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Original

An adaptive neuro-fuzzy inference system applied for the design of a firefighting robot using a photovoltaic panel

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Abstract: Firefighting robots are one of the most effective tools for extinguishing early fires that cause loss of life and property, as well as permanent disability to the affected victims. These robots are used to save the lives of engineers in industrial sites with hazardous conditions. This paper aims to design and implement a mobile robot that detects and extinguishes fires using artificial intelligence and solar energy techniques. A mobile robot capable of moving is designed using a rotary motor, a flame sensor, a pump and a solar panel to supply power to the electronic components, all controlled by an Arduino Uno microcontroller and programmed using Adaptive Neuro-Fuzzy Inference System (ANFIS) using MATLAB, where the inputs for training the network were the front, right and left flame sensors and the output is a pump (pump off, pump on). In this study, the performance of the solar panels is first tested using MATLAB and then experimentally under various weather conditions. The performance of the pump is also experimentally tested. The robot is also tested to detect and extinguish fires. The results showed the effect of temperature change on the solar panel, as when it increases, the panel's ability to produce decreases, as well as the effect of the reduction in solar radiation resulting from clouds and others, and the extent of its impact on the efficiency of solar panel performance, and monitoring the pump performance in terms of flow rate and height. From this, it can be observed that the designed robot can effectively detect fire sources and extinguish them with minimal errors. Thus, it can be applied in industrial settings to prevent fire damage and extinguish it when it occurs.

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Keywords: **Robot, Solar cell, Fire, Gas sensor, Flame sensor, ANN.**

1. Introduction

The development of a solar-powered firefighting robot has become an attractive factor for startup companies. To utilize solar cells for recharging (Bagdadee et al., 2024), these robots soon began to play a significant role in various sectors (Kulkarni, 2020). With solar panel installations rising rapidly over the past few years, the total electricity produced by solar energy has increased rapidly. The rapid rise of zero-emission energy sources is beneficial to our planet in many ways. Applying solar panel technology to firefighting robots is crucial for preventing loss of life and property, and for extinguishing fires quickly and safely to prevent further damage and destruction (Victoria et al., 2021). Detecting and extinguishing fires is a dangerous task that always puts the lives of firefighters at risk. Fire sensing in most industries is absolutely essential to prevent catastrophic losses. Robots with this type of built-in system can save the lives of engineers in industrial sites with hazardous conditions (Baballe et al., 2023). Many researchers are studying firefighting robots using various techniques and methods. For instance, Sarwar et al. (2019) employ ANFIS to identify fire incidents based on data from smoke, temperature, and humidity sensors. A model was constructed using sensor data and fuzzy logic in neural networks within MATLAB. The model then sends alerts directly to the user's smartphone. The results were good. (NavyaSree et al., 2023) A robot was designed to put out fires by relying on smoke and fire sensors to pump water over the flames. (Jawad et al., 2024) Using fuzzy logic control with a solar cell for a firefighting robot.

This study focuses on designing a firefighting robot that utilizes AI and solar panel technologies to provide energy and maintain a long-lasting duration. It employs an infrared flame sensor, similar to those used in smart systems, to provide a reliable, cost-effective, and 24/7 fire safety system. Therefore, it can be applied in various fields, including residential, commercial, and industrial applications. It is particularly applicable in areas with a high probability of fires. The rest of this study is structured as follows: Section 2 provides the photovoltaic cell, Section 3 describes the firefighting robot, Section 4 presents the artificial intelligence techniques, Section 5 describes the experimental setup, Section 6 describes the programming, Section 7 discusses the findings and analyses, and Section 8 concludes the article.

2. Photovoltaic Cell

Photovoltaic (PV) and renewable energy sources have experienced significant development in recent years (Goswami, 2015; Kadhum et al., 2019). Present photovoltaic technology has been well developed since 1941. Photovoltaic (PV) panels are used to generate electricity by semiconductors that convert solar radiation into electricity without the use of any thermal engine. A photovoltaic cell consists of at least two layers of semiconductor material, with the first layer having a positive charge and the second layer having a negative charge. The semiconductor atoms on the surface direct part of the photons absorbed from the sunshine, causing the electrons in the cells to become free, as shown in Figure 1.

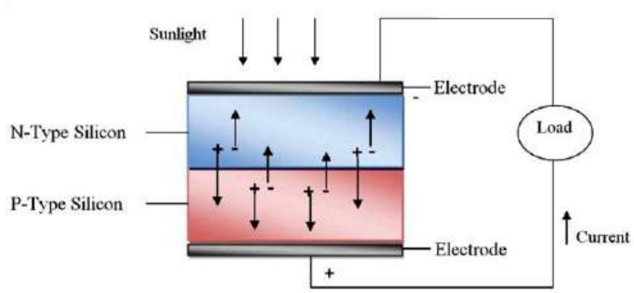

Figure 1. Photovoltaic cell (Kadhum et al. 2019).

2.1 Types of Photovoltaic

Solar panels are divided into three main types, as shown in Figure 2:

- Crystalline silicon tablet: Samsung smart touch panel, black non-contact smart solar cell technology. It is specifically designed for this type of 22.5% solar panel, but the careful design gives it a capacity of 17.5% wide, lasting for 25 years, yet it remains lightweight. It is also known as the most expensive of the three types mentioned in our article.

- Polycrystalline crystal panel: The solar cells consist of stacked squares, and they are less expensive than the first type. Its efficiency is estimated at 16.9%, its lifespan is 25 stops, and the color of its cells is blue.
- Silicone sheet in the form of a wafer: cells that are thin and streamlined, and take the shape of the surface on which they are installed, and their efficiencies do not affect 12%, and their lifespan is less than 15 parts; It will be expensive (Maksumic et al., 2018). Three types of specifications are shown in "Table 1", and the arrangement is shown in "Figure 3".

