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Design and Validation of Advancing Autonomous Firefighting Robot

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Abstract
The quest for enhanced fire-fighting capabilities led to the design and validation of an autonomous firefighting robot in this study. Proteus software was leveraged for rigorous simulation, and the prototype integrated an array of components, including an IR flame sensor, servo motors, a submersible water pump, and a microcontroller-driven navigation system. Comprehensive testing was conducted with meticulous attention to component integrity and functionality, confirming the robot's ability to detect fires, navigate toward them, and effectively extinguish them using water. The robot utilized a 12V DC power supply and was powered by three 4V lithium rechargeable batteries. It seamlessly transitioned from breadboard testing to a soldered board configuration. Preliminary tests, conducted with a candle flame, validated the robot's efficacy in real-world fire detection and suppression scenarios. This innovative design highlighted the potential for robotic solutions in enhancing firefighting capabilities and ensuring safer environments.

1.0 Introduction

In an era marked by rapid technological advancement, integrating robotics into critical sectors such as emergency response is not just a vision for the future but a pressing necessity of the present (Burke, *et al.,* 2004). The realm of firefighting, traditionally a domain reliant on human expertise and bravery, is witnessing a transformative shift with the emergence of autonomous firefighting robotics. These cutting-edge robotic systems promise not only to enhance the efficiency and effectiveness of firefighting operations but also to mitigate the risks faced by human firefighters in hazardous environments (Liu, *et al.,* 2016).

Fires present a significant hazard to both lives and property in various environments (Martin, *et al., 2016*), (Gill, *et al.,* 2009). Hence, early detection and swift response are crucial in minimizing their impact. Traditional fire monitoring and extinguishing methods often depend on human intervention, which can be limiting (Eze, et al., 2023) (Archibald, 2016) (Enerst, *et al.,* 2023). There is an urgent need for an autonomous solution capable of promptly detecting fires and responding effectively. The advent of autonomous firefighting robotics signifies a paradigm shift in firefighting methodologies, transcending traditional limitations and augmenting the capabilities of human responders (Yahaya, 2020). These robots possess the agility to navigate complex environments, the intelligence to assess fire dynamics, and the precision to execute targeted firefighting maneuvers autonomously. By harnessing state-of-the-art technologies such as machine learning, thermal imaging, and sensor fusion, these robots exhibit an unprecedented ability to detect, suppress, and extinguish fires with exceptional efficiency and speed.

This project aims to develop an autonomous fire monitoring and suppression robot equipped with advanced flame sensors to address this critical requirement. The primary objective is to design a reliable, cost-effective, and efficient robot that can autonomously navigate environments to detect fire outbreaks and extinguish them promptly. By focusing on the creation of such a robot, this project aims to improve fire safety measures and reduce response times in diverse settings, including residential areas, industrial complexes, and forested regions. Ultimately, this initiative seeks to minimize the risks associated with fire incidents and their subsequent effects.

Moreover, deploying autonomous firefighting robots promises to revolutionize risk management strategies in fire-prone areas, offering a proactive approach to fire prevention and containment (Feldman, 2023). Through their continuous monitoring capabilities and rapid response mechanisms, these robots can identify fire outbreaks in their early stages, thereby averting potential disasters and minimizing the spread of flames. Furthermore, their ability to access hazardous or inaccessible locations ensures that no fire remains beyond the reach of firefighting efforts, enhancing overall operational effectiveness and reducing the reliance on human intervention in perilous environments

2.0 Literature Review

In recent years, the field of robotics has gained significant attention due to its wide range of designs and technological advancements. The idea of developing autonomous firefighting robots is rooted in the commitment to enhance community safety by providing efficient and rapid response mechanisms while minimizing risks to human life. Research has highlighted the use of tracking lines to guide these robots in extinguishing fire (Altaf, *et al.,* 2007). Autonomous firefighting robots have emerged as crucial solutions in improving firefighting effectiveness and reducing hazards faced by human responders. This literature review aims to elucidate recent advancements in this field, focusing on the design intricacies, functionalities, and practical applications of firefighting robots.

