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# Mountable Drone Mechanism: A Sustainable Approach

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**Abstract:** Urbanization has led to an increase in high-rise buildings, posing significant challenges for firefighting, particularly in inaccessible locations. This study presents the development of a drone-mounted fire-extinguishing mechanism, aimed at enhancing firefighting efficiency in high-rise environments. The system integrates a lightweight servo-controlled gripper mounted on a hexacopter drone, designed to eject fire-extinguishing balls upon detecting fire. The mechanism was developed using SolidWorks and Fusion 360, ensuring optimal weight distribution and structural stability. A flame sensor was integrated with the Arduino-based control system, allowing real-time fire detection and automated deployment of the extinguishing agent. Experimental validation involved gripping force analysis, fire detection accuracy, and response time evaluation, ensuring system reliability under operational conditions. Simulation results confirmed minimal displacement and stress, demonstrating the structural integrity of the mechanism. Performance tests indicated that the fire detection and ejection mechanism responded within 2–4 seconds, with a consistent gripping force to secure the extinguishing ball during flight. The drone successfully navigated towards fire hotspots, precisely deploying fire-extinguishing balls, making it a viable alternative for first-response firefighting operations. This research highlights the potential of UAV-assisted fire suppression in high-rise firefighting, reducing human risks and improving response efficiency. Future improvements will focus on multi-ball deployment, AI-based autonomous navigation, and integration with thermal imaging for enhanced fire detection.

## 1. Introduction

Urbanization has led to a proliferation of high-rise buildings, presenting challenges for firefighting services. The major challenges are limited accessibility to reach high altitudes (Sivananth *et al.*, 2024), properties evacuation difficulties, and the scale of potential fire outbreaks. The occurrence of a fire outbreak is not possible to be eliminated completely especially in developing countries (Nimlyat *et al.*, 2017) possible to reduce the damages caused by putting safety measures in place (Obasa *et al.*, 2020). Firefighters have used different traditional firefighting methods—such as hoses, ladders, and sprinkler systems but these methods often fall short in smart cities (Patil *et al.*, 2020; Sivananth *et al.*, 2024). Urban fire incidents need proactive and innovative approach particularly using unmanned aerial vehicles (UAVs), commonly known as drones (Akhter, 2014; Zadeh *et al.*, 2021). Drone has emerged as transformative tools in various industries (Manimaraboopathy *et al.*, 2017) and their potential in fire safety is yet to be fully harnessed. The drone can easily access high-rise buildings and can have full information on the scope and size of the fire which makes it easy to put off the fire (Patil *et al.*, 2020). The ability of the UAV to be operated without a pilot on board makes it suitable for application in emergency situations or very risky situations where lives or properties might be endangered (Barmpounakis *et al.*, 2016). According to (Oluwunmi, 2023), urban fire incidents pose significant risks to lives, infrastructure, and economies, particularly in high-rise environments due to the delayed response time and limited reach of conventional methods. Fire incidents at high-rise buildings rely heavily on manual intervention, which becomes increasingly hazardous and put the life of the firefighters at high risk since the elevator or other means of reaching the top floor might not be accessible during the fire outbreak (Akhter, 2014). Even due to the intricate and multi-directional nature of personnel evacuation behavior in high-rise buildings, coupled with potential signal transmission issues that may arise when using equipment such as an interphone at the fire scene, ensuring the safety of human evacuation during a fire in such buildings has become a significant concern. This has been a disaster that has raised concerns both locally and globally and as a result innovative solution is needed to deliver extinguishing agents to fire sources quickly and efficiently while minimizing human risk. Therefore, it is imperative to address various issues related to human evacuation and safety in high-rise building fire outbreak (Hu *et al.*, 2017).

The use of drones initially began in the military and became widespread today in various sectors, including commercial and agricultural sectors. The evaluation of the scientific research on Scopus indicated that around 50,000 articles are related to “drone” reflecting their interest in time and money savings through drone technology. A bibliometric study proves beneficial to discover the leading authors, collaborations and countries that published innovative research within various disciplines (Nimlyat *et al.*, 2017; N’diyae *et al.*, 2022; Chakir *et al.*, 2023; Niandiyanto *et al.*, 2024; Traoré *et al.*, 2025). The addition of "sensor" to "drone" within a Scopus search returned 7,700 articles that demonstrate an increased publication rate since 2024 with more than 1,400 articles as shown in **Figure 1**. An expansion in applications occurs currently and will intensify further in the future. Recent high cyclone numbers in the United States have generated the most drone sensor publications worldwide followed by India due to its frequent flood and fire occurrences. **Figure 2** displays the nations which supplement the total number of articles in research publications.

