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# EARLY FIRE DETECTION MOBILE ROBOTIC SYSTEM WITH HYBRID LOCOMOTION

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**Abstract:** In this study, a mobile robotic structure with fire detection and hybrid locomotion capabilities designed and developed. The hybrid locomotion system is an adaptive three-wheeled structure, and it has been structured to provide obstacle climbing and linear motion. The paper puts forward a structure for obstacle avoidance and path planning named "Direction Based Angle Computation". The system is designed to categorize obstacles as either negligible or surmountable, with this classification determined by the height and shape of the obstacles. The objective of the "Fire Search and Find" and "Fire Detection" systems is to identify potential fire locations and calculate the associated probabilities. Experimental tests are conducted for the mechanical structure and architecture of robotic systems. The experimental test results demonstrated that the motion systems have proficiency in both rolling-climbing and linear motions. The Direction Based Angle Computation approach is a proper methodology for the tasks path planning and obstacle avoidance. The proposed fire detection algorithm with the usage of Faster R-CNN machine learning model, has been shown to determine the probability of a fire source with 93% accuracy.

**Keywords:** Early fire detection, Faster R-CNN machine learning model, Fire detection robot, Hybrid locomotion, Mobile robotic system, Path planning and obstacle avoidance

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## 1. Introduction

Fire is a type of disaster which causes damage in a variety of locations, including residential dwellings, industrial zones and forests (Haukur et al., 2010; Mishra et al., 2013; Zhou et al., 2020). Despite the hazardous nature of firefighting, which encompasses activities such as fire extinguishing and casualty rescue, it is a vocation that is still primarily undertaken by human operators. These individuals, known as firefighters, are engaged in a profession that entails the risk of personal injury and fatality (Li et al., 2023; Ibitoye et al., 2024). It is imperative to acknowledge that the containment of a fire disaster once it has spread is an insurmountable task. Additionally, the recovery of the affected area is a difficult endeavor. Therefore, the most effective method of firefighting is to detect a fire before it reaches a dangerous level. Different devices have been used for detecting fire at early stages (Bertram et al., 2013; Sucuoglu et al., 2019). Flame and smoke detectors, camera systems are some of these systems. However, those systems have their usage disadvantages as costs and maintenance requirements. This causes the requirement of the usage of mobile systems for early detection purposes (Sulthana et al., 2023).

Early fire detection systems can be grouped into two main methodologies (Dampage et al., 2022; Lee et al., 2023). The first is the physical detection of events of smoke, temperature fluctuations, the presence of flame, or combination of them. The usage of ion, smoke, gas, ultraviolet, and heat sensors has effective performance for early fire detection tasks (Sowah et al., 2016; Fonollosa et al., 2018). However, it is an important requirement that these systems must be placed close to the fire source. These devices are generally good options for indoor environment usages. (Zhang et al., 2019; Sucuoglu et al., 2020; Khan et al., 2022; He et al., 2023). The second is detection of fire sources with images. The process of determining the presence of fire is facilitated by the analysis of various physical phenomena, including the color, shape, behavior and combinations of flame and smoke properties (Cetin et al., 2013; Rehman et al., 2020; Alqourabah et al., 2021). Nowadays, machine learning algorithms, such as CNNs (Convolutional Neural Networks), have been also used for fire detection in video streams (Luo et al., 2018; Park et al., 2020; Li et al., 2023; Buriboev et al., 2024).

Recent studies have also focused on the usage of mobile robots to perform various tasks such as surveillance, reconnaissance, patrol, firefighting, homeland security, entertainment, and service. Mobile robotic systems for early fire detection and firefighting purposes have certain advantages over stationary systems. Those advantages are lower cost, minimal maintenance requirements, and the capacity for versatile applications

such as patrolling, security, and early fire detection (Alqourabah et al., 2021; Nguyen et al., 2024; Pandian, 2025). For locomotion of the mobile robotic systems, various mechanical structures have been proposed. Within these structures, three primary categories are:
W (wheeled), T (tracked), and L (legged). Furthermore, hybrid structures have been created, namely LW (leg-wheel), LT (leg-track), WT (wheel-track) and LWT (leg-wheel-track). Each of them has its own advantages and disadvantages when evaluated with performance criteria such as velocity, obstacle avoidance, climbing, motion and slope adaptation, motion adaptation and energy efficiency. A performance comparison table of the motion systems is presented in Figure 1.