2.2 Advantages of Solar Energy

- Clean.
- Sustainable.
- Free.
- Provide electricity to remote places.

2.3 Disadvantages of Solar Energy

- Less efficient and costly equipment.
- Part-time.
- Reliability depends on location.
- Environmental impact of PV cell production.

Figure 2. Types of photovoltaic cellMono-Si, Poly-Si, thin film cell (Amorphous Silicon) (Goswami, 2015).

	Monocrystalline	Polycrystalline	Amorphous	CdTe	CIS/CIGS
Typical module efficiency	15-20%	13-16%	6-8%	9-11%	10-12%
Best research cell efficiency	25.0%	20.4%	13.4%	18.7%	20.4%
Area required for 1 kWp	6-9 m2	8-9 m2	13-20 m2	11-13 m2	9-11 m2
Typical length of warranty	25 years	25 years	10-25 years		
Lowest price	0.75 $/W	0.62 $/W	0.69 $/W		
Temperature resistance	Performance drops 10-15% at high temperatures	Less temperature resistant than monocrystalline	Tolerates extreme heat	Relatively low impact on performance	
Additional details	Oldest cell technology and most widely used	Less silicon waste in the production process	Tend to degrade faster than crystalline-based solar panels Low availability on the market		

Table 1. Specification Types of photovoltaic cell (Dunlop, 2010).

2.4 PV System Components

Figure 4 shows the components of the PV system, which consists of five main components: solar panel, organizer, battery, AC adapter (inverter, electricity load) (Dunlop, 2010; AbouJieb & Hossain, 2022).

2.5 Application of Photovoltaic Panel

The use of photovoltaic energy technology has become a reliable alternative solution in many applications, some of which are highlighted in Figure 5, including independent energy systems in urban, rural, and even remote areas (Lazaroiu et al., 2023; Jawad et al., 2019).

- Pumping systems aim to feed drinking and irrigation water, pumping facilities, and water desalination systems.
- Outer space, where these cells constitute an essential power source for space applications such as the International Space Station, spacecraft, and satellites.

Figure 3. Types of arrangements of photovoltaic cells (AbouJieb & Hossain, 2022).

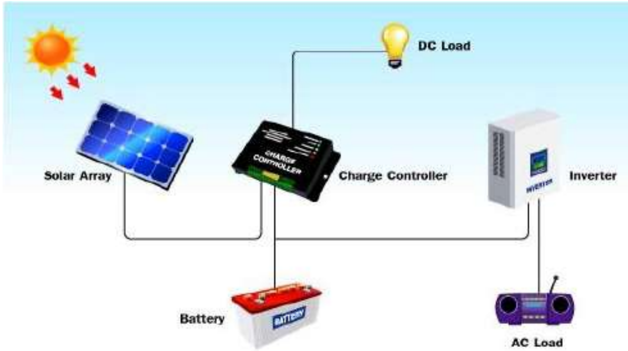

Figure 4. Components of photovoltaic cells (AbouJieb & Hossain, 2022).

- Photovoltaic solar farms produce reasonable amounts of electrical energy that feed directly into the grid.
- Terrestrial communications such as calling and receiving stations.
- Protection and safety devices.
- Solar photovoltaic energy is used in civil and military alarm and warning systems.
- Marine uses provide energy for lighting, optical guidance, and monitoring devices.

2.6 Mathematical Equation of Photovoltaic Panel

A PV module is the basic unit of a power PV generation system. PV module has non-linear characteristics which depend on solar radiation and cell temperature. The parameters of the PV module that is employed in this study are defined in Equations 1 and 2 (Teo et al., 2018).

$$I = I_{ph} - I_{rs}\ [\exp\left(\frac{V+IR_s}{aV_T}\right) - 1] \qquad (1)$$

where:

$$V_T = \frac{N_s k T_c}{q} \qquad (2)$$

The output power is

$$P_m = I_{max} V_{max} \qquad (3)$$

Fill Factor (FF) represents the ratio of maximum power divided by the open circuit voltage and short circuit current.

$$F.F = \frac{P_m}{P_{th}} = \frac{V_{max} I_{max}}{V_{oc} I_{sc}} \qquad (4)$$

I, I_{ph} and I_{rs} are the output, photo-generated and the diode saturation currents respectively, V is the output voltage, R_s is the series resistance, N_s is the number of cells, V_T is the junction thermal voltage, A is the ideality factor, k is the Boltzman constant ($1.3806503\times10^{-23} J/K$), T is the cell temperature and q is the electron charge (1.6021765×10^{-19} C).

3. Fire Fighting Robot

A robot is a system that combines software, power supply, manipulators, control systems, and sensors to carry out a task. Physics, mechanical, electrical, structural, mathematical, and computer sciences are all used in the design, construction, programming, and testing of robots (Malik & Kumbalkar 2013; Singh et al., 2015).

Figure 5. Application of photovoltaic cell (Jawad et al., 2019).