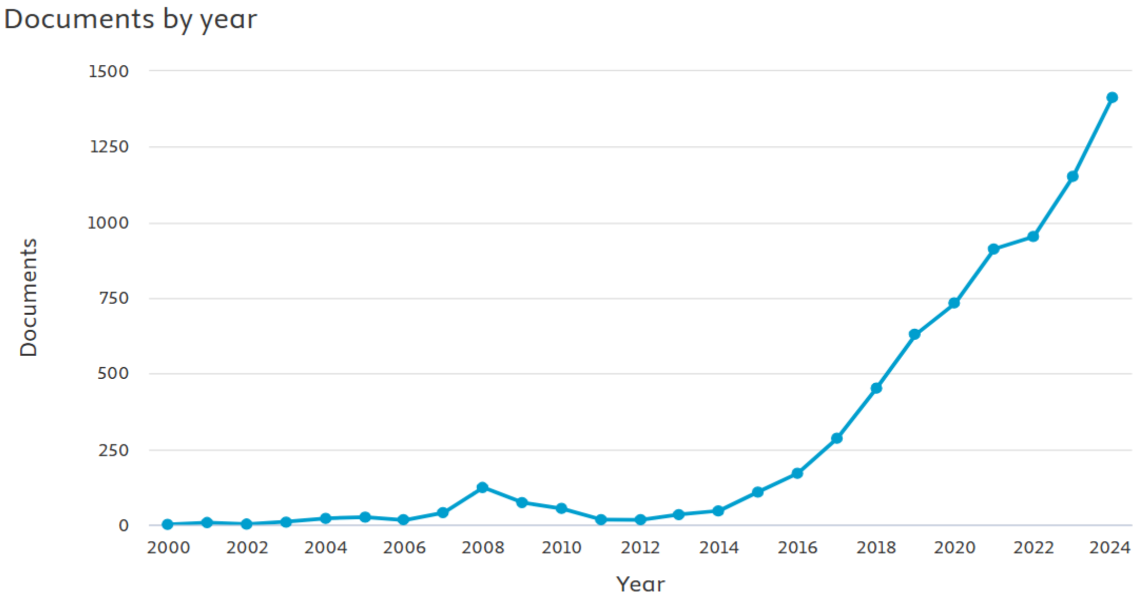



**Figure 1**. Increase of articles from 2000 to 2024 on “drone & sensor”

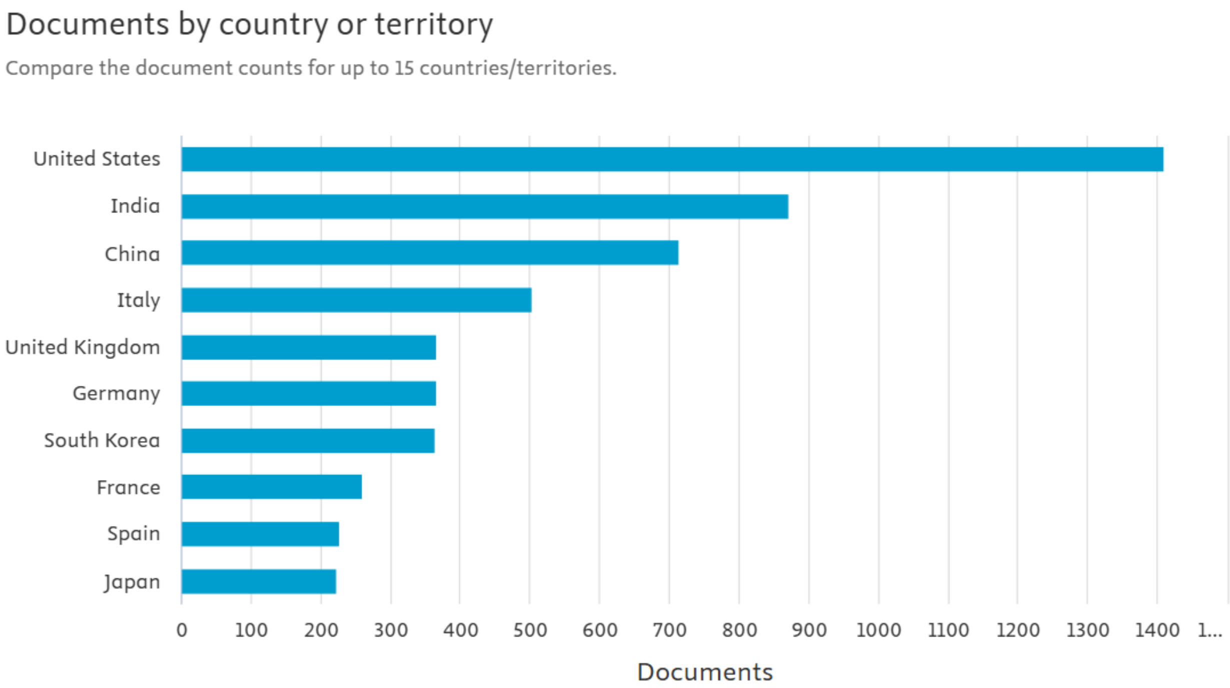



**Figure 2**. Countries contributing on "drone & sensor" from 2000 to 2024

**Figure 3** summarize the name of authors with the most published articles on drone and sensors from 2000 to 2024. It's known that forests are affected by strong and extensive fires emitting large amounts of smoke into the atmosphere last decades due to the climate change. In this way, more than thousand articles are gathered on Scopus. The number of articles attained around 250 papers in 2024 as shown in **Figure 5. Figures 4 and 6** illustrate the network visualizations of author collaborations generated using VOS viewer. In these visualizations, each node represents an individual author, while the links between nodes represent co-authorship relationships.

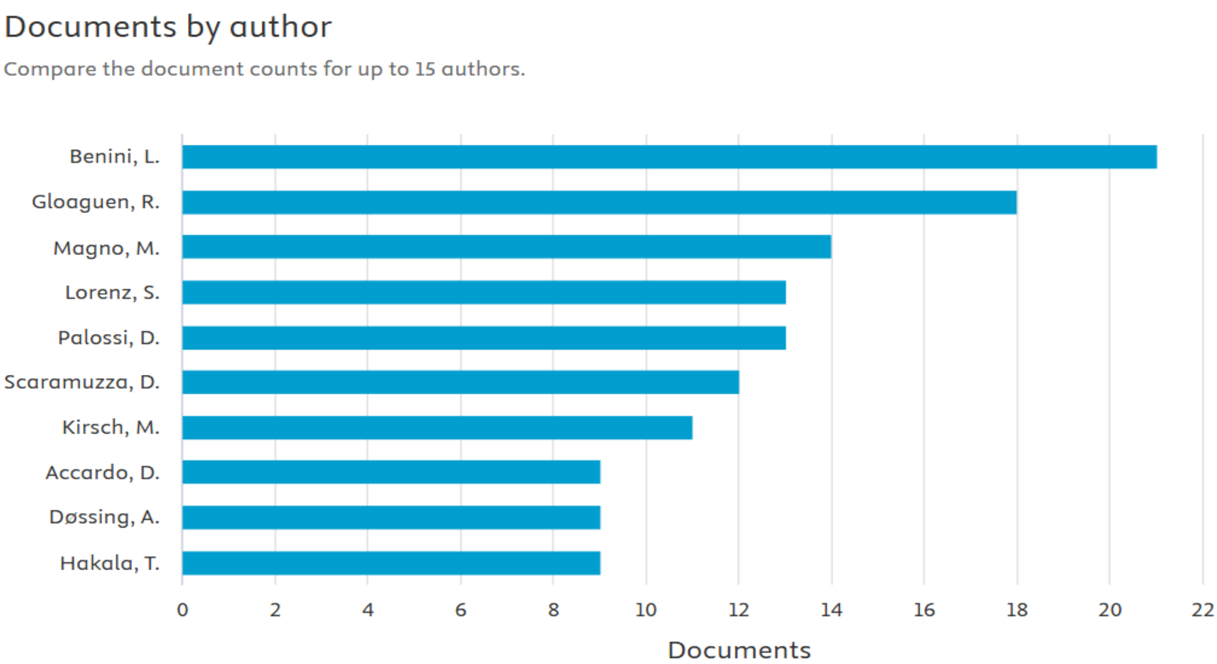



**Figure 3**. Most authors publishing articles from 2000 to 2024 on "drone & sensor"

As shown in **Figures 4**, Benini Luca (mustard color) and Palossi Daniele (green color) appear as central figures with strong collaborative networks, indicating their significant contributions and active partnerships in the research field. The nodes having the same color indicate the collaboration forming the cluster and the links with others show the international cooperation (Adams *et al.*, 2014; Lino *et al.*, 2021; Lrhoul *et al.*, 2023; Plakias, 2023). Similarly, **Figures 6** presents an alternative network visualization, emphasizing the structure of research communities. Authors like Afghah Fatemeh and Razi Abolfazl are positioned centrally, suggesting they play key roles in connecting various research clusters. Afghah Fatemeh and Razi Abolfazl are most published and innovative in Drone & Sensors domain.