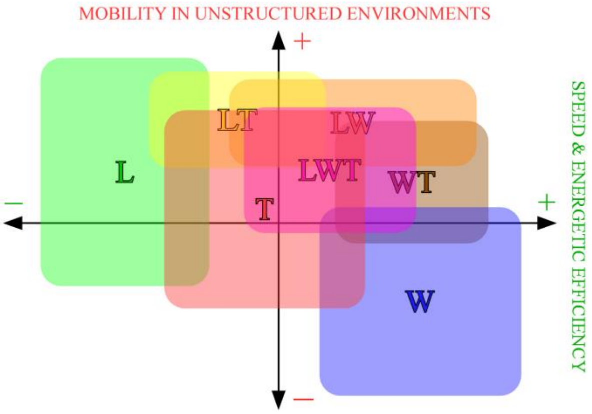


**Figure 1**. Performance chart of locomotion systems (Bruzzone et al., 2022).

As demonstrated in Figure 1, the hybrid categories have been designed and developed to utilize the main categories of wheeled, tracked and legged. Nevertheless, it is not possible to fully realize the total gain, due to the extra load effects of the additional motion elements. These hybrid systems are well-suited for operational environments that demand rapid movement and the ability to overcome obstacles. The construction of hybrid systems can be achieved through the following four methodologies (Raibert et al., 1986; Manchester et al., 2011).
1.Connection of the legs to main structure of the wheeled robotic system
2.Combination of the wheel and legs to operate together
3.Utilization of retractable modules
4.Wheel placement at the end of the legs

In this study, an early fire detection mobile robotic system with hybrid locomotion is proposed. Hybrid locomotion structure is developed by a three-wheeled mechanism. A transition system with a decision structure for classifying the obstacles has been proposed for adaptive motion. This study also includes path planning and obstacle avoidance structure with the name of "Direction-Based Angle Computation". This structure is constructed for the classification of paths and obstacles in the operation environment. The "Fire Search and Find" structure is also designed to decide the probability of fire sources. The location of the fire source is detected by flame sensors. Then, the "Fire Detection" structure created using Faster R-CNN machine learning model determines the probability of a fire. The operator can also monitor the system via wireless connection.

## 2. Materials and Methods

### 2.1. Mechanical Structure

The design and assembly of parts are conducted using Autodesk Inventor Software. The overall design and 3D details of the robotic structure are shown in Figure 2. The engineering drawings including part list and exploded view and dimensional information are also prepared. These documents involve detailed information of the sizes and used parts-hardware. These are useful for sourcing the required hardware and parts. The dimensions and weight of the robotic system are important parameters as they affect mobility and energy consumption. The total weight of the system, including all mechanical and electronic components, is approximately 10.5 kilograms. The overall dimensions, parts list, and exploded view of the robotic system structure are presented in Figures 3,4, and Table 1, respectively.