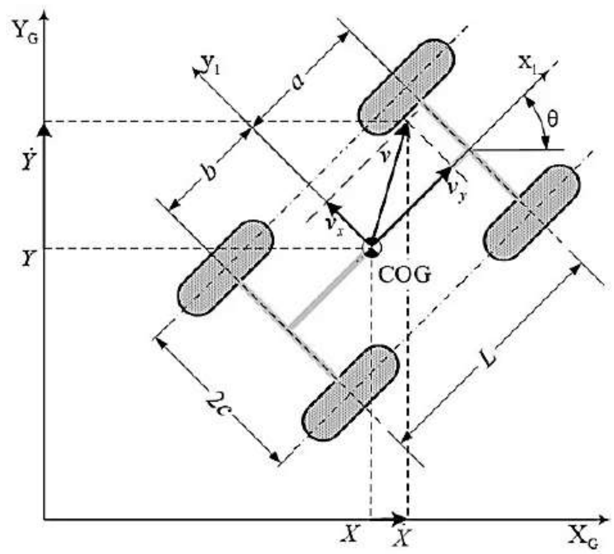

Figure 6. Scheme of Fire Fighting Robot (Alexa et al, 2023).

3.1 Mathematical Equation of Fire Fighting Robot

For the analysis model of the firefighting robot that has a four-wheeled robot shown in Figure 6, the following formula is used to calculate the absolute speed for the firefighting robot, taking into account the hypothesis that it executes a planar movement, $v=[v_x\, v_y\, 0]^T$, and the angular velocity as equation is $\omega = [0\ 0\ \omega]^T$. As well as $\dot{q}=[\dot{X}\ \dot{Y}\ \dot{\theta}]^T$, $q=[X\ Y\ \theta]^T$ as velocity and state vector. So, the motion, the velocities and the angular velocity in the inertial frame of reference (X_G, Y_G) is show as "Eq. 5":

$$\left\{ \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} cos\theta - sin\theta \\ sin\theta cos\theta \end{bmatrix} . \begin{bmatrix} v_x \\ v_y \end{bmatrix} \right. \qquad (5)$$

where $\dot{\theta}=\omega$.

3.2 Advantages of Firefighting Robot

- Firefighters are less likely to encounter hazardous circumstances when there are robots around.
- Firefighters' workload decreased.
- In a major disaster, it is impossible to put out a fire and save a large number of victims at once.
- Those could be devices with remote controls.
- The vehicle can reach positions that firefighters cannot, such as petrochemical complexes and big warehouse fires.
- Robotics can function on its own (Alexa et al, 2023; Xu et al., 2011).

4. Artificial Intelligence Techniques

The field of Artificial Intelligence (AI) has advanced dramatically in the last several years. It is a fruitful field of study, with a growing number of significant studies, basic technology domains, and application areas, as well as algorithmic advancements. Artificial intelligence's capacity to handle large amounts of data, complexity, high precision, and processing speed is being leveraged to advance sciences and technologies (Kanwar & Agilandeeswari, 2018).

Artificial Neural Networks (ANNs), Fuzzy Logic (FL), Genetic Algorithm (GA), Neuro-Fuzzy Interference System (ANFIS), Particle Swarm Optimization (PSO), and other well-known artificial intelligence tools are used in a variety of fields, including engineering, science, medicine, computing, finance, and economics (Xu et al, 2021).

4.1 Adaptive NeuroFuzzy Inference System (ANFIS)

Many strategies combine fuzzy logic with neural networks. In this study, the Adaptive Neuro Fuzzy Inference System (ANFIS) will be utilized, which was implemented by Jang (1993), and it is a functionally equivalent mechanism to Sugeno's Inference, shown in Figure 6. Sugeno and Takagi used these rules (Abbas et al, 2020).

Rule (1): if x_o is A_1 and y_o is B_1 then $Z_1=a_1x_o+b_1y_o$
Rule (2): if x_o is A_2 and y_o is B_2 then $Z_2=a_2x_o+b_2y_o$ (6)

A hybrid neural fuzzy is equal to this type, as shown in "Figure 7".

If a crisp training set $\{(x^k,y^k),k=1,\ldots,K\}$ is known. The variables for the hybrid neural (that calculated a shape for the membership function of premises) may be learned by the descent-type method. These architectures and learning procedures are called ANFIS (Adaptive Network-based Fuzzy Inference System) (Mewada et al., 2013).

The error function for pattern can be given by:

$$E_k = \left(y^k - O^k\right)^2 \tag{7}$$

Where y^k output and O^k output are computed by a hybrid neural net.

4.1.1 Implementation of ANFIS in MATLAB

For development to represent firefighting robot using Adaptive Neuro Fuzzy Inference System (ANFIS) first step is load data for training from workspace in MATLAB that consist of three variables (right, left and forward flame) then generate fuzzy logic type (Sugeno's Inference) by determined the number of membership function [3,3,3] for each input and type of membership function is trimf

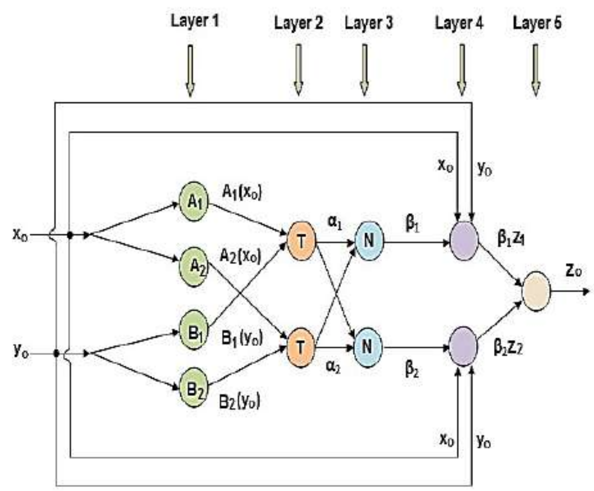

Figure 7. ANFIS Architecture.