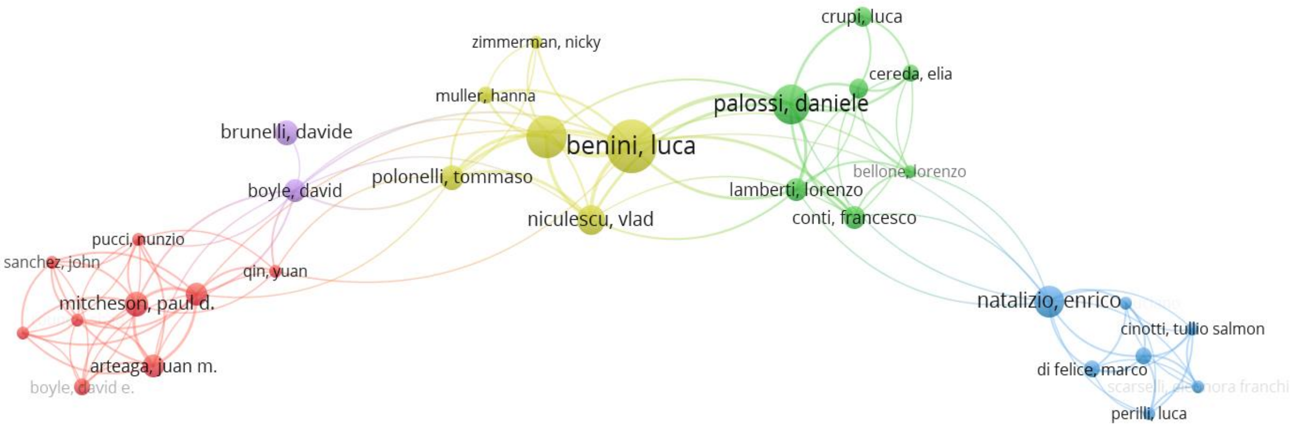



**Figure 4**. Network visualization of the authors articles from 2000 to 2024

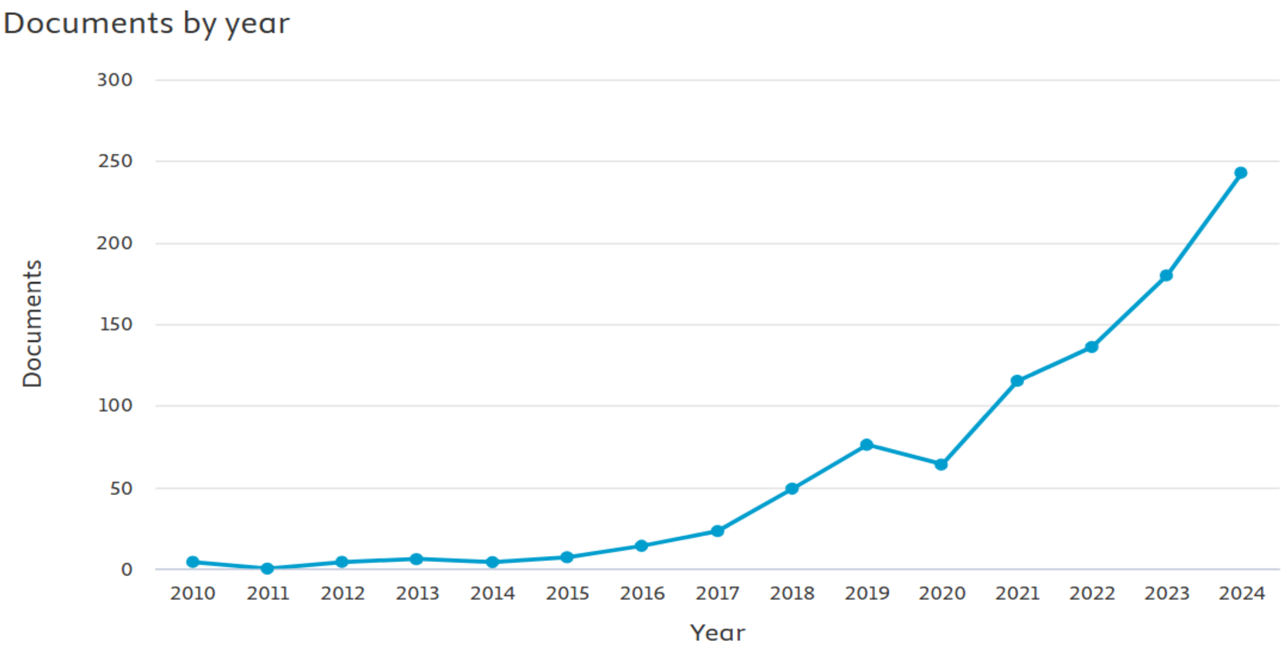



**Figure 5**. Evolution of the articles with time

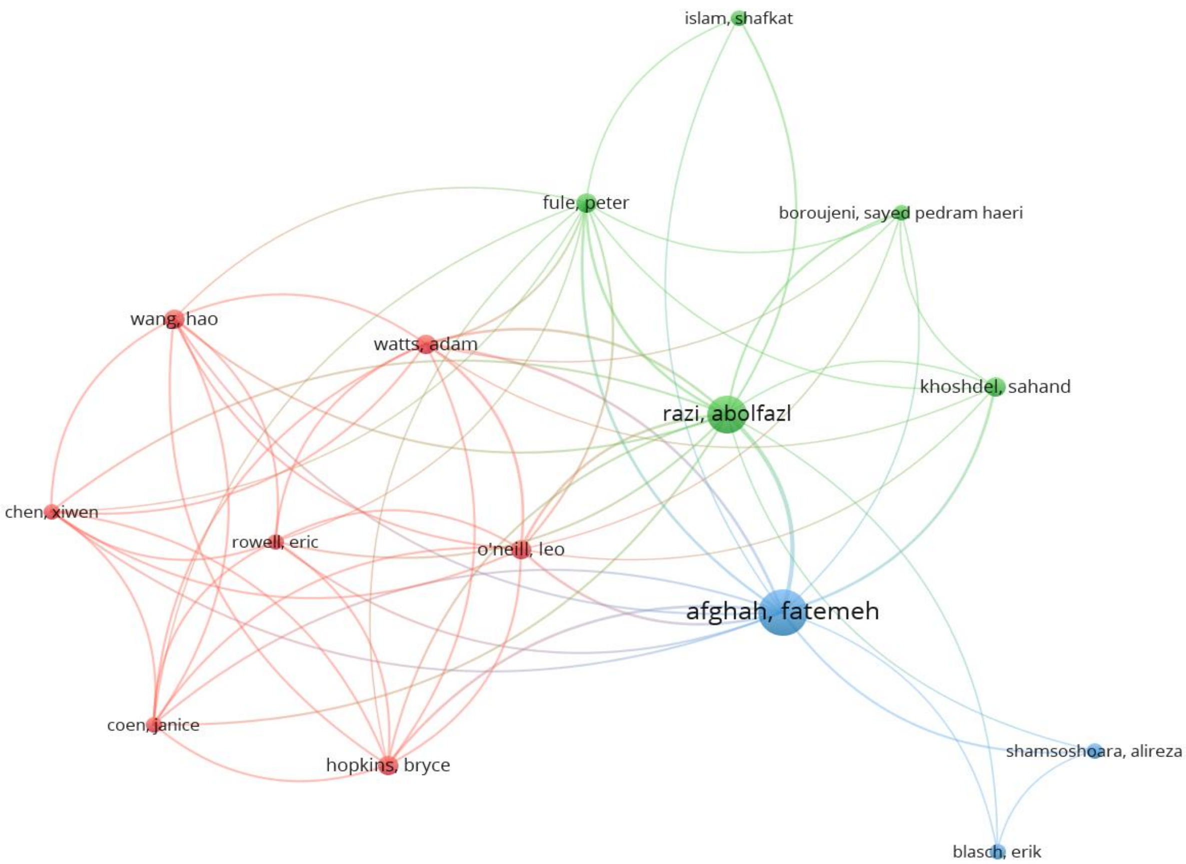



**Figure 6**. Network visualization and author's mapping on VOS viewer

This study aims to design and evaluate a drone-mounted fire-extinguishing system. This approach incorporated a lightweight and sustainable ejection mechanism compatible with drones. By leveraging the addictive manufacturing in the development, sensors and control systems will be integrated for automated fire detection and suppression. Studies highlight drones' utility in surveillance and disaster management. UAVs equipped with infrared cameras have been used to locate fire hotspots, but drone-based systems for direct fire suppression are underexplored. This research addresses this gap by evaluating the performance of the proposed integrated ejection mechanism through simulations and practical tests.

## 2. Materials and Methods

### *2.1 System overview*

The UAVs are classified into rotor wings and fixed wings based on the propulsion system and lifting mechanism. By the number of propulsion motors, the multirotor that make up the wing rotor group are divided into helicopter, tricopter, quadcopter, hexacopter, and octocopter categories (Suprapto et al., 2017). The proposed system comprises a hexacopter drone which is used because of its stability and payload capacity. The drone is equipped with the following units:

- Ejection Mechanism:

A servo-controlled gripper showed in the overall system in **Figure 7** below is designed and printed using Trony X5SA-500 printer. It is mounted on an hexacopter drone to deploy fire extinguishing balls during fire outbreak. The AFO fire extinguishing ball in **Figure 8** below is a fully automatic fire extinguisher, it will burst and instantly put out the flames if thrown or rolled into it. This