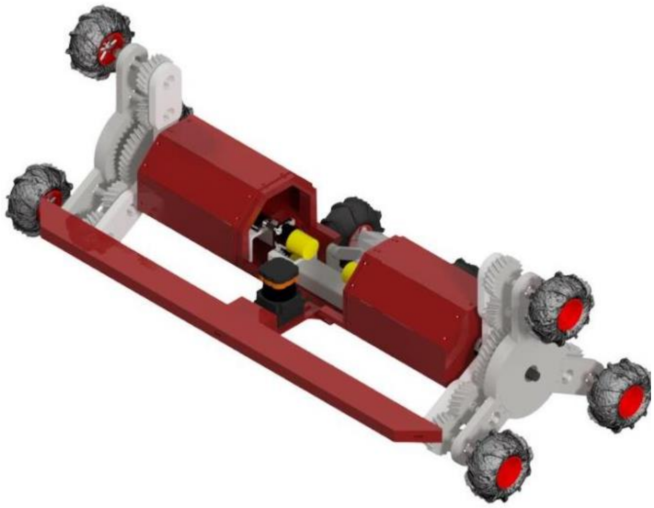

**Figure 2**. Overall design view of the robotic structure.

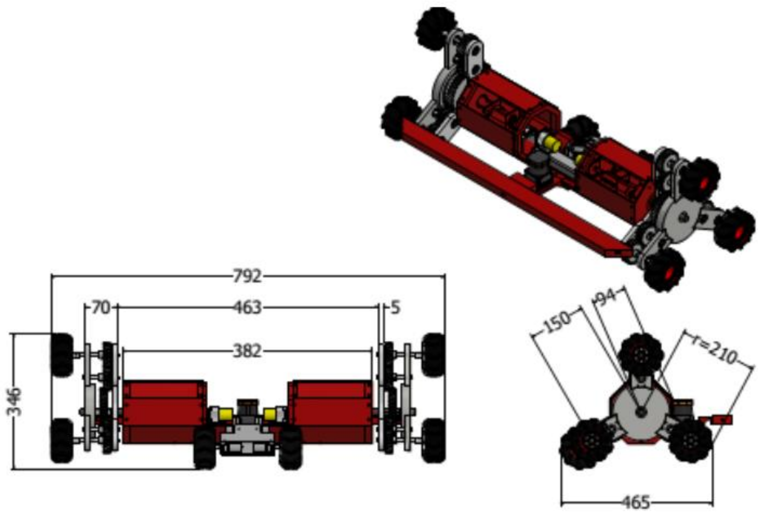


**Figure 3**. General dimensions.

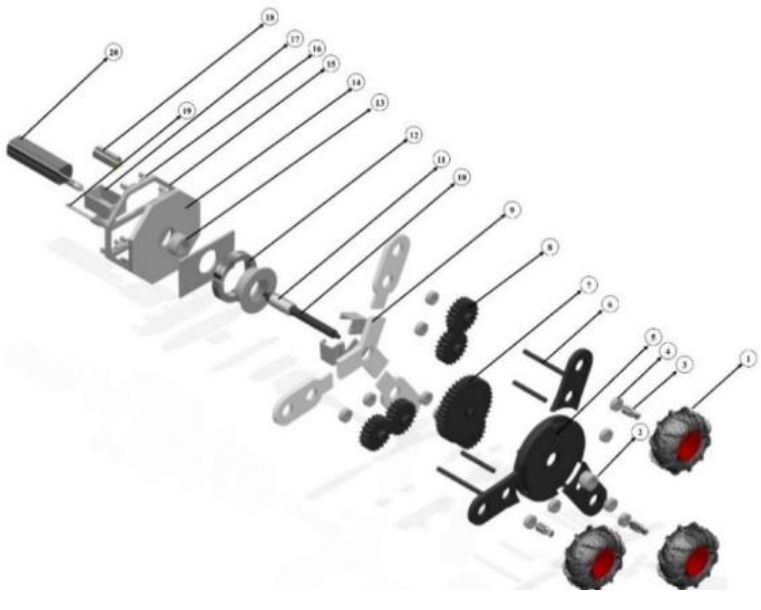

**Figure 4**. Part list and exploded view.

**Table 1**. Part list of the robotic system

| No | Name of the Components | Pieces |
|---|---|---|
| 1 | Wheels | 8 |
| 2 | Housing rubbers | 2 |
| 3 | Shaft to wheel connectors | 8 |
| 4 | Bearings | 24 |
| 5 | Outer covers | 2 |
| 6 | Shafts | 12 |
| 7 | Gears | 2 |
| 8 | Inner-outer gears | 12 |
| 9 | Inner covers | 2 |
| 10 | Main shafts | 2 |
| 11 | Couplings | 2 |
| 12 | Axial bearing | 2 |
| 13 | Ball bearings | 2 |
| 14 | Covers | 2 |
| 15 | Frames | 2 |
| 16 | Brackets | 18 |
| 17 | Motor covers | 2 |
| 18 | DC motors | 2 |
| 19 | Linear motion guides | 2 |
| 20 | Linear actuators | 2 |

**2.2. Material Selection and Manufacturing**

Mechanical components of the robotic system, apart from motor wheel connector and shaft, the prototype is structured using the thermoplastic polylactide acid (PLA) material and the fused deposition modelling (FDM) method. The reason behind this choice is to take advantage of the benefits of PLA material, such as its biodegradability, high printing speed and lower layer height requirements. The infill type and density are specified as hexagonal and 50%, respectively, with the objective of reducing material consumption while ensuring adequate structural strength. The motor wheel connectors and shafts are produced using S 235 steel, with the wheels being selected to have a diameter and width of 120 and 60 mm, respectively.

