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Design and Development of a Radiation Survey and Rescue Robot with Shielding of Electronic Equipment from Radiation Damage with Image Radiation Mapping Facility

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Abstract

The use of remote-controlled robots in emergency fields is a necessary requirement at present, which includes the nuclear engineering field because the radioactive environment creates adverse effects on human health. This work describes the development of a remotely controlled rover capable of detecting ionizing radiation, isolating radiation sources using a robotic arm, and sufficient shielding for its internal components. A custom-made Geiger–Muller counter has been used to detect ionizing radiation. The radioactive environment is not only harmful for humans but also can cause severe damage to the electronic circuit mounted on the robot. Therefore, a custom concrete material sandwiched between lead sheets has been employed to shield internal electronic components. The rover is connected to a web application to visualize data such as background radiation, location, and surveillance; thus, the operator can perform their actions from a remote and safe location by using Internet of Things devices. The rover is expected to be used in nuclear facilities to monitor background radiation data and help workers to minimize exposure from unshielded radiation sources. Other than this use, in case of emergency, the rover can find the radiation source in a highly radioactive environment, pick it up using its arm, and isolate it by putting it on the shielded box mounted over the rover. In a nuclear medicine facility,
the rover can handle radiation sources and reduce unwanted exposure to occupational exposure groups.

**Keywords:** Radiation detection robot, radiation shielding, IoT devices

### 1. Introduction

In nuclear facilities, it is frequently necessary to investigate and characterize a space with limited access because of the potential of extremely high radiation exposure [1]. Any environment with excessive radiation is dangerous for humans to work in. Radiation is an unseen threat that can cause varying health effects to humans. These effects can be broadly classified into two groups—stochastic and deterministic. Contrary to severity, the probability of severe health effects caused by stochastic effects is a function of dose. In the case of deterministic effects, a threshold dose is required for a particular health effect, and the severity of the health effects is a function of the dose received, unlike stochastic effects [2, 3]. Examples of stochastic effects are cancer and hereditary effects. In the case of deterministic effects, examples are acute radiation syndrome, hair loss, infertility, skin reddening, and development issues in unborn children [4]. Therefore, early notification about any unwanted radioactive source in a place, especially in nuclear facilities, can reduce risk to the workers [5]. A rover that can detect radioactive sources by measuring background radiation can help achieve this objective. Additionally, the rover can handle the source using a robotic arm. A widely used term in the radiation protection field is ALARA, which stands for as low as reasonably achievable. ALARA strongly emphasizes reducing ionizing radiation exposure to a reasonable level while still achieving the exposure goal [6].

The motivation of this work is to monitor the radiation of a nuclear facility continuously, measure the fatality of the radiation, and depict the radiation doses in a radiation map. In case of emergency, this robot will be able to go to a highly radioactive area to isolate the radiation source and contaminated object without damaging the electronic circuits of the robot.

To implement this goal, the time, distance, and shielding principle will be considered throughout the design to maximize radiation protection for workers and the general public [7, 8, 9] with the help of practical robots [10, 11]. An autonomous robot that is actually able to generate the radiation cost map in combination with a normal cost map is proposed in terms of a radiation heat map [12, 13]. However, this method does not ensure the safety of the robot itself in a highly radioactive area [14, 15, 16]. In a highly radioactive environment, radiation hardening is a very important phenomenon [17, 18]. It causes significant damage to structures. In the case of radiation mapping, low counts and noisy data are problems that are diminished by adopting the Gaussian regression technique [19]. Moreover, detecting a source position using the robot is also a key point; it can be achieved using four steps [20]. The steps are (1) building an occupancy grid map, (2) collecting data along the appointed direction, (3) estimating the source position coordinates, and (4) evaluating intensity using a probabilistic approach and depicting the map where high intensity determines the position of the source. All these robots are prone to damage owing to high radioactivity because the semiconductor devices are
susceptible to high radiation, which can damage the lattice structure of the semiconductor devices instantaneously [21, 22]. Gaining stakeholder confidence requires testing and verification of robotics in real-world situations but is hampered by the limited availability of facilities housing radioactive materials [23]. For this reason, a wireless network system is useful in controlling the adverse situation of high radiation [24]. The safety of the operators who are operating the robot is another important point of concern, so implementing the Internet of Things (IoT)-based device is also done for the sake of their safety [25, 26, 27].