ball is capable to extinguish the flames on its own, protecting people and property. It can be either used actively or passively. In active use, the ball is thrown into the fire whenever the fire erupts. In passive use, the ball is positioned at the appropriate height or in an area where a fire is likely to start such that the ball activates automatically whenever a fire erupts.

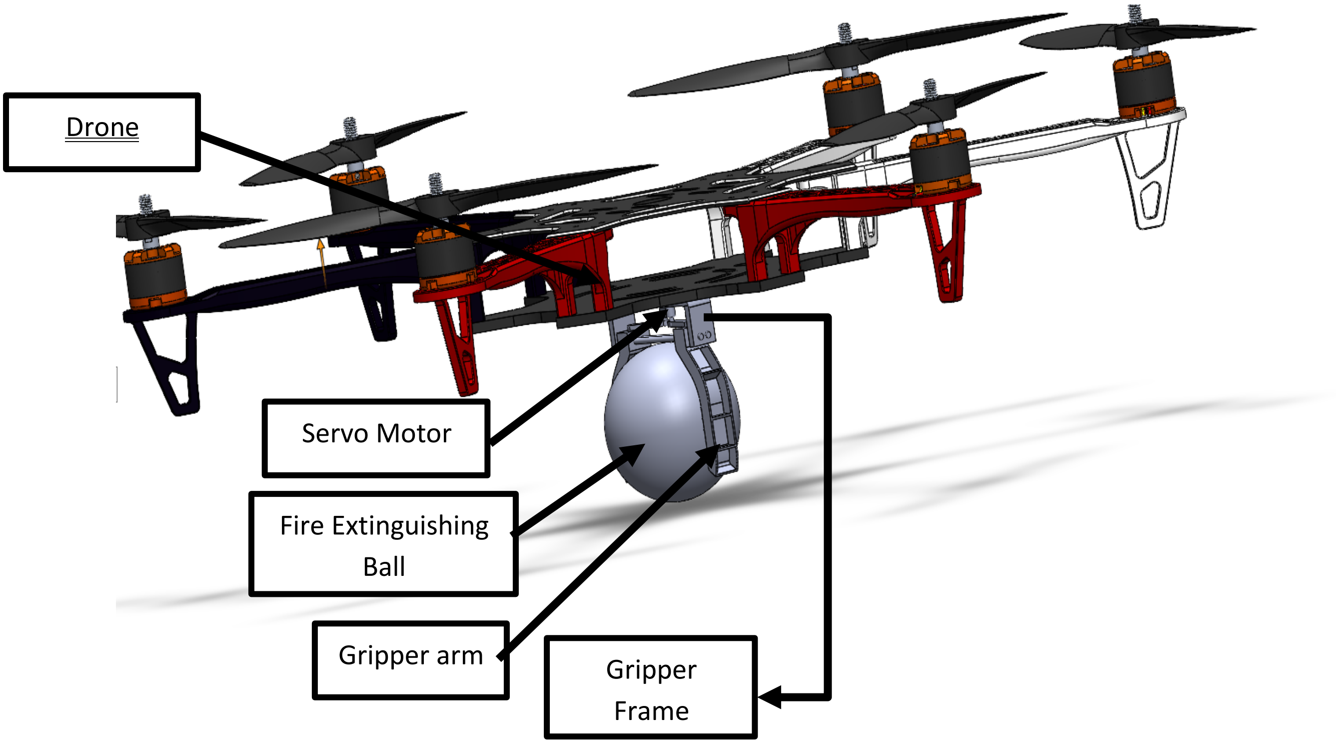



**Figure 7.** Hexacopter drone

**Figure 8.** Flame sensor


**Figure 9.** Arduino Uno board

- Flame Sensors:

A camera with a real-time situation report and flame sensors are integrated in the unmanned aerial vehicle (UAV) to assess fire intensity and guide interventions effectively. The flame sensor in **Figure 8** above is a type of detector that is primarily made for both detecting and responding to the occurrence of a fire or flame. This sensor detects flame when the light source's wavelength is between

760 and 1100 nanometers. This sensor produces a digital or analog signal and serves as a flame alert in firefighting robots. The flame is seen at a distance of 100 cm with a detection angle of 600 degrees.

- Arduino-Based Control System:

Arduino Uno is a microcontroller board based on the Atmega328P. Arduino Uno board in **Figure 9** controls the servo motor to either hold or release the ball. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, 16 MHz ceramic resonator (CSTCE16M0V53-R0), USB connection, power jack, ICSP header, and rest button. Arduino-Based Control System is for automated operation.

**Figure 10.** MG995R servo motor

### *2.2 Design methodology*

The ejection mechanism was designed using SolidWorks and Fusion 360, focusing on weight optimization and structural stability. The gripping arms operate on a slider mechanism powered by an MG995R servo motor shows in **Figure 10** above with a maximum stall torque of 11 kg/cm. The mechanism was integrated with a flame sensor to enable real-time fire detection and response.