**2.3. Electronic Hardware of Robotic System**

The robotic system is comprised of two primary electronic systems. The initial approach involves the utilization of Lidar and ultrasonic distance sensor data for the purpose of movement control. The second is for the purpose of fire detection via webcam and Raspberry Pi. The list of the electronic components is given in Table 2.

**Table 2**. Electronic component list of the robotic system

| No | Name of the Components | Pieces |
|---|---|---|
| 1 | Hokuyo UTM-30 LX Lidar (detection range of 0.1 to 30 m) | 1 |
| 2 | Raspberry pi 3B | 1 |
| 3 | Flame sensors (detection range up to 1 m) | 3 |
| 4 | Lipo batteries | 3 |
| 5 | Ultrasonic distance sensors (detection range of 0.2 to 4 m) | 2 |
| 6 | Power bank | 1 |
| 7 | Arduino Mega 2560 | 1 |
| 8 | Motor Drivers | 3 |
| 9 | DC Motors | 3 |
| 10 | Linear actuators | 2 |

**2.4. Operational Architecture of the Robotic System**

The robotic system is comprised of four primary algorithms. The following subjects are covered: "Motion Mode Decision", "Direction-Based Angle Computation", "Fire Search and Find" and "Fire Detection". Initially, the motion mode decision algorithm determines the type of motion based on the measured obstacle height. The movement may be either climbing or linear. The hybrid locomotion structure is capable of operating for those two cases. In the absence of any obstacles or if the height of the obstacle falls within the passable range (up to 120 mm), the robotic system can traverse the obstacle through linear motion. In instances where the height falls within the range of 120-200 mm, the transition is initiated by a transmission system. The center gear is pushed by the linear actuator, which positions the gear at the center of the transmission system. Subsequently, the entire roll is activated, enabling the robotic system to ascend an obstacle or traverse terrain with the three-wheeled roll motion. For obstacles measuring over 200 mm, the obstacle avoidance mode is initiated, enabling the robotic system to navigate by employing a direction-based angle computation algorithm structure. In instances where the movement is categorized as obstacle avoidance, the robotic system endeavors to ascertain the safest route to the target by employing a direction-based angle computation approach. In the direction-based angle computation approach, the robot's field of view, obtained through Lidar, is divided into five regions for the purpose of determining the shape of obstacles and deciding on the required movement types (Figures 5 and 6). Figures 5 and 6 present the detailed region indication and the responses of the robotic system according to the obtained data. The determination of the types of motion path is contingent upon the obstacle occurrence zone and distance. The linear velocity has been adjusted as 0.5 m/s for experimental tests. The "Fire Search and Find" structure has been designed to find the locate the fire source using the data from IR flame sensors. The activation of this algorithm occurs in the "No Obstacles" state within the field of view.