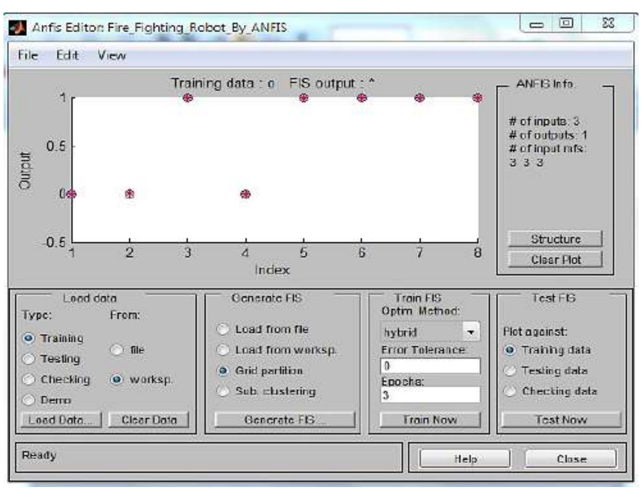

Figure 8. Adaptive Neuro Fuzzy Inference System (ANFIS) for firefighting robot.

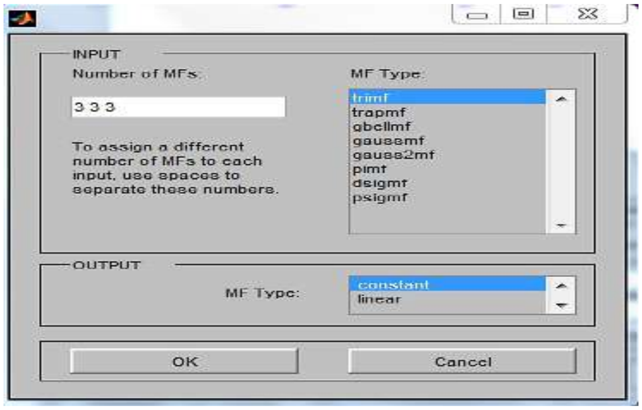

Figure 9. Number of membership function for inputs.

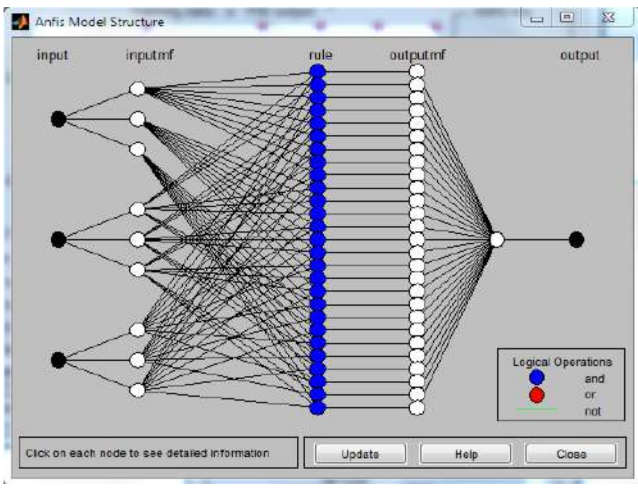

Figure 10. Structure of (ANFIS) for a firefighting robot.

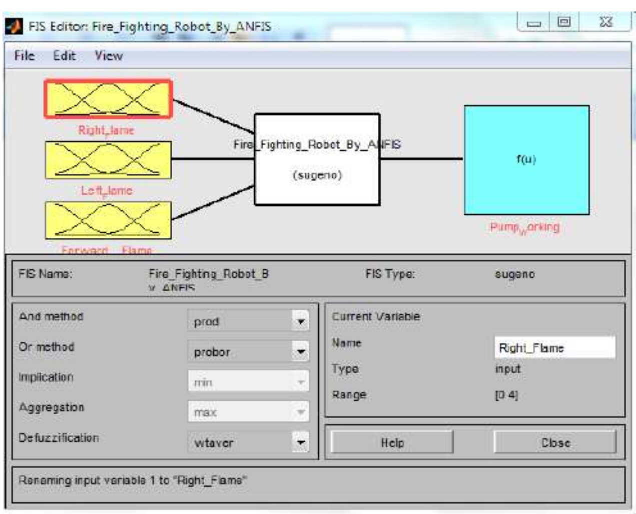

Figure 11. Inputs and outputs of fuzzy logic system.