A noteworthy study focused on the development of a Bluetooth-controlled spraying robot for pest control in greenhouse environments (Raju, *et al.*, 2023) (Udoka, *et al.*, 2023). This robot, equipped with a spraying nozzle, a Bluetooth module, and a camera for obstacle detection, enabled remote control through a Bluetooth-enabled mobile device (Aguilar, *et al.,* 20). WIFI spraying robots have demonstrated significant potential in various sectors such as agriculture, pest management, and industrial sanitation, ushering in a transformative era of efficiency, precision, and sustainability (Zhihua, *et al.,* 2022). Further exploration and refinement could position these robots as indispensable assets, particularly in sectors like healthcare, where containing outbreaks is critical.

In the realm of fire detection and suppression, Diwanji, *et al.,* (2019) outlined the construction of an automatic fire-detecting robot. This wireless robotic vehicle integrated a robust battery system to meet power demands. Equipped with a flame sensor and a buzzer for notification purposes, the robot functioned wirelessly, executing commands based on sensor inputs. Similarly, a study by Rai, *et al.,* (2020) proposed the design and implementation of an autonomous disinfection robot system tailored for extensive disinfection applications. This system consisted of an autonomous moving platform and a disinfection module, utilizing simultaneous localization and mapping (SLAM) for navigation. The disinfection module, powered by an ultrasonic atomizer, dispersed hydrogen peroxide liquid into a micrometer-sized dry mist, ensuring thorough space disinfection.

Researchers Roldán-Gómez, *et al.,* (2021), Kim (2014), and Queralta, *et al.,* (2020) have prioritized the integration of various sensors into firefighting robots to improve their environmental perception. By incorporating smoke detectors, temperature sensors, and gas sensors, these robots can quickly detect and assess the severity of fires. The use of Arduino-based systems has proven effective in processing sensor data, establishing a solid foundation for informed decision-making. The implementation of robust control algorithms is crucial for autonomous navigation and effective firefighting maneuvers (Madridano, *et al.,* 2021), (Fang, *et al*). Arduino's versatility has played a significant role in developing algorithms that enable precise movement, obstacle avoidance, and tactically sound firefighting strategies. These algorithms greatly enhance the adaptability of robots in dynamic fire scenarios.

The current advancements in firefighting robotics highlight significant progress in sensing technologies, mobility, fire suppression mechanisms, communication systems, and AI integration. However, further research and development are necessary to overcome obstacles and optimize their effectiveness in various firefighting situations. A detailed examination of ongoing projects reveals crucial design challenges and performance constraints. Researchers have encountered issues including excessive power consumption, durability in harsh environments, human intervention in navigation protocols, and the need for real-time decision-making. Understanding these challenges is essential to enhance the capabilities of autonomous firefighting robots.

The field of firefighting robotics has witnessed considerable advancements in sensor technology, mobility, fire suppression methods, communication protocols, and AI integration (Enyi, *et al.,* 2021). While these innovations hold promise, continuous research efforts are indispensable to address and overcome the diverse challenges that impede their optimal performance in different firefighting scenarios. A comprehensive analysis of ongoing projects uncovers a range of design challenges and operational limitations. Resolving issues such as power efficiency, resilience in challenging conditions, human oversight in navigation processes, and the need for timely decision-making has been a central focus for researchers. A nuanced understanding of these challenges forms the foundation for advancing the effectiveness and adaptability of autonomous firefighting robotics.

3.0 Materials and Method

3.1 Hardware Implementation

Hardware is a crucial component of design and implementation consisting of a carefully selected set of essential elements that work together seamlessly. The hardware ensemble includes an Arduino UNO board, Car Chassis, L298N motor driver for precise robot movement control, Flame sensor for environmental monitoring, battery power source, breadboard for circuit prototyping, soldering board for secure connections, jumper wires for interconnectivity, Servo motor for precise actuation, submersible water pump for fluid handling tasks, motors for robot locomotion, and a Spraying Nozzle for controlled dispensing. The block diagram below provides a comprehensive overview of the hardware implementation, with the Arduino serving as the central processing unit of the robot. This intelligent hub receives commands from input peripherals like the IR Flame Sensor (Eze, *et al.,* 2017). Using its processing capabilities, the Arduino executes algorithms and coordinates the activation of output peripherals, such as the motor driver and the submersible water pump, to achieve the desired responses and functionalities.