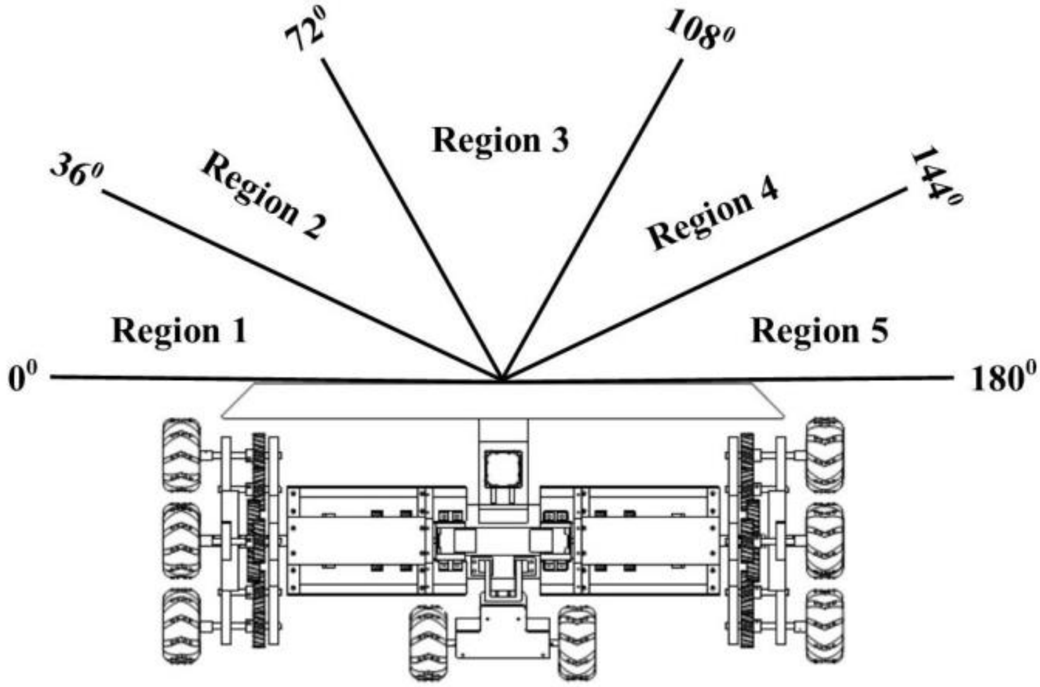


**Figure 5**. Regions of path planning and obstacle avoidance structure.

| Name of the Situation | Regions | | | | | Reaction of the System |
|---|---|---|---|---|---|---|
| | Region 1 | Region 2 | Region 3 | Region 4 | Region 5 | |
| Fire Search | | | | | | Try to Find the Fire Source |
| Front Obstacle | | | ■ | | | Turn Right (Smooth) |
| Front Left Obstacle | | ■ | | | | Turn Right (Smooth) |
| Left Obstacle | ■ | | | | | Turn Right (Smooth) |
| Front Left Obstacle | ■ | ■ | | | | Turn Right (Smooth) |
| Front Right Obstacle | | | | ■ | | Turn Left (Smooth) |
| Right Obstacle | | | | | ■ | Turn Left (Smooth) |
| Front Right Obstacle | | | | ■ | ■ | Turn Left (Smooth) |
| Left Corner | | ■ | ■ | | | Turn Right (Sharp) |
| Right Corner | | | ■ | ■ | | Turn Left (Sharp) |
| Obstacle | | ■ | ■ | ■ | | Turn Right (Sharp) |
| Left Corner | ■ | ■ | ■ | | | Turn Right (Sharp) |
| Right Corner | | | ■ | ■ | ■ | Turn Left (Sharp) |
| Corridor | | ■ | | ■ | | Move Forward |
| Corridor | ■ | | | | ■ | Move Forward |
| Corridor | ■ | ■ | | ■ | ■ | Move Forward |
| Trap | ■ | ■ | ■ | ■ | ■ | Stop the Motion |

**Figure 6**. Motion types of path planning and obstacle avoidance structure.

The Fire Detection structure is proposed to calculate the probability of fire candidates. Fire Detection structure created using Faster R-CNN machine learning model determines the probability of a fire. The experiment was conducted using a system with the following specifications: NVidia GeForce GTX 1070 Ti with 17 GB onboard memory. The required environments and tools (Python 3.5, Tensorflow 1.13.1, OpenCV, CUDA-cuDNN toolkits) were installed on the Anaconda virtual environment. The fire scenes on the images were labeled as fire and non-fire using LabelImg software. The converter function was selected as Softmax, number of steps for the learning was determined as 40,000 and the number of epochs was used as 3. 80% of images were used for training and 20% of the images were dedicated for test processes.

Fire Candidates are indicated with the data from the Fire Search and Detection structure. If any object is identified as a “Fire Candidate”, the Fire Detection structure is activated to calculate the probability of the fire. The flowchart of the fire detection is illustrated in Figure 7.

