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RESEARCH ARTICLE **Open Access**

Implementation of the Sugeno Fuzzy Method in a Firefighting Robot Prototype with an All-Wheel Drive System

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Abstract: The purpose of this study is how to implement the Fuzzy Sugeno method to a fire-fighting robot prototype with all wheel drive system. Resculpts by transferring academic input to specific fields of knowledge, as many problems have become increasingly adaptable due to technology or the growth of AI, which is fast becoming the dominant productivity tool. Fuzzy method is a mathematical method used to overcome the problems of small uncertainties and imprecision. The first prototype of the fire-fighting robot which will be able to use all-wheel drive system is meant to mitigate the risk of large fire and to detect as soon as possible. Observational results verify that the Robot prototype follows its intended workflow as well as can complete its mission to both detect and eliminate fire hazards. The speed of the wheel is controlled on three levels slow (0 RPM), moderate (50 RPM), and fast (100 RPM) using Fuzzy Sugeno method. Also, in response time is set by using Fuzzy Sugeno method which is set to 1 second, 2 seconds, and 3 seconds.

Keywords: Robotics; Fuzzy Sugeno Method; Robot Prototype; Fire-Fighting; All-Wheel Drive System.

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1. Introduction

The rapid advancement of science and technology, particularly in the field of artificial intelligence, has significantly impacted the way complex problems are addressed, making them easier to solve and more adaptable to various disciplines. With the growth of such technologies, the use of computers as data processing tools has greatly assisted humans in completing various tasks, and robotics has experienced rapid development in both the industrial and higher education sectors. The multitude of research and development efforts, including hypotheses, techniques, and the introduction of new equipment, are aimed at assisting humans in completing tasks more efficiently and autonomously [1].

One of the most pressing challenges today is the occurrence of disasters caused by human error, which can jeopardize the safety of those involved in mitigating these disasters. A prime example is the fire-fighting profession, where personnel are exposed to significant risks when confronting fires. The very nature of fires presents a danger to the personnel involved in the task of extinguishing them. Consequently, the need arose to explore ways to assist fire-fighting personnel in controlling large-scale fires, specifically through technology that can locate and extinguish fire sources. A potential solution to this problem is the development of fire-fighting robots. This study aims to examine the performance of robots in detecting and extinguishing fire sources during a fire incident, utilizing Fuzzy Sugeno control systems to guide the robot's route with four driving motors [2]. A fire-fighting robot is designed to automatically locate and extinguish fires within a designated area, often a simulation of a building or structure. In order to build such an autonomous robot, an accurate navigation system is essential to enable the robot to quickly and precisely identify the fire source. Furthermore, the robot must be equipped with an all-wheel-drive system to ensure stability and maneuverability across various terrains. One of the key methods for determining the robot's path and controlling its motion is the use of the Fuzzy Sugeno technique. Fuzzy Sugeno is a type of intelligent control system that emulates human decision-making processes in managing uncertainty, applying fuzzy rules to control a system in a natural manner.

The primary advantage of using Fuzzy Sugeno is its adaptability and flexibility, allowing the system to adjust to changing input conditions in real-time [3][4]. This is especially relevant for a fire-fighting robot, as it must navigate through unpredictable environments such as uneven surfaces, high heat, and various fire intensities. The ability of Fuzzy Sugeno to dynamically adjust the robot's behavior makes it an ideal solution for handling the complexities involved in fire detection and extinguishment tasks. Additionally, the robot must be able to follow walls and move in complex environments, which requires a control system capable of continuous adaptation to the environment. Given that many companies still lack the knowledge and infrastructure for implementing automatic fire suppression systems, there is a strong need for the development of fire-fighting robot prototypes. In fire situations, employees who are not adequately trained to handle fires are limited in their ability to respond effectively, posing serious safety risks. As a result, companies are increasingly focusing on advancing technology to streamline the process of fire management and enhance workplace safety. The development of fire-fighting robots offers a significant advantage, not only in terms of facilitating the extinguishment of fires but also in ensuring the safety of both employees and the surrounding environment.