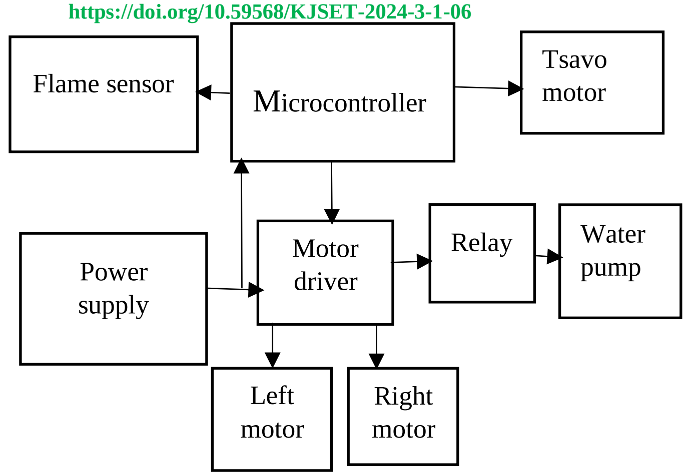


Figure 1: Block Diagram of Autonomous Firefighting Robot

Figure 1 is the block diagram showing the components used for the design of an autonomous firefighting robot. The functions of each component used in this design as illustrated in Figure 1are discussed below:

Microcontroller: Serving as the central processing unit, the microcontroller orchestrates the operations of the robot by interpreting instructions received from input sensors and subsequently coordinating the activation of output components (Enerst, *et al.*, 2023), (Eze, *et al*, 2023).

Motor Driver: The motor driver serves as an essential output interface, regulating the movement of the robot by controlling the four motors integrated into the wheels, thus enabling precise maneuverability.

Submersible Water Pump: Functioning as a direct current (DC) motor, the submersible water pump plays a crucial role in firefighting operations by extracting water from a reservoir and delivering it to the designated fire source, thereby aiding in extinguishing flames.

4WD Car Chassis: The 4WD car chassis serves as the structural foundation of the robot, providing a robust framework conducive to locomotion and accommodating various components such as batteries, thereby facilitating seamless integration and operational efficiency.

Flame Sensor: Acting as a pivotal input device, the flame sensor detects the presence of flames and transmits corresponding signals to the microcontroller, serving as a critical switch mechanism that triggers appropriate responses from the robot in fire detection and mitigation scenarios.

Batteries: The power source of the robot, batteries supply the necessary electrical energy to drive its operations, ensuring sustained functionality and mobility across diverse environments and tasks (Eze, *et al*, 2016).

Relay: Employed as a pivotal component in the operational setup, the relay serves as a reliable switching mechanism specifically tasked with controlling the activation of the submersible water pump, thereby regulating its functionality and optimizing its utilization in firefighting applications.

