Recent Works on Emergency Response Robots at Nuclear Robotics Laboratory of KAERI

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Abstract: Following the Fukushima accident, the importance of safety and emergency preparedness of nuclear power plants (NPPs) has been increasingly emphasized. In 2012, the Nuclear Robotics Laboratory (NRL) at Korea Atomic Energy Research Institute (KAERI) initiated research on an unmanned emergency response robotics system. This research is fully funded by the government and is aimed at providing a practical means which countermeasure the initial accident stages of NPPs. Considering that the robotic systems that tried to mitigate the damage caused by the Fukushima accident did not work adequately, the robotic system to be developed should be robust, be supportive to human operators, and perform unmanned operations in a remote manner. In this research, three key features are emphasized considering the lessons learned from the Fukushima accident: the mobility of robotic systems, remote monitoring capability, and reliability of the sensing modules and mobile platforms. For mobility, commercially available mobile platforms such as an all-terrain vehicle (ATV) and a forklift were adopted and modified for remote operation. For remote monitoring, a range-gated image (RGI) camera system was introduced for obtaining visual information in an invisible environment due to dense fog inside a reactor confinement building. For reliability, radiation hardened electronics were investigated and adopted. In this paper, the recent works on this system are briefly introduced.

Keyword: Emergency response robot, Range-gated imaging camera, ATV

1. Introduction

Nuclear Robotics Laboratory (NRL) was established in the early 1990s at Korea Atomic Energy Research Institute (KAERI) for facilitating the operation and maintenance of nuclear power plants (NPPs) by utilizing robotic technology. Since its establishment, NRL has grown to be a national nuclear robotic laboratory engaging in a wide range of research and development (R&D) activities. In the early stages of NRL's research, it had concentrated on the maintenance work of the NPPs such as steam generator pipe cleaning, inspection and maintenance of reactor pressure vessels, etc. [1, 2].

Since the Fukushima accident, the importance of safety and emergency preparedness of NPPs has been increasingly emphasized. Accordingly, the main scope of NRL's research has gradually changed to an unmanned robotics system for emergency response. In this paper, NRL's recent R&D activities on this system are briefly introduced.

The main lesson learned from the Fukushima accident was that three core technologies were needed to adequately respond to an NPP accident: remote monitoring capability, mobility, and reliability.

Remote monitoring is of the utmost importance in the early phases of the NPP accidents. Remote monitoring should provide the following functions and information:

- maintaining visibility in the foggy environment inside the reactor containment building
- measuring contamination level of radiation to verify the possibility of human operation
- detecting hydrogen for possible explosions

- measuring coolant pipe flow to check for malfunction of coolant valves

For visibility, a range-gated imaging (RGI) camera is introduced in this paper. Thus far, this camera is able to recognize an object 10 m away in a densely foggy environment, which cannot be realized by charge-coupled device (CCD) cameras. In terms of radiation monitoring, detection modules measuring 10 uSv/h~100 Sv/h have been designed, which can be carried by unmanned mobile platforms such as an ATV and a drone.

With respect to mobility, two commercially available mobile platforms are modified to be operated in an unmanned manner. These are an ATV with a speed of up to 60 km/h and a forklift with seven remotely controlled driving modules. To enhance the reliability of the sensing modules and mobile platforms, radiation hardened electronics were investigated and used for motor controllers and CCD cameras. In this paper, the current achievements of the research on this system and further research are briefly introduced.

2. Mobile Platforms

2.1 Remote Accident Monitoring (RAM) Vehicle

In the early stages of an NPP accident, radiation monitoring is important to detect possible radiation leaks. In order to monitor the wide NPP site in a short time, quick accessibility to the areas of interest, such as the ground surface and the top surface of high building, is needed. NRL recently proposed the Remote control system for (rapid ground to aerial) Accident Monitoring (RAM) [3]. The RAM consists of an unmanned ground vehicle (UGV), an unmanned aerial vehicle (UAV), and two radiation detectors, as shown in Fig. 1. An ATV was selected as the UGV because of its excellent speed and adaptability to various types of terrains, and its driving mechanism was modified for remote control. For the UAV, a drone was adopted to cover the area around high buildings. A radiation detector was mounted on top of the UAV. The UAV sits on the rear side of the UGV while it is carried. The UGV is delivered by a truck to the area of interest and is remotely controlled by a human operator at the supervisory control station in the truck.