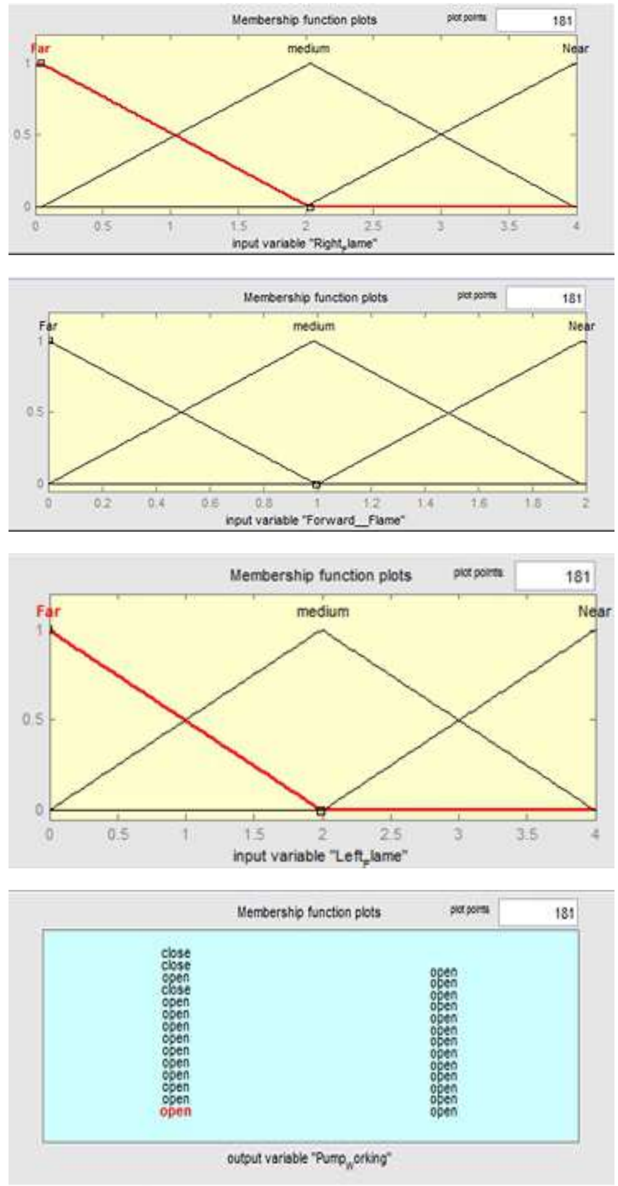

Figure 12. Membership function of inputs and output.

as well as chose a train fuzzy by hybrid method with three epochs, with number of nodes: 78, number of linear parameters: 27, number of nonlinear parameters: 27, total number of parameters: 54, number of training data pairs: 8, number of checking data pairs: 0, number of fuzzy rules: 27, that is shown in Figures 8, 9, 10, 11, 12, 13, and 14, respectively.

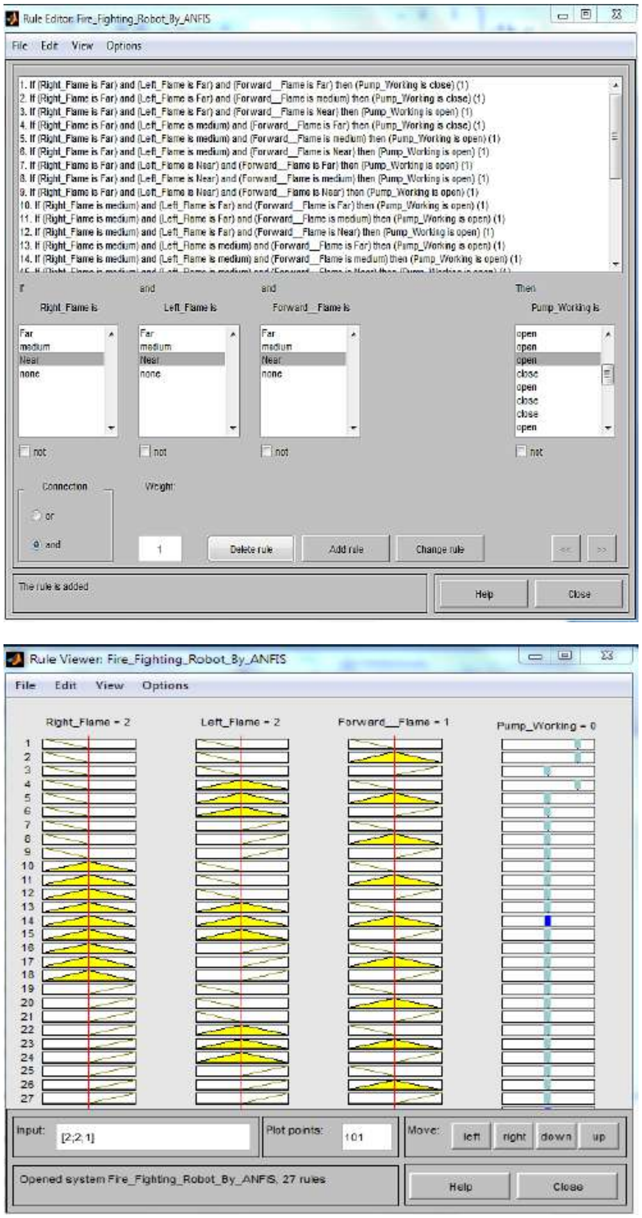

Figure 13. Rules of ANFIS for firefighting robots.

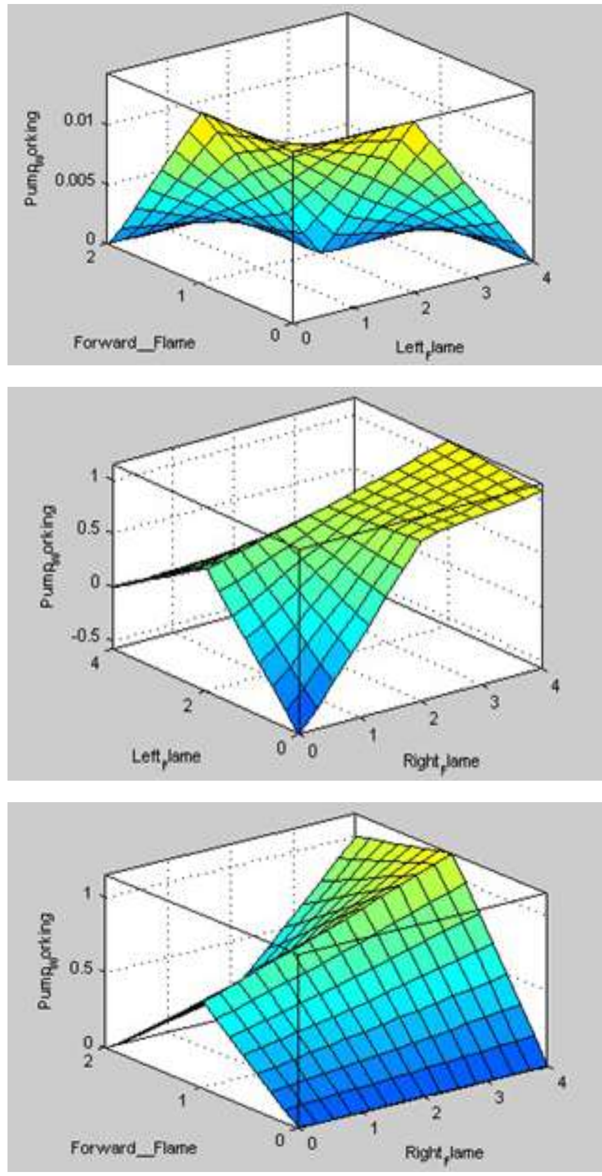

Figure 14. Surface view of inputs with output.

