JST: Smart Systems and Devices
Volume 32, Issue 1, January 2022, 085-093

An IoT System for Radioactive Material Detection in Scrap Metal Recycling and Production Facilities

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Abstract

A radioactive source that is not under regulatory control because it is abandoned, lost, misplaced, stolen, or transferred without proper authorization is referred to as an orphan source. The melting of an orphan source, when mixed with scrap metal, has resulted in contaminated recycled metal and wastes and the consequences will be very serious for humans and the environment. In this paper, we propose and develop an Internet of Radiation Sensor System (IoRSS) to enhance the use of nuclear detection systems to detect nuclear and other radioactive materials out of regulatory control at points of entry/exit and other trade locations of scrap metal recycling and production facilities. The proposed IoRSS creates a robust and flexible network architecture along with advanced data fusion algorithms that combine information from many detectors. The test results show that the IoRSS system allows for accurate detection of radioactive sources and provides appropriate radiation incident response plans.

Keywords: LoRa protocol, radiation detection, radiation incident response plans, IoT system.

1. Introduction

A radioactive source that is not under regulatory control, either because it has never been under regulatory control or because it has been abandoned, lost, misplaced, stolen, or transferred without proper authorization, is referred to as an orphan source [1]. Orphan sources have led to accidents with serious, even fatal, consequences as a result of the exposure of individuals to radiation. The melting of an orphan source with scrap metal or its rupturing, when mixed with scrap metal, has also resulted in contaminated recycled metal and wastes [2]. Concern over accidents occurred in the metal recycling and production industries, led to the establishment of an international undertaking Code of Conduct on the Safety and Security of Radioactive Sources [3]. In the general principles section of the Code, it is also stated that each country must have technical systems in place to respond quickly with the goal of controlling stolen and abandoned radioactive sources and eliminating or minimizing their consequences. Nevertheless, the possibility of orphan sources being present in scrap metal remains [4]. The lost radioactive sources are usually sealed sources, made in the form of metal rods and pellets, and their containers are also of metal. Therefore, when the radioactive source is lost, it is usually sold to a steel scrap collector for recycling [4]. This is the reason why all countries are very interested in controlling radioactive sources in scrap metal recycling facilities. The IAEA has technical guidelines for dealing with this in its document [5]. In Vietnam, there are also regulations on the responsibility for detecting radioactive sources out of regulatory control for scrap metal recycling and production facilities.

With the advancement of science and technology, many specialized technologies and equipment have been developed to ensure the safety and security of radioactive sources such as radiation portal monitors (RPMs), personal radiation detectors (PRDs), handheld radioisotope identification devices (RIIDs), mobile and transportable detectors, radiographic imaging systems employ x-rays or gamma rays [6]. These devices operate individually, have high operating and maintenance costs, and are not suitable for small and mediumsized scrap metal recycling facilities.

In this paper, we propose and develop an Internet of Radiation Sensor System (IoRSS) to enhance the use of nuclear detection systems to detect nuclear and other radioactive materials out of regulatory control at scrap metal recycling and production facilities. To maximize the ability to detect, identify, locate, and respond to radiation incidents, we propose and apply advances in computing, communications, algorithm development, software tools, and hardware in an integrated network of distributed sensors [7]-[10] and LoRa [11], [12] wireless communications that contribute to improved radiological and nuclear detection capabilities and response activities. The IoRSS demonstration has facilitated improved situational awareness and better capabilities to detect, identify, locate, and respond to incidents by integrating data from multiple portable and stationary radiation detectors across distributed sensors.

ISSN: 2734-9373
https://doi.org/10.51316/jst.155.ssad.2022.32.1.11
Received: September 24, 2021; accepted: November 2, 2021