1. Structure and working principle

To ensure good performance, grasping strength, and stability of the gripper, a slider mechanism was used to transfer motion between the three links of the gripper. The structure of the gripper is primarily composed of three rigid links. The three links are 00 02, 02 03, and 03 04, where they represent link1, link2, and link3 respectively. 00, 02, and 03 represent the joints between the three links, all the joints are connected through a revolute joint, and the links could rotate 360 degrees about their respective joints.

2. Gripper Parameters

In the design of the structural parameters of the gripper, the structural size of the gripper and that of the fire extinguishing ball were all considered. The geometric parameters of the gripper as given by Barmpounakis *et al.*, (2016). are shown in **Table 1**.

**Table 1.** Geometric Parameter of the Gripper

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Length of link1 | L1 | 30 |
| Length of link2 | L2 | 45 |

3. Control system design

The gripper has two fingers that are dependent on a single drive source which is the servo motor. The control hardware is shown in **Figure 11** below and it has a power source, microcontroller, flame sensor, and servo motor. The microcontroller handles the command and event servo motor and the flame sensor are attached to the pins of the microcontroller. The flame sensor sends a signal to the microcontroller through the attached pin and based on the signal sent the microcontroller controls the servo motor through the PWM method to achieve the gripping and ejecting of the gripper.

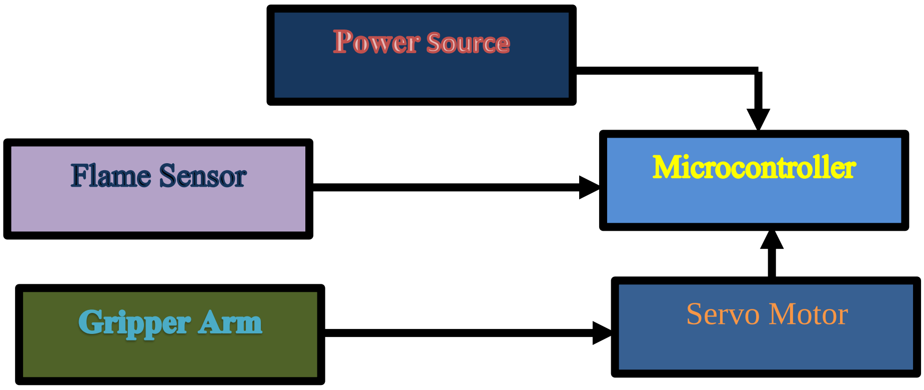



**Figure 11.** The control and the hardware component of the drone gripper

4. Forward kinematics

Since the structure of the two gripping arms is identical, in this analysis only one of the gripping arms was considered for the forward kinematics analysis.

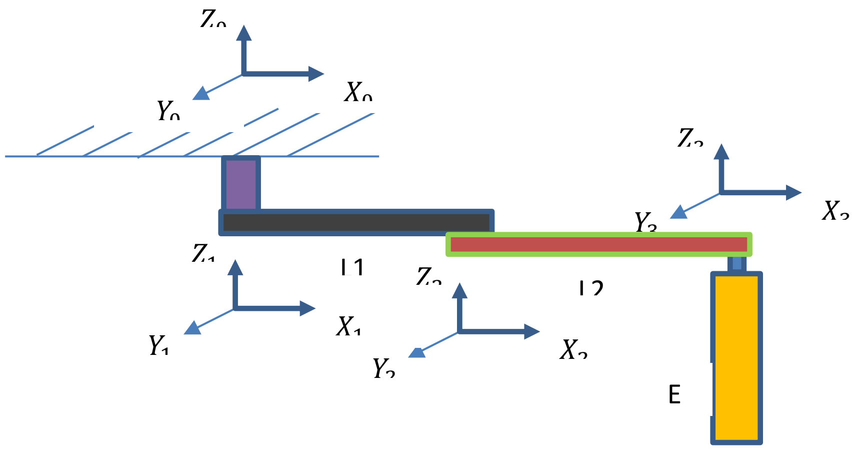



**Figure 12.** Reference frame of the gripper

**Figure 12** represents the gripper arm attached to the servo and the links. four reference frames were attached to the gripping arms to determine the D-H parameters and to calculate the forward kinematics. The reference frame was taken to be the point the links were attached to the servo, it was made to be fixed and also taken to be the base. It was assigned frame coordinates $Z_0$ $X_0$ $Y_0$. $Z_0$ was assigned to the axis of rotation, $X_0$ was assigned to be perpendicular to $Z_0$ and $Y_0$ was determined from the right-hand rule and assigned to be the base frame. The second frame was assigned to the first joint between the base and the link1. It was assigned frame coordinates $Z_1$ $X_1$ $Y_1$. $Z_1$ Was assigned parallel to $Z_0$ $X_1$

was assigned perpendicular to $Z_1$ while $Y_1$ was determined from the right-hand rule. The third frame was attached to the joint between link1 and link2, $Z_2$ was aligned to the rotation axis, $X_2$ was assigned perpendicular to $Z_2$ and $Y_2$ was determined from right-hand. The fourth frame was assigned to the joint between the link2 and the gripper arm (end effector). $Z_3$ was aligned with the axis of rotation, $X_3$ was assigned to be perpendicular to $Z_3$ and $Y_3$ was determined using the right-hand rule. L1 represents the length of the first, and L2 represents the length of the second link. **Table 2** summarizes the D-H parameters.

**Table 2**. D-H Table

| Joints | A | a | D | θ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | $\theta_1$ |
| 2 | 0 | L1 | 0 | $\theta_2$ |
| 3 | 0 | L2 | L2+d | 0 |

The general form of the homogenous transformation matrix is given by **Eqn. 1**

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & a_{i-1} \\ S\theta_i C\alpha_{i-1} & C\theta_i C\alpha_{i-1} & -S\alpha_{i-1} & S\alpha_{i-1} d_i \\ S\theta_i S\alpha_{i-1} & C\theta_i S\alpha_{i-1} & C\theta_i S\alpha_{i-1} & C\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Eqn. 1}$$

After substituting the values of a, α, d, and θ from the D-H table into **Eqn. 1** we have

$$^{0}T_1 = \begin{bmatrix} C\theta_1 & -S\theta_1 & 0 & 0 \\ S\theta_1 & C\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Eqn. 2}$$

**Eqn. 1** represent the transition from the origin (point 0) to the first joint (point 1).

$$^{1}T_2 = \begin{bmatrix} C\theta_2 & -S\theta_2 & 0 & L_1 \\ S\theta_2 & C\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Eqn. 3}$$

**Eqn. 2** represents the translation from the first joint (point 1) to the second joint (point 2).

$$^{2}T_3 = \begin{bmatrix} 1 & 0 & 0 & L_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_2 + d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Eqn. 4}$$

