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Analysis of Strength and Flight Time for Hexacopter Fire Fighting Drone with Fire Extinguisher Ball

Irsa Talib[1]*, Jawad Hussain[2], Syed Asjad Ali Shamsi[1], Zeshan Ahmad[1], Fizza Ghulam Nabi[3], and Iqra Ramzan[1]

[1]Mechanical Engineering Department, University of Management and Technology, Lahore 54000, Pakistan,
[2]Department of Biomedical Engineering, Riphah International University, Islamabad, Pakistan
[3]Industrial Department of Engineering and Management, Institute of Quality & Technology Management, Punjab University.

*Corresponding author: Irsa Talib (E-mail: irsatalib@gmail.com)

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Abstract— **This research article is aimed to contribute to the improvement of human life by addressing the growing number of fire incidents caused due to increasing human population and advances in modern technology. This study proposes the use of drone with a hexagonal design configuration for firefighting purpose. Two design concepts for the firefighting drone were proposed. The 3D models were developed for both the designs using SolidWorks. The design 1 was made to carry an FEB of 0.5 Kg and design 2 was made to carry 1.3 Kg FEB. The strength of drone structure was analyzed using Ansys software. The static structural analysis showed the maximum total deformation and stresses on the arms while minimum total deformation and stresses on the top and bottom plates in both design 1 and design 2. The dynamic analysis performed for 0.0002 seconds of flight time. The total deformation was observed to be maximum on the arms and the bottom plate while minimum on the top plate of the drone. However, the stresses were observed to be maximum on the arms and minimum on the top and bottom plates. A prototype was developed based on design 1 for experimental purpose. The drone's flight control and stability were managed by a Pixhawk 2.4.8 flight controller, alongside GPS for precise navigation. A wireless radio telemetry system facilitates communication between the drone and a mobile phone or PC, with power supplied by a 5200mAh capacity battery. To carry out firefighting operations, the drone was equipped with a wooden box that utilized servo motors to drop a fire extinguisher ball accurately from an initial point to a designated target location. In conclusion, the research proposes an efficient and cost-effective solution to combat fire incidents using a drone. By integrating advanced technologies and equipment, the drone demonstrates the potential to protect the environment and preserve life from the destructive effects of fire.**

Index Terms— **Deflection, Fire Extinguisher Ball, Fire Fighting Drone, Hexacopter, Strength**

I. Introduction

Drones, also known as unmanned aerial vehicles (UAVs), have rapidly gained popularity for their diverse applications, including aerial photography, package delivery, and racing [1, 2]. Equipped with various hardware components and controlled through sophisticated software, drones can fly autonomously, eliminating the need for human pilots [3, 4]. Their intelligence, speed, and advanced technology have made them valuable tools for surveillance and monitoring tasks [5]. Expanding their capabilities, researchers propose enhancing drones for firefighting purposes, creating fire extinguisher drones (FEDs) by integrating fire detection sensors [6].

The pressing need for fire extinguisher drones stems from the limitations of traditional firefighting methods [7]. When fires break out due to natural disasters or human negligence, it often escalates rapidly, causing substantial damage. Large-scale wildfires, triggered by events like lightning strikes, prove especially challenging, unpredictable and uncontrollable [8]. Present firefighting methods, relying on sprinklers, chemical agents, and gaseous agents, often fall short in effectively combating extensive fires and pose considerable risks to the safety of firefighting personnel.

In addition to these challenges, urbanization and taller building constructions have complicated firefighting efforts. Traffic congestion leads to delayed responses, hampering firefighting teams' ability to reach affected areas promptly [9]. The rising population density, with buildings constructed closer together, creates further obstacles for conventional firefighting equipment [10]. To address these critical issues, researchers envision fire extinguisher drones as a potential transformative solution.