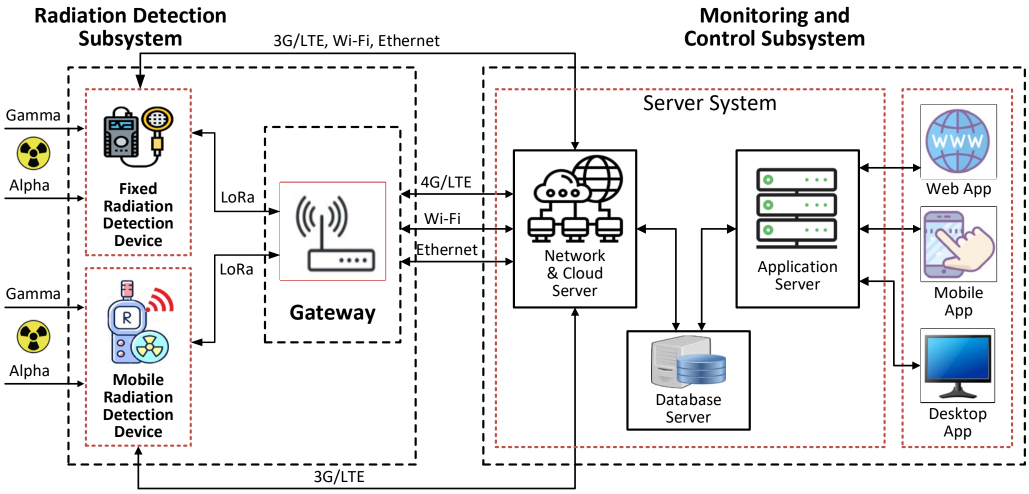

Fig. 1. Architecture and components of the IoT based radiation sensor system (IoRSS).

2. Design of IoRSS Architecture and Components

The overall architecture and components of the IoRSS as depicted in Fig. 1 consists of a radiation detection subsystem, a flexible network of wirelessly connected portable and stationary radiometric devices, and a monitoring and control subsystem.

2.1. Radiation Detection Subsystem

The radiation detection subsystem consists of the following components:

- Fixed radiation detection device (fixed device): This is the stationary device integrated with large, passive detectors, and a wide energy range of measurements for gamma detection and neutron detection. The stationary devices are mounted at points of entry/exit and other trade locations used of scrap metal recycling and production facilities to scan large scrap vehicles such as cars and trucks. Operationally, the stationary devices scan for the presence of radiation and are typically coupled with mobile radiation detection devices used in a secondary scanning mode to identify radiation sources. Stationary devices are equipped with wireless (3G/LTE, LoRa) and wired (Internet/WiFi) communications, sensor systems, and other actuators to support their operation and information sharing among system components.

- Mobile radiation detection device (mobile device): This is a mobile and transportable detector that generally uses gamma-sensitive detectors for gamma and neutron detection. They can be used as a handheld device for area surveillance, search, or other temporary deployments, such as between metal scrap yards and vehicle entrance/exit gates, or at smelting preparation areas. This device also has built-in radioisotope capabilities suitable for the isotopic identification of nuclear and radioactive materials. Operationally, the handheld device is typically coupled with a fixed radiation detection device used in a secondary scanning mode to identify radiation sources and to confirm for activating corresponding incident response procedures. The handheld device is integrated wireless communication technologies, such as LoRa and ZigBee to communicate with a Gateway and 3G/LTE to communicate with the network and cloud server. The mobile radiation detection device is designed with compact size, portable, easy to move, capable of mounting on an unmanned aerial vehicle (UAV), suitable for the tasks of searching for radioactive sources in spread out, unfocused space, or radioactively contaminated areas.

- The centralized gateway device (gateway): The gateway device acts as a centralized station to receive data from radiation detection devices and then perform data aggregation and data forwarding functions to the operation and control center (Server). The gateway also receives control data and configuration commands from the Server and then forwards these commands to the corresponding radiation detection devices. The gateway is integrated with multi-radio communication platforms, such as 3G/LTE and LoRa, to communicate with radiation detection devices. In addition, the gateway is also integrated with WiFi and Ethernet modules to ensure reliable communication with the server.

Fig. 2 is a prototype of the fixed device and the mobile device equipped with radiation detectors. Fig. 3 (a) is the layout design and actual image of the gateway device, and Fig. 3 (b) is the layout design and actual image of the integrated communication module LoRa, 3G/LTE and GPS receiver. The integrated communication module is used on both the gateway, fixed radiation detection device and mobile radiation detection device.

Fig. 2. A prototype of the fixed device and the mobile device equipped with radiation detectors.

