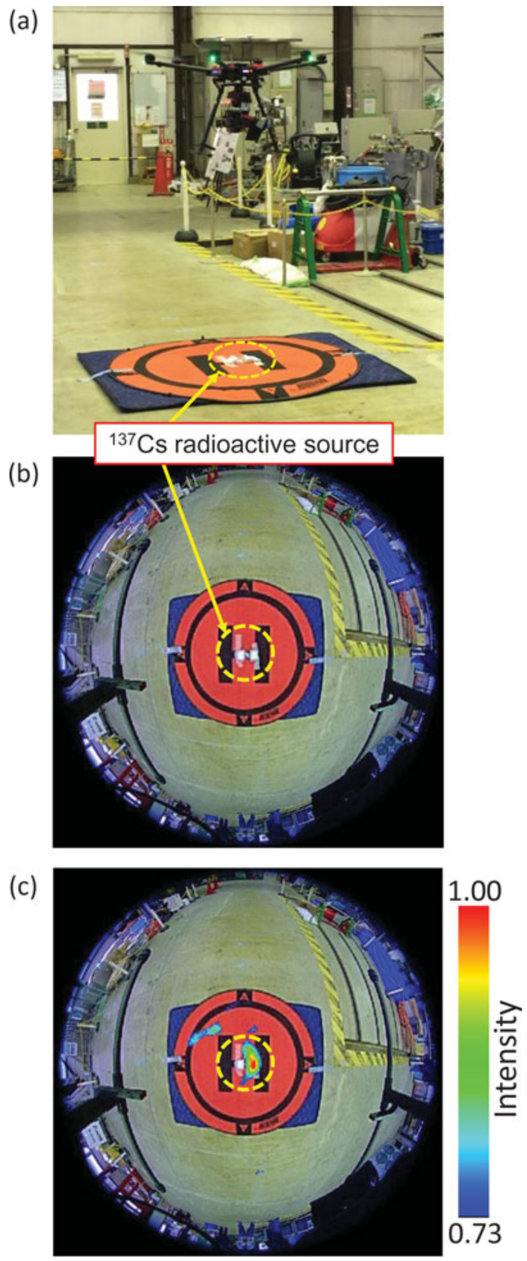

Figure 4. (a) Photograph of actual experimental conditions. (b) Optical image measured with an optical camera when a drone is hovering approximately 1.5 m above ground surface. The ^{137}Cs-radioactive source is located on the floor. (c) The radiation image is observed on the position of the ^{137}Cs-radioactive source. The time required for the image reconstruction is approximately 10 min.

Moreover, a measurement of radioactive contamination spreading along the ground surface outdoors in the Hamadori region of Fukushima was also performed. Figure 5 shows the measurement location. There are three hotspots at the boundary of the road and the fallow farmland. The dose rates of the hotspots measured at 1 cm above the ground surface are 30–55 μSv/h, as shown in the panel of the figure. In contrast, the dose rates on the road surface and in the farmland are approximately 10–15 μSv/h. The drone system hovered over the hotspots to perform radiation imaging. In general, position information of the drone system is obtained using global positioning system (GPS),