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Irsa Talib, Syed Asjad Ali Shamsi, Zeshan Ahmad and Iqra Ramzan are with Mechanical Engineering Department, University of Management and Technology, Lahore ,54000, Pakistan. Jawad Hussain is with Department of Biomedical Engineering, Riphah International University. Fizza Ghulam Nabi is with Industrial Department of Engineering and Management, Institute of Quality & Technology Management, Punjab University. (Correspondence email: irsatalib@gmail.com)

The concept of drones has a history spanning over 150 years, starting as communication devices and evolving into military tools during World War I. Advancements incorporating radio signals and GPS technology led to the development of modern UAVs and drones. The recent advancements in fire drone technology are important, detailing type of drone, flight controller and fire extinguisher technique adopted. The authors in [1] used fire extinguisher ball with UAV used wall mount-direct throw method to extinguish fire in forests and buildings. While the authors in [3] attached fire ball with hexacopter drone with camera, transmitter, receiver and used remote control to control the flight. the authors in [11] and [12] performed a simulation based study with hexacopter and quadcopter drones. A gripping module was used in [11] while Thrust efficiency of drone using different propellers was estimated in [12]. The fire extinguisher ball and a water storage tank was attached to octocopter for fire extinguisher purpose [13] . Thermal imaging camera, LEDs, radio transmitter, receiver and Pixhawk controller were accompanied with the octocopter while a shell was used to hold the fire ball. Human detection was a key feature of the assembly. The authors in [14] attached a fire ball release mechanism with a quadcopter. Camera, GPS and Ardupilot controller were attached to the assembly for fire detection and extinguisher purposes. Fire extinguisher drones promise various advantages over traditional firefighting methods. Their ability to access remote and hazardous locations makes them invaluable in combating wildfires and hard-to-reach fires [9]. Swift response times allow for early fire suppression, limiting the spread of flames and reducing overall damage. Furthermore, the autonomy of these drones eliminates the need for human firefighters to venture into dangerous situations, ensuring the safety of personnel.

This research article aims to analyze the strength of drone structure and flight time of drone through simulations and prototype. And then, propose the design and development of fire extinguisher drone prototype, equipped with advanced fire detection sensors and a drop mechanism controlled by servo motors for precise firefighting. The feasibility of local manufacturing of the drone needs to be investigated to enhance accessibility and affordability. The effectiveness of the fire extinguisher drone in mitigating fire impact on human lives, wildlife, and the environment will be thoroughly evaluated. In this endeavor, eco-friendly materials will be used to promote environmental sustainability.

In conclusion, fire extinguisher drones hold tremendous potential to revolutionize modern firefighting efforts. By leveraging drone technology, we can enhance firefighting efficiency, minimize risks to human life, and mitigate the impact of fires on the environment. This research aims to contribute to a safer and more effective approach to fire suppression, ultimately safeguarding lives and preserving nature. The findings will pave the way for future advancements in firefighting technology, ensuring a better-prepared response to fire emergencies.

II. DESIGN OF HEXACOPTER DRONE STRUCTURE

Two hexacopter drone structures were made including fire extinguisher ball (FEB) weighing 0.5 kg (Design 1) and 1.3 kg (Design 2) respectively.

A. Cantilever Beam Analysis

The structure of the drone consists of the top plate, bottom plate and arms of the drone. The arms of the drone act as a cantilever beam [15], therefore cantilever beam calculations would help in selection of appropriate length for the arm of the drone that could bear the stress due to the applied. The area moment of inertia, flexural rigidity, moment at fixed point, reaction at fixed point, deflection slope and stress are calculated in equation (1) through equation (7).

$$I = \frac{\pi}{4}(Ro^4 - Ri^4) \quad (1)$$

$$Flexural\ Rigidity = E \times I \quad (2)$$

$$M_A = P \times L \quad (3)$$

$$V_A = P \quad (4)$$

$$\delta = \frac{PL^3}{3EI} \quad (5)$$

$$\theta = \frac{PL^2}{2EI} \quad (6)$$

$$\sigma = \frac{y_{max} \times PL}{I} \quad (7)$$

The theoretical cantilever beam calculations for design 1 were not performed as the design has standard dimensions. Therefore, a software-based cantilever beam analysis was done only for design 1. The cantilever beam calculations were done for design 2, using different diameters and the length of the beam. Through hit and trial and various combinations of inner/ outer diameters and lengths of beam were analyzed using equation (1) through (7). The cantilever beam or the arm of the drone was modelled in 3D as design 1 to hold 0.5 Kg FEB and design 2 to hold 1.3 Kg FEB. Then in the static structural module of ANSYS Workbench, the material chosen for design 1 was Nylon 6 and design 2 was carbon fiber. The material properties of both design 1 and design 2 are listed in TABLE 1.