2. Design and Development

a. Rover Chassis
A rocker-bogie design was developed, keeping cost-effectiveness in mind. This design aimed to make a rover that could access any place of a nuclear facility. A computer-aided design (CAD) model of the developed rover is shown in Figure 1(a), and Figure 1(b) depicts the developed robot. The main parts of the rover’s structure are the body, circuit box with shielding, isolation box, robotic arm, radiation detector, and camera mounting mechanism.
Figure 1. (a) CAD model of main body and (b) developed radiation monitoring rover.

The main body of the rover is built with stainless steel, ensuring its rigidity and structural integrity. To build the rover’s frame, 1 × 1 in., 1 mm thick stainless steel, square-shaped tube was used. The main platform of the rover has a dimension of 24 in. This platform is used to place all the components of the rover, such as the arm, isolation box, circuit box, and more. The frame has the same dimension as the platform. Necessary holes were made on the platform to attach the components above it and to route the cables.

To maximize the frame’s strength and accommodate all the necessary components, a crossbar was welded in the inner section of the frame using the identical square-shaped tube of the same thickness of that used to build the frame, as shown in Figure 2. As a result, the main platform can be appropriately placed on the frame. Additionally, the frame is 12 in. above the ground, which offers great ground clearance. Three legs have
been used in the rover, and the front two legs are identical. All the motors used are attached to those legs. Necessary screws, nuts, and shafts of the required size and shape have been used to assemble the abovementioned parts.

![Figure 2. CAD model of (a) main frame, (b) leg mount housing, (c) front leg, and (d) rear leg.](image)

To attach the legs of the rover with the frame, stainless steel shafts of 16 mm diameter and 140 mm length were fabricated in a lathe machine, along with a side-mounted bearing located on the legs. The factory-built motor mounts were used to mount the motors with the leg. To attach motor mounts, 3 × 1.8-in., 2 mm thick stainless steel plates were welded to the legs. Following that, necessary holes were drilled to attach the motor mounts with screws.

Each front leg of the rover contains two square tubes, each 19.25 in. long. This length allows the ground clearance of 12 in. Two 1.5 mm thick triangular plates were welded to make a place for the bearing and the shaft. A hole with an 18 mm diameter was created at the center of the triangle to insert the shaft. The CAD model of the front leg is shown in Figure 2(c).

The rear leg was built similarly; its dimension is shown in Figure 2(d). To attach the legs to the frame, rectangular stainless steel tubes measuring 1 × 2 × 6 in. and having a thickness of 2 mm were drilled to make a hole for the shaft and the 8 mm threaded bolts. Next, bearings were added to the legs to support the weight and reduce friction,
allowing for smooth relative motion between the parts. Three of these were added for each leg. Figure 2(b) shows the entirely constructed rover.

**b. Rover Control Unit**

An Arduino MEGA, six DC geared motors, four BTS7690 motor drivers, and a radio frequency (RF) transmitter and receiver unit are the main components of the rover’s control system. An RF transmitter and receiver were used to control the rover remotely, with the transmitter sending user commands to the control system via the microcontroller. The transmitted signal was received by a Flysky receiver, which was then processed by the Arduino MEGA using the “pulseIn” function to generate commands for driving the motor drivers in forward, rearward, right, and left directions. Directional movement is depicted in Figure 3.

Figure 3 shows that in the case of forward or backward movement, wheels for both the left and right sides need to rotate in the same direction. However, to maneuver the rover in a left turn, the left wheels of the rover will turn anticlockwise, but the right wheels will turn clockwise. For a right turn, the opposite will take place. Four BTS-2550s drivers were chosen to supply power to the motors because they could supply a large amount of current. Six geared DC motors with 300 rotations per minute were employed for the drive system. The entire construction, including shielding, weighs around 40 kg, necessitating a very high current to provide the required torque, which is why the BTS driver was chosen. A 12 V, 7000 mAh lead acid powder battery was used for power delivery, providing power for approximately 25 min. The BTS motor drivers delivered power to the motor from the battery. Vero board was used to create custom power rails of 12 V and 5 V to deliver power to the four motor drivers efficiently.
The major components of the control systems are highlighted in Figure 4, which explains the general pathway via which the rover operates. A very simple and efficient control system has been designed, as shown in the diagram.