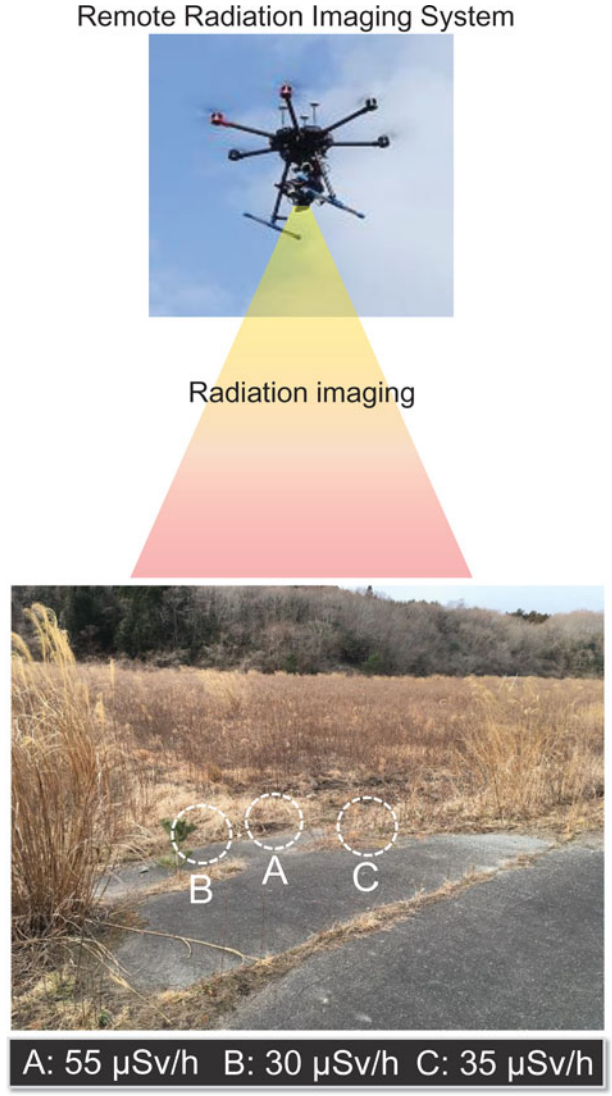

Figure 5. Photograph of the measurement location. There are three hotspots on the boundary of the road and the fallow farmland.

and the drone automatically controls self-position using GPS. The accuracies of the position estimation using GPS are within ±0.5 and ±1.5 m for vertical and horizontal directions, respectively.

Figure 6(a) shows the optical image measured from a 9-m flight altitude of the drone system. The FOV was a circle with a diameter of approximately 50 m. The reconstructed radiation images obtained in different measurement times are shown in Figure 6(b–e). The measurement times are given in each panel. These images are reconstructed using the 662-keV-photopeak event to observe the contamination due to ^{137}Cs.

Figure 6(b) shows the result obtained by a short measurement time of 100 s. In the result, only region (A) was imaged strongly, which has a higher dose rate than that of regions (B) and (C). The intensities of reconstructed radiation images on regions (B) and (C) increase as time proceeds; three hotspots are clearly observed as shown in Figure 6(d) and 6(e). The time required for the image reconstruction was approximately 550 s. The region with hotspots was imaged strongly in comparison with