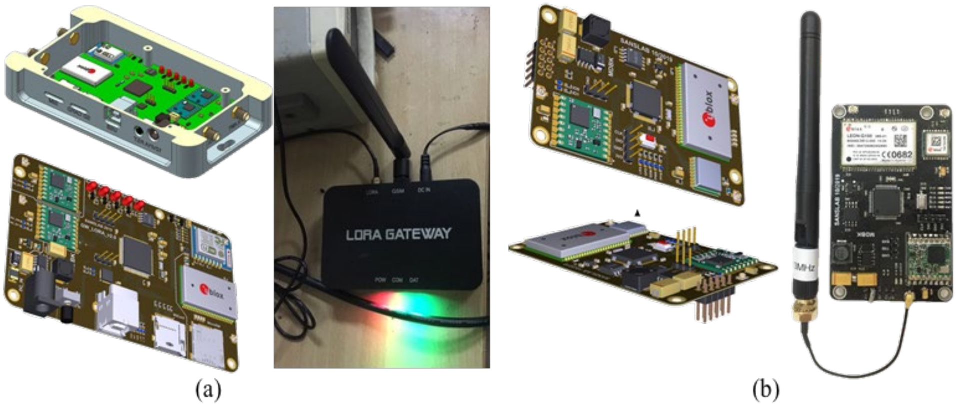

Fig. 3. Layout and prototype images of (a) the gateway and (b) LoRa, 3G/LTE, and GPS modules equipped for mobile and fixed devices.

Within the limited scope of this paper, we do not show in detail the design of the IoRSS hardware components and the energy-efficient LoRa communication protocol specifically designed for this radiation detection system.

2.2. Monitoring and Control Subsystem

The monitoring and control subsystem (servers) is a system of servers and software tools that support information exchange, the development of protocols, design advanced data fusion algorithms that combine information from many detectors, automate information processing to optimize limited resources, and improve the use of data analysis in radiation incident assessment and response plans. The servers also provide services to develop applications for end users. Their detailed components and functions are as follows.

- The network and cloud servers are responsible for communicating with radiation detection devices through the gateway or directly communicating with radiation detection devices through the 3G/LTE mobile communication network infrastructure. The network and cloud servers are also responsible for sending control commands from the users to devices.
- The database server is responsible for storing data received from radiation detection devices through a network server. The database server is also a place to organize and store the system and user databases.
- Application server is the center of the monitoring and control subsystem. The application server provides system administration and management tools, data monitoring, data processing models, warning models, and radiation incident response. The application server creates an environment that allows users to interact with the system and provides services and data for user applications.
- The desktop app, mobile app, and web app provide real-time environment monitoring, control system, and configure devices' operation modes to review the history of detection parameters and search for devices' location on a digital interactive map. The user application software also provides interfaces that allow users to interact and operate the system, such as creating and sending control commands, creating commands to configure device operating modes,

and configuring processes radiation detection and warning services.

3. Proposed IoRSS Operation Protocols

Based on the IAEA technical guidelines for dealing with the problem of controlling orphan sources and other radioactive materials in the metal recycling and production industries [2], [4], [13] and our actual survey results at metal recycling and production facilities in Vietnam, we propose processes of radiation detection, identification, and warning. These processes are designed, developed, and integrated into the IoRSS system mentioned in Section 2.

3.1. Objects Management and Configuration

Objects in a radiation incident response plan include human, materials and specialized equipment. The specialized equipment in the proposed IoRSS system is the fixed and mobile radiation detection devices, gateway, and server service system. The objects involved in the radiation incident response plan can be managed and configured by functional software with the activity flowchart described in Fig. 4.

3.2. Radiation Detection and Warning Procedures

The algorithm for detecting and monitoring radiation sources to trigger a primary warning level of the fixed radiation detection device is shown in the flow diagram in Fig. 5. In this algorithm, the fixed device plays a role in continuously detecting and measuring radiation parameters and sending them to the server through a gateway using LoRa radio communication technology or transmitting directly to the network server through a 3G/LTE mobile communication network infrastructure. After receiving data, the network server stores the data on the database server. At the same time, data is also sent to the application server for processing, analysis, and providing real-time monitoring services for application software. The application server provides an online monitoring map with the following information: current value, the average value over a given period of time, and maximum value of measured radiation, device location and measurement time. The application server also performs data analysis algorithms on the received data. If the measured value exceeds a predefined threshold, the application server will generate a primary warning level so that users can use the mobile device to confirm the existence of the radiation source, to identify radiation type, type of radioisotope (based on the spectral graph analysis algorithm), and the exact location of the radiation source. When the main warning level is initialized, the application server also sends a command to control the corresponding devices to turn on their local alarm with a loudspeaker, buzzer or flashlight. Speed warnings can also be generated when a scrap metal transport vehicle is detected moving too quickly through the fixed radiation detection device.