This research recognizes the urgency of addressing the challenges outlined above and will therefore focus on applying the Fuzzy Sugeno strategy in the development of a fire-fighting robot prototype. The research aims to explore how the Fuzzy Sugeno method can improve the robot's performance in detecting and extinguishing fire sources autonomously. Additionally, the integration of an all-wheel-drive system will be examined for its ability to provide better mobility and stability for the robot, particularly in difficult terrains that may be encountered during a fire-fighting mission. The study will be conducted as a case study on PT. Cipta Tekno Mandiri, which is working on developing such a robot prototype.

2. Research Method

This research follows a systematic approach to ensure that the experimentation process aligns with the intended objectives. Each stage is designed to facilitate the achievement of the research goals and ease the process of testing the prototype. The steps followed in this study include several important phases, each playing a crucial role in developing the fire-fighting robot prototype with an all-wheel-drive system. The research begins with the identification of the problem faced by PT. Cipta Tekno Mandiri, which focuses on the difficulties the company faces in addressing fire hazards and the risks posed to their personnel during fire-fighting operations.

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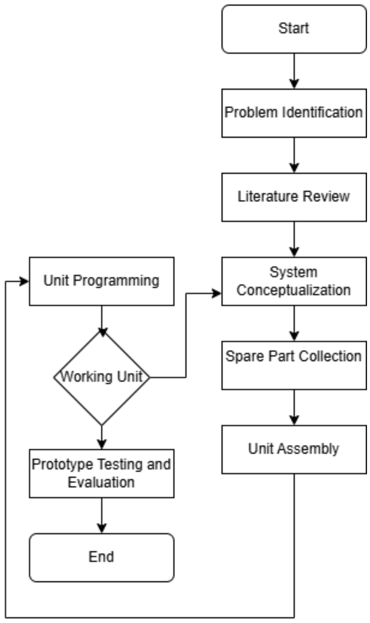

Figure 1. Research Design

The first step in the research process is problem identification, where the company acknowledges its challenges in extinguishing fires efficiently. The presence of fire hazards that can endanger the safety of personnel is the primary reason for seeking more effective solutions. In this phase, the main issue to be resolved is the creation of a system that can assist in fire-fighting by using a robot equipped with an all-wheel-drive system and controlled by Fuzzy Sugeno to improve the robot's detection and response capabilities to fire incidents. The second phase is literature review, where the researcher studies various academic articles and references related to the application of the Fuzzy Sugeno method in fire-fighting robot prototypes with an all-wheel-drive system. This literature serves as a theoretical foundation for designing and testing the prototype, guiding the methodology and providing insights into established research findings. Following the literature review, the third phase is system conceptualization, which focuses on designing the fire-fighting robot prototype with an all-wheel-drive system. The proposed system concept is to create a robot capable of detecting fire sources automatically and moving towards the fire to extinguish it. The system will integrate Fuzzy Sugeno for controlling the robot's movement based on inputs such as temperature and environmental conditions, allowing the robot to adapt to various fire scenarios. The next stage is collecting spare parts, where the necessary components for assembling the robot are gathered. These parts are sourced from various suppliers and are intended to build the fire-fighting robot prototype. This stage ensures that all required components are available and ready for the assembly process.

Once the parts are collected, the next phase is unit assembly, in which the gathered spare parts are assembled into a functioning prototype. This stage involves integrating hardware components with Arduino software to control the robot's movement and operate the Fuzzy Sugeno algorithm. The hardware and software are tested together to ensure the robot functions correctly. Following the assembly phase, the programming of the unit takes place. The assembled robot is programmed using Arduino software to manage how the robot will respond to sensor inputs and move accordingly. The Fuzzy Sugeno algorithm is also programmed to control the speed of the robot based on the inputs received, ensuring smooth and adaptive movement in response to changes in the environment. After the unit is tested, the prototype fire-fighting robot is ready for evaluation. This new prototype at PT. Cipta Tekno Mandiri is expected to detect fire sources automatically and navigate toward them to carry out extinguishing tasks. Further testing will be conducted to ensure that the robot meets the design specifications and functions as expected in various fire scenarios. Finally, the reporting and conclusion phase is carried out, where the results of the prototype's performance are documented. The fire-fighting robot prototype with an all-wheel-drive system is evaluated periodically to provide feedback to the development team. If necessary, modifications will be made to improve the functionality and efficiency of the robot. The results of this research will be useful for the company in understanding how to develop an automated fire-fighting system that can be safely and effectively operated in various situations.