TABLE 1
THE MATERIAL PROPERTIES OF BOTH DESIGN 1 AND DESIGN 2

Sr.	Material Properties	Design 1	Design 2	Unit
1	Density	1130	2000	kg/m^3
2	Young’s modulus	2400	79000	MPa
3	Poisson’s ratio	0.39	0.27	$-$
4	Bulk modulus	3636	47000	MPa
5	Shear modulus	863	32000	MPa
6	Ultimate tensile strength	59	4000	MPa

For design 1, the cantilever beam stress was yielded as 7.413 MPa (Fig. 1) and total deformation was observed as 5.0 mm (Figure 2). The results for the cantilever beam of the drone structure for 0.5 kg can’t be compared, but as we can see the deformation is too much for the load applied. However, now that we have analyzed the cantilever beam, we can develop a 3D model of the drone structure for 0.5 kg. For design 2, various combinations of diameters and lengths of beam analyzed along with stresses developed and deformations are listed in TABLE 2. It was observed that the increase in diameter of the beam and decrease in the length of the beam affected the stress the most. Hence, the last entry of TABLE 2 showed optimal deformation and stress values. The stress and total deformation that occurs on the arm of design 2 are shown in Figure 3 and Figure 4, respectively.

TABLE 2
CANTILEVER BEAM RESULTS FOR DIFFERENT LENGTHS AND DIAMETERS

Sr.	Beam Diameter (mm)	Length (mm)	Stress (MPa)	Total deformation (mm)
1	16 x 12	400	57.841	0.55669
2	16 x 12	450	67.308	0.83933
3	16 x 12	500	75.476	1.2035
4	12 x 8	450	127.51	2.2479
5	20 x 14	450	29.585	0.31318
6	20 x 14	400	26.801	0.2082