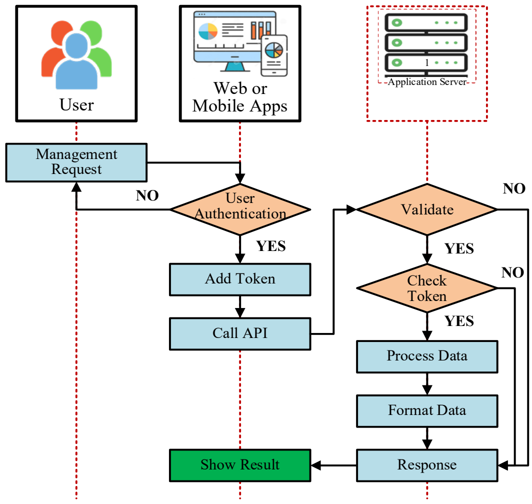

Fig. 4. Flowchart of object management and configuration in the IoRSS.

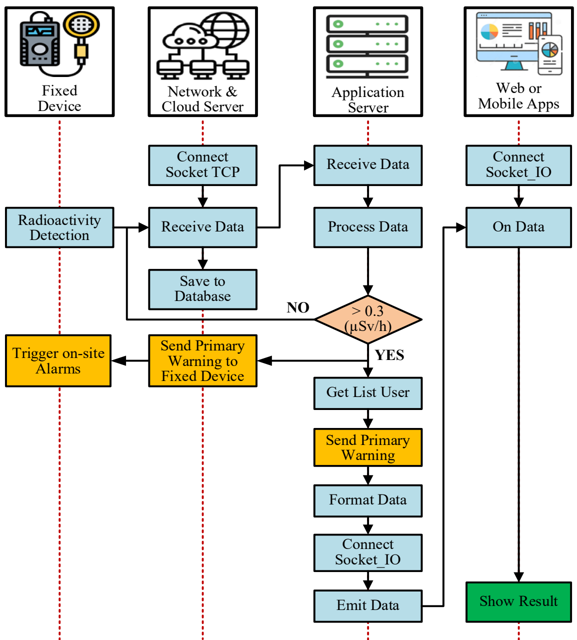

Fig. 5. Flowchart of radiation detection and primary warning activation in the fixed device.

When the primary warning is received from the system, users will use the mobile device to check and re-confirm. The measured parameters from mobile devices will continue to be sent to the network server and processed by the application server. Based on the confirmed radiation dose rate compared to the level of preconfigured thresholds, the system will activate an incident response procedure corresponding to the level of danger of the detected radiation source. The algorithm to confirm the radiation source and activate the radiation incident response process of the mobile device is shown by the flowchart in Fig. 6.

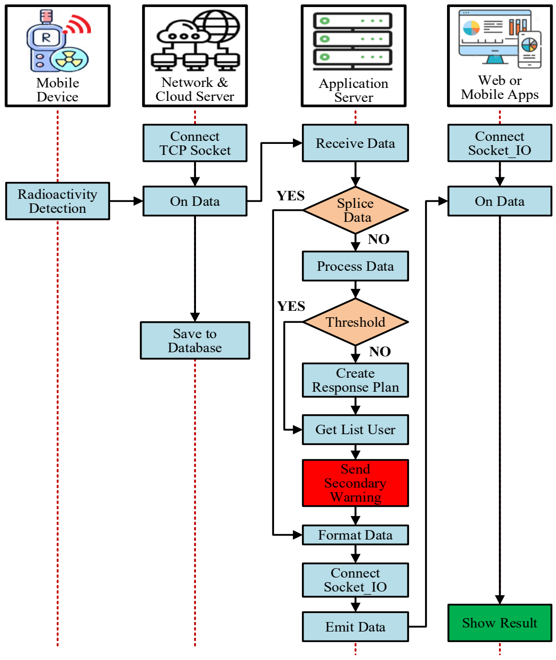

Fig. 6. Flowchart of radiation confirmation and secondary warning activation on the mobile device.