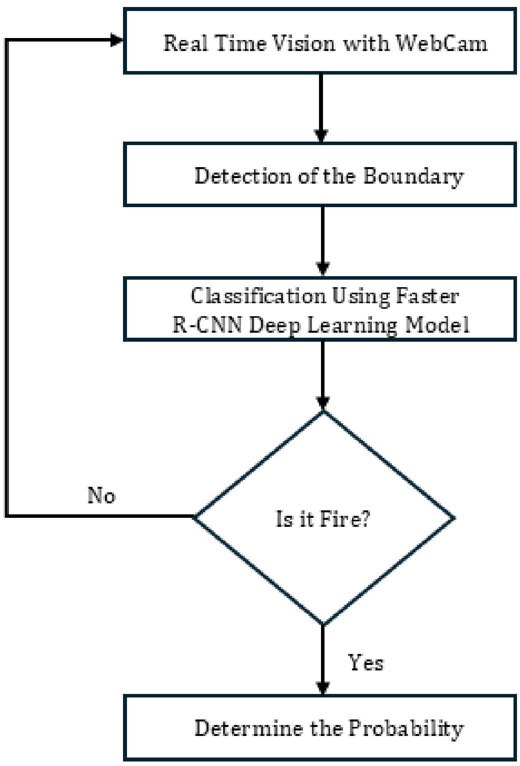


**Figure 7**. Flowchart of fire detection.

## 3. Results and Discussion

Real-time experiments are used to test the overall performance of the mechanical structure, hybrid motion system, obstacle avoidance and path planning, and fire detection. A test bench is built to test the motion decision and hybrid motion. A side transmission system is placed on the test bench. Distance sensors are also placed to trigger transitions from linear motion to climbing motion and vice versa, as shown in Figure 8. The test bench was designed and produced with proper mounting places for the transmission system and required hardware. It was produced using 1050 steel material for mounting parts and wooden material for the base.

**Figure 8**. Test bench of the motion decision and hybrid motion systems.

It is evident from the experimental tests that the motion decision algorithm is capable of seamlessly initiating transitions between motion modes in accordance with the measured height data. The center gear can correctly locate the center of the transmission gear system, thereby enabling the full rolling motion to be realized. In the absence of any impediments or steps, the center gear is retracted, thereby initiating linear motion.

The structure of obstacle avoidance and path planning is built on the data obtained from the Hokuyo lidar. The system's architecture is predicated on the direction-based angle computation algorithm that has previously been proposed. Preliminary and real motion tests are performed. The proposed path planning and obstacle avoidance algorithm is tested based on the lidar data, with obstacles placed in various directions. The results obtained for the stop area and front right obstacle conditions are presented in Figures 9 and 10, respectively. The results obtained demonstrate that the proposed structure can respond appropriately to regional obstacles.


**Figure 9.** Case of stop area.

**Figure 10.** Case of front right obstacle.

After the bench tests of the hybrid locomotion tests and preliminary tests of the path planning and obstacle avoidance structure, the real-life operational experiments are conducted. The obstacles, including dynamic, are placed in different directions. The obstacle avoidance and climbing performances of the robotic structure are tested. It has been demonstrated through experimental investigation that the robotic system has the capacity to locate obstacles using direction-based angle computation algorithms. The system is also capable of navigating such obstacles with precision, identifying their type, and climbing over them by utilizing the full range of rolling motion (Figures 11 and 12).

**Figure 11.** Obstacle avoidance.

**Figure 12.** Climbing motion.

Preliminary and real fire detection tests are performed to evaluate the fire detection capability. First, fire detection capacity is tested with lighter and candidate flames. As demonstrated in the empirical findings (Figure 13), the fire detection structure demonstrates an exceptional capacity to accurately categorize fire sources, exhibiting a 99% accuracy rating. With this obtained result, it is evident that the fire detection capacity of the robotic system is reliable for fire detection tasks.