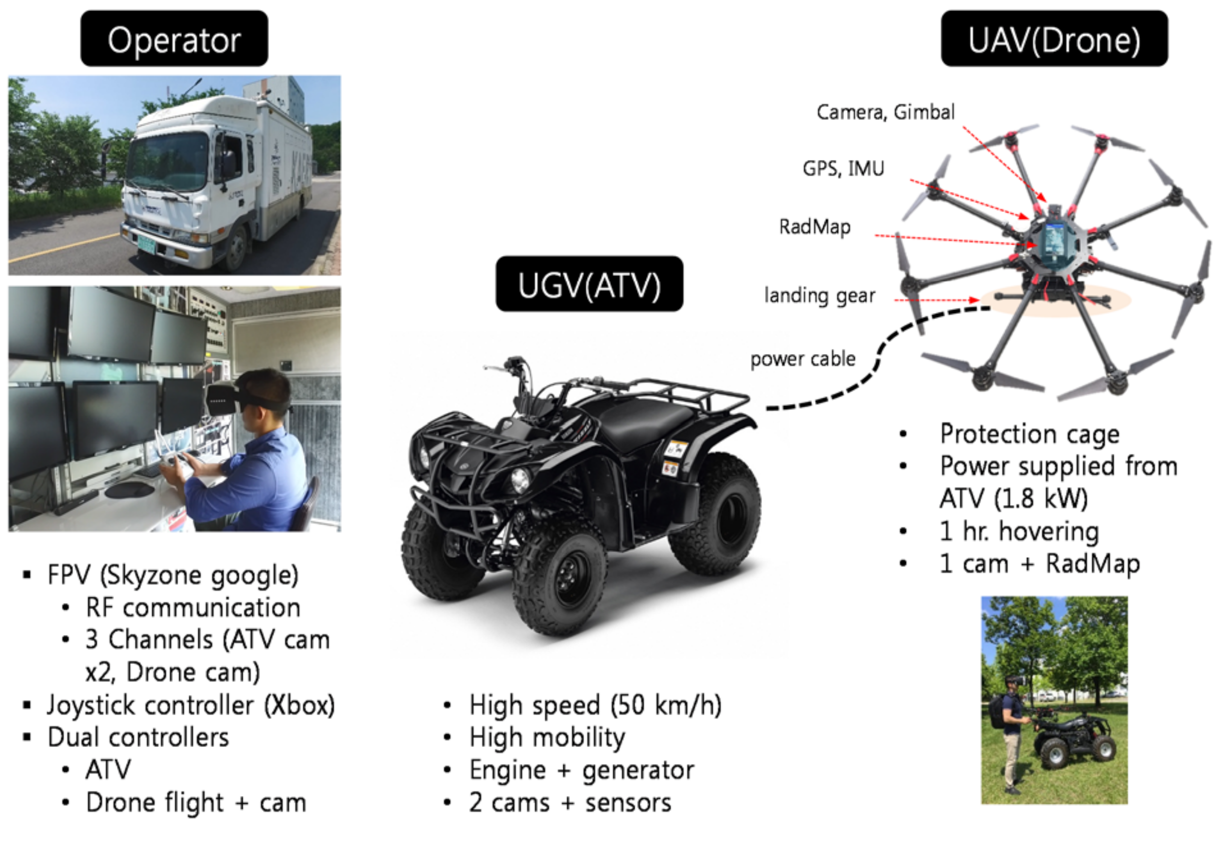


Fig. 1 Remote Accident Monitoring system.

2.1.1 UAV

Drone

The S1000 DJI model with an octocopter was used. Its take-off weight is 6~11 kg, and hovering time is about 15 min. However, after mounting the self-designed protect cage and the radiation detector on the frame of drone, its hovering time was reduced to 9 min. This is not sufficient for radiation measurement operation. To increase the hovering time, electric power was supplied to the drone through a power cable. This delivered a maximum power of 1.8 kW the drone, and the hovering time of the drone is increased to over 0.5 hr. A cable winding machine with a feeding distance of 50 m was mounted on the ATV, which is sufficient to monitor the top surface of the building.

Radiation Resistance Test

The test results of the effects of the radiation dose to the electronic parts of the drone show that the motors and batteries operated normally over 2,000 Gy, but the processors and communication modules failed at 280 Gy [4].

