DESIGN and ANALYSIS of OPTIMIZED QUADCOPTER TYPE DRONE STRUCTURE

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***Abstract*— In this study, a quadcopter structure-type drone was designed and developed, with all constituent parts and assembly models created using Computer Aided Design (CAD) tools. The thrust calculations were conducted for the purpose of selecting the most suitable components and creating the load sets in the engineering analysis and optimization processes. The electronic hardware (RGB camera, Raspberry Pi, brushless motors, motor drivers, flight and power distribution boards) was selected and integrated into the structure using appropriate mounting elements. Finite element analyses (FEA) were conducted to confirm the strength and stability of the system, and topology optimization was applied to decrease the weight and energy consumption of the system. A drone power analysis tool was designed for the purpose of calculating and comparing the energy consumption of non-optimized and optimized structures. When compared to existing literature, a useful drone power analysis tool was designed for the validation of the results of topology optimization studies with regard to aspects of energy consumption and power requirement. The tool has been developed as a GUI (graphical user interface), enabling researchers to consider their results and optimized structure outputs with the parameters of power requirements and energy consumption. FEA and power analyses results showed that an optimized new quadcopter type drone structure was designed and developed with 41% lightening and 20% less energy consumption.**

***Index Terms*— Computer Aided Engineering, Finite Element Analysis, Graphical User Interface, Topology Optimization, Quadcopter Type Drone**

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are defined as aircraft that are capable of operating without the necessity of a human pilot on board. These vehicles can be either remotely controlled by human operators or can function autonomously [1]. The first UAVs were designed and developed by the United States in the 1910s, with the first models being utilized during the Second World War and subsequently in wars of Vietnam, Afghanistan and Iraq. After this, there has been an increase in the utilization of UAVs in a variety of areas, including observation, early fire detection, entertainment, and so on. Consequently, the UAV trade market has experienced rapid growth, fostering confidence in its applications across diverse sectors [2].

UAVs can be categorized into various types, including Smart Dust (SD), Nano (NAV), Pico (PAV), Micro (MAV), Micro Unmanned (MUAV), and Unmanned Aerial Vehicles (UAV) [3]. The utilization of Unmanned Aerial