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DETECTION AND LOCALIZATION OF RADIOACTIVE SOURCE USING A GEIGER MULLER COUNTER INTEGRATED ON MOBILE ROBOT BASED ON KALMAN FILTER

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Abstract- International Atomic Energy Agency (IAEA) claims that the Illegal Trafficking Database (ITDB) documented 3686 nuclear incidents in 2019 [1]. Among these accidents, radioactive waste concentrates radiation to levels higher than those found naturally in the environment. Humans are subjected to external irradiation when they are in close proximity to the radiation released by the waste's chemicals, internal contamination when they inhale or eat radioactive substances present in food or air, and external contamination when they are subjected to the waste's substances. Because radioactive waste contains chemical constituents that might be poisonous, it can potentially pose a threat. As a result, having a security system is critical. As a result, in the application of nuclear technology, it is critical to have a security system. For this, we have adopted as a solution a robot carrying a radioactive detector called a Geiger Muller counter, which makes successive detections during the robot's navigation and sends a message indicating the value of the doses read. Due to the high cost of Compton gamma cameras, we decided to introduce an autonomous research modeling of radioactive sources using a navigator robot carrying a Geiger Muller radioactive detector on a limited space. The Filter of Kalman is also used to properly locate the sources after radioactive radiation detection.

Keywords: Fuzzy Logic, Obstacle Avoidance, Kalman Filtering, Radioactive Sources.

1. INTRODUCTION

For the past thirty years, there has been a concentrated push in the domains of academia and industry to develop mobile robots that adapt with minimal human interaction. A first generation of robots consisted of devices capable of evolving in well-known environments: these carry out predefined missions (laboratories) or are content to follow a trajectory (handling robots). These robots all have one thing in common: they evolve in an environment that is entirely dedicated to them.

When the environment grows more complex (i.e., partially known, dynamic, etc.), it appears that the robot must be equipped with appropriate decision-making capabilities for the past thirty years, there has been a concentrated push in the domains of academia and industry to develop mobile robots that adapt with minimal human interaction. A first generation of robots consisted of devices capable of evolving in well-known environments: these carry out predefined missions (laboratories) or are content to follow a trajectory (handling robots). These robots all have one thing in common: they evolve in an environment that is entirely dedicated to them.

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When the environment grows more complex (i.e., partially known, dynamic, etc.), it appears that the robot must be equipped with appropriate decision-making capabilities as of December 31, 2019, the ITDB has 3,686 confirmed instances reported by Participating States dating back to 1993 [1]. Medical operations (x-rays and scanners), the nuclear industry (nuclear reactors), baggage inspection at airports, as well as defense workers and workers exposed to natural sources of ionizing radiation at their workplace are all affected by occupational exposure to ionizing radiation [2].

According to IRSN's most recent report [2], the occurrences primarily affect the nuclear sector, which has far better-established reporting systems for radiation safety events than other industries, including radioactive waste. The topic of our post, and which can lead to an over-representation of occurrences in different areas of activity.

The radioactivity of the samples collected in this context must be measured by accredited laboratories (such as CNESTEN in the case of Morocco). National Networks for Environmental Radioactivity Measurements RNM [3] manage this monitoring, which is usually done as close as possible to potential sources of inadvertent emission. Nuclear installations involved in the industrial stages of electricity production (former uranium mining sites; nuclear fuel fabrication, enrichment, or reprocessing plants; nuclear power stations; processing and storage of nuclear waste), nuclear research centers, and military ports housing nuclear naval bases are monitored in this context.

This article intends to develop a mobile robot utilizing Mamdani's proposed controller in order to evaluate the product's navigation system. The robots will be able to walk around in a radioactive environment thanks to a movement system that recognizes radioactive sources as objects in its route and calculates the distance, location, and default radiation dose value, all of which are sent to a laptop. To continue its trip, it takes the appropriate detours to avoid clashing with these sources. Based on the fuzzy controller concept, which should not be mistaken with the Fuzzy-Kalman filter, which combines the benefits of both principles. The assumptions put on the Kalman filter's internal model are a significant drawback. In the suggested combined Fuzzy-Kalman formulation, these assumptions are avoided by employing fuzzy logic, and the system parameters were calculated using Mat Lab software.