5. Experimental Setup

To design a firefighting robot that monitors areas where natural disasters and bomb explosions occur. It senses the fire at the disaster site and then extinguishes it when it occurs. An Arduino Uno microcontroller, three flame sensors, a PV panel, a DC driver, and a pump were used. As shown in Figure 15. If a fire is detected with the help of sensors, the microcontroller operates the water pump mechanism depending on the energy from the solar cell and extinguishes the fire.

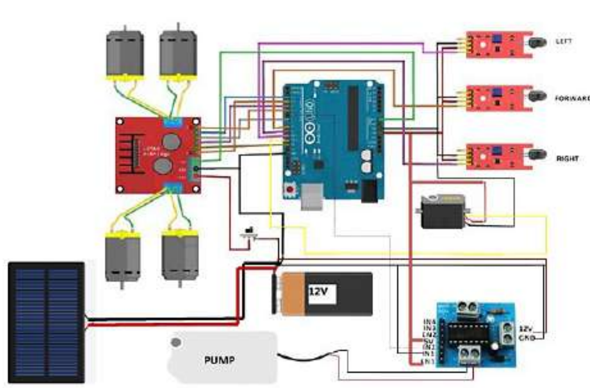

Figure 15. Block diagram of experimental setup.

6. Programming

The Arduino software offers basic libraries and an integrated development environment (IDE) for programming. It is easy to write code and upload it to the Arduino Uno for implementation using the open-source Arduino IDE, as shown in Figure 16, and to utilize ANFIS in MATLAB. Hardware configuration is performed using Arduino IDE version 1.8.5, after which the board is loaded and the flow chart shown in Figure 17.

Figure 16. Arduino IDE program and upload code to microcontroller.

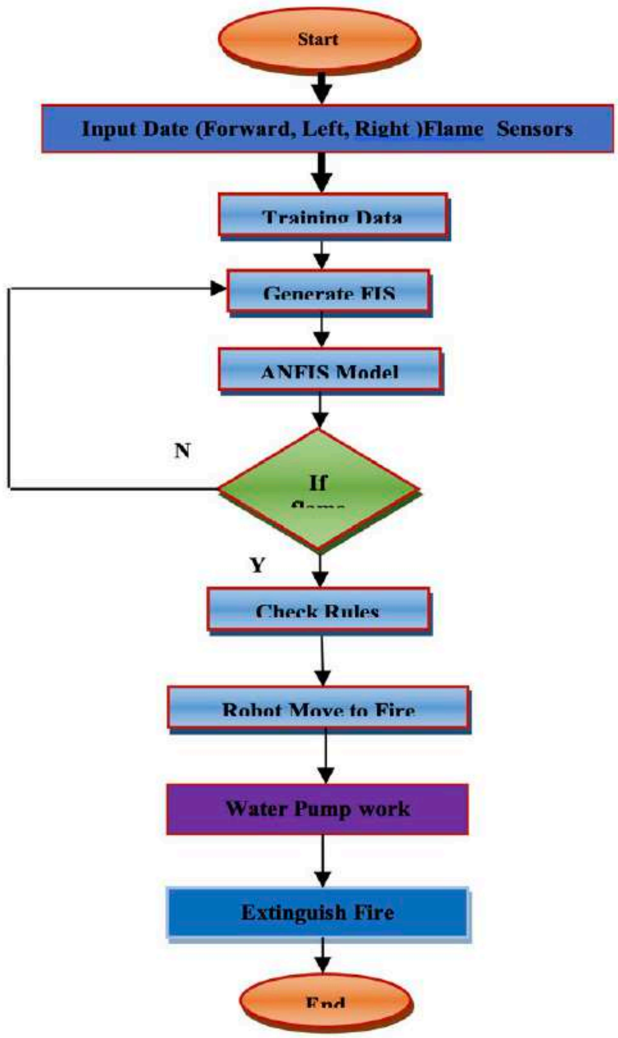

Figure 17. The flowchart for algorithm

6. Results and Discussion

Firstly, test the performance of the photovoltaic cell in different climates theoretically and experimentally. The maximum temperature of the sun is measured according to the Standard Test Conditions (STC). The temperature of the PV module also depends on its efficiency. These tests are conducted theoretically using the MATLAB program using a code in m-file, as shown in “Figure 18”, to show I-V, P-V characteristics curve at T=25 $°C$ and changing the radiation from 200 to 1000 W/m^2 gradually, when it is noted that the amount of solar radiation when clouds are covering the sky, the result shows. The voltage is very small. When the solar radiation is 1000 W/m^2, the current increases, and the voltage increases by a very small percentage. Therefore, increasing the amount of solar radiation leads to an increase in the panel’s productivity, and decreasing it leads to a decrease in the panel’s productivity.

As can be show in Figure 19 changing the temperature (25 $°C$, 50 $°C$, 75 $°C$) and solar radiation is 1000 W/m^2 on the I-V, P-V characteristics, the result show the temperature of the crystalline PV module is generally reduced by 0.3-0.5 percent for each temperature increase.