3. Result and Discussion

3.1 Results

3.1.1 Results of the Fire-Fighting Robot with All-Wheel Drive System

The consequences of the fire-fighting robot model with the All-Wheel Drive Framework involve ongoing strategic improvements aimed at providing identification or mitigation of fire hazards. These actions are carried out once the framework testing phase has been completed. The author will present new analysis results based on the ongoing system analysis from previous chapters. The performance results are expected to address several fire-related problems encountered earlier.

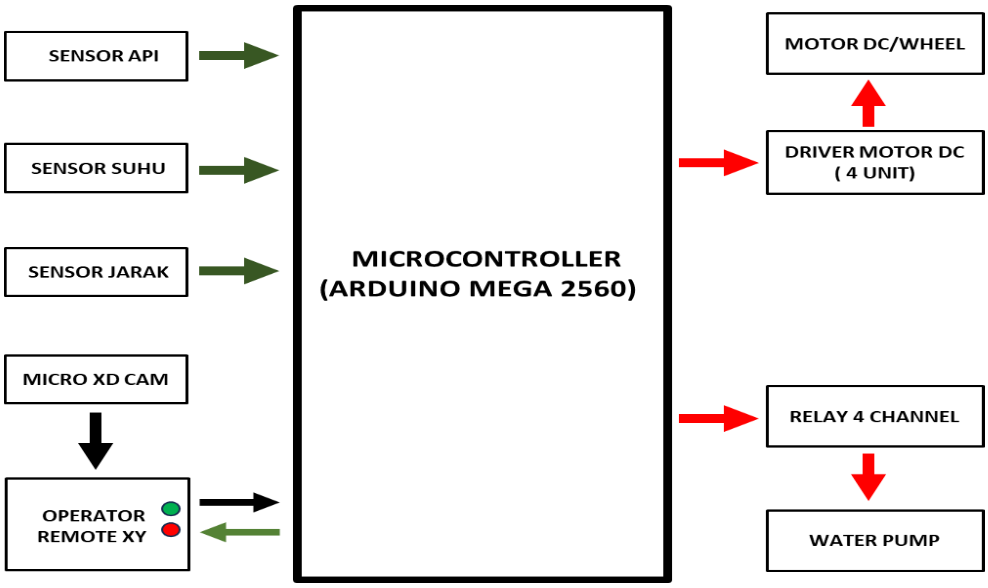

Figure 2. Research Design

3.1.2 Development of the Electronic System

The electronic system is designed according to the required functions. For example, to drive the motors in the All-Wheel Drive system, sensors are required. These sensors are studied to understand their functioning. The components used in the system are as follows:

1) Microcontroller: The Arduino Mega 2560 microcontroller is used.
2) Bluetooth Shield HC-05: Used for Bluetooth communication.
3) Distance Sensor (Ultrasonic): The HC-SR04 sensor is used for distance measurement.
4) Infrared Thermometer: The MLX90614 infrared thermometer is used for temperature measurements.
5) Flame Sensor: Used for fire detection.
6) 12V Battery: A GS 12V battery is used for ignition.
7) Step-down Buck DC Adjustable: A step-down voltage converter for power regulation.
8) Switch (DC On/Off), Fuse Holder, Motor Driver BTS7960, Gearbox Motor, Tricycle Wheels, Wheel Connectors, Long Shaft, Nuts & Bolts, Angle Iron, Pipe Clamp, Sprayer Nozzle, PVC Board, Spacer, Jumper Cables, Mini Water Pump, Relay 4-channel, Micro Servo, Servo Bracket, Camera, Bluetooth Shield HC-05, Cable Strips, Flux, Soldering Wire, USB Cable for Arduino.
9) Buzzer: For sound notifications.

For the fuzzy Sugeno method calculations, the author selected data to be processed as sample calculations. Below is a sample calculation for the fuzzy Sugeno method.