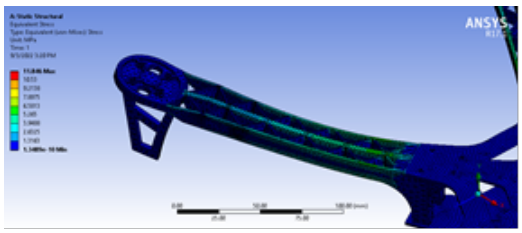

Figure 1. Total stress on the concentrated region in design 1

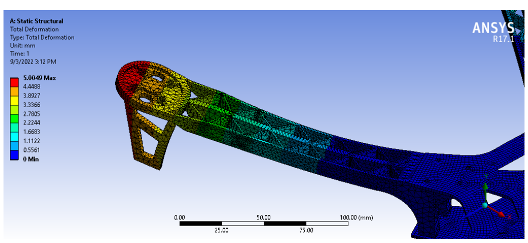

Figure 2. Total deformation on the concentrated region in design 1

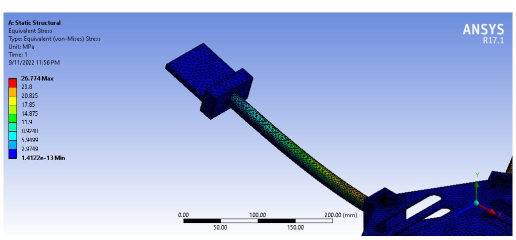

Figure 3. Stress on the concentrated region in design 2

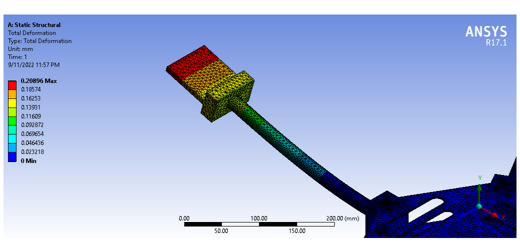

Figure 4 Total deformation on the concentrated region in design 2

TABLE 3
CALCULATIONS OF DIFFERENT PARAMETERS FOR THE BEAM

Sr.	Distance of point load L (mm)	MOI (mm^4)	Deflection δ (mm)	Slope θ (rad) e^{-3}	Stress σ (MPa)
1	365	2199.11	0.6681	2.74	60.179
2	415	2199.11	0.9820	3.55	68.423
3	465	2199.11	1.3814	4.45	76.666
4	415	816.81	2.6439	9.56	138.16
5	415	5968.24	0.3618	1.31	31.514

The theoretical results for cantilever beam analyses of design 2 are mentioned in TABLE 3. A beam length of 400 mm with outer diameter of 20 mm and inner diameter of 14 mm yielded a deflection of 0.246 mm and stress of 27.7 MPa. Comparing the theoretical results with simulated results shows negligible difference. Hence, the results obtained from the analysis verified the theoretical results. Therefore, an arm of this length and diameter can be used for the drone model as it experiences the least deformation and stress compared with all other combinations.

B. Development of 3D Models

The 3D models were developed for both designs using SolidWorks (Fig.5, Fig. 6). The top and bottom plates of drone were made with glass fiber while arms were made with nylon in design 1. The top plate, bottom plate and arms were made with carbon fiber in 3D model of design 2. The final assembly of design 2. The final assembly for design 1 is shown in Fig. 7.

Figure 5. 3D model of hexagonal structure of design 1

Figure 6. 3D model of hexagonal structure of design 2

The thrust, load and cantilever beam analyses were performed on both design 1 and design 2. It helped to select the optimal design and further the choice of drone components including battery, motors and propellers [16]. The thrust to weight ratio (TWR), battery output and flight time of drone were calculated using equation (8), (9) and (10) respectively.

Figure 7. Final assembly of design 1

$$TWR = \frac{T}{W} \; ; \quad (8)$$

Where $T = Thrust\ and\ W = weight$

$$Battery\ capacity\ \times Discharge = \frac{Ans}{1000} = Amperes \quad (9)$$

$$Flight\ Time = \frac{Battery\ output}{Current\ consumption\ of\ motor} \quad (10)$$

Further static and dynamic structural analyses were done to choose the optimal design among design 1 and design 2. The optimal design was then translated into physical prototype. The prototype developed was tested for flight and FEB drop during flight.

C. Results For Static Structural Analysis

The load P calculated as 5.9841 N was then applied for design 1 and a load of 45.32 N was applied to design 2, at the free ends of all six arms in an upward direction. The top and bottom plates were made fixed. The Stress was observed as 11.84 MPa, and total deformation was observed as of 5.00 mm for both designs 1 and 2. The total deformation and stress that occurs on the drone structure were analyzed. The deformation and stress on the concentrated region were also observed, for design 1 and design 2, respectively. The total deformation and stress are maximum on the arms and minimum on the top and bottom plates [17] in both design 1 and design 2.

The load P calculated as 5.9841 N was then applied for design 1 and a load of 45.32 N was applied to design 2, at the free ends of all six arms in an upward direction. The bottom plate was applied with a weight of 23 N and 67.2 N in design 1 and design 2, respectively. The end time was selected as 0.0002 seconds due to limitation of computational resources. The stresses and strains in both designs are shown in Table 4.

The total deformation is observed to be maximum on the arms and the bottom plate while minimum on the top plate of the drone, in design 1. However, the stress is observed to be maximum on the bottom plates and minimum on the top plate.

The total deformation and stress that occurs on the drone structure in design 2, for 0.0002 seconds were analyzed. The maximum total deformation was observed on the arms and the bottom plate while minimum was observed on the top plate of the drone. The maximum stress was observed on the arms and minimum was observed on the top and bottom plates.