The detection for sources of radioactivity is challenging since the location and direction of the radioactive source are unpredictable, putting the search technique complicated [4]. A robot navigator carrying a radioactive detector across a confined environment uses the Kalman Filter to construct an autonomous searching modeling of radioactive sources. This article is planned as follows to study the above topics: Prototype robot placed in the affected region, as well as its equipment and attachments, as well as the technique to be followed, will be presented in section 2. Regardless of its strength, an automatic guided robot should be able to communicate with its environment, in order to collect relevant knowledge about the environment it has encountered for decision-making reasons [5, 6].

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Ionisant Radiation

Non-ionizing and ionizing radiation are the two types of radiation that can be found in the environment. Both natural and manmade sources of non-ionizing radiation are included in this category. One of the primary sources of background radiation is the sun. Alpha, beta, and gamma particles make up ionizing radiation.

The gamma radiation discussed in this article is at the far end of the electromagnetic spectrum, i.e., it has the greatest frequency and shortest wavelength. Although gamma rays may penetrate through almost any object, only materials with a large atomic weight, like lead, are capable of efficiently guarding or absorbing them. All Geiger counters can detect this very intense and potentially lethal kind of ionizing radiation. This happens when the tube is exposed to a constant amount of radiation and the voltage provided to the sensor is steadily raised [7]. Figure 1 depicts and discusses the Geiger Muller Counter's inside.

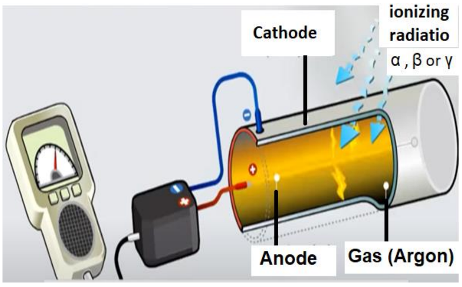


Figure 1. Description of detector Geiger Muller

The Geiger counter has a modest gamma discriminating capacity [7]. We powered the Geiger Muller sensor with 11 V battery and then sent radiation data to the laptop using a ZigBee transmitter device. Figure 1 presents conventional Geiger Muller-detector. The pulses sent by the detector on each count are shown in Figure 2.

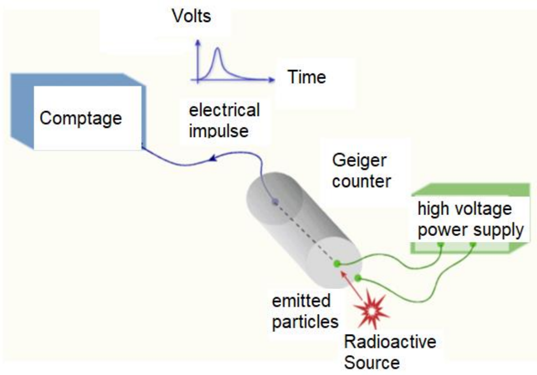


Figure 2. Detector Geiger Muller [7]

2.1.2. Mobile Crawler

Because the crawler mobile robot has a larger footprint Then other mobile robots, we chose it. They're employed when the ground is disturbed, which normally happens in an outdoor setting, and the robot is better balanced when it comes navigating comes to navigating stairwells or other potentially dangerous obstacles. The robot's navigation is aided by tracks till it reaches its destination (Sources of Radioactivity). A speed differential between the right and left lanes is used to gain control. The adopted robot model is shown in Figure 3.

Figure 3. Mobile robot platform

Two green plates store solar energy and transform it into electrical energy to power the mobile robot's batteries, enabling all of the required components to fit on a single platform. To send and receive data, the components will communicate wirelessly with a computer. Following that, the data will be used to create a radiation dispersion map. Arduino Mega 2560 board, DC motor with encoder, Arduino Uno board and Geiger Muller sensor are all part of the mobile robot platform. The radiation data on the Geiger Muller sensor's surrounds will be read at the designated waypoints. The information was transferred wirelessly to a laptop computer. The ZigBee module can be readily integrated into the system after the input-output link is completely functional. A ZigBee connection with the correct baud rate was formed after the USB connection was severed. The Matlab software was used to map the intended position. Our mobile robot is equipped with crawler driving wheels. To improve the mobile robot's stability, two wheels are put in front of it.