2.1.2 Radiation Detector

Radiation Detector

Two radiation detectors were designed for the UAV and the UGV, as shown in Fig. 2. Each detector incorporates both low and high range Geiger Muller counters for wide range measurement. The measuring range of the detector is 10 uSv/h ~ 100 Sv/h for the UAV and 1 uSv/h ~ 100 Sv/h for the UGV. Specifically, the UAV detector was designed to have small dimensions (90 x 100 x 27 mm) and to be light weight (150 g), and it was mounted on top of the drone.

Fig. 2 Radiation detector.

Radiation Map

A smartphone application for the radiation level display was developed. In this application, detected radiation data from the detector mounted on the UAV is transmitted to the Smartphone (Samsung A5) and is overlaid onto a Google map as shown in Fig. 3. In the figure, the radiation level along the flight trajectory is displayed with different colors [4].

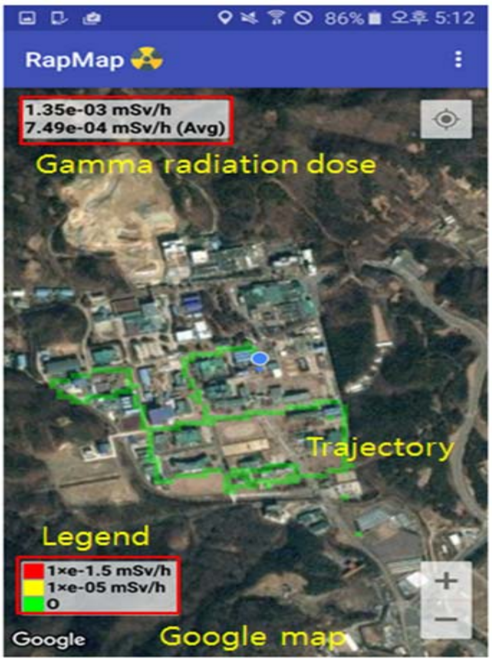


Fig. 3 Radiation map.

2.1.3 Remotely Operated All-Terrain Vehicle (ATV)

Selection of Platform

Thus far, the main mission of the ATV is to measure the radiation on the ground surface and to deliver the UAV to the location within a range of 50 m from the point of interest. Additionally, it can be used for many other operations in the future. While considering future missions, quantitative evaluations of the performance of various types of vehicles were conducted in terms of terrain adaptability, ease of control, speed, payload, turning radius, and reliability in order to select the most attractive vehicle [5]. The vehicle candidates were cars, forklifts, mini excavators, robot vehicles, and ATVs. As a result, the ATV was selected because of its excellent terrain adaptability, speed, reliability, and controllability.

Modification for Remote Operation

The Allcourt 100 with a maximum speed of 50 km/h was used and modified for remote operation. Prior to modification, the ATV has 14 degree of freedom (DOF) controls in four different modes (engine start, gearshift, driving, and parking). To have full remote control of the ATV, all 14 DOFs must be modified. In this case, operability at the remote station is too complicated. Hence, only basic control units, such as the steering, the brake, and the accelerator, were modified. For steering, two motors were directly mounted on the steering handle, as shown in Fig. 4. Additionally, two motors are used to pull the wires that pull the throttles of the accelerator and the brake [6]. These motors are remotely controlled by the joystick through the RS485 communication at a maximum distance of 330 m [7].

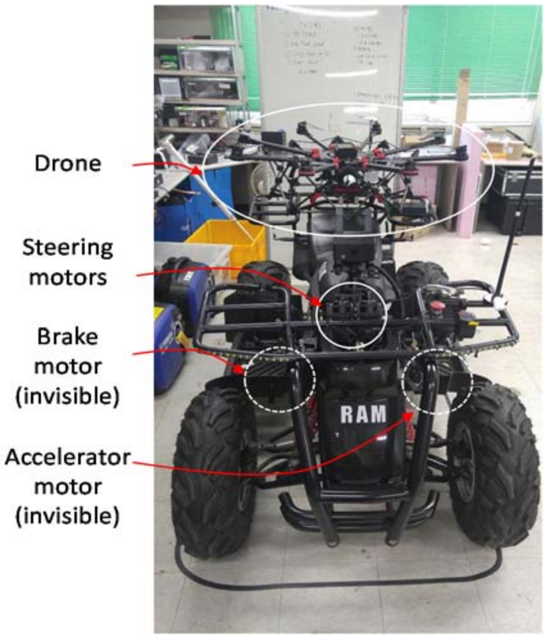


Fig. 4 Remote accident monitoring vehicle.

