Design and Optimization of a Directional Radiation Detection System

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Abstract – *Radiation detectors are essential for upholding nuclear security and safety. The main objective of this study is to design and develop a new radiation detection system that can locate the position of a radioactive source using Geiger-Muller (GM) detectors. Three GM detectors are utilized in this system, with their relative angles known. The system collects data on radiation exposure levels in the immediate area surrounding the GM detectors and sends it to a Raspberry Pi 4 processor. After that, a MATLAB algorithm analyzes the data using localization methods to determine the source direction. To provide a user-friendly experience when using the system, a graphical user interface (GUI) was designed and implemented to be used with the system. The benefit of the localization methods that can be applied with MATLAB algorithms is that they offer great accuracy, rapid response, and low cost. The methods can be applied in fields like environmental monitoring, homeland security, and nuclear power plant safety, in addition to locating lost radioactive materials and other radiation security and safety concerns. An experimental setup is prepared to test the radiation detection system in a laboratory environment. A Cs-137-point source was used to study the system response. The results show that the system can detect a point source accurately when the source is stationary, while the location is not as accurate while the source is moving.*

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Keywords: Directional Radiation Detection System, Localization algorithm, Geiger–Müller (GM) Detectors, Raspberry Pi 4, Signal Processing.

I. Introduction

Radiation detection has been of interest to scientists and professionals since the discovery of radioactivity back in 1896 by Henri Becquerel [1]. Furthermore, engineers and scientists have designed and created several types of radiation detection systems, which came of interest to many industries such as nuclear security applications, environmental monitoring, facility monitoring, and emergency response. These radiation detection systems can benefit the workers to avoid unnecessary radiation exposures, and many of these systems might as well be attached to an unmanned aerial vehicle (UAV), which can help the workers monitor sites that are contaminated with high levels of radiation. Many radiation detection systems have been proposed in the past years, while only a few have been made commercial to the public. Becker et al. developed a radiation detection system that used 16 scintillation detectors to locate a missing radioactive source [2], this system uses a directional sensitive method to predict the direction of the radiation source; however, the main concern with this radiation detection system is that it uses 16 detection material to achieve that goal. Kunze et al. developed a new radiation detection system that can help Central Asian countries in monitoring and surveying the areas near the uranium mining zones. The main purpose of this proposed system is to help workers in looking for any type of radioactive materials that have leaked into the environment, this system creates a heat map of the surveyed area, which can show the contaminated area; however, this proposed system is considered not to be budget-friendly [3]. Chierici et al. proposed attaching a radiation detection system to a UAV, which is controlled by a ground station. The events detected can then provide a heat map of radiation levels in the surveyed area [4].

In this study, we have developed a radiation detection system that can predict the direction of a radioactive source by using only three Geiger-Muller (GM) Counters and a localization algorithm. The system detects photons emitted by a source and then analyzes them using a microprocessor (Raspberry Pi 4). After that, a localization algorithm predicts the position of the radioactive source. To make the system user-friendly, a graphical user interface (GUI) application was developed using Python language. This system was built and designed to be budget-friendly and can be attached to any unmanned aerial vehicle (UAV) system.

II. Design

II.A. Overview

The radiation detection system uses three GM detectors to locate the source of radiation. The detectors are arranged at specific angles concerning each other, which allows the system to determine the source's direction in two dimensions (2D). The system first converts the incident radiation into electrical signals, which are then converted into counts by the microprocessor. The microprocessor processes the counts produced by each detector using a localization algorithm to determine the source's direction. The result of the source's direction is displayed in the specially developed GUI for the user to view and interact with the system.

II.B. Mechanical Design

The mechanical design of the radiation detection system is crucial for its proper functioning and reliability. The system's structure must be robust to support the detector's weight and withstand environmental conditions, such as temperature changes and vibrations.