2.2. Methods

2.2.1. Navigation by Adopting the Procedures of a Mobile Robot

Based on an extended Kalman filter, this study provides a probabilistic approach for the localization of the radioactive source in structures exposed to these rays near nuclear reactors (EKF). The suggested method iteratively estimates the source location using an EKF.

The capacity to account for uncertainties in GM (Geiger Muller) measurements, reduce mistakes in radioactive source location, and effectively merge this data to perform real location are all advantages of the proposed technique over existing methods. Simulations using Matlab Simulink on a rectangular path using a ginput function confirm the performance of the proposed strategy by placing radioactive sources on the path of the robot during its movement.

The robot peripherals provide a fully functional input-output connection, and the ZigBee module may be readily incorporated into the system.

The robot peripherals offer a fully functioning input-output connection, and the ZigBee module is simple to incorporate into the system. A ZigBee-connection with correct baud rate was formed after USB connection was severed. Matlab software was used to map the intended position.

Geiger Muller counter measured radiation and stored it in Arduino UNO, which then communicated the data to Arduino Mega 2560 board [8]. The 2 values of radiation intensity (calculated dosage in mSV) and the locations of the sources calculated by the robot are then sent to the laptop from ZigBee for small distances and SIM card for long distances using the Arduino Mega 2560 card. Figure 5 depicts the whole designed framework of the ionizing radiation mobile robot.

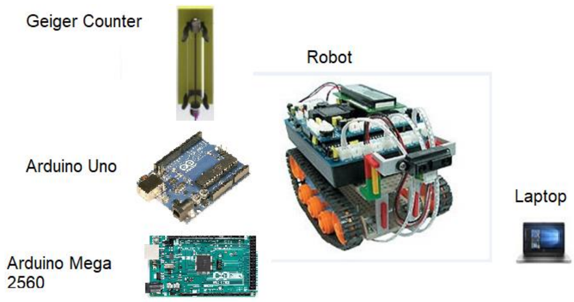


Figure 4. Complete system

2.2.2. Flow Chart

Below is a general flowchart used to guide the robot on its trajectory and tell it to locate the radioactive sources found during its navigation:

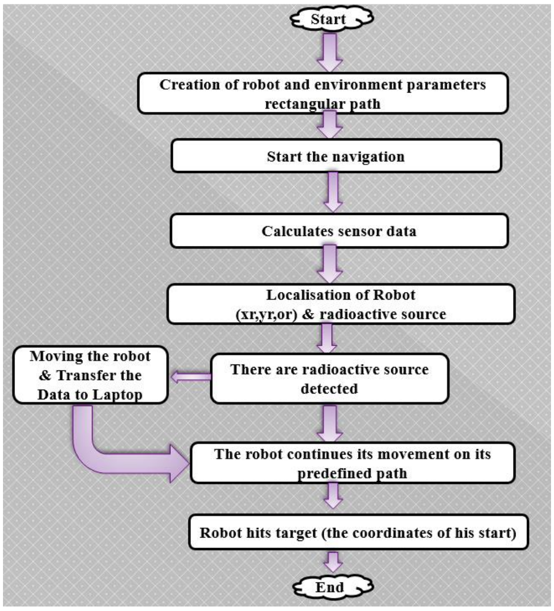


Figure 5. The path to be followed by robot

To offer the robot a better performance to focus on the location of radioactive sources, we assume that there are no barriers in the robot's route. We also assume that radioactive sources are equivalent to objects (the robot considers them as obstacles)

As illustrated in Figure 6, the robot moves along a rectangular track, checking the condition of the source (whether it exists or not) at each point along the path and computing the distance using its location as the starting point. Using the formula in Equation (1), calculate the time of departure and the time of arrival of the radioactive source as a target:

The robot's distance from the radioactive source is computed as follows:

$$r = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2} \tag{1}$$

where, x_i and y_i are coordinates of the robot and x_0 are y_0 coordinates of the source.