D. Prototype Development

Design 1 was selected for prototype development due to budget constraints. AQ drone structure was designed for a payload of 0.5 kg. The chosen materials for the drone's construction were nylon 6 for the arms and glass fibre for the top and bottom plates. These materials were selected due to their fire-retardant properties, making the drone suitable for firefighting operations in areas affected by fire.

The Fire Extinguisher Drone (FED) prototype consisted of various components, including the Flame wheel F550 with six arms, a top plate, and a bottom plate equipped with a PCB from DJI. Other components included the ESC (40A) from EMAX, a DJI BLDC motor of 920 KV, and a DJI propeller with a diameter of 9.4 inches and a pitch of 4.3 inches. The 3S lipo battery used was 5200 mAH 50C from VANT battery. The fire extinguisher ball, weighing 0.5 kg with a diameter of 110mm, was sourced from AFO. Additionally, a wooden box (185×185×175 mm) from SQ arcade, Pixhawk 2.4.8 with sensors like magnetometer, accelerometer, gyroscope, and barometer from Ardupilot, a built-in compass M8N GPS, a 10CH RC transmitter/receiver with a 2.4 GHz range from Flysky, and a Runcam 1080p @ 60fps camera for monitoring and surveillance were included in the prototype.

The fire extinguisher ball was preferred over traditional methods due to its lightweight and environmentally friendly nature. Upon contact with fire, the ball self-activates within 10 seconds, producing a loud warning sound. The advantage of using fire extinguisher balls lies in their compact design and the absence of training requirements, enabling anyone to use them effectively. These balls can be employed for various classes of fires, including Class A, B, C, E, and K fires. For this project, a 0.5 kg fire extinguisher ball was utilized to extinguish the fire within a one-meter radius.

The Pixhawk Flight Controller (FC) featured a 32-bit ARM Cortex M4 core with FPU, operating at 168 MHz with 256 KB RAM and 2 MB Flash. The FC also had a 32-bit failsafe co-processor and various sensors, such as MPU6000 for the main accelerometer and gyroscope, ST Micro 16-bit gyroscope, ST Micro 14-bit accelerometer/compass (magnetometer), and a MEAS barometer. Configuration of the Pixhawk was done through the mission planner, offering different frame types, such as X or + type frames, based on project requirements. The motors were connected in a specific pattern, one clockwise (CW) and the other counter-clockwise (CCW). Pixhawk was linked to a Wi-Fi radio telemetry for wireless communication between the pilot and the drone. The Q Ground Control application on mobile provided drone status updates, warnings, and errors communicated to the Pixhawk. Flight modes could be set, and drone commands, such as take-off and RTL/Land, could be executed using this application. The drone was equipped with a lightweight and compact 1080p camera known as Runcam Thumb. This camera, with a 60fps display, allowed video recording during the drone's flight to monitor the surrounding area, aiding the operator in assessing the situation. Additionally, this camera held potential for future applications in surveillance and military operations. Following component selection, the drone was assembled, with ESCs soldered to the Power Distribution Board (PDB). The Pixhawk was powered using a 3DR power module, providing 5V. The other connections were established as per the schematic diagram, ensuring proper power supply and signal transmission. The wooden box was powered by servos, and these servo motors were connected to ports 7 and 8. Upon successful completion of all connections, the drone was calibrated using mission planner software, marking its readiness for its inaugural flight. The fully developed prototype was a result of meticulous design and integration of components, represented in Fig. 8. During testing, the drone effectively lifted the 0.5 kg fire extinguisher ball to a specific height before dropping it, validating its performance. The Theoretical Thrust-to-Weight Ratio (TWR) of 1.56, indicating acceptable lifting capability, was substantiated through testing. The prototype demonstrated its potential for firefighting applications, showcasing a significant step forward in unmanned firefighting technology.