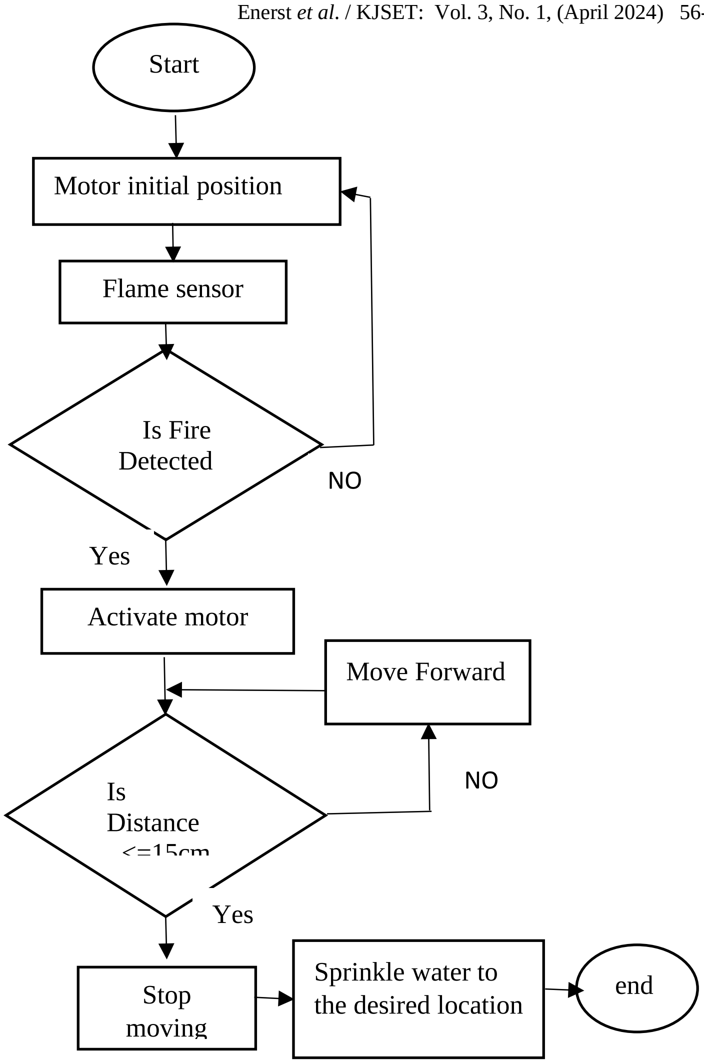


Figure 2: Flowchart of Autonomous Firefighting Robot

Figure 2 is the flowchart of the Autonomous Firefighting Robot which shows the operation flow of the system. The first decision that the system makes is to check if there is a fire signal detected by the sensor, if yes it will activate the motor but if NO, no action will be taken. Furthermore, if yes, is the distance between the robotic machine and the action point less than 15 cm? If yes stop moving and start sprinkling water to the action point but if NO keep moving till it gets to 15cm closer to the action point.

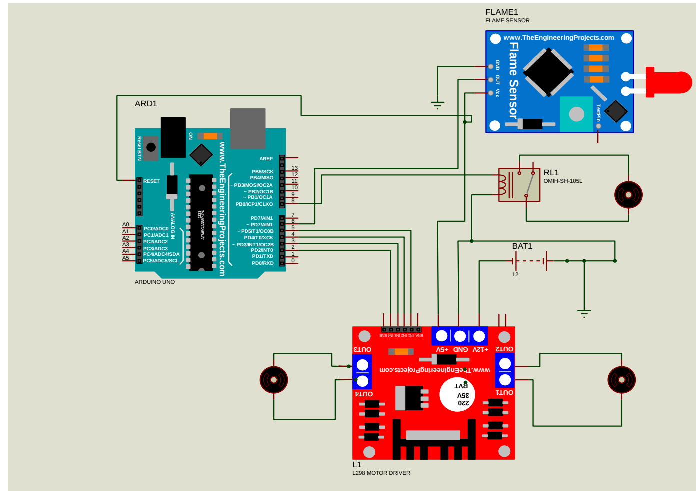
Methods

Component Selection

The appropriate components were selected based on their technical specifications and compatibility with the system. The robot will be built based on the different specifications of different components by analyzing each component's datasheet. The selection process will consider factors such as efficiency, cost, availability, and reliability.

3.2 Circuit Design

The selected components will be integrated into a circuit design that represents the proposed prototype as shown in figure 3. The circuit design will be developed using Proteus simulation software, which will allow for easy modification and testing of



the design.

Figure 3: Circuit Diagram of Autonomous Firefighting Robot

Simulation

The circuit design was simulated using Proteus software to verify its efficiency, effectiveness, and reliability. The simulation will involve inputting different scenarios and parameters to observe the response of the system. This is done basically to be sure that the outcome of the prototype will come out.

Design

In this section, the prototype of the robotic system is presented, which consists of an IR flame sensor, servo motors, a submersible water pump, a motor driver, a mini breadboard, BO motors, rubber wheels, a processor, and communication module for exchanging data between the fire-fighting robot and Arduino software. Below is the figure that shows how the basic prototype of our firefighting robot. The robot carries four main functions: First, it initializes itself which means that the sensors get initialized as the power is supplied. Secondly, the robot senses the surrounding environment (the temperature level) and identifies the fireplace. Thirdly, the robot sends the sensed danger zone information and starts navigating towards the fireplace. Finally, the robot begins to extinguish the fire with the help of servo motors and a submersible water pump.