2.1.4 Further Study

In order to make the RAM practical, the following factors should be considered:

- radiation hardening of the processors and the communication electronics of the drone
- increased communication distance between the UGV and the control station
- increased accuracy of the radiation detectors

2.2 Remotely Operated Forklift

The forklift (Doosan Pro 5) with a 1.5 ton payload was modified for remote operation [4]. Seven motors were used to control the steering, brake, accelerator, forward/reverse gears (two), and fork lift and tilt (two), as shown in Fig. 5. Two laser range finders are mounted on each side of the forklift. The forklift is used to move heavy structures and to remove the debris of wrecked structures in order to open the passage for the UGV and mobile robots.

Fig. 5 Remotely operated forklift.

3. Range-Gated Imaging Camera

3.1 Motivation

If a severe accident such as the loss-of-coolant accident happens at an NPP, visibility is lost within the area inside the reactor containment building due to the vaporized water. The coolant water sprayed to cool the reactor core is vaporized into steam when it hits the high-temperature structure. The vaporized steam generates fog while it cools down. This fog makes the inside of the reactor building invisible. The visibility in severe accident scenarios is only in the range of 0.4 ~ 4 m [8]. In 2015, three years after the Fukushima accident, a robot equipped with an LED illuminator and a camera attempted to make a video inside the reactor building; however, it failed due to the foggy environment [9, 10]. Thus, when an accident occurs, it is essential to provide visual information. Infrared technology is a possible solution because of its high penetration capability in foggy and/or smoky environments. However, it may be too sensitive to temperature conditions. We tried to investigate possibility of applying the RGI technology to obtain the visual information in a densely foggy environment.

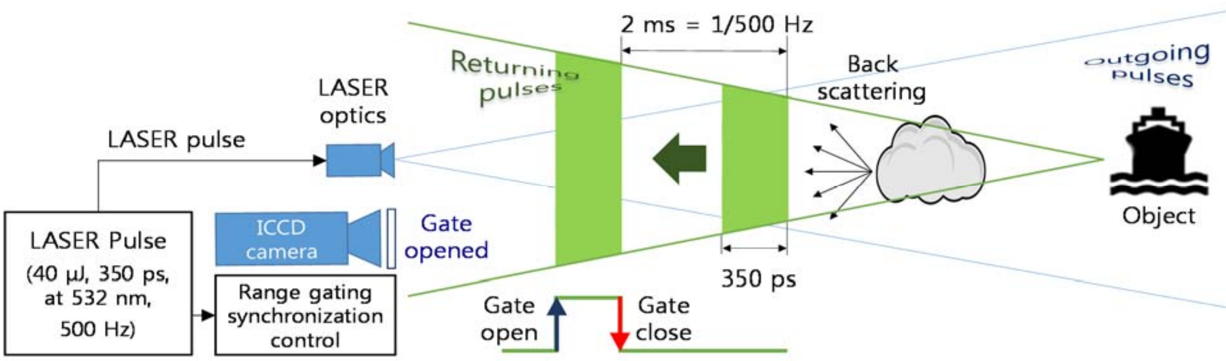
3.2 Principle

As shown in Fig. 6, the RGI system uses an ultrashort pulse laser as an illuminator and an intensified CCD (ICCD) camera. Laser light is irradiated to the object to be observed, and the ICCD camera only takes the light which is returned from the object of interest. The other reflected light, such as the light reflected from particles or objects located at a closer or farther distance, is not taken. This can be done by the gate control that synchronizes the shutter opening of the ICCD camera with the instant that the returned laser light from the object reaches the ICCD camera. In the other words, the ICCD camera opens the shutter in synchronization with the rising edge of the laser pulse that is reflected back from the object and closes the shutter with the falling edge [11]. Because the intensity of the reflected light from the object is too low, the ICCD camera is used to amplify the image. Thus, the object images can be obtained since it is not influenced by the scattering light from the fog in the space between the camera and the object.