The experimentally tests shown in Figures 20 and 21 the effect of the solar radiation decreases to 250 W/m^2, 500 W/m^2, 750 W/m^2 and 1000 W/m^2 with changing the temperature (25 $°C$, 50 $°C$, 75 $°C$) on the I-V, P-V characteristics, so it can be seen from the curve that at temperature change when increase caused reduce productivity and reduce performance and efficiency of solar panel. Secondly, show the test performance of the working pump theoretically and experimentally, and the firefighting robot shown in Figure 22, based on the performance of the sensors, flame as shown in Figure 23. To test the

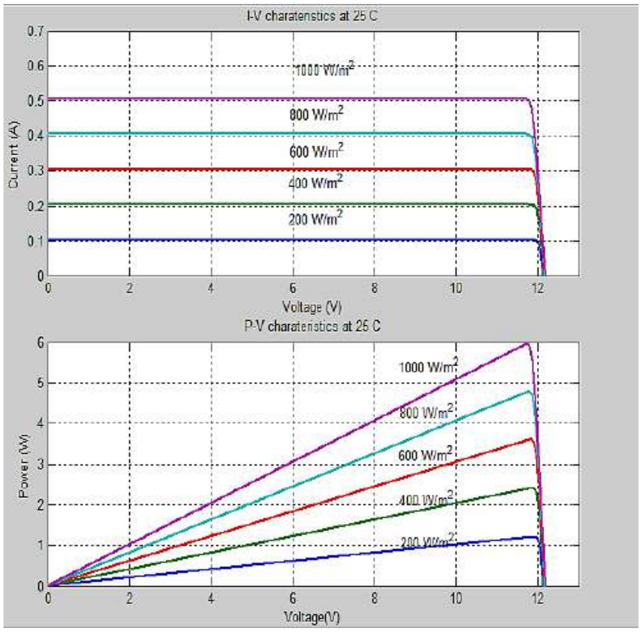

Figure 18. Power and current theoretical at different solar radiation and T = 25° C.

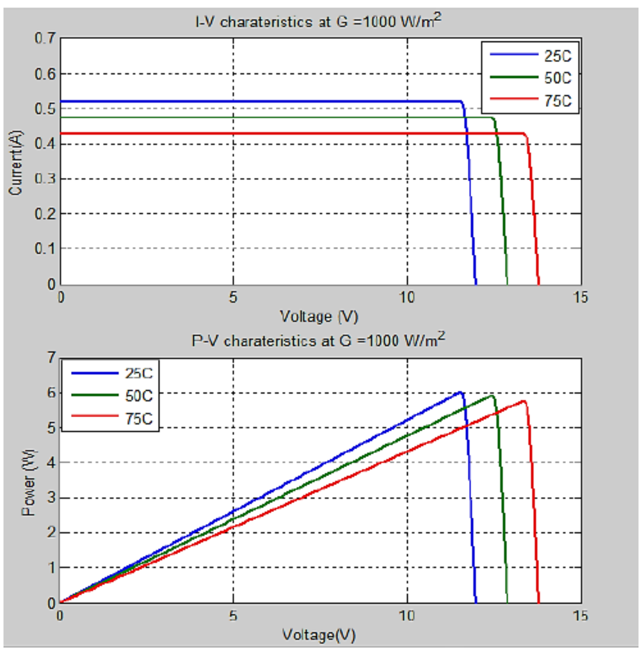

Figure 19. Power and current theoretical at different temperatures and G = 1000 W/m^2.

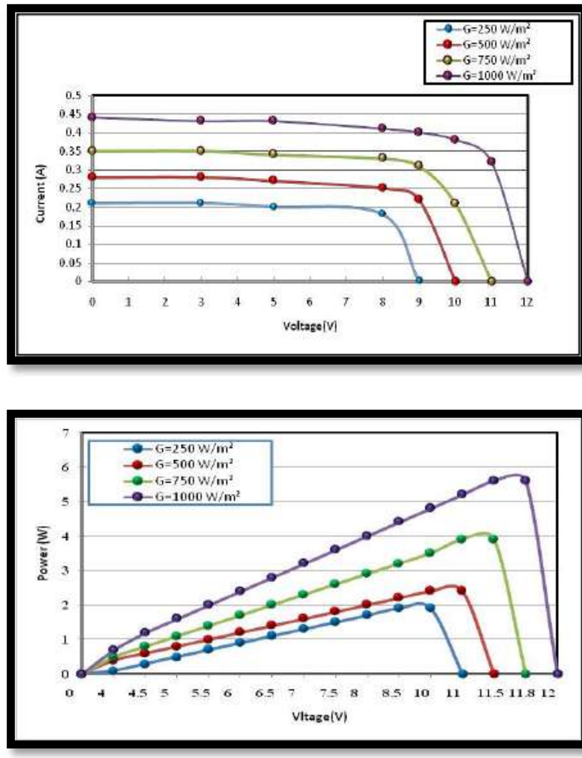

Figure 20. Power and current experimentally at solar radiation different and T = 25° C.