Table 1. Fuzzy Set for Flame Sensor (Fire Detection)

No.	Status	Output Pin Status
1	Detected	HIGH
2	Not Detected	LOW

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Table 2. Fuzzy Set for MLX90614 Sensor (Temperature)

Temperature Range	Fuzzy Set Status
< 28°C	Warm
≥ 28°C - 33°C	Hot
> 33°C	Very Hot

The fuzzy set of MLX90614 sensor inputs can function well or not function so that the temperature range is warm < 28 °C, hot < >=28 °C- 33°C and very hot >33°C. The results of the fuzzy set of MLX90614 sensor inputs are produce. The resulting fuzzy set for the MLX90614 sensor is shown below:

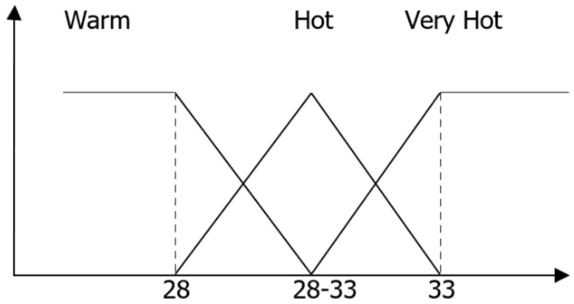

Figure 3. Fuzzy Set for MLX90614 Sensor (Temperature)

As shown in Figure 2, the fuzzy set represents the temperature readings from the MLX90614 sensor: "Warm", "Hot", and "Very Hot."

Table 3. Fuzzy Set for Ultrasonic Sensor (Distance)

Distance Range	Fuzzy Set Status
< 20 cm	Close
20 cm - 40 cm	Medium
> 40 cm	Far

The fuzzy set of MLX90614 sensor inputs can function well or not function so that the temperature range is warm <20 °C, hot >=20 °C- 40°C and very hot >40°C resulting from the fuzzy set of ultrasonic sensor inputs. The resulting fuzzy set for the ultrasonic sensor is shown below:

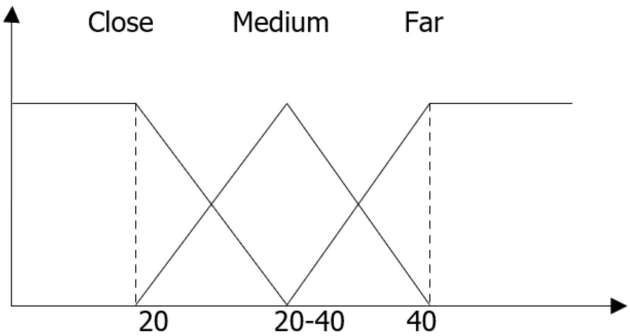

Figure 4. Fuzzy Set for Ultrasonic Sensor (Distance)

As seen in Figure 4, the fuzzy set illustrates the distance categories "Close," "Medium," and "Far."

Table 4. Fuzzy Set for Distance and Temperature Action for Pump Duration

No.	Distance	Temperature	Pump Duration
1	Very Close	Warm	1'
2	Very Close	Hot	2'
3	Very Close	Very Hot	3'
4	Close	Warm	4'
5	Close	Hot	5'
6	Close	Very Hot	6'

7	Far	Warm	7'
8	Far	Hot	8'
9	Far	Very Hot	9'

Table 5. Fuzzy Set for Distance and Temperature Action for Wheel Speed

No.	Distance	Temperature	Wheel Speed
1	Very Close	Warm	0 RPM
2	Very Close	Hot	0 RPM
3	Very Close	Very Hot	0 RPM
4	Close	Warm	50 RPM
5	Close	Hot	50 RPM
6	Close	Very Hot	50 RPM
7	Far	Warm	100 RPM
8	Far	Hot	100 RPM
9	Far	Very Hot	100 RPM