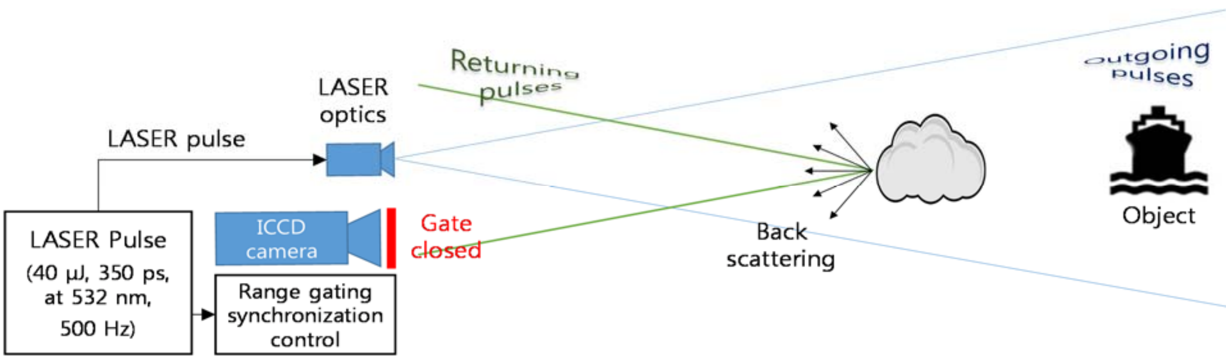
3.3 Experimental Setup

To simulate the foggy environment, an experimental setup was made, as shown in Fig. 7. In the control room, the pulse laser module and the ICCD camera are placed so that they can be separated from the fog room. This is to protect the expensive laser and the ICCD camera system from the high humidity of the fog room. Between the control and the fog rooms, two circular windows with a 120 mm diameter were made to provide the passage of LASER and reflected light.

Two fog generators and the target are located in the fog room (12.5 m L x 2.5 m W x 2.5 m H). To quantitatively measure the visibility in the fog room, a He-Ne laser and a photo detector are



(a) Gate opened when reflected light returns from the object



(b) Gate closed when reflected light returns from the particles located between camera and object

Fig. 6 Operation principle of RGI system.

installed. The CCD camera is placed to compare the target image of the RGI system with a visual image.

As shown in Fig. 7, a high-power laser pulse of 40 μJ and wavelength of 532 nm (350 ps) is emitted to the object at a repetition rate of 500 Hz. The laser light reflects off the object and reaches the ICCD camera at an elapsed time of [2 x travel distance / 3×10^8 cm/sec], and the ICCD camera opens the shutter at this instance until the falling edge of the laser pulse is detected (350/2 ps elapsed). For example, if an object is located 10 m in front of the camera, the captured image of the ICCD camera is only that of the object located in the range between 10 m and 10 m + 5.25 cm (350/2 ps x 3×10^8 cm/sec).

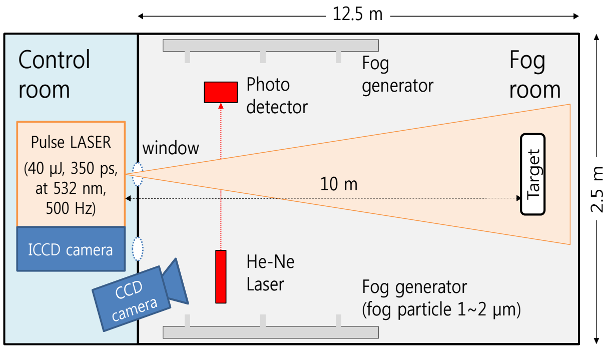


Fig. 7 Experimental setup (top view).

3.4 Test and Results

The images taken without the fog condition are shown in Fig. 8. As shown in Fig. 8(a), a chess board and the target marked as '10 m' are located 10 m apart from the camera. At this distance, the image of the ICCD is too small, so it was zoomed-in, as shown in Fig. 8(b).

(a) CCD camera (b) ICCD camera

Fig. 8 Image of CCD(a) and ICCD(b) without fog.

The image taken in foggy conditions is shown in Fig. 9. Fig. 9(a) is the CCD camera image of the chess board located 3 m in front of the CCD camera. As shown in the figure, it is invisible even at a 3 m distance from the camera. On the other hand, the ICCD image can be seen (Fig. 9(b)). To capture this image, the ICCD camera gain was increased to 250 times higher than that of the condition without fog. Additionally, the raw image of the ICCD camera was processed, and eight frames of the raw image data were taken and averaged for noise removal. Details of the test results can be found in [8].

(a) CCD camera (b) ICCD camera

Fig. 9 Image of CCD(a) and ICCD(b) with fog.

3.5 Further Study

When applying the RGI system to an unknown environment, there seem to be several limitations. Because the RGI system can capture an image only at a short distance (for example, 5.25 cm) from the target, to obtain the images of objects located at arbitrary positions, the system needs to scan many times while changing the distance until it finds the target. Hence, another means, such as sonar technology, may be needed to find the object in front of the ICCD camera.