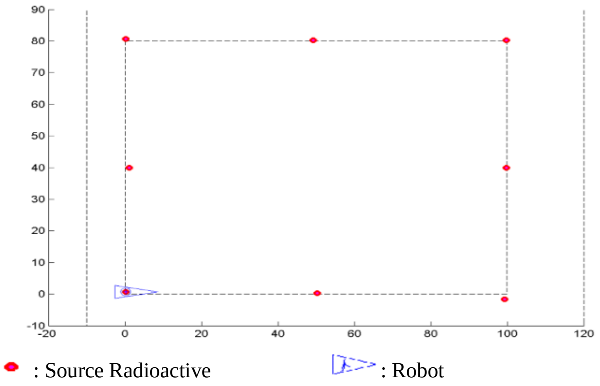


Figure 6. The path of the robot [9]

Knowing that the robot's locations are [x_i, y_i] and the radioactive source's coordinates are [x_0, y_0]. The robot then uses an RFID sensor to compute the distance. We will have a new distance value with a new angle value, as well as updated coordinates of the robot's locations, as a result of the call to fuzzy logic (X_r, Y_r).

The robot can detect radioactive sources in its path, evaluate the surrounding environment (based on sensor data), and make judgments based on engine performance. All inputs to operate the outputs can be determined at the same time utilizing a FL controller and EKF.

On entrance, we utilized the distance and direction registered by a function that analyzes data supplied by the RFID of the closest barrier to the robot, and on leaving, we utilized the direction and distance to be carried by a function that analyzes data given by the RFID of the closest barrier to the robot. As a consequence, the structure of output will be like input variables. FL model, not to be confused with the EKF model, is utilized in this study for correction. In order for the robot to have more autonomy, reduce errors, and arrive at its estimated position, the mobile robot's movement must be exact. A mobile robot will move from one spot to another in order to collect radiation levels. The greater the number of sites, the more data on radiation levels may be collected.

3. DETECTION STRATEGY AND CALCULATION OF THE LOCATION OF A RADIOACTIVE SOURCE USING EKF EXTENDED

Using a Matlab Simulink algorithm based on FL with EKF, the mobile robot traveled between designated waypoints to detect radiation intensity and find radioactive sources in our studies. The mobile robot is utilized to detect the radiation level (dosage) and the distance between the robot and the source, as shown in Figure 7.

Figure 8 which shows the location of the source in relation to the different positions of the robot carrying the Geiger Muller counter.

Before true radiation sources, like fluorescent light, are deployed in the testing regions to identify the background radiation source, this procedure is required. The radiation measured by Geiger Muller in mSv/h should be uploaded to a laptop on a regular basis, as indicated in Figure 4.

Once the background radiation source's radiation intensity is established, the background radiation source is placed at a specified location among the selected waypoints. The radiation source was represented by a circle on Matlab Simulink in this experiment (actually comparable to cobalt-60 (C_0-60) for example).
The sources were positioned at coordinates x_0 and y_0 when using the ginput function to click during robot movement.

Higher radiation data is captured as the robot approaches closer to sources, and lower radiation activity is captured as the robot travels away from sources, as seen in Figure 9.

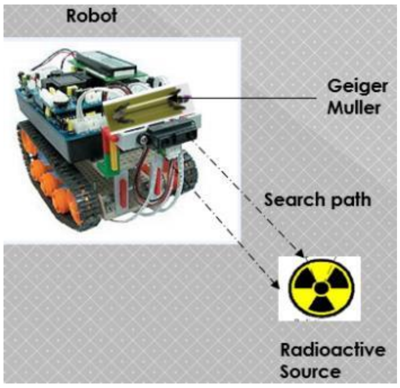


Figure 7. symbol of robot with Geiger Muller and the source

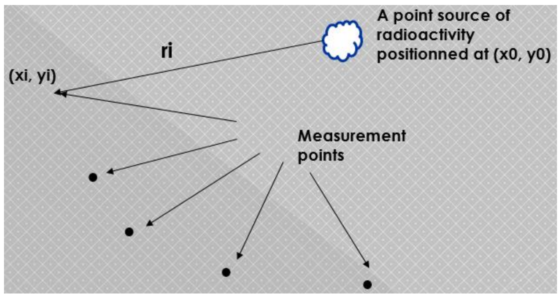


Figure 8. The geometry of the radiological point source localization issue [10]