Figure 8. Final assembly of prototype based on design 1

E. Thrust And Load Analysis

The weight of different components of the drone for design 1 and design 2 is shown in Table 5. For design 1, motor specifications included a propeller size of 9443, a battery of 11.1 V, and a motor of 920 KV. It yielded a thrust of 610g at 100% throttle. For design 2, motor specifications included a propeller size of 2055, the battery of 22.2 V, motor of 340 KV. It yielded a thrust of 4620 g at 100% throttle. The drone parameters, included TWR and battery output calculated using eq (8) and (9) are presented in Table 6. While the TWR obtained using equation (1) was 1.56 for design 1, which was observed acceptable for drone lift. The flight time with 3S battery was observed acceptable as the throttle is at 100% with utilization of more power. If the throttle is lowered to 75%, the TWR would decrease and it wouldn't be able to lift the drone [12]. Better flight times might be achieved by using a battery like 4S battery with higher capacity, even at 75 % throttle. While using a 3S battery at 100% throttle was observed to add around 1 minute to the flight time, in comparison to a 3S battery at 75 % throttle. Hence, using a 4S battery doesn't seem to be a smart choice. A 3S battery was observed to fit in a prototype for experimental purpose and gave promising results while testing.

TABLE 4
DYNAMIC STRESSES AND STRAINS IN DESIGN 1 AND DESIGN 2

	Stress (MPa)	Total deformation (mm)
Design 1	1.7858	0.016029
Design 2	2.2941	0.010975

TABLE 5
WEIGHT OF THE DRONE STRUCTURE FOR DESIGN 1 & DESIGN 2

Sr.	Components	Quantity	Weight design 1	Weight design 2
1	ESC	6	246g	156g
2	Battery	1	338g	2500g
3	Motors	6	324g	1380g
4	Propellers	6	69g	150g
5	Drone frame	1	478g	850g
6	Camera	1	9.8g	16g
7	Wooden Box	1	380g	500g
8	Fire extinguisher ball	1	500g	1300g
	Total weight (g)		= 2344.8	6852

TABLE 6
PARAMETERS OF DRONE FOR DESIGN 1 AND DESIGN 2

Drone design	TWR	Battery Output (A)	Flight Time (min)
Design 1	1.56	240	6 min 5 s
Design 2	4	660	10 min

III. Discussion and Conclusions

The research study involved the analysis of two design concepts for drones, one with a structure for carrying a 0.5 kg load and the other for a 1.3 kg load. Both designs underwent thorough theoretical analysis and software-based simulations to evaluate their performance. While the drone structure for 1.3 kg had potential for various applications, it was deemed cost-prohibitive and not feasible within the allocated budget. Consequently, the drone structure for 0.5 kg was chosen as the most suitable option for further development. Prototype testing was conducted to assess the performance of the selected design. The drone demonstrated excellent capabilities during testing, successfully carrying a load of 2.3 kg with a Thrust-to-Weight Ratio (TWR) of 1.56. The achieved flight time of just over 7 minutes surpassed expectations and aligned with the theoretical flight time calculations, validating the design's efficiency and effectiveness. Based on these results, it may be concluded that the 0.5 kg drone structure is well-suited for functioning as a fire extinguisher drone. Its remarkable performance in handling additional weight indicates its potential to fulfill national needs in firefighting operations.

For future advancements, the proposed drone structure for 1.3 kg should be considered as an upgrade to replace the current 0.5 kg structure. Integrating specialized sensors, such as an Industrial flame sensor, would enable early detection of fires, enhancing the drone's firefighting capabilities. A LiDAR sensor for obstacle avoidance would further enhance its navigation and safety features. To aid firefighters in gaining real-time insights into the affected area, the drone can be equipped with a video transmitter and receiver, allowing live video feed through a mini OSD. This would provide crucial information and improvement in decision-making during firefighting missions [18].

Additionally, the wooden box used to carry the fire extinguisher ball could be replaced with a Para crate, which can carry up to 6 simultaneously. It would significantly increase the drone's firefighting capacity and effectiveness. Moreover, the drone's versatility extends beyond the firefighting [19]. It has the potential for package delivery and surveillance applications, contributing to a wider range of functionalities and societal benefits [3, 20-26].

In conclusion, this research presents a well-analyzed and cost-effective drone design with potential for firefighting and various other applications. The drone's capabilities can be further augmented by incorporating proposed advancements, making it an invaluable asset for addressing national needs and ensuring public safety.

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