The system comprises three Geiger-Muller (GM) tubes placed in a triangular shape, and they are arranged at an angle of 45 degrees from the middle one. The middle tube is placed above the two others at a distance of 10 cm (See Fig. 1).

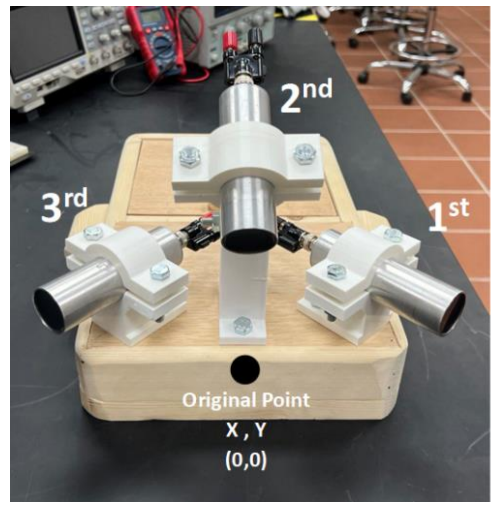

*Fig. **1** Front view of the radiation detection system, which shows the formation of the detectors.*

Moreover, a stage was designed to hold both circuits and the detectors in one container, so that it can be portable and can be attached to any UAV system (See Fig. 2). The stage was built using wood to make it an insulator for electrical current to reduce the electrical noise of the detectors. In addition, the holders of the detectors were designed and printed using the 3D printer to fix the position of the detectors inside the stage.

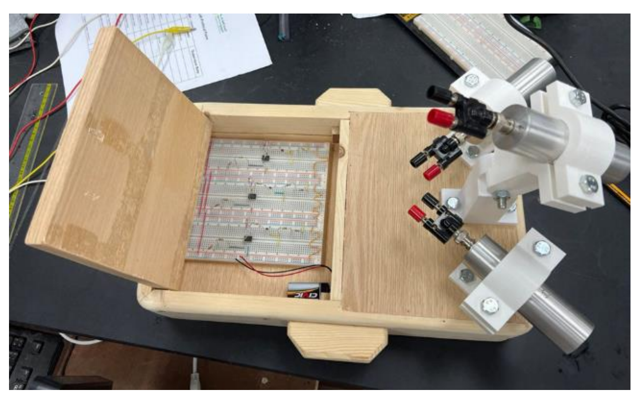

Fig. 2. The final design of the radiation detection system's stage from the top view.

II.C. Radiation Detectors

Several detector types were suggested in the literature to be suitable for finding lost sources. However, GM counters are considered more cost-effective, and therefore, were preferred over other alternatives.

Geiger-Muller tubes are radiation detectors that use the ionization of gas to identify ionizing radiation, such as neutrons, alpha, beta, and gamma rays. In addition to monitoring radiation levels in the environment, they may be used for a range of purposes, such as finding radioactive materials for use in industry, security, and the medical field. The LND 7232 is one of the most widely utilized GM tubes due to its superior sensitivity and durability. The LND 7232 is an alpha, beta, and gamma detector that uses Ne + Halogen as a fill gas. Also, the detector is equipped with a mica window of an effective diameter of 28.6 mm and can operate in a range of 850-1000 Volts [5].

II.D. Microprocessor

To detect and analyze radiation levels reliably and effectively, a radiation detection system must be built with the right microprocessor. The Raspberry Pi and Arduino are two of the most popular options for microprocessors.

With a Linux operating system, the Raspberry Pi is fully working on a computer with better processing and memory than Arduino. This makes it a suitable choice for tasks like radiation detection that are needed for rapid data processing and storage of large volumes. Additionally, compared to Arduino, the Raspberry Pi has a larger ecosystem and community that provides more resources and support for challenging projects. The Raspberry Pi also comes with a wide range of input and output connectors that make it straightforward to connect to various sensors and modules required for radiation detectors, such as Geiger-Muller tubes. As a result, the system architecture is more straightforward and easier to interact with other system components [6].