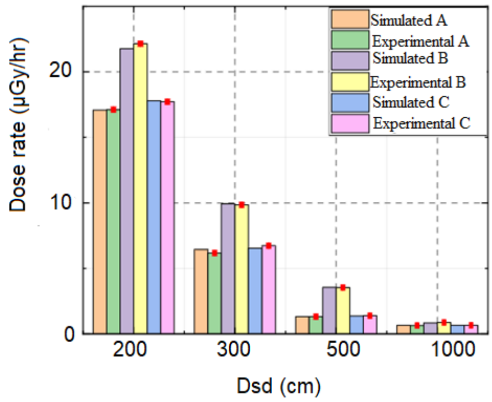


Figure 9. Dose rates simulated and experimentally at various source–detector distances [14]

At a distance r(m) from a source gamma point, the dosage rate D (measured in Sv/h) may be stated as [11]:

$$D = \frac{ME}{6r^2} \tag{2}$$

where, the source activity is measured in MBq, while the gamma energy per decay is measured in MeV.

The Equation (2) can be rewritten as the inverse squared distance law in the following familiar form Equation (3)

$$D = 1/r^2 \tag{3}$$

where, $I = ME/6$.

Original product radioactivity and gamma energy through decay is described by the single parameter I, and an estimation of I may be used to determine the source activity M. Count rates given in counts / minute will make up the survey data (CPM). In this scenario, Equation (1) must be tweaked to account for the probe's energy response (CPM Sv/h).

$$CPM = \frac{ME}{6r^2} \times \text{Energy Response} \;\Rightarrow\; I/r^2 \tag{4}$$

$$I = \frac{ME}{6} \times \text{Energy Response} \tag{5}$$

We may define I as the count rate recorded at a distance of 1 m from the source using Equation (4). Equation (5) and the predicted value of I may be used to determine the source radiative activity M if the energy of the observed radiation is known. As a result, we can define a parameter vector to describe the unknown point gamma radiation source as follows:

$$x = [x_0, y_0, I]T \tag{6}$$

The matrix transpose is denoted by the letter T. Our purpose is to use measurements to estimate vector x. The z_k ; k = 1,..., N taken at coordinates (x_k, y_k); k = 1,..., N.

We employ as in [12] a simplified approach from [13], assuming that RFID sightings aren't feasible across walls. The robot moves on a plane and perceives the direction of point landmarks (TAG). The state of the robot is represented by its position and orientation [13] as indicated in the Equation (7) [9]:

$$X_t = \left[x_t ; y_t ; \theta_t\right]T \tag{7}$$

The robot's movement between times t and t + 1 is measured using RFID given in the reference of the robot at time t in the Equation (8) [9]:

$$X_t = [x_u ; y_v ; \theta_u]T \tag{8}$$

The prediction stage of the Kalman Filter is used to set this Equation (9) [9]:

$$\begin{aligned} X_{t+1} &= AX_t + Bu \\ Z_t &= HX_t \end{aligned} \tag{9}$$

where, A is the matrix of the system, $U_t = (U_1, \ldots, U_t)$ is the input, B is input matrix, and H is output matrix. The Z is the observation: in our case, these are the measurements given by Geiger Muller for dose and RFID value for coordinates

As a result, the Kalman filter is a particularly effective set of equations for obtaining the optimal solution to a situation about which we only have a partial understanding. Its efficiency stems from its adaptability to the number of sensors processed, the accuracy of the information gathered, and the system modeling, which can be linear or nonlinear, thanks to the extended filter.