Based on an online-available unistepper model, an articulated arm was developed. It consisted of three stepper motors, 3D printed gears, brackets, a base, and links. It also consisted of a commercially available articulated claw, which was operated using two 9 kg servo motors. The whole arm was controlled using an Arduino UNO and CNC shield v4, along with an A4988 stepper driver. The controls for the arm came from the Flysky FS-CT6B transmitter and were received by an FS-CR6B receiver. For live video surveillance of the rover and its surroundings, two sets of ESPs-based cameras were employed; one set was mounted on the arm link, and the other set was put on an actuated platform that was 3D printed and managed by the server used for the camera’s live feed, which is shown in Figure 5.
c. Radiation Detection and Telemetry Unit

To enable continuous environmental monitoring and remote visualization of the radiation data from the control room on the web, a Geiger–Muller (GM) counter, which is an IoT-based detector, was designed for the Rover. The GM counter was developed by modifying the design of the smartGiger [28]. The GM counter system workflow diagram is shown in Figure 6.

Figure 5. View from onboard ESPs-based camera.

Figure 6. GM detector workflow diagram.
The Rover uses the SIM868 GPRS (general packet radio service) module in the GPS (Global Positioning System) tracker system depicted in Figure 7, which enables the detection system to not only measure the radiation exposure but also display the information on a map on the operator server.

![Sim868 GPS Module]

**Figure 7. SIM868 GPS (Global Positioning System) module.**

Data communication from the custom-made GM counter depicted in Figure 8 to the operator requires an internet connection. The GM counter also features a buzzer device to warn of dangerous radiation levels. The GM counter transmits radiation data using an internet-connected ESP32 module, which it subsequently shares through the machine-to-machine protocol with a local server and a web server. Radiation data are first received, and then the data are processed for visualization.

![Custom Circuit Board and SBM20 GM Tube]

**Figure 8. The custom circuit board and the SBM20 GM tube.**

A simple user interface shown in Figure 9 was developed for the operator to monitor the radiation dose and visualize a map to detect the radiation source position.

![User Interface]

**DOI:**
The rover constantly scans the region and transmits data at regular intervals. The operator can quickly assess the received data from the data table depicted in Figure 10.

A radiation heat map was embedded onto the map using the rover’s data so that the operator may quickly locate the location of the high-level radiation source while looking at the map. Figure 11 shows that the radiation source with the value of the activity is displayed in the map.
d. Radiation Shielding Unit

**Shielding Design for Rover**

Electronic equipment can malfunction when exposed to radiation. Electronic equipment that can face radiation damage are transistors, resistors, capacitors (mainly electrolytic capacitors), inductors, connectors, switches and relays, and semiconductor-based equipment. To protect the electronic components of the rover, shielding is required. The absorption dose of all electronic equipment in the rover is independent of their mass. However, it is a function of geometrical parameters such as size, orientation, and arrangement of shielding in the device.

To safeguard the electronics, a circuit box is made of 2 mm thick lead sheet. One sheet is placed at the bottom of the box on top of a 1 mm thick stainless steel sheet that serves as the rover’s platform depicted in Figure 12(a) and Fig. 12(b). On either side of the shielding box, two sheets with a gap of 10–20 mm are used. These gaps are meant to house a different combination of shielding materials; together with the lead sheets, this combination increases the effectiveness of overall radiation shielding. The bottom of the circuit box comprises two sheets of $10 \times 10$ in. lead sheets with no space in between; two identical sheets are also used as the top lid of the circuit box. The dimension of the circuit box is $10 \times 10 \times 5$ in., which was formed by cutting, rolling, and finally shaping two lead sheets. In Figure 13, a CAD model of the circuit shielding box is
shown. Experimental samples of shielding material were placed in the gap to effectively limit the radiation exposure, as shown in Figure 14.

![CAD model of circuit shielding box and construction](image)

**Figure 12.** (a) CAD model of circuit shielding box and (b) construction of circuit shielding box.

![CAD model of container shielding box and construction](image)

**Figure 13.** (a) CAD model of container shielding box and (b) Construction of container shielding box.
The container follows the ALARA principle, which states that radioactivity should be kept as low as reasonably achievable, to decrease the effect of radiation on a person.