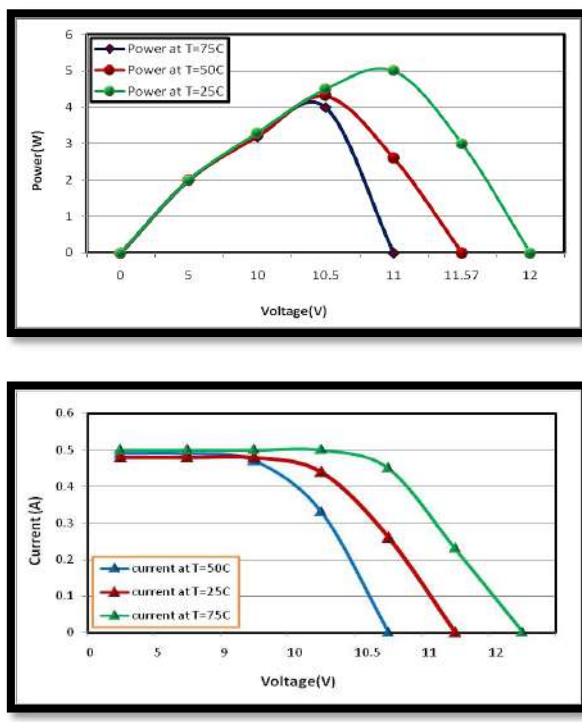

Figure 21. Power and current experimentally at different temperatures and G = 1000 W/m^2.

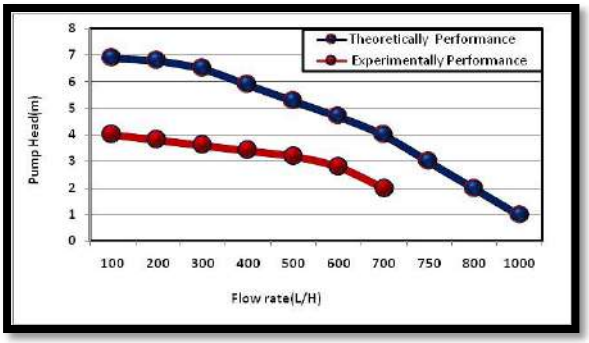

Figure 22. Theoretically and experimentally pump performance.

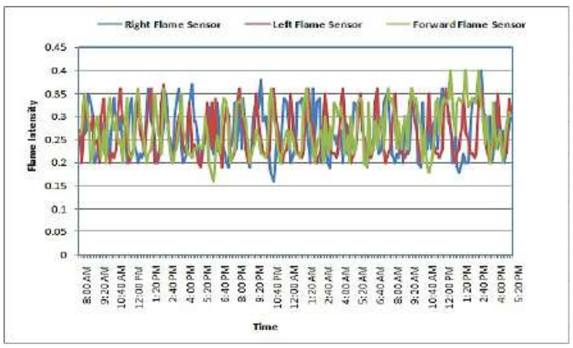

Figure 23. Performance flame sensors.

Figure 24. Firefighting robot implementation.

proposed system, a different time set is chosen to show flame detection. These practical results are taken from operating the proposed system for several days, monitoring the flame sensors, and then recording the readings. Also, when a fire approaches the system. Finally, in Figure 24 shows a firefighting robot implementation.

7. Conclusion

This robotic firefighting project aims to create a system that can identify and extinguish fires before they spread. Through this paper, we can conclude the benefit of the robot by relying on solar energy to provide energy and its operation at all times, as the fire can be extinguished first. Most fires can be extinguished without spreading thanks to the fire extinguishers that can be installed on the robot, depending on the water pumping mechanism through the electrical circuit relay and the pump, thus obtaining stable and rapid fire extinguishing and accurate sensing ability with increased flexibility when applying the well-known artificial intelligence technology as ANFIS and giving the result more effectively, reliably and efficiently, thus avoiding the possibility of error. This study applied the basic data of the system in the MATLAB program by entering the flame sensors in ANFIS and then connecting them to the arduino controller in the experimental setup, then monitoring the performance of the flame sensors for several days, as well as recording the readings, and the results obtained were 97% accurate to the actual data, which proves the suitability of using this method. Comparison this study with other authors as (Zhao et al., 2024; Tanyıldızi, 2023) as shown in “Table 2”. In this study used Arduino Uno for very easy, with just a few lines of code, and no need to download some libraries and software to programmatically connect these sensors and components and write the software code, just a connection, it works as a device that can be turned on and off at any moment without any danger, and the code can be started again by resuming the power, also is cheaper and needs less power theses advantage for used in this study tan Raspberry Pi. Exerted by firefighters, as it is reliable, economical, and insensitive to weather conditions. This work can be applied in daily life as well as in all industrial applications such as closed parking lots, shops, and supermarkets. This robot also fully assists in these natural areas where disasters and bomb explosions have occurred.

Table 2. Comparison this study with others.

<table>
<tr><th>Authors</th><th>Methods</th><th>Advantage of this paper</th></tr>
<tr><td>Ref. (Zhao et al., 2024)</td><td>Using CG-DALNet lightweight network model achieves significant That give More accuracy but time delay for analysis image that taken from UAV also need more power for working.</td><td rowspan="4">This paper First, used artificial intelligence methods to program the robot's movement to ensure accuracy and reach the target with high accuracy and reliability compared to robots used in other papers. Second, used a solar panel to provide energy at all times and avoid the robot stopping when the batteries used in other research run out. Finally this paper designed and implemented in a real time, which is the difference between this paper and others</td></tr>
<tr><td>Ref. (Zhang et al., 2023)</td><td>Simulation study of dual-track driving system of a fire-fighting robot is proposed, and the composition of its local control system is introduced.</td></tr>
<tr><td>Ref. (Yun et al., 2023)</td><td>Simulation study using ROS For development a firefighting robot for indoor use based on the abovementioned issues. Need more power for working</td></tr>
<tr><td>Ref. (Tanyıldızı, 2023)</td><td>Simulation study of fire extinguisher ball in the Matlab Simmechanic environment.</td></tr>
</table>

Conflict of interest

The authors declare no conflicts of interest.

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