4.0 Tests, Results and Discussions

4.1 Tests

During testing, all the components were tested using a multimeter to confirm continuity, and the sensors were tried on the breadboard to confirm that they working normally with Arduino. After compiling the working state of all the components, the whole system was combined and a robot was made using a breadboard. The robot was tested in a different environment to come up with the required prototype. Figure 4, shows a combined robotic setup using a breadboard during testing.

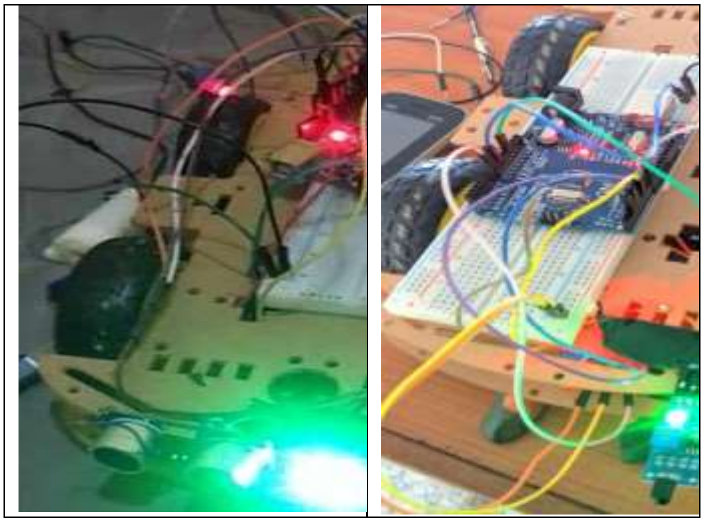


Figure 4: Robotic Setup of Autonomous Firefighting Robot

4.2 Results

The results were obtained from a series of meticulously conducted tests. Initially, each component underwent a thorough examination and adjustment process until the desired outcomes were achieved. A digital multimeter was used to ensure continuity and as well used to verify the integrity of each component, confirming that none of them were faulty. Subsequently, the datasheets of every component were diligently referenced to fully understand pin descriptions, connection configurations, and required voltages in order to preemptively avoid any potential short circuits. This systematic approach, executed on a component-by-component basis, prevented any misunderstandings during termination and ensured optimal functionality. Components that did not meet performance criteria were meticulously fine-tuned until the desired objectives were met. Once individual components were successfully validated, they were seamlessly integrated to be centrally controlled by a single microcontroller. This integration was facilitated using a breadboard, offering flexibility for future scalability and accommodating any necessary modifications. As a result of these efforts, an autonomous firefighting robot was developed. This innovative robot is capable of autonomously detecting fires, navigating toward their source, and effectively extinguishing them using water as a firefighting agent. It is important to note that a candle flame was used as the fire source for testing purposes, serving as a reliable benchmark for the robot's effectiveness.

This complete robotic design as shown in Figure 5, utilized three lithium rechargeable batteries, each with a voltage of 4V, resulting in a total of 12V DC power supply. This power supply was then connected to a driver motor L298N, which also provided power to the microcontroller through its power output port. The flame sensor and water pump were powered by the microcontroller's 5V pins. After conducting multiple tests, the entire system was relocated from the breadboard to the soldering board.

Figure 5: Complete diagram of the Autonomous Firefighting Robot

4.3 Discussions

Working Principles of Complete Autonomous Firefighting Robot

A microcontroller works as the heart of this robot since all the input and output components send and receive their instructions to and from the microcontroller. A flame sensor is a component that initializes the process since the robot is always packed before sensing the fire. When the sensor detects fire, it measures the distance to the fire source, if the distance is greater than 100mm, it sends a signal to the microcontroller which will trigger the driver motor to navigate towards the fire source up to 100mm close and then stop. Then the microcontroller will trigger ON the relay switch which is connected to the water pump to push water from the tank to the fire source hence extinguishing the fire