The extended Kalman filter, like the ordinary Kalman filter, allows us to get a minimal variance estimate from non-exact observations. On the other hand, it is an approximation method that does not always converge because the precision of the model is highly dependent on the initial state values that are chosen in a more or less empirical manner. But the Kalman filter is above all a very important physical tool, used in many fields of industry, in particular in ballistics and more generally in all fields which require very precise localization (radar, navigation, etc.).

Based on the current estimates of location of the RFID source $m_i = (x_i, y_i)$ and the position of the robot with RFID $l = (x, y, \theta)$ the observation is predicted by the measurement function next:

$$r = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2} \tag{10}$$

$$\theta = \tan^{-1}\theta\left(\frac{y_i - y}{x_i - x} - \theta\right) \tag{11}$$

The point source estimate problem can be simplified to the estimation of three unknown parameters (x_0, y_0, and I) [11]. To get an exact solution, you'll need to know these three unknowns. Because the dose rate, which would be the count rate z_k observed at any place (x_k, y_k), is inversely related to the three unknown elements, only three measurements are needed to identify the source's position and strength. Since solving these equations necessitates a large number of square root operations, it creates a number of incorrect answers in addition to the right approximation, making this approach challenging to use.

$$z_k = \frac{I}{{r_k}^2}, \; k = 1, 2, 3, 4 \tag{12}$$

$$r_k = \sqrt{(x_k - x_0)^2 + (y_k - y_0)^2} \tag{13}$$

The range between (x_0, y_0) and the kth measurement point is denoted by the symbol $r_k\left(x_k, y_k\right)$.

$$I = z_1[(x_1 - x_0)^2 + (y_1 - y_0)^2] \tag{14}$$

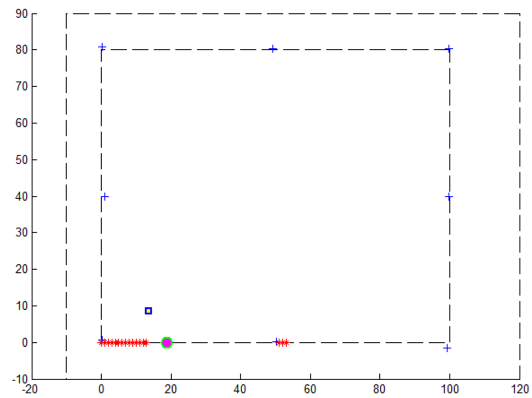
4. RESULTS AND DISCUSSION

To assess the performance of the suggested methods, we used Matlab Simulink to run various Monte Carlo simulations. We will focus on the tests carried out on Matlab Simulink on the location of the radioactive source on several positions of the robot, it is assumed that there will be no obstacle along the path of the robot.

Normally the robot each time receives an indication from the Geiger Muller detector that there is a dose around, it begins its search to determine the source of these Gamma rays. On the program, we do Start, the robot begins its movement by indicating its position at each moment (really it is using its cartography card), and at any moment we place a radioactive source at the using a ginput function.

An illustration of the algorithm of the ginput function that puts the source on the path of the robot is:

```
Using a ginput function
function Ps (obj, event)
x
y
[v, u] =ginput (1);
hold on; plot (v, u,'*k')
```



: Radioactive source

: Position of the robot

: Position of the robot after detection

Figure 10. The first radioactive source detected

Table 1. Data recorded by robot concerns the location of the radioactive source 1 during source localization

γ-ray radiation sources	Position robot after detection radioactive source		Position Source rayon Gamma		Distance entre robot and source (cm)	Angle θ (°)
	x axis	*y* axis	*x* axis	*y* axis		
Source 1	14	0	16.74	-0.31	2.75	-0.11

After placing the first radioactive source on the path of the robot, the data obtained are presented in Table 1.

To avoid colliding with the source, the robot changes its path to locate itself again and take new coordinates: new distance plus angle from the source, the new coordinates of the robot, and the coordinates of the source remain unchanged, the data after detection and localization of the source is illustrated in Table 2.