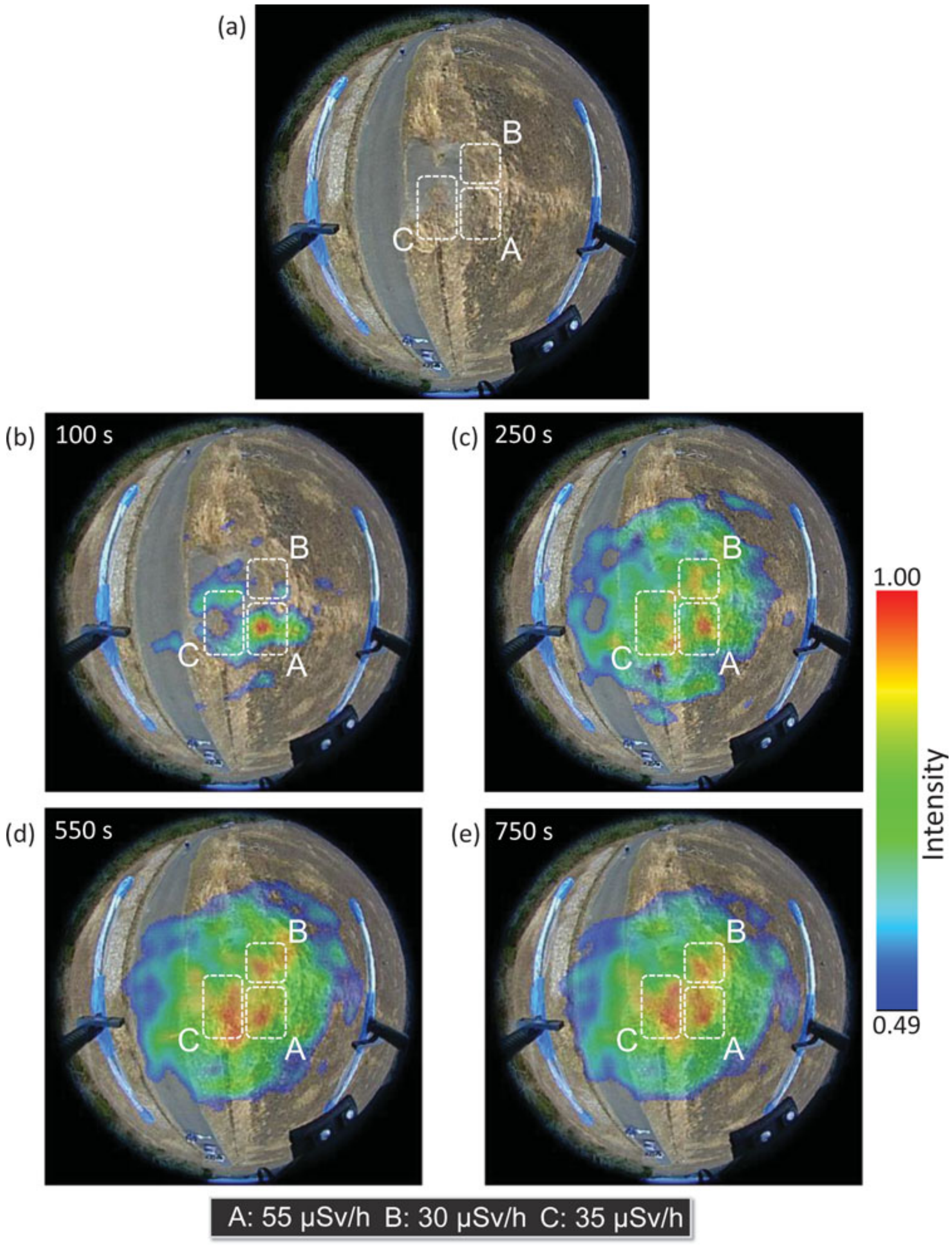

Figure 6. (a) Optical image measured with an optical camera as the drone system hovers above the hotspots. (b–e) Radiation images measured using the drone system. The measurement times are given in each panel.

other regions, road surface, and farmland. These results are consistent with the results of a ground survey. At this stage, the drone system succeeded in remote observation of hotspots from the sky in outdoor environments.

The short operable time of only approximately 16 min is a drawback of the system, a limitation imposed by the battery run time. There is room for improvement to use this system to measure the hotspots with several tens of μSv/h outside the site of the FDNPS, such as using a wired power supply for efficient radiation imaging.

In the case of the flight inside the FDNPS buildings, the distance between contaminated objects and the Compton camera becomes short due to the restriction of the narrow space inside the buildings. The time required for image reconstructions also decreases. In Figure 2, the Compton camera can visualize a hotspot of approximately 60 μSv/h with a measurement time of 180 s. If the distance between the hotspot and the Compton camera is halved, it is expected that the camera can reconstruct the radiation image by the measurement less than 1 min. In addition, the contamination levels inside the buildings are incomparably larger by more than several hundred μSv/h than that on the outside of the buildings. This drone system can likely measure the plural hotspots inside the buildings of the FDNPS during the operable flight time of the system. The compact drone system will be a promising device for the measurement inside the building of the FDNPS.

4. Conclusion

A remote radiation imaging system comprising a Compton camera and a multicopter drone was developed. This novel equipment can be used to remotely and quickly measure radioactive distributions inside the FDNPS buildings. Performance evaluation tests and radioactive contamination measurements were performed outdoors in the Hamadori region of Fukushima, Japan. The drone system succeeded in observation of hotspots in a field, which have higher dose rates than do other regions. The dose rates of the hotspots measured at 1 cm above the ground surface are 30–55 µSv/h, and the flight altitude in the measurement was approximately 9 m. The drone system used herein can hover during radiation measurement.

The distinct advantage of using drone devices is the superior mobility in the narrow areas due to the compact size of the drones compared to helicopters. To reconstruct radiation images by using the Compton camera while moving of the drone system, information about the incident angle of gamma rays and each drone position are necessary. Therefore, a simultaneous localization and mapping technology for drones is currently under development to perform image reconstruction of radioactive substances when the drone system is in motion.

In addition, it is desirable that the drone-mounted gamma-ray sensor has an all-around-view (4π) sensitivity for 4π radiation imaging around the drone because the contaminants are present in all directions and on a variety of structures. A 4π Compton camera is also under development. The 4π Compton camera will greatly improve the efficiency of the radiation imaging inside the buildings due to the wide FOV compared with that of previous system. The time required for the imaging will also reduce. In addition, a high-speed signal processing circuit will be installed that makes signal processing possible for each gamma-ray event in a high-dose-rate environment.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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