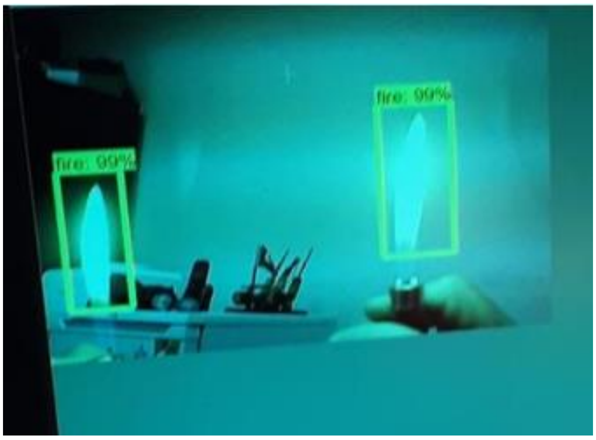


**Figure 13**. Preliminary fire detection test.

Real-life performance tests are conducted for three different fire sources: candle, wood and complex (Figures 14,15 and 16). The term "complex fire" is a combination of candle, paper and wood.

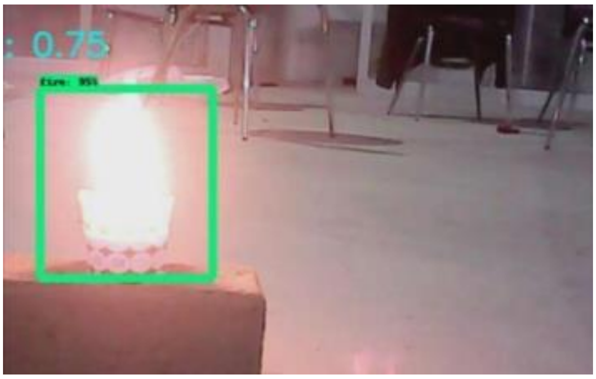


**Figure 14.** Candle fire detection.


**Figure 15.** Wood fire detection.


**Figure 16.** Complex fire detection.

The average detection values obtained for candle, wood and complex fires were 86%, 90% and 93%, respectively as presented in Figures 14,15 and 16. The candle fire detection process has been found to demonstrate the lowest detection accuracy. This can be explained with the reduced size of the flame and the number of flickering scenes in detection process. The detection accuracy increases to 90% for wood and 93% for complex fire detection.

## 4. Conclusion

The present study involves the design and development of a mobile robotic structure with fire detection and hybrid locomotion capabilities. The hybrid locomotion system is an adaptive, three-wheeled structure designed to provide obstacle climbing and linear motion capabilities. The paper proposes a structure for obstacle avoidance and path planning called "Direction Based Angle Computation". The system categorizes obstacles as either negligible or surmountable based on their height and shape. The objective of the "Fire Search and Find" and "Fire Detection" systems is to identify potential fire locations and calculate the associated probabilities. The location of the fire source is detected by flame sensors. Consequently, the "Fire Detection" structure is created using a Faster R-CNN machine learning model, which determines the probability of a fire. A series of experimental tests were conducted on the mechanical systems and algorithms of the mobile fire detection robotic system. In accordance with the results obtained, the following conclusions are reached:

- The transmission and motion systems can climb over obstacles and move in a straight line.
- The motion decision algorithm can determine the required motion type successfully according to the situation of the obstacle.
- Direction-based angle calculation approach is both suitable and satisfactory for local path planning and obstacle avoidance applications.
- The fire search and find algorithm has been demonstrated to detect the fire source when placed on the front, right and left sides of the robotic system, successfully activating the fire detection algorithm.
- The developed fire detection algorithm, employing the Faster R-CNN deep learning model, has been demonstrated to achieve a 93% accuracy in determining the probability of detected fire sources.

As future research directions:

- The creation of a hybrid fire detection algorithm is planned, which will use thermal and RGB images in the training and detection processes.
- It is also planned to use the ROS (Robotic Operation System) for the mapping, localization and path planning applications of the robotic system.

**Author Contributions**

The percentages of the authors' contributions are presented below. All autho() reviewed and approved the final version of the manuscript.

| | H.S.S | I.B. |
|---|---|---|
| C | 50 | 50 |
| D | 50 | 50 |
| S | 50 | 50 |
| DCP | 50 | 50 |
| DAI | 50 | 50 |
| L | 50 | 50 |
| W | 50 | 50 |
| CR | 50 | 50 |
| SR | 50 | 50 |
| PM | 50 | 50 |
| FA | 50 | 50 |

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

**Conflict of Interest**

The authors declared that there is no conflict of interest.

**Ethical Consideration**

Ethics committee approval was not required for this study because there was no study on animals or humans.

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