Table 6. Input and Output for Fuzzy Sugeno

Rule	Input 1 (Fire Detection)	Input 2 (Distance)	Input 3 (Temperature)	Output 1 (Pump Duration)	Output 2 (Wheel Speed)
1	Detected	Very Close	Warm	1 minute	0 RPM
2	Detected	Very Close	Hot	2 minutes	0 RPM
3	Detected	Very Close	Very Hot	3 minutes	0 RPM
4	Detected	Close	Warm	4 minutes	50 RPM
5	Detected	Close	Hot	5 minutes	50 RPM
6	Detected	Close	Very Hot	6 minutes	50 RPM
7	Detected	Far	Warm	7 minutes	100 RPM
8	Detected	Far	Hot	8 minutes	100 RPM
9	Detected	Far	Very Hot	9 minutes	100 RPM
10	Not Detected	Very Close	Warm	Off (0 minutes)	0 RPM
11	Not Detected	Very Close	Hot	Off (0 minutes)	0 RPM
12	Not Detected	Very Close	Very Hot	Off (0 minutes)	0 RPM
13	Not Detected	Close	Warm	Off (0 minutes)	50 RPM
14	Not Detected	Close	Hot	Off (0 minutes)	50 RPM
15	Not Detected	Close	Very Hot	Off (0 minutes)	50 RPM
16	Not Detected	Far	Warm	Off (0 minutes)	100 RPM
17	Not Detected	Far	Hot	Off (0 minutes)	100 RPM
18	Not Detected	Far	Very Hot	Off (0 minutes)	100 RPM

The following set of rules defines the behavior of the fire-fighting robot based on the input conditions of fire detection, distance, and temperature. These rules determine the corresponding actions for the robot, specifically the duration of the pump operation and the speed of the wheels, in response to various environmental scenarios.

1 If fire is detected and distance is very close and temperature is warm, then pump duration = 1 minute and wheel speed = 0 RPM
2 If fire is detected and distance is very close and temperature is hot, then pump duration = 2 minutes and wheel speed = 0 RPM
3 If fire is detected and distance is very close and temperature is very hot, then pump duration = 3 minutes and wheel speed = 0 RPM
4 If fire is detected and distance is close and temperature is warm, then pump duration = 4 minutes and wheel speed = 50 RPM
5 If fire is detected and distance is close and temperature is hot, then pump duration = 5 minutes and wheel speed = 50 RPM
6 If fire is detected and distance is close and temperature is very hot, then pump duration = 6 minutes and wheel speed = 50 RPM
7 If fire is detected and distance is far and temperature is warm, then pump duration = 7 minutes and wheel speed = 100 RPM

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8 If fire is detected and distance is far and temperature is hot, then pump duration = 8 minutes and wheel speed = 100 RPM
9 If fire is detected and distance is far and temperature is very hot, then pump duration = 9 minutes and wheel speed = 100 RPM
10 If no fire is detected and distance is very close and temperature is warm, then pump duration = 0 minutes and wheel speed = 0 RPM
11 If no fire is detected and distance is very close and temperature is hot, then pump duration = 0 minutes and wheel speed = 0 RPM
12 If no fire is detected and distance is very close and temperature is very hot, then pump duration = 0 minutes and wheel speed = 0 RPM
13 If no fire is detected and distance is close and temperature is warm, then pump duration = 0 minutes and wheel speed = 50 RPM
14 If no fire is detected and distance is close and temperature is hot, then pump duration = 0 minutes and wheel speed = 50 RPM
15 If no fire is detected and distance is close and temperature is very hot, then pump duration = 0 minutes and wheel speed = 50 RPM
16 If no fire is detected and distance is far and temperature is warm, then pump duration = 0 minutes and wheel speed = 100 RPM
17 If no fire is detected and distance is far and temperature is hot, then pump duration = 0 minutes and wheel speed = 100 RPM
18 If no fire is detected and distance is far and temperature is very hot, then pump duration = 0 minutes and wheel speed = 100 RPM.