Compared to Raspberry Pi, the open-source electronics platform Arduino is easier to use and more affordable. It comes in a variety of sizes and shapes, contains input and output pins, and is helpful for a range of sensors and modules. Both inexperienced programmers and creative types can utilize Arduino since it can be written in a compressed version of C++. Arduinos usually use less electricity and have less processing power and memory than the Raspberry Pi 4 [7]. As a result, it is less suitable for challenging jobs that need the speedy processing and storage of large amounts of data.

As a consequence, it was chosen to power the system using a Raspberry Pi 4 B. The Raspberry Pi 4 B has far more processing and memory than the Arduino Uno Rev3, allowing us to detect and assess radiation levels with more accuracy. In comparison to the Arduino Uno Rev3, which has a maximum clock speed of 16 MHz, the Raspberry Pi 4 B has a maximum clock speed of 1.5 GHz, giving it a far better capacity for signal processing [6,7].

II.E. Electronics

Electronics are a must for GM detectors to run and perform as intended. The multiple electrical components that are included in these detectors allow for the detection and measurement of ionizing radiation. An often-used mode in GM detectors is the pulse mode. In this mode, the detector captures each distinct particle or photon interaction as a single pulse [8]. By counting and looking at these pulses, one can get crucial information regarding the type and activity of radiation. To utilize pulse mode the circuit in Fig. 3 was implemented for each detector. First, the circuit will need a high-voltage source to operate the detectors in the Geiger region. Then a resistor and capacitor are needed to eliminate the current from the high-voltage source and to have some type of trigger for the pulse. As a result, for the previous circuit, the pulse will turn out to be a negative voltage pulse, which is nonfunctional to be processed later with a Raspberry Pi 4 microprocessor. Therefore, an operational amplifier is used to reverse the signal and amplify it to saturation. Then, the voltage pulse will go through a voltage divider to reduce the amplitude of the pulse to the range of Raspberry Pi 4 input range (0 to 3.3 V [6]). Finally, a Python code was written inside the Raspberry Pi 4 to acquire signals and decide whether it is a count or not and present it in the GUI, which will be discussed next in this paper. In addition, the Raspberry Pi 4 will control the dead time of the detectors, which is fixed at 30 us but also can be adjusted easily to different values using the code.

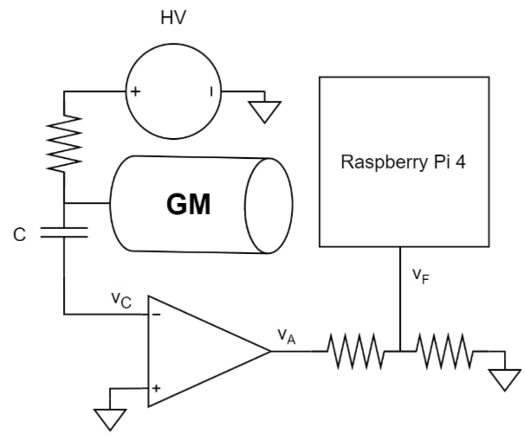

Fig. 3. Simplified schematic of GM counters circuit.

II.F. Simulation

To determine the direction of a radiation source using different angles with respect to different positions of the radioactive source, there are procedures needed to follow to achieve the objective. Therefore, a simulation has been done to achieve one of the main objectives of this study which is to utilize localization algorithms to identify the direction of the radiation source. This simulation was done by using Gate simulation.

Moreover, two simulations were done, and all simulations were based on one model, but with minor differences in the geometries, so it can achieve the objective of that specific simulation. The first simulation focused on finding the best angles between the detectors, and the least number of detectors needed to identify the direction of the radiation source accurately. The second simulation was developed to generate as much data as possible to test the localization algorithm in identifying the direction of the radiation source.