**Eqn. 3** represents the translation from the second joint (point 2) to the third joint (point 3).

Multiplying **Eqn. 2, 3, and 4** the final transformation matrix will be presented, which establishes the relationship between the gripper's coordinates and those of the global origin.

$$^{0}T_3 = \begin{bmatrix} C(\theta_1 + \theta_2) & -S(\theta_1 + \theta_2) & 0 & L_2 C(\theta_1 + \theta_2) + L_1 C\theta_1 \\ S(\theta_1 + \theta_2) & C(\theta_1 + \theta_2) & 0 & L_2 S(\theta_1 + \theta_2) + L_1 S\theta_1 \\ 0 & 0 & 1 & L_2 + d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Eqn. 5}$$

But, $\theta_1 = \theta_2 = \theta$ Therefore

The position on X axis is given by:

$X = L_2 \cos 2\theta + L_1 \cos\theta$ **Eqn. 6**

The position on Y axis is given by:

$Y = L_2 \sin 2\theta + L_1 \sin\theta$ **Eqn. 7**

The position on Z axis is given by:

$Z = L_2 + d$ **Eqn. 8**

The velocity along X is given by:

$$\frac{dx}{d\theta} = -2L_2 \sin 2\theta - L_1 \sin\theta$$

The velocity along Y is given by:

$$\frac{dy}{d\theta} = 2L_2 \cos 2\theta + L_1 \cos\theta$$

The velocity along Z is given by:

$$\frac{dz}{d\theta} = 0$$

The acceleration along X is given by:

$$\frac{d^2x}{d\theta^2} = -4L_2 \cos 2\theta - L_1 \cos\theta$$

The acceleration along Y is given by:

$$\frac{d^2y}{d\theta^2} = -4L_2 \sin 2\theta - L_1 \sin\theta$$

The acceleration along Z is given by:

$$\frac{d^2z}{d\theta^2} = 0$$

5. Circuit design and flowchart

**Figure 13** shows the circuit connection for controlling the servo motor. Both the flame sensor and the servo are been controlled by the Arduino microcontroller to either release or hold the fire extinguisher ball.

**Figure 14** shows a detailed flow chart of the operation of the mounted mechanism system. The drone picks up the fire extinguishing ball, fire incident detection with the help of infrared cameras, then the flame sensor sends a command through the Arduino microcontroller to the servo to release the fire extinguishing ball.

## 4. Results and Discussion

### *4.1 Design*

**Figure 15a-b** and **Figure 16a-b** show the 3D printed drone mountable mechanism. **Figure 15a-b** shows what the mechanism looks like before the fire extinguishing ball is been attached while **Figure 16a-b** shows the fireball being attached to the mechanism. The drone-mounted mechanism demonstrated lightweight construction and effective gripping capabilities, capable of securely holding and deploying a fire-extinguishing ball.