3.2 Discussion

The general framework configuration represents the final design of the system to be developed. Below is the overall system layout:

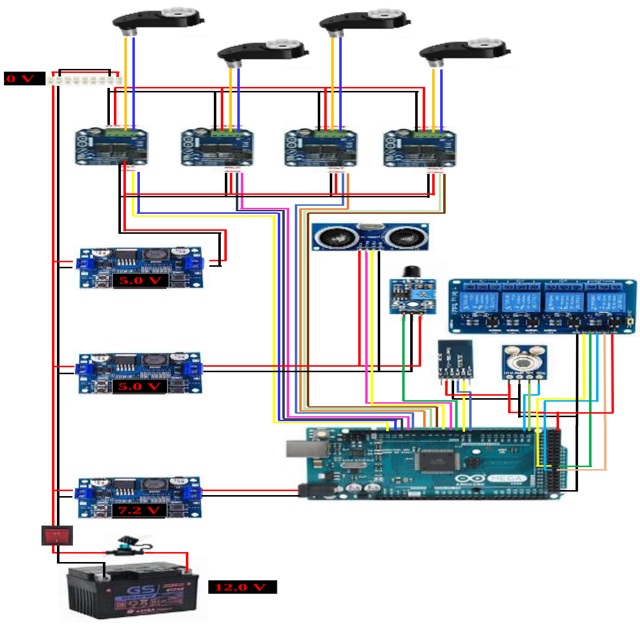

Figure 5. Wiring Design of the Fire-Fighting Robot Prototype

This figure illustrates the hardware design of the fire-fighting robot prototype. The prototype has been adjusted to match its real-world design, as shown in the following images:

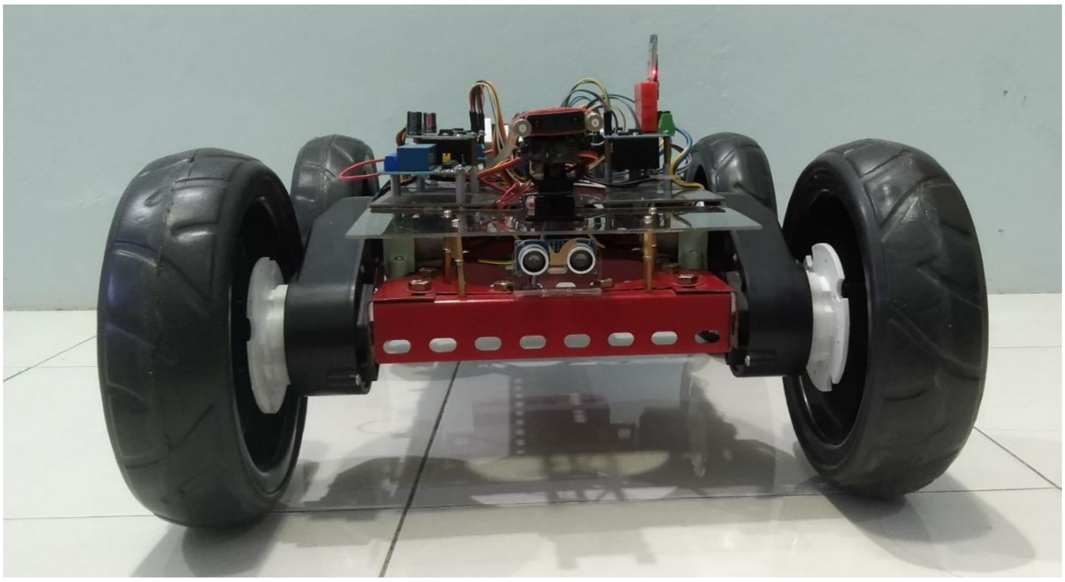

Figure 6. Front View of the Fire-Fighting Robot Prototype

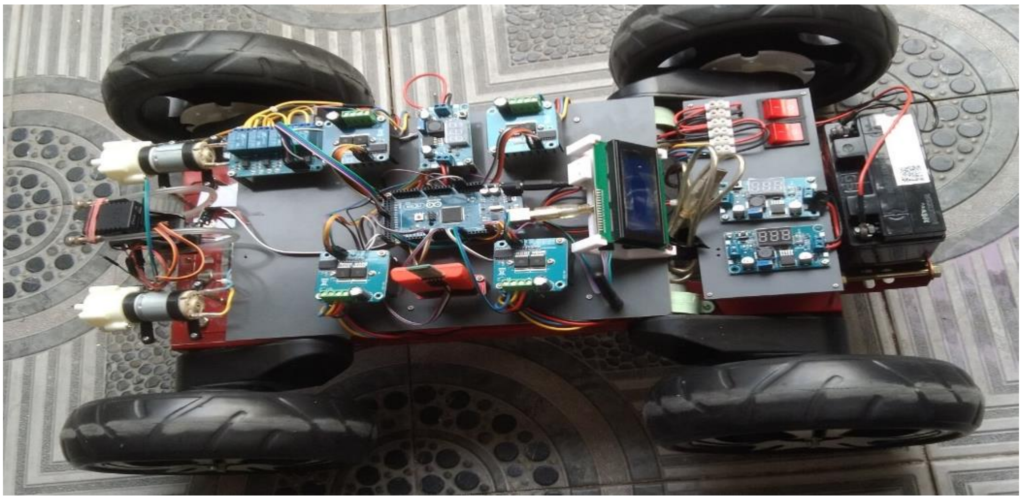

Figure 7. Top View of the Fire-Fighting Robot Prototype

The XY remote control manages the movement of the fire-fighting robot once all system components have been executed and the robot returns to its starting position.

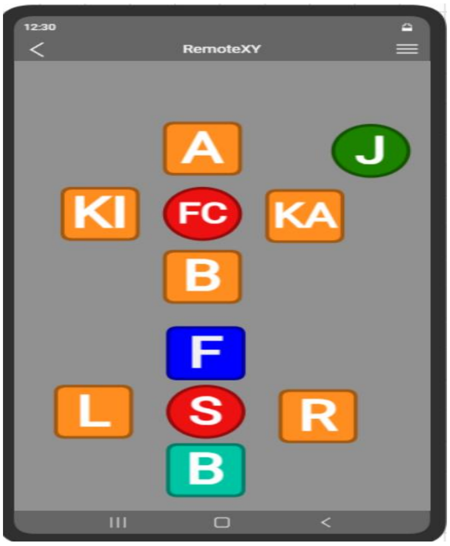

Figure 8. Remote XY

At this stage, testing is conducted on the developed tool to determine whether it meets the expected specifications. If the results are unsatisfactory, a redesign may be required. The testing is carried out by simulating a fire scenario, where the robot must detect fire placed on the floor. Each robot is expected to accurately detect the presence of the fire. Below are the results of the fire-fighting robot prototype tests:

Table 7. Test Results of the Fire-Fighting Robot Prototype

Test No.	Flame Detection Status	Distance (cm)	Temperature (°C)	Pump Duration (seconds)	Wheel Speed (RPM)	Extinguishing Result
1	Detected	19.50	27.80	1	20	Successful
2	Detected	31.25	29.60	2	60	Successful
3	Detected	39.00	37.33	3	60	Successful
4	Detected	43.20	27.44	1	100	Successful
5	Detected	18.40	38.88	3	20	Successful
6	Detected	77.40	38.20	3	100	Failed
7	Detected	26.28	30.55	2	60	Successful
8	Detected	52.50	26.44	1	100	Successful
9	Detected	33.50	30.60	2	-	Successful
10	Detected	37.00	36.40	3	60	Successful
Success Rate						90.00%

Given the consequences of the perception implemented in the robot's model cycle, success is expected as long as the device operates according to the provided strategy, with negligible errors. The testing results show that the robot's operational interactions align with the planned process and can complete its mission, where the robot must detect fire to prevent further spread. Testing is an essential part of the equipment enhancement cycle, aimed at ensuring the device's quality. This testing also verifies that the device can correctly interpret every interaction during the model's execution, from details, investigation, planning, to coding. The testing system is focused on the fire-fighting robot model with an all-wheel-drive system and its capability to meet the required application standards.