5.0 Conclusion

In conclusion, this study conducted a comprehensive review of relevant literature, utilized an experimental research design, and conducted meticulous data analysis to shed light on the potential and challenges of firefighting technology. The research underscored the importance of selecting appropriate sensor materials, optimizing transducer placement, and ensuring cost efficiency. These factors were essential in creating a practical, efficient firefighting tool capable of effectively mitigating fire hazards using water as the primary extinguishing agent. The study also explored real-world applications to identify the most suitable components. Traditionally, human navigation was employed, which proved costly and risky. Consequently, autonomous navigation with object avoidance capabilities was developed. This automatic navigation was guided by instructions from the flame sensors. The integration of advanced materials, the development of user-friendly designs, the assessment of economic implications, and the exploration of diverse applications all hold great promise for the future of autonomous firefighting robots.

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Declaration of conflict of interest

The authors have collectively contributed to the conceptualization, design, and execution of this article. They have worked on drafting and critically revising the article to include significant intellectual content. This manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors have unanimously declared no conflict of interest.

Reference

Aguilar, J. O., Castillo, J. V., Puc, F. C., Atoche, A. C., Cardeña, M. P., & Villanueva, C. R. (2011). Wireless Data Acquisition System for Greenhouses. In *Emerging Technologies in Wireless Ad-hoc Networks: Applications and Future Development* (pp. 136-147). IGI Global.

Altaf, K., Akbar, A., & Ijaz, B. (2007, July). Design and construction of an autonomous fire fighting robot. In *2007 International Conference on Information and Emerging Technologies* (pp. 1-5). IEEE.

Archibald, S. (2016). Managing the human component of fire regimes: lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150346.

Burke, J. L., Murphy, R. R., Coovert, M. D., & Riddle, D. L. (2004). Moonlight in Miami: Field study of human-robot interaction in the context of an urban search and rescue disaster response training exercise. *Human–Computer Interaction*, *19*(1-2), 85-116.

Diwanji, M., Hisvankar, S., & Khandelwal, C. (2019, September). Autonomous fire detecting and extinguishing robot. In *2019 2nd International Conference on Intelligent Communication and Computational Techniques (ICCT)* (pp. 327-329). IEEE.

Enerst, E., Eze, V. H. U., & Wantimba, J. (2023). Design and Implementation of an Improved Automatic DC Motor Speed Control Systems Using Microcontroller. *IDOSR Journal of Science and Technology*, *9*(1), 107–119.

Enerst, E., Eze, V. H. U., Okot, J., Wantimba, J., & Ugwu, C. N. (2023). DESIGN AND IMPLEMENTATION OF FIRE PREVENTION AND CONTROL SYSTEM USING ATMEGA328P MICROCONTROLLER. *International Journal of Innovative and Applied Research*, *11*(06), 25–34. https://doi.org/10.58538/IJIAR/2030

Enyi, V. S., Eze, V. H. U., Ugwu, F. C., & Ogbonna, C. C. (2021). Path Loss Model Predictions for Different Gsm Networks in the University of Nigeria , Nsukka Campus Environment for Estimation of Propagation Loss. *International Journal of Advanced Research in Computer and Communication Engineering*, *10*(8), 108–115. https://doi.org/10.17148/IJARCCE.2021.10816

Queralta, J. P., Taipalmaa, J., Pullinen, B. C., Sarker, V. K., Gia,

Eze, V. H. U., Edozie, E., & Ugwu, C. N. (2023). CAUSES AND PREVENTIVE MEASURES OF FIRE OUTBREAK IN AFRICA: REVIEW. *International Journal of Innovative and Applied Research*, *11*(06), 13–18. https://doi.org/10.58538/IJIAR/2028

Eze, V. H. U., Enerst, E., Turyahabwe, F., Kalyankolo, U., & Wantimba, J. (2023). Design and Implementation of an Industrial Heat Detector and Cooling System Using Raspberry Pi. *IDOSR Journal of Scientific Research*, *8*(2), 105–115.