Algorithm 1 Validation and activation algorithm for radiation incident levels from a mobile device.

```
Require: measurement from detectors
Ensure: activation of radiation incident warning levels
while 1 do
    data_receive = waitReceiveData()
    if data_receive then
        get data = data_receive()
        send data to web/app
        get level = getLevelRadidation()
        create Socket.IO connect: socket
        if data_id = fixed_node_id then
            if data.Gamma_Cur > 0.3 then
                profile = getProjectManagementNode()
                if profile.plan_radiation = null then
                    generate radiation_response_plan()
                    send notification()
                    call socket.emit(notification)
                    get listUser = getListUser()
                    send notification to listUser
                end if
            end if
        else if data = mobile_node_data() then
            if data.Gamma_Avr > 0.3 then
                response ="Confirm incident radiation"
                send response to web/app
                if data.Gamma_Arv > 100 then
                    level = 3
                else if data.Gamma_Arv > 1 then
                    level = 2
                else if data.Gamma_Arv > 0.3 then
                    level = 1
                end if
                message ="incident radiation: level"
                socket.emit(message)
            end if
        end if
    end if
end while
```

According to IAEA recommendations [2], radiation incidents are divided into 3 levels: level 1 is dangerous when measured values are in the range: 0.3–1 μSv/h; level 2 is a very dangerous level when the measured value is in the range of 1–100 μSv/h; level 3 is an extreme dangerous level when the measurement value is greater than 100 μSv/h. However, the threshold levels can also be adjusted correspondingly (by remote configuration command) to the environment background in each specific area. The algorithm to analyze and process data on the application server to trigger radiation incident warning levels is shown in Algorithm 1.

3.3. Radiation Incident Handling Procedure

During the radiation incident handling procedure, the person in charge is responsible for notifying and directing relevant units to promptly handle the incident. The IoRSS system provides an interface that allows the administrator to create message contents and send them to the application server. The system will automatically send this information to relevant units and individuals by SMS and e-mail. The flowchart of creating and exchanging information to support radiation troubleshooting is shown in Fig. 7.

The IoRSS system also provides commands to control radiation detection devices and query radiation parameters remotely through the interface of application software. This mechanism allows the user to know the device's status, configure the operating mode for the devices, and collect information about the operating environment of the device without having to approach the devices, on the assumption that the environment is radioactively contaminated.

3.4. Radiation Incident Control and Update

In the procedures of controlling and updating troubleshooting information, the administrator can also use the system's interface to update information on the progress of control and troubleshooting, radiation source recovery, clean the environment and finish the problem according to the algorithm shown in Fig. 8.

4. Test Results and Analysis

In this section, we present the results of comprehensive field tests in scrap metal recycling and production facilities to evaluate the performance of the proposal.

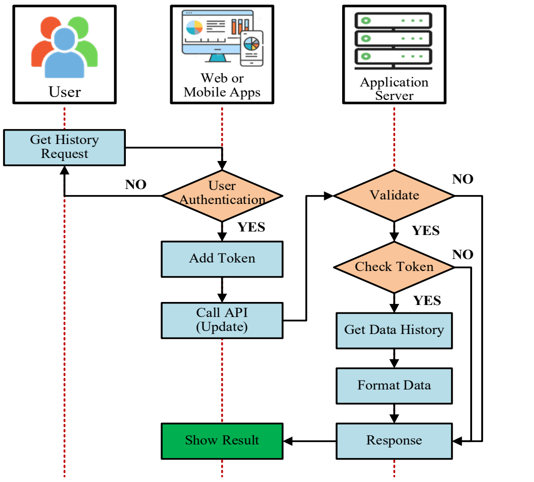

Fig. 7. Flowchart of support information channels and radiation incident handling process.

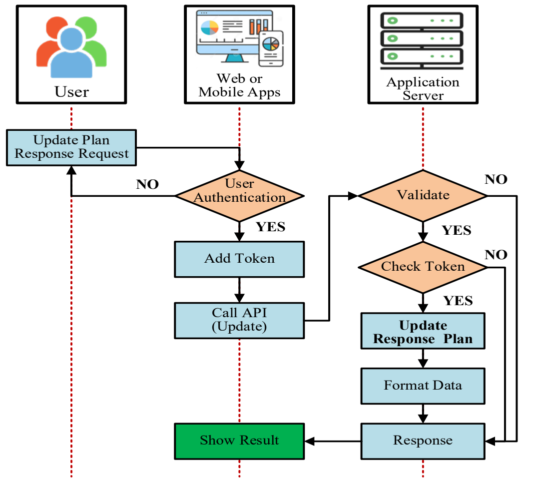

Fig. 8. Flowchart of radiation incident control and update processes.