For safety and security purposes, the container box has a lid that can only be opened and closed by the operator from the control system. The lid opener uses a servo motor and lever mechanism to lift the 1 kg lid. Additionally, plastic boards are used to cover the entire shielding to minimize exposure to lead, which has toxic effects on the human body.

**Shielding Materials**

To improve the shielding efficiency and reduce overall shielding weight, a set of the concrete board with varying compositions were fabricated and are placed in the gap of the circuit shielding and container box.

The compositions that were prepared in different ratios are shown in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sand (gram)</th>
<th>Cement (gram)</th>
<th>Iron (gram)</th>
<th>Water (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>40.25</td>
<td>40.15</td>
<td>29.95</td>
<td>45</td>
</tr>
<tr>
<td>P2</td>
<td>64.89</td>
<td>29.90</td>
<td>15.65</td>
<td>36</td>
</tr>
<tr>
<td>P3</td>
<td>55.02</td>
<td>24.90</td>
<td>40.35</td>
<td>40</td>
</tr>
<tr>
<td>P4</td>
<td>55.55</td>
<td>20.65</td>
<td>52.15</td>
<td>40</td>
</tr>
<tr>
<td>P5</td>
<td>41.55</td>
<td>14.8</td>
<td>60.93</td>
<td>45</td>
</tr>
<tr>
<td>P6</td>
<td>90.3</td>
<td>31.2</td>
<td>0</td>
<td>45</td>
</tr>
</tbody>
</table>

The boards are placed in the gap between the sheets of the box after being fabricated and placed in a plastic bag.
3. Results and Discussion
The accomplishments of this rover include the following:

- Remote operation and measurement of radioactivity with a custom-made GM counter
- Visualization of radiation data using a web app in conjunction with the GM counter
- Representation of the radiation data in the form of a heat map with the location of the source
- Ensuring protection from radiation with shielding to avoid failure of the rover’s electronics because of ionizing radiation

a. Shielding Effectiveness Analysis
Figure 15 shows that lead is very effective in reducing the radiation dose that the rover’s internal electronics are exposed to. Lead can decrease the radiation dose by a very significant amount.

The concrete samples of different compositions can increase the effectiveness of shielding when used alongside lead, resulting in a reduced overall radiation dose. The concrete boards were chosen instead of lead of the same thickness to reduce the shielding weight by some amount. The attenuation coefficient can describe the effectiveness of the shielding by the lead sheets. Figure 16 shows the change of attenuation in lead with respect to incident radiation energy.
Figure 16. Attenuation coefficient for lead.

Figure 16 was generated using uFinder, which is free software used to calculate the mass attenuation coefficient at different energies for different compositions of materials [29, 30]. The mass attenuation coefficient measures the effectiveness of any radiation shielding, referring to the loss of energy of a radiation beam while propagating through a medium. The higher the mass attenuation coefficient, the better a material provides shielding. The total mass attenuation coefficient of the lead material used is higher for low-energy radiation. With an increase in photon energy, the attenuation coefficient decreases until it reaches equilibrium. However, several instances of abrupt spikes and subsequent falls can be observed within the energy range of 1 KeV to 10 MeV. The number of spikes can vary with varying material compositions.

4. Conclusion and Recommendations

The following accomplishments are considered:

- The six-wheeled rover was developed, which can operate in rough terrain and can be operated remotely with the mounted cameras, and operation of the rover can be observed remotely. With the custom-made GM counter, radiation measurement and monitoring is completed. Data are observed in the form of a radiation heat map, which is depicted in a web app. Moreover, the robot can be operated from distant places using IoT devices.
- The rover ensures shielding to the electronic equipment mounted on it from the radiation with the customized lead and concrete shielding boards. The result is shown in the Results and Discussion section.
- In case of emergency, the rover can be deployed in a radioactive environment, where it can find the radioactive source with a GM counter and can isolate the radioactive source by picking it up with the robotic arm mounted on the rover.
Additionally, the source and contaminated object can be stored in the lead-shielded box mounted on the rover.

Future recommendations include the following:

- With the inclusion of the map, full automation of the rover may be included with the object detection capability.
- The result of the shielding with the lead is validated in this work; however, in the future, shielding of the other materials may be validated.
- An air sample collector may be added for further data collection.

5. Acknowledgments

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6. References