Eze, V. H. U., Olisa, S. C., Eze, M. C., Ibokette, B. O., Ugwu, S. A., Eze, H. U., Olisa, S. C., Eze, M. C., Ibokette, B. O., & Ugwu, S. A. (2016). Effect of Input Current and the Receiver-Transmitter Distance on the Voltage Detected By Infrared Receiver. *International Journal of Scientific & Engineering Research*, *7*(10), 642–645.

Eze, V. H. U., Onyia, M. O., Odo, J. I., & Ugwu, S. A. (2017). DEVELOPMENT OF ADUINO-BASED SOFTWARE FOR WATER PUMPING IRRIGATION SYSTEM. *International Journal of Scientific & Engineering Research*, *8*(8), 1384–1399.

Eze, V. H. U., Umaru, K., Edozie, E., Nafuna, R., & Yudaya, N. (2023). The Differences between Single Diode Model and Double Diode Models of a Solar Photovoltaic Cells : Systematic Review. *Journal of Engineering, Technology & Applied Science*, *5*(2), 57–66. https://doi.org/10.36079/lamintang.jetas-0502.541

Fang, Z., Yang, S., Jain, S., Dubey, G., Roth, S., Maeta, S., ... & Scherer, S. (2017). Robust autonomous flight in constrained and visually degraded shipboard environments. *Journal of Field Robotics*, *34*(1), 25-52.

Feldman, M. (2023). Intelligence Versus Inferno: How Artificial Intelligence Can Be Used to Monitor and Manage Wildfires in Europe.

Gill, A. M., & Stephens, S. L. (2009). Scientific and social challenges for the management of fire-prone wildland–urban interfaces. *Environmental Research Letters*, *4*(3), 034014.

Kim, J. H. (2014). *Autonomous Navigation, Perception and Probabilistic Fire Location for an Intelligent Firefighting Robot* (Doctoral dissertation, Virginia Polytechnic Institute and State University).

Liu, P., Yu, H., Cang, S., & Vladareanu, L. (2016, September). Robot-assisted smart firefighting and interdisciplinary perspectives. In *2016 22nd international conference on automation and computing (ICAC)* (pp. 395-401). IEEE.

Madridano, Á., Al-Kaff, A., Flores, P., Martín, D., & de la Escalera, A. (2021). Software architecture for autonomous and coordinated navigation of uav swarms in forest and urban firefighting. *Applied Sciences*, *11*(3), 1258.

Martin, D., Tomida, M., & Meacham, B. (2016). Environmental impact of fire. *Fire Science Reviews*, *5*, 1-21. (3)

T. N., Tenhunen, H., ... & Westerlund, T. (2020).

Collaborative multi-robot systems for search and rescue: Coordination and perception. *arXiv preprint arXiv:2008.12610*.

Rai, A., Chaturvedi, C., Maduri, P. K., & Singh, K. (2020, December). Autonomous disinfection robot. In *2020 2nd International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)* (pp. 990-996). IEEE.

Raju, K., Tulaskar, R. R., & Sherwin, C. (2023). Solar-Powered Pesticide-Spraying RFID Robot. In *Smart Village Infrastructure and Sustainable Rural Communities* (pp. 283-307). IGI Global.

Roldán-Gómez, J. J., González-Gironda, E., & Barrientos, A. (2021). A survey on robotic technologies for forest firefighting: Applying drone swarms to improve firefighters' efficiency and safety. *Applied Sciences*, *11*(1), 363.

Udoka, E. V. H., Edozie, E., Davis, M., Dickens, T., Janat, W., Wisdom, O., ... & Yudaya, N. (2023). Mobile Disinfectant Spraying Robot and its Implementation Components for Virus Outbreak: Case Study of COVID-19. *International Journal of Artificial Intelligence*, *10*(2), 68-77.

Yahaya, I. (2020). Autonomous safety mechanism for building: Fire fighter robot with localized fire extinguisher. *International Journal Of Integrated Engineering*, *12*(1), 304-314.

Zhihua, D., Jiaonan, Y., Meng, Z., Zhendong, H., Taishan, L., & Qing, W. (2022). Structural design and analysis of corn weeding robot based on WiFi communication. *Journal of Chinese Agricultural Mechanization*, *43*(4), 131.