In order to obtain a clear image, many frames of raw images should be processed. This requires a fast image processing.

Furthermore, the system should be portable so that it can be carried by mobile robots. In this case, the RGI system, which consists of precise electronics and optics, should be sufficiently robust to withstand the vibration caused by the moving mobile robot.

Finally, protection of the system from the humidity and radiation should be considered.

4. Radiation Hardened Electronics

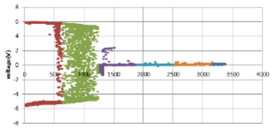
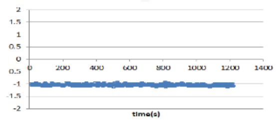
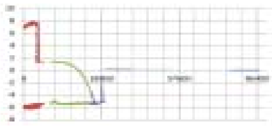
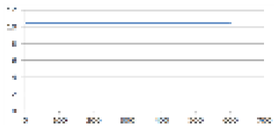
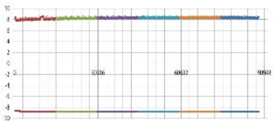
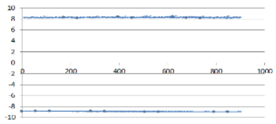
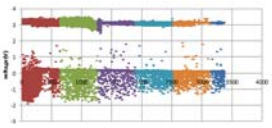
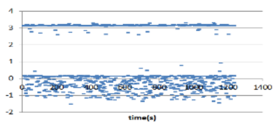
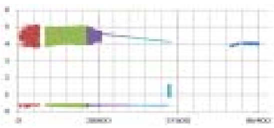
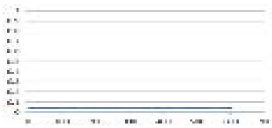
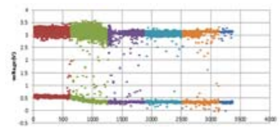
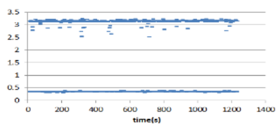
4.1 Irradiation Test of Electronic Chips

Even though there is a large amount of information on the radiation resistance of electronics, some of the data is outdated. Additionally, it is difficult to find customized information suitable for certain purposes. In this paper, irradiation characteristics of over one hundred electronic parts, which can be used for our application, are investigated. The tested IC includes power regulators, communication chips, oscillators, transistors, operational amplifiers, buffers, processors, FET drivers, etc. Additionally, irradiation characteristics of laptop computers and color CCD cameras are also investigated. The test was performed in the following way. The test chips and equipment were irradiated while they are working until the total dose reaches 1,000~3,000 Gy using the Co sources with 50~150 Gy/hr. The total dose was recorded when the chip and equipment showed malfunction.

4.2 Irradiation Test Results of Electronic Chips

The test results can be found in [12]. Only one example is shown herein. The irradiation effects on the communication chips are shown in Table 2. MAX232, SN65HVD75, and SN65HVD230 do not fail until the total dose reaches over 3,000 Gy. On the other hand, MAX3232 and ICL3232 fail at 500 Gy and 200 Gy, respectively. This result was used for selecting the chips or the control board of the above-mentioned robot or sensing modules.

Table 2 Irradiation test result of communication ICs.

Type	Model No.	Exposure (Gy)	Fail start (Gy)	Output while irradiated	Operation after irradiation	Output after irradiation
RS-232 transceiver	MAX3232	3,320	500		×	
	ICL3232	3,040	200		×	
	MAX232	2,850	2,850		○	
RS-485 transceiver	SN65HVD75	3,320	3,320		○	
	MAX485	3,040	1,800		×	
CAN transceiver	SN65HVD230	3,320	3,320		○	

5. Concluding Remarks

The recent work of NRL/KAERI on the unmanned emergency response robotics system is introduced. This work aims at providing a practical means by which the initial accident stages of an NPP can be counter measured. In this work, three key features are emphasized considering the lessons learned from the Fukushima accident: mobility of robotic systems, capability of remote monitoring, and reliability of the sensors and the mobile platforms.

For mobility, an ATV and a forklift were modified for remote operation. Combining this ATV and a drone, a RAM vehicle was developed to monitor the wide NPP site and to measure the radiation distribution of the NPP site in a short time.

To obtain visual information in an invisible environment due to dense fog inside the reactor confinement building, the RGI camera system was suggested.

Additionally, to enhance the reliability of sensors and robots, radiation hardened electronics were investigated. Most of this research will continue till the end of 2019.

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