4. Related Work

The development of fire-fighting robots has gained significant attention in recent years, particularly due to advancements in artificial intelligence and robotics. Several studies have examined the use of robotic systems for fire detection and suppression, utilizing various techniques to improve accuracy, speed, and efficiency in such systems. One of the prominent approaches is the use of fuzzy logic systems, especially the Fuzzy Sugeno method, to manage uncertainties in environmental factors such as fire detection, temperature, and distance measurement. Shema (2022) implemented fuzzy logic for controlling the actions of a fire-fighting robot, using temperature and distance sensors to adjust its movement and fire-fighting activities. This method, similar to the approach used in our research, enabled the robot to adjust its behavior in response to the changing conditions of the fire and the surrounding environment [5]. Sutarmin *et al.* (2023) developed a fire-fighting robot prototype that uses Arduino-based controllers and fuzzy logic for autonomous fire detection and suppression. Their design, like our prototype, incorporates sensors such as flame detectors and infrared thermometers, combined with an all-wheel-drive system for mobility. The fuzzy logic controller in their system, much like ours, adjusts the pump duration and wheel speed based on the proximity and intensity of the detected fire [6].

In another study, Hartono & Firdaus (2018) explored the integration of ultrasonic sensors and infrared thermometers in fire-fighting robots to measure distance and temperature. Their robot used these sensors to determine the best strategy for fire suppression, adjusting its speed and activating the water pump when necessary. Similarly, our fire-fighting robot uses the MLX90614 infrared thermometer and ultrasonic sensors to assess temperature and distance, which are then processed by fuzzy logic to control the robot's actions [11]. Additionally, Safarudin and Patah (2020) focused on developing a fire-fighting robot controlled by a microcontroller, similar to the Arduino Mega 2560 used in our design. They applied fuzzy logic to control the robot's speed and pump duration, improving its adaptability to different fire scenarios. Their work demonstrated the effectiveness of fuzzy logic in enhancing the robot's performance during fire-fighting operations, which aligns with our approach [16]. Our research advances previous work by integrating a fully autonomous fire-fighting robot that uses an all-wheel-drive system combined with Takagi-Sugeno (T-S) fuzzy logic for controlling the robot's actions. The T-S fuzzy logic model is advantageous due to its simplicity and effectiveness in controlling nonlinear systems, as demonstrated in multiple applications including robotics and automation. Studies by Vafamand (2020) and Chiu & Peng (2019) have shown the robustness and efficiency of T-S fuzzy logic in real-world control systems, making it an ideal choice for our robot's control mechanism [17][18]. The fuzzy inference rules used in our system, which control the pump duration and wheel speed based on the fire's intensity, distance, and temperature, build upon methodologies from earlier research but are tailored to the unique configuration and operational tasks of our fire-fighting robot [19][20].

The T-S fuzzy model enables the robot to incorporate human-like reasoning in its decision-making process, allowing it to make accurate judgments based on imprecise inputs such as temperature readings and fire detection. This method has been successfully applied to other robotic systems, demonstrating its versatility and reliability in diverse real-world scenarios [24][25]. Moreover, the all-wheel-drive system enhances the robot's mobility and stability, which is crucial for maneuvering through difficult environments commonly encountered during fire-fighting operations, as demonstrated by Adamu *et al.* (2018) [26]. Uur research builds upon existing fuzzy logic methodologies and introduces innovative applications to enhance the operational capabilities of fire-fighting robots. By integrating Takagi-Sugeno fuzzy logic with an all-wheel-drive system, our design significantly improves the efficiency and effectiveness of autonomous fire-fighting robots, ensuring reliable performance during fire emergencies. This approach represents a notable step forward in the development of advanced fire-fighting technologies [27][28].

5. Conclusion

Based on the results of the research conducted, it can be concluded that the fire fighting robot with an all-wheel drive motion system can be applied at PT Cipta Tekno Mandiri. The results of the observation show that the prototype of this fire fighting robot works according to the designed flow and is able to complete its mission, namely detecting and extinguishing fires to prevent the potential for wider fires. The implementation of this robot also facilitates early detection of fires, so that the risk of damage can be minimized. Tests show that the use of the Sugeno fuzzy method is successful in controlling the speed of the robot's wheels at three speed levels, namely slow (0 RPM), medium (50 RPM), and fast (100 RPM). In addition, Sugeno fuzzy also succeeded in regulating the robot's response time, with a speed setting of 1 second for a fast response, 2 seconds for a medium response, and 3 seconds for a slow response. The results of this study prove that the application of the Sugeno fuzzy method to a fire fighting robot with an all-wheel drive motion system can be an effective solution in increasing the responsiveness and efficiency of fire fighting.

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