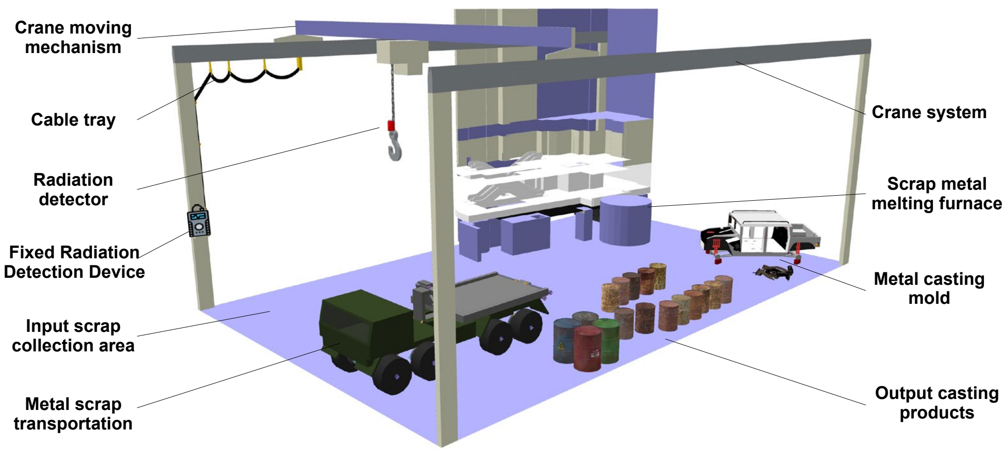

Fig. 9. Diagram of the IoRSS deployment and installation in a scrap metal recycling facility.

4.1. Testing Scenario and Installation

Radioactive sources, if present in metal scrap, are usually shielded by metal materials, resulting in very low levels of radiation released into the environment. Therefore, to increase the probability of being detected, the location of the radiation detection system installation in this case is essential. Based on the actual survey results, we suggest some of the best installation locations, which are at the entrance of the incoming scrap truck, next to the weighing station, on the crane used to transport materials, next to the input/output slider or in front of the metal furnace door. Radiation detection devices installed at these locations provide the highest detection efficiency while ensuring little impact on the production activities of the facility.

Fig. 9 illustrates a scenario for the installation a radioactive detection system in a scrap metal recycling facility. Consequently, a fixed radiation detection device is arranged on one side of the entrance to measure the radiation levels of vehicles that transport metal scrap when entering the recycling facility. The radiation detector can be installed on the crane hook, which is moved by the crane moving mechanism. The radiation detector is connected to the central processing unit of the fixed device via a cable arranged in the hanging chute. Crane system brings scrap metal from the transport vehicle to the input scrap collection area to prepare for putting into the furnace or transporting the output cast product to the output yard. According to this installation, the radioactive detector is always approached to the input scrap and the output product at the best distance to be able to detect the smallest radioactive source, if any, either in the scrap or in the product output (in the worst case, the ability to detect radioactivity at the input is missed). If radiation is detected, the fixed device will issue a local alert and send a primary warning to the server. Radiologists can use mobile devices to verify the primary warning and to accurately detect the location, level, and type of radiation source. In addition, cameras and accelerometers (not shown in the figure) can also be placed at suitable locations to record images and determine the speed of each vehicle when exiting and going to the recycling facility.