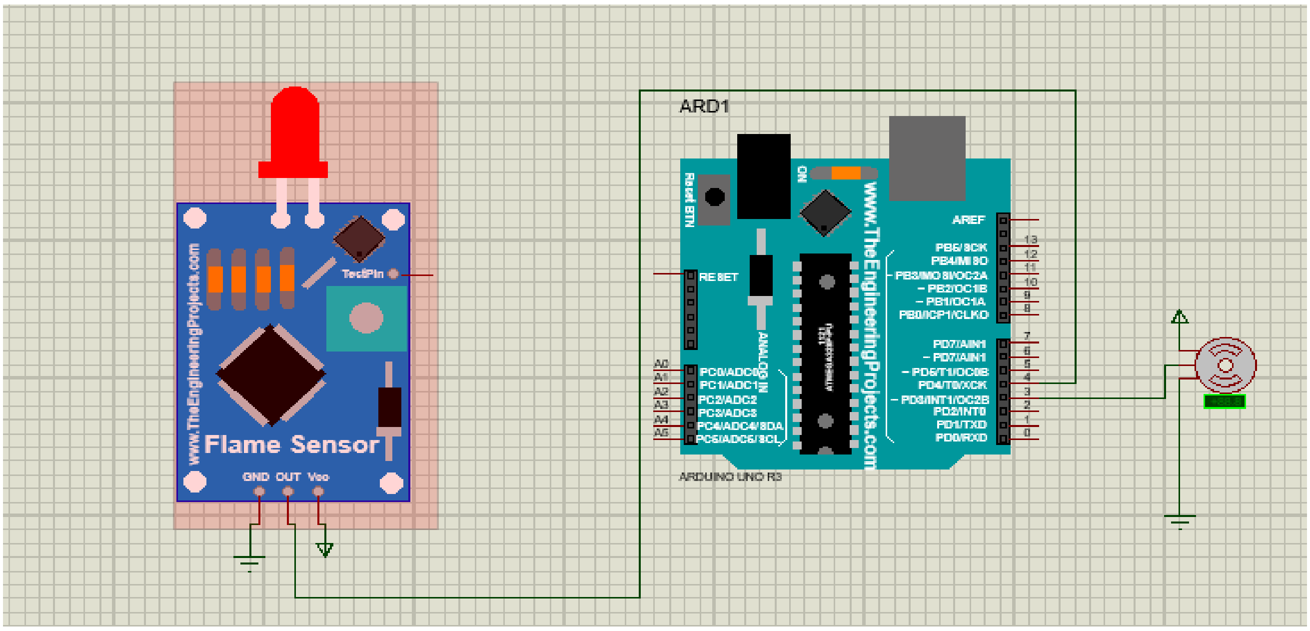



**Figure 13.** Circuit for motor control

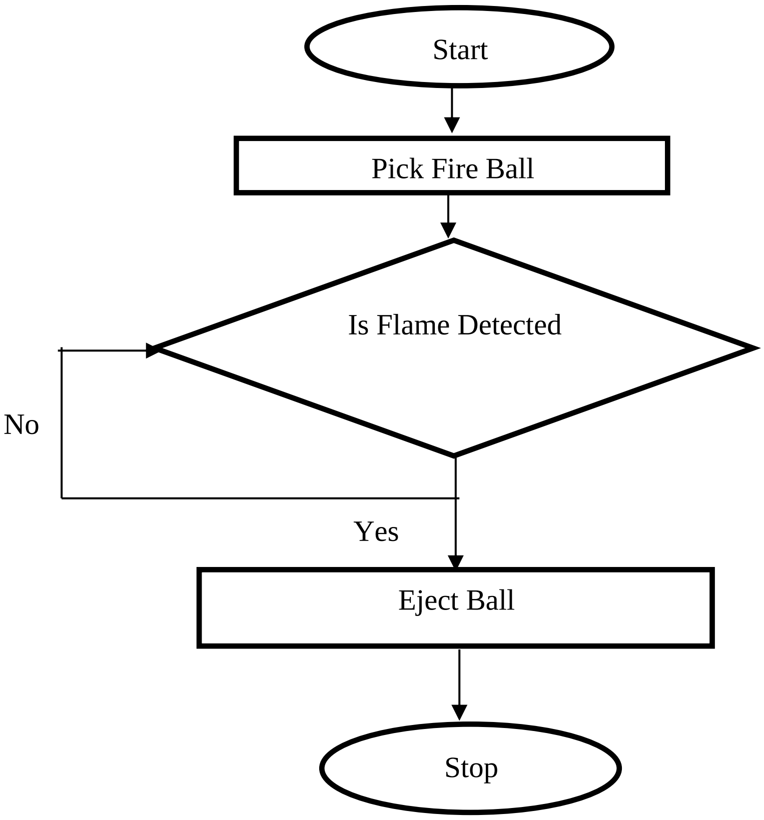
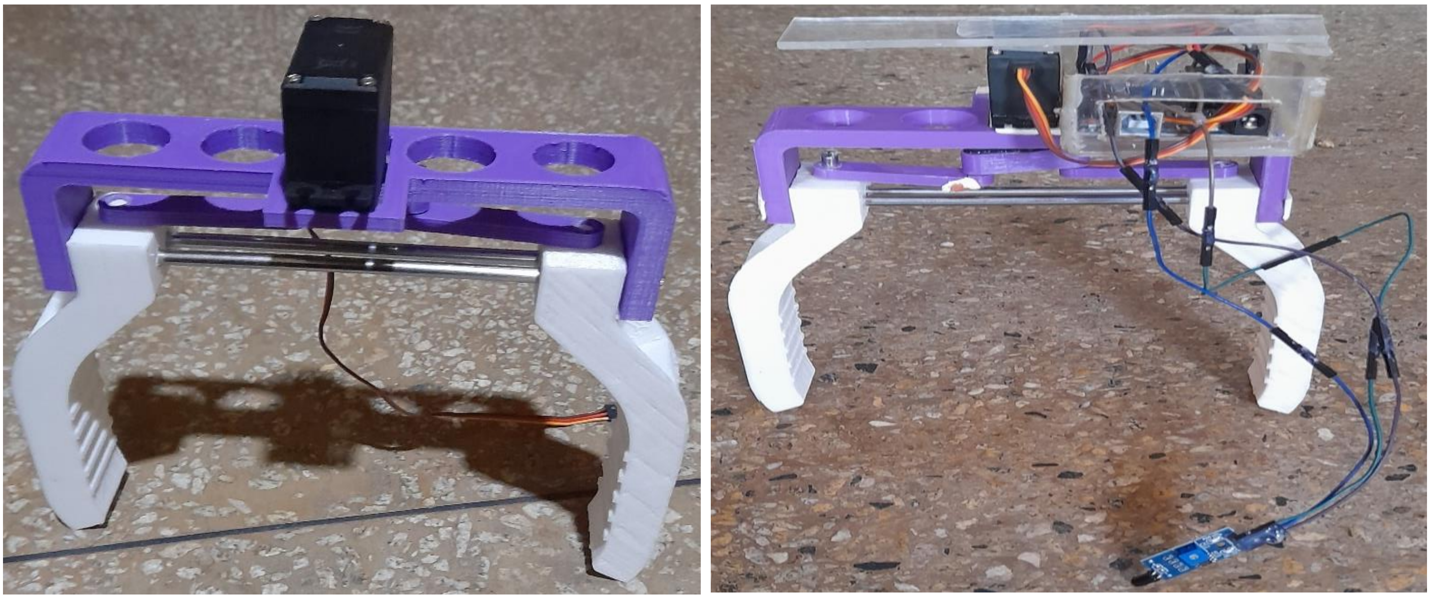
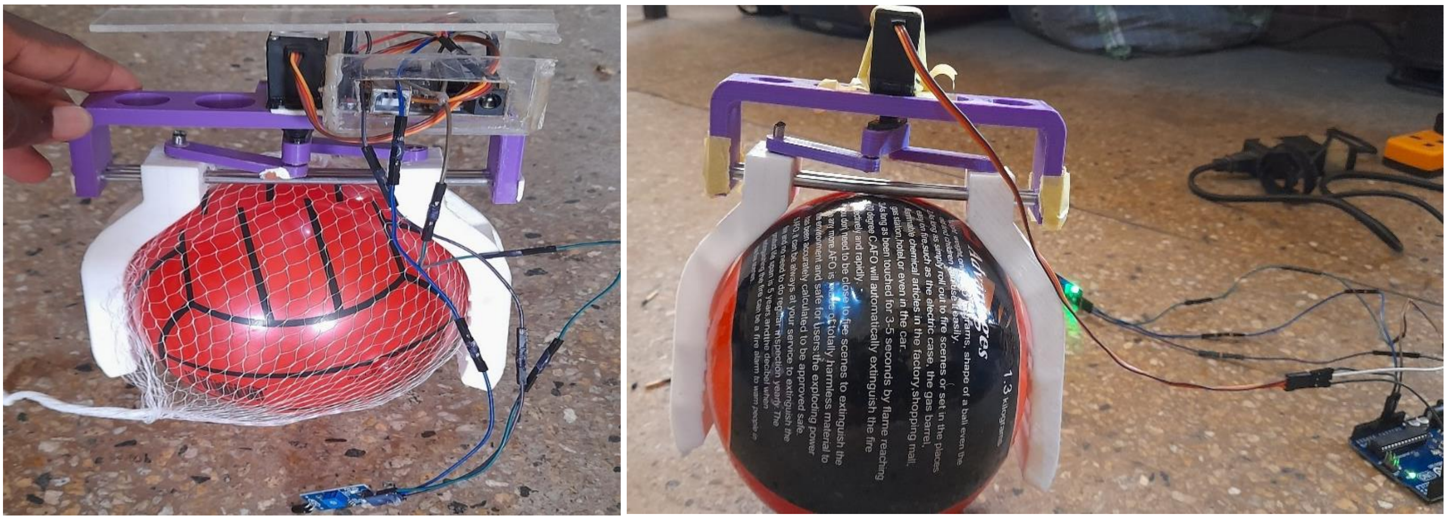



**Figure 14.** Flowchart of the system



a. b.

**Figure 15.** 3D printed mechanism



**a.** **b.**

**Figure 16.** The gripper with the fire extinguishing ball

### *4.2 Performance evaluation*

Simulation results showed consistent performance with minimal displacement and stress under load. The simulation results further validated the structural integrity and performance of the designed mechanism. **Figures 17, 18, and 19** illustrate the maximum displacement, strain, and stress distribution on the gripper structure under operational conditions. These results confirm that the system can withstand the forces experienced during fire-extinguishing missions.