Table 2. Data recorded by the robot concerns the location of the radioactive source 1 after localization

γ-ray radiation sources	Position robot after detection radioactive source		Position Source rayon Gamma		Distance entre robot and source (cm)	Angle θ (°)
	x axis	*y* axis	*x* axis	*y* axis		
Source 1	43.76	-0.31	58.76	-0.31	15	0

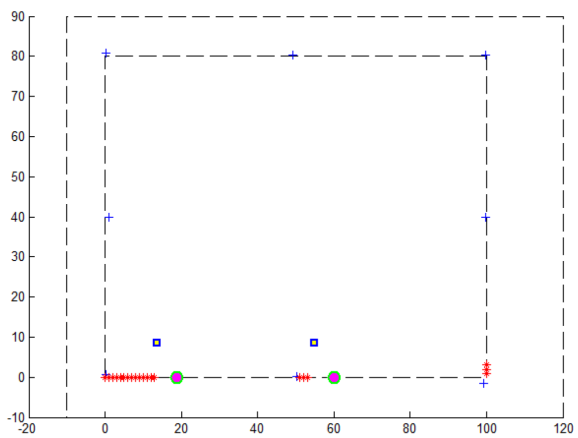


Figure 11. The 2nd source detected

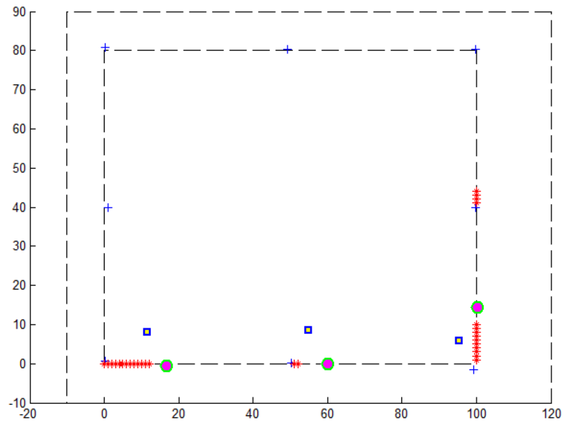


Figure 12. The 3rd source detected

Table 3. Data read by the robot concerns the location of the 3 readings (3 different positions of the source) during localization

γ-ray radiation sources	Position robot after detection radioactive source		Position Source rayon Gamma		Distance entre robot and source (cm)	Angle θ (°)
	x axis	*y* axis	*x* axis	*y* axis		
Source 1	14	0	16.74	-0.31	2.75	-0.11
Source 2	11	0	58.76	-0.31	47.76	-0.007
Source 3	100	4	100.27	20.26	51.43	0.4

Table 4. Data read after detection by the robot concerns the location of the 3 readings (3 different positions of the source) during localization

γ-ray radiation sources	Position robot after detection radioactive source		Position Source rayon Gamma		Distance entre robot and source (cm)	Angle θ (°)
	x axis	*y* axis	*x* axis	*y* axis		
Source 1	10.41	8.2	16.74	-0.31	9.9	59.4
Source 2	43.76	-0.31	58.76	-0.31	15	0
Source 3	25.27	20.26	100.27	20.26	15	0

Figures 11 and 12 show the 2nd and 3rd radioactive sources, respectively. So, if we took a simulation of 3 sources, below is a summary in Table 3 at the time of detection.

We have adopted an algorithm which also integrates the Kalman Filter, considering that the source of the rays will be detected by the robot system, in particular RFID, as an object or an obstacle, taking into consideration the measurement errors to make its correction and give the most precise coordinates. The Filter simultaneously estimates the location of the source, especially in the event of surrounding noise. Both methods are applied to datasets and demonstrated to improve performance over classical methods such as Fuzzy Logic [15] and Artificial Intelligence, AI [16] research also contributes to the need to know more about human brain activity. According to the simulation adopted with the ginput function, we have location of the source is known (it is assumed y_t in Figure 13), we have the location of the robot (x_t) and the value of the intensity given permanently by Geiger Muller (J_t).