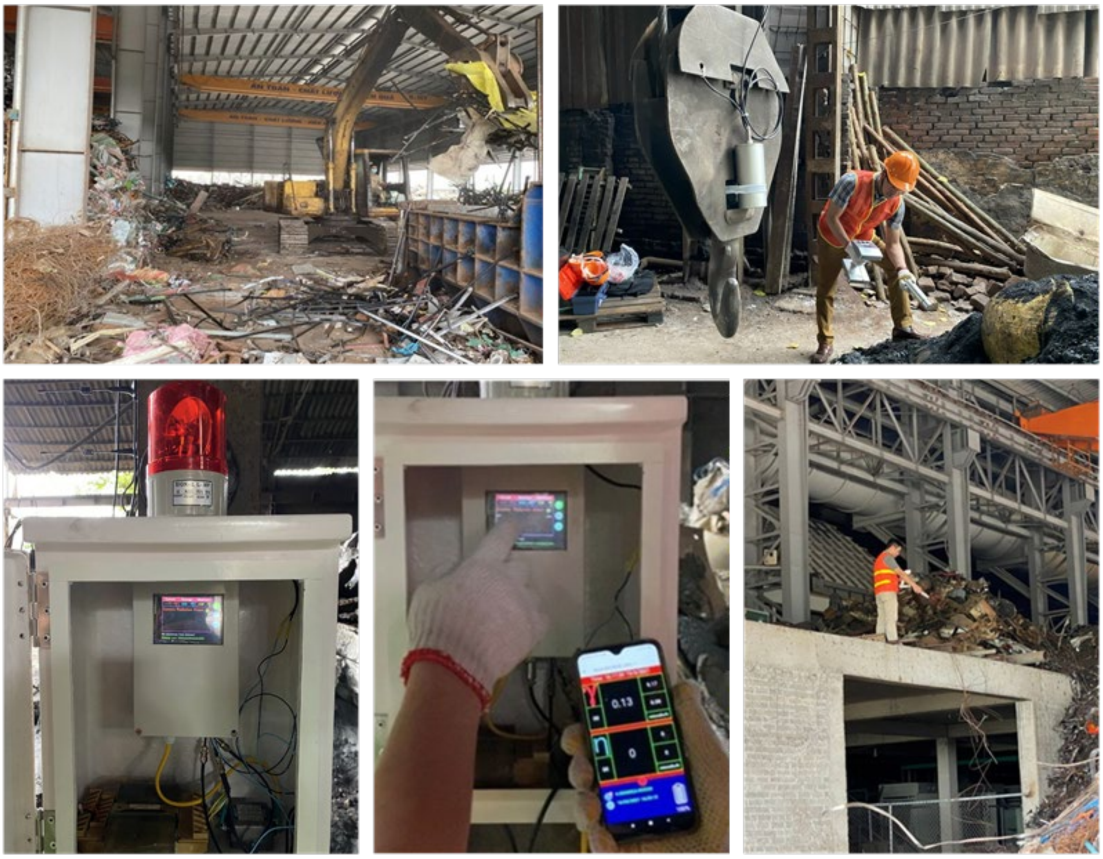

Fig. 10. Images of testing the radioactive detection system in a scrap metal recycling facility.

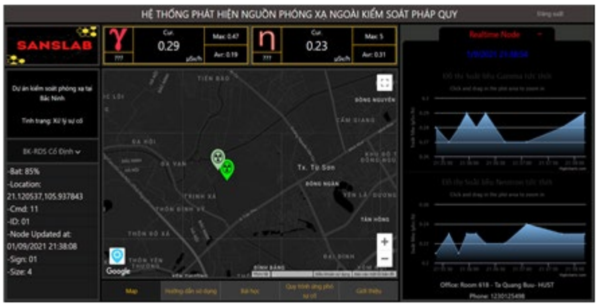

Fig. 11. Images of the user application on a web-based interface.

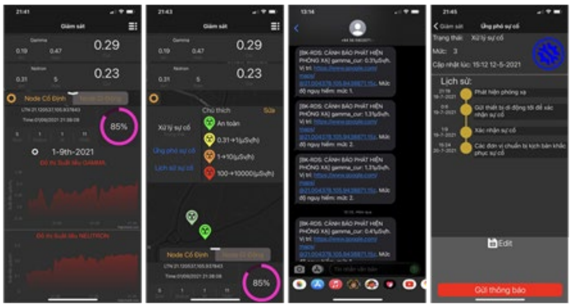

Fig. 12. Images of the user application on a smartphone.

4.2. Operation Activities

After being assembled and dosed in the laboratory, the proposed system was tested several times in the field. The test configuration includes one fixed device and two mobile devices. The fixed device is installed according to the recommended scheme as shown in Fig. 9., Fig. 10 includes images of a test system at a scrap metal casting facility. The results show that the radiation detection system works stably and does not affect the operation of the foundry. The main test activities and their results are shown in Table 1.

4.3. Web-based and Mobile Applications

Fig. 11 and Fig. 12 are some images of the web-based application and smartphone application, respectively, which show the functions of object management and configuration, radiation detection and warning, radiation incident handling, radiation incident control and update, and real-time radiation source surveillance.