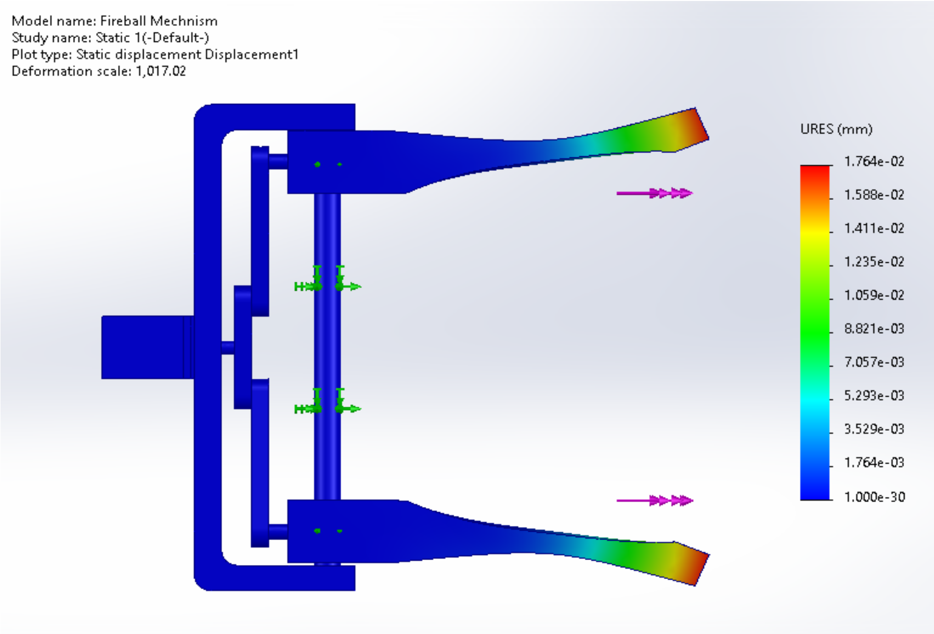



**Figure 17.** Simulation of displacement on the mechanism

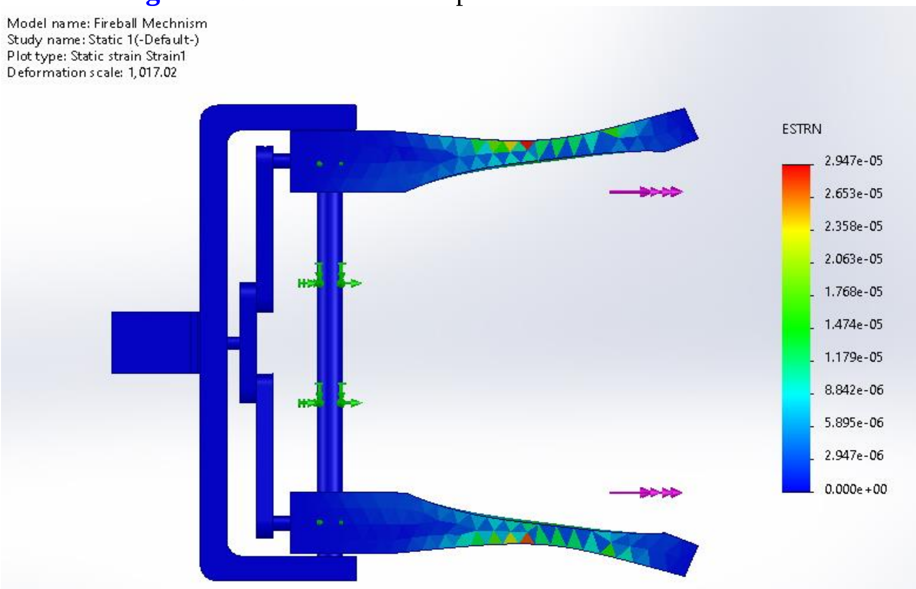



**Figure 18.** Simulation of the strain on the mechanism

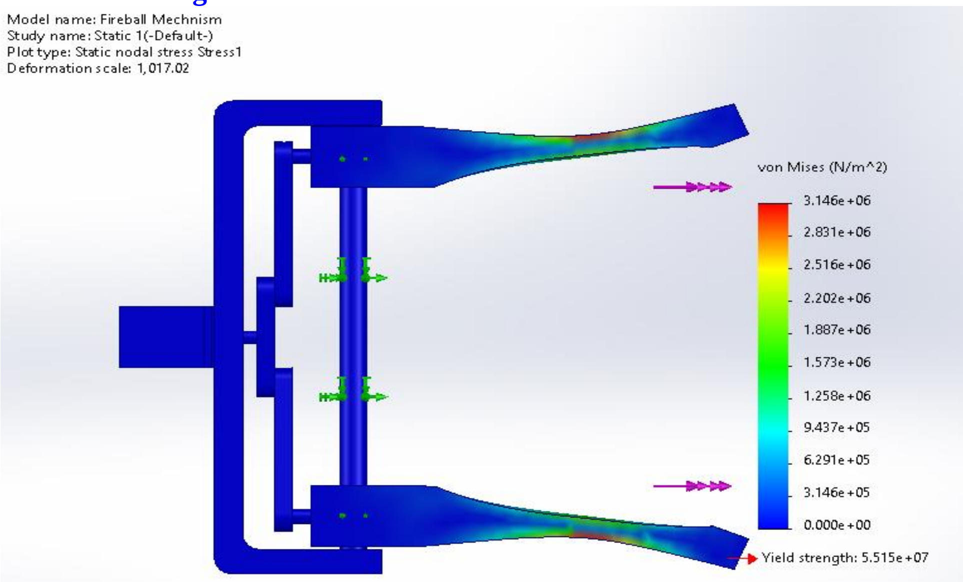



**Figure 19.** Simulation of the stress on the mechanism

#### *4.6 Experimental test results*

**Table 3** presents the response time and movement of the gripper arm upon detecting fire. The distance covered by the gripper and the corresponding time taken are recorded for three separate trials. These results highlight the system's consistency and efficiency. The results indicate that the fire detection mechanism promptly triggers the release mechanism, with response times ranging between 2 to 4 seconds. The incremental increase in time corresponds to slight variations in the distance covered, suggesting minor latency in actuation. However, the overall response remains within an acceptable range for fire suppression operations. These findings confirm the system's reliability and potential effectiveness in real-life applications.

**Table 3.** Result of the test

| Test No. | Altitude Covered (m) | Response Time (s) |
|---|---|---|
| 1 | 50 | 2 |
| 2 | 55 | 3 |
| 3 | 60 | 4 |

## Conclusion

This study presents a novel drone-mounted system for urban fire safety, addressing the critical challenges of high-rise firefighting. The integration of mechatronic components enables efficient fire suppression, minimizing risks to human life and infrastructure. The mechanism implemented has a unique design for the ejection of the fire-extinguishing ball. A flame sensor was interfaced with the mechanism to help detect the presence and absence of fire. Depending on the presence or absence the drone gripper then releases or keeps holding the ball as the case may be. One of the challenges faced during the project was getting a suitable mechanism to suit the purpose of the project. Moreover, the designed system outperformed existing drone-mounted systems by incorporating a compact design and autonomous operation. Its ability to detect fire and deliver extinguishing agents without manual intervention highlights its potential in urban firefighting.

## Recommendations

The mechanism deployed in this study is currently limited to single-ball deployment and relies on line-of-sight operation. Future work should focus on the following to improve performance:
Mechanism: Multi-ball deployment mechanisms to enhance efficiency.
Intelligence: Integration of AI for autonomous navigation and decision-making.

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