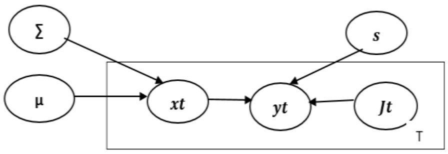


Figure 13. Interaction between different peripheries in environment radioactive

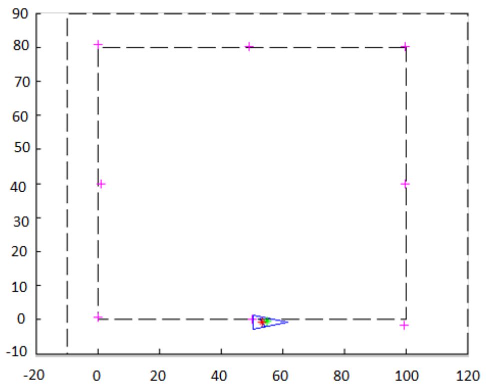
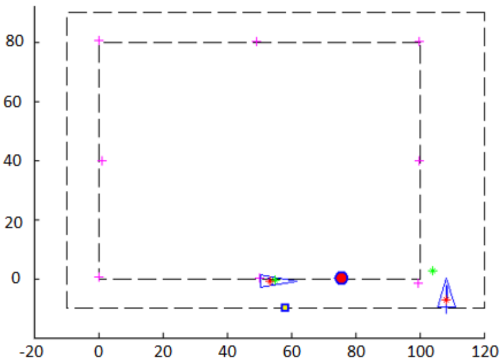


Figure 14. path of the robot



*: Position predicts of the robot
*: Robot's predicted location
+: Positions to be followed by the robot
●: Radioactive source position

Figure 15. Path of the robot after detection of radioactive source

It is considered that the path to be followed by the robot is illustrated in Figure 14.

After we put the first radioactive source on the path of the robot using the Kalman filter, the following results are obtained. The first result displayed is the predicted covariance matrix already mentioned.

$$P_{pred} = \begin{pmatrix} 0.35 & 0 & 0 \\ 0 & 0.1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Capture on the algorithm used to obtain P_{pred} as:

```
x_P (1:3) = tcomp (x_P (1:3), u, x_P (3));
      Ppred = A1 (xEst, u)*QTrue*A1 (xEst, u)'+B1
(xEst, u)*Pest*B1 (xEst, u)'
Ppred = A1 (xEst, u)*Pest*A1 (xEst, u)'+B1 (xEst,
u)*QTrue*B1 (xEst, u)'
 xEst (1:3) = tcomp (xEst (1:3), u, xEst(3));
```

where, A is matrix which shows the evolution of the state t to $t-1$ and B matrix which shows how the control U_t change of state from $t-1$ to t, and QTrue is the noise assigned to the displacement.

We use a Jacobian matrix (nonlinear system), the latter is calculated at each moment around the current estimation point with the objective of linearizing the system. The result obtained from the Jacobian matrix:

$$H = \begin{pmatrix} -0.36 & -0.92 & 0 \\ 3.46 & -1.37 & -1 \\ 0 & 0 & 0 \end{pmatrix}$$

Note that to obtain autonomous error equation, the innovation has been defined:

$$I = \begin{bmatrix} 1.39 \\ -0.92 \end{bmatrix}$$

At the end, we get the new coordinates of the robot, also the new distance and angle to have the estimated position of the robot illustrated in Table 5.

Table 5. Data of the robot after the localization of radioactive source

γ-ray radiation sources	new estimated position robot		new Distance entre robot and source (cm)	new Angle θ (°)
	x axis	*y* axis		
Source 1	59	-9.9	20	-30

5. CONCLUSION

This article explains how to use fuzzy Logic and a Kalman Filter in a radioactive medium to control the navigation of a mobile robot with route correction. The evaluation's idea and findings reveal that the robot traverses effectively the predefined path and that system produces source localization by giving the user the DATA recorded on Arduino (intensity, source localization) leads to positive outcomes. The goal is to create a robust robot strategy for reasonably difficult terrain that can discern between an impediment and a radioactive source and deviate if it's an obstacle while moving forward to take action if it's a radioactive source.

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