Table 1. List of test contents and achieved results of the IoRSS system

Testing and Assessment	Results and Achieved Parameters
Radioactive background measurement	Change around the value of 0.1 μSv/h; Minimum dose rate: 0.05 μSv/h Maximum dose rate: 0.36 μSv/h; Average dose rate: 0.12 μSv/h
Radiation detection and primary alarm generation functions of the fixed device	Display and update the measured value continuously on the screen; Trigger the main alarm when the measured value exceeds the pre-set threshold
LoRa communication connections	Send data and receive control commands with transmission delay less than 4.8 s
3G/LTE communication connection	send messages directly to the network server; receive control command response and send ACK reply correctly
Operate the crane and observe the operation of the fixed device	The fixed device still operating stably
Radioactive source identification and secondary warning generation functions of mobile devices	Radioactive sources (test samples) are identified by spectroscopy and the device generates a secondary alarm
GPS positioning function	Displays the correct current coordinates of devices on the digital map of applications
Energy consumption of mobile devices	Battery power drop after 1 hour of operation is less than 2% of 3400 mAh rechargeable battery, the capacity loss is around 1.5%

5. Conclusion

In this paper, we have designed and developed the Internet of Radiation Sensor System (IoRSS) to detect radioactive sources outside regulatory control in scrap iron and steel recycling and collection facilities. The test results show that with the proposal of algorithms, software tools, and automation of the information processing to optimize the limited resources, the IoRSS provides a more robust detection capability and improves the use of data analysis in the assessment of radiation incident detection and response. In the future, various types of sensors and detectors will also be integrated into the system to enable the detection of other types of hazardous materials such as explosives, biological agents, and weapons. We will also develop algorithms and advanced data processing models using artificial intelligence to provide smart services and applications.

Acknowledgement

This work was supported by Bac Ninh Department of Science and Technology (DOST) under Contract number 44/HD-2018.

References

[1] IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, IAEA, Vienna, 2007.

[2] Recommendations on Monitoring and Response Procedures for Radioactive Scrap Metal, ECE/TRANS/NONE/2006/7, Vienna, 2006.

[3] Code of Conduct on the Safety and Security of Radioactive Sources, IAEA/CODEOC/2004, Vienna.

[4] E. Brewitz, J-C. Lindhé, E. Welleman, Swedish experience and lessons learned from contaminated scrap metal, in Proc. Int. Conf. Tarragona, Spain, 2009, pp. 253–261.

[5] Control of Orphan Sources and other Radioactive Material in the Metal Recycling and Production Industries, IAEA Safety Standards: Specific Safety Guide, No. SSG-17, Vienna, 2012.

[6] Huban A. Gowadia and Kimberly Koeppel, Nuclear detection technologies, UNSCR 1540 COMPASS, Issue 3, pp. 29–33, 2014.

[7] V. Tran-Quang and T. Miyoshi, APREES: Adaptive routing protocol for large-scale wireless sensor networks, in 2007 Commun. Society Conf. of IEICE, 2007, pp. S–154.

[8] V. Tran-Quang, T. Ngo-Quynh, and M. Jo, A lateration-localizing algorithm for energy-efficient target tracking in wireless sensor networks, Ad Hoc & Sensor Wireless Networks, vol. 34, no. 1-4, pp. 191–220, 2016. https://doi.org/10.1186/s13638-016-0517-4

[9] V. Tran-Quang and T. Miyoshi, Energy balance on adaptive routing protocol considering the sensing coverage problem for wireless sensor networks, in Proc. Commun. and Electron., 2008, pp. 86–91. https://doi.org/10.1109/CCE.2008.4578938

[10] T. Ngo-Quynh, V. Tran-Quang, and Q. Nguyen-Trung, A low-latency communication protocol for target tracking in wireless sensor networks, EURASIP Journal on Wireless Commun. and Netw., vol. 2016, no. 1, p. 33, 2016. https://doi.org/10.1186/s13638-016-0517-4

[11] A. Holst, Number of IoT connected devices worldwide 2019-2030, Jan 20, 2021. [Online]. Available: https://statista.com/statistics/1183457/iot-connected-devices-worldwide/

[12] Q. Zhou, K. Zheng, L. Hou, J. Xing, and R. Xu, Design and implementation of open lora for IoT, IEEE Access, vol. 7, pp. 649–657, 2019. https://doi.org/10.1109/ACCESS.2019.2930243

[13] Security of Radioactive Sources: Implementing Guide, IAEA Nuclear Security Series, Vienna, vol. 11, 2009.