To enhance the realism of these simulations, a simulated world has been carefully crafted to replicate real-world conditions typically found in a laboratory setting. The simulated environment, including air to imitate laboratory conditions, has been meticulously designed. The default shape for the simulated world is a box, set at dimensions of 200 cm x 200 cm x 200 cm. Furthermore, the specifications outlined in this study (refer to Section II.C) are closely matched by the detectors employed to measure radiation within this simulated environment.

II.G. Graphical User Interface (GUI)

A Graphical User Interface (GUI) has been developed using the Python language and the Tkinter library. This GUI application, named KASHEF SYSTEMS, will provide the user with easier access and control over the system. KASHEF SYSTEMS will display to the user live average counting from each detector and a live plot of the counting. This will allow the user to read the previous counts of each detector more easily. Additionally, the user will also have the ability to adjust the collection time of the detectors and can start and stop the process of the system. Additionally, KASHEF SYSTEMS will provide the user with localization results from the localization algorithm, so that it can predict the position of the source. Fig. 4 shows the final design of the KASHEF SYSTEMS application.

Moreover, further features are expected to be added in the future, such as isotope identification and accurate position prediction, as shown in Fig. 4.

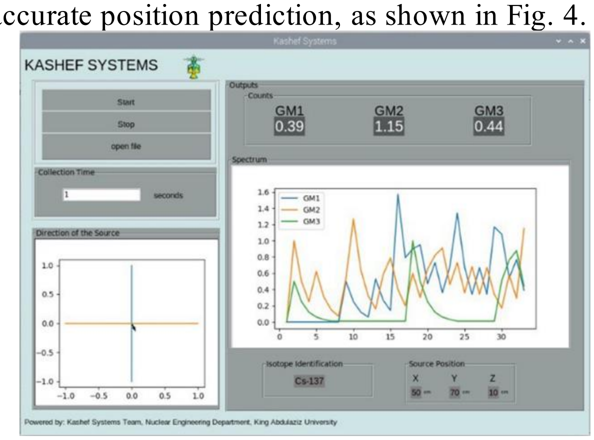

Fig. 4. The final design of the GUI application (KASHEF SYSTEMS)

III. Results

III.A. Location results

Several laboratory experiments have been performed to test the performance of the radiation detection system. A Cs-137-point source with an activity of 10.8 uCi was used to run the experiment. First, the source is placed 10 cm to the right of the system in the direction of the x-axis, which means that it is closer to the third and right detector as in Fig. 1. Importantly, Fig. 5 shows the direction of the radioactive source represented as an arrow pointing to the direction of the source. Moreover, each arrow represents the position of the source at each second while it moves at 10 cm/s toward the detectors. When the source moves closer to the detectors the accuracy and the precision of the predicted direction get higher. Another important factor is the main position of the source (x, y), where another experiment has been performed with the same conditions as the last experiment but this time with a different x-axis position of - 30 cm to the left of the system, which means it is closer to the first and left detector as in Fig.1 to evaluate the method performance with farther positions from the system. Fig. 6 shows the same behavior as Fig. 5 but with higher precision due to the farther x-axis position, which resulted in a higher difference between the three detector counts.

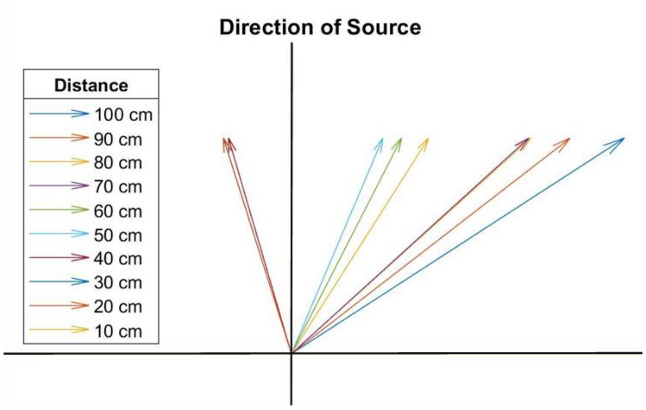

Fig. 5. Results of the predicted directions of a source placed 10 cm to the right of the system while the source is moving toward it.

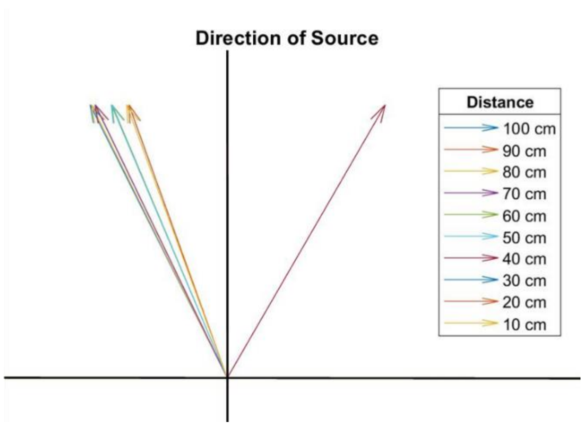

Fig. 6. Results of the predicted directions of a source placed 30 cm to the left of the system while the source is moving toward it.

III.B. Geiger-Muller Efficiency

One of the most important aspects to analyze in any radiation detection system is the detector's efficiency. The efficiency of the GM tubes could change with any slight changes in the circuit or coding part of the GUI. Therefore, a total efficiency calculation has been done including all the factors that affect it like the circuit and the GUI. Efficiency was calculated using the following equations:

$$\varepsilon = \frac{C_d}{A_{th}} * f * 100 \quad (1)$$

$$f = \frac{1}{2} - \frac{d}{2*\sqrt{x^2+d^2}} \quad (2)$$

where C_d represents the counts detected by the detector and A_{th} the theoretical activity of the source., moreover f counts for the fraction of emitted radiation that interacts with the GM tube window [9], where it consists of only two parameters to be calculated x and d, the radius of the GM tube window and the distance between the source and the GM window respectively. As a result of these calculations, the efficiency of GM tubes turned out to be around 0.585%.

IV. Discussion

IV.A. Circuitry

To be employed as a count, the captured charge must go through several signal-processing stages. The primary voltage source was first attached as a high voltage source with a 1000 Volt output. The circuit is then completed with a 2M Ohm resistor to eliminate the current flow. The Geiger-Muller tube receives around 840 volts due to the voltage drop after the resistor, which is sufficient to enter the Geiger region. A 5-pF capacitor located in the same tube node will also experience a reduction in voltage (See Fig. 7) when a current is sent through it due to radiation interaction within the GM tube.

Fig. 7. Voltage drops due to radiation interaction after the capacitor, captured using Siglent SDS2202X-E Oscilloscope.

First, the Raspberry Pi 4 cannot sustain the negative voltage drop in Fig.7. Therefore, the signal is reversed using a general-purpose single operational amplifier of type ST UA741CN. The amplifier used a 9-volt battery as power source and employed 150K and 1M ohm resistors to achieve a gain of -6.67 volts. Another crucial point to be aware of is the Raspberry Pi 4's limited operating voltage range of 0 to 3.3 Volts. As a result, a voltage divider made of 65K and 22K ohm resistors must be used to reduce the voltage coming from the op-amp from 9 volts to around 2.276 volts as shown in Fig.8. Finally, the output voltage signal will go through the Raspberry Pi 4 to be processed as a counter. The same circuit can be repeated for any number of GM tubes as much as needed until the Raspberry Pi cannot handle the processing well.

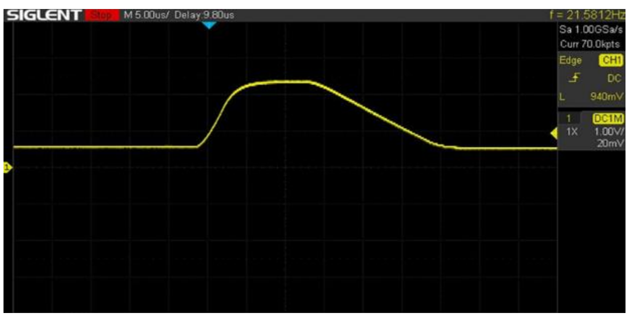

Fig. 8. Radiation interaction signal at the voltage divider after the op-amp, captured using Siglent SDS2202X-E Oscilloscope.

IV.B. Localization Algorithm

One of the main points of this paper is to develop and optimize a radiation detection system to be able to utilize different localization algorithms. Therefore, to test the functionality of the system, a simple direction prediction method has been used as in Fig. 5 and Fig. 6. When the system detects some radiation, it will first analyze the general direction, as if it is “right” or “left”, using a simple count comparison between the outer detectors, and if counts are very close to each other the decision will be in the middle. However, if the decision is either “right” or “left”, another comparison will be applied, but this time using the ratio of the outer detector with the middle one. For example, if the ratio is 1 that means the source is in the direction exactly between the outer and middle detector. Therefore, any increase or decrease in the ratio will result in a higher or lower angle of direction. However, this method has low precision in some cases, especially when the source is close to the system. In general, both accuracy and precision are good if the source is relatively far from the detectors.

Moreover, the authors of this paper are working on a futuristic algorithm that is called the Curve Similarity method, which is able to detect the position of an unknown radioactive source within three dimensions x, y, and z-axis. The method will be applied to the system as soon as it is ready and published.

IV.C. Simulation

In the first simulation, it was concluded that the best angle for the detectors that could collect the most data for all source positions was an angle of 45 degrees; in addition, it was concluded that the least number of detectors needed to have accurate data were 3 Gieger-Muller detectors (See Fig. 9).

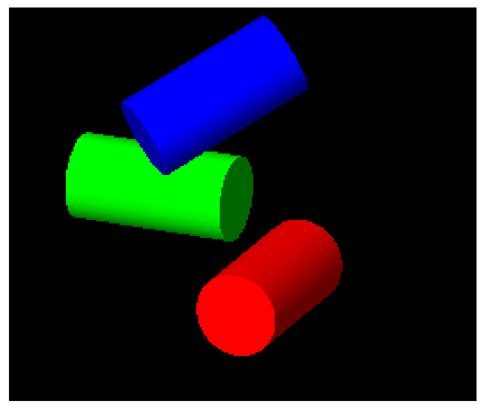

Fig. 9 The geometry of the simulated GM detectors in the simulation environment.

Moreover, the second simulation as mentioned in section II.F focused on generating data using a simulated environment to see whether the localization algorithm would work or not. It was concluded after analyzing the data, the localization algorithm could identify the direction of the radioactive source.

V. Conclusion

This study investigated the design and optimization of a directional radiation detection system that uses three GM detectors to identify the position of a radioactive source. The system was tested, and the results showed that it was able to successfully identify the direction of the source by using a localization algorithm which resulted in good accuracy. The system has several advantages over other radiation detection systems, including the ability to identify the source's direction, and it has its own graphical user interface. The system has potential applications in a variety of fields, including nuclear power plant safety, environmental monitoring, and homeland security. It could also be used to locate lost radioactive materials. The system is still under development, but it has the potential to be a valuable tool for the field of radiation detection.

Future work

The radiation detection systems field is considered a narrow field that carries a lot of potential to be developed in the future. The detection system which has been introduced in this study has many developing potentials as well. Soon the system will contain more detectors like NaI, and CZT detectors to serve as sources of new valuable data, which can be used for example to draw energy spectrums of specific types of radiation and predict the radioactive isotope. In Addition, a new method will be developed to predict the position of the radioactive in the three dimensions (x, y, and z). Finally, there will be more development on the graphical user interface (GUI) to provide the user with all the new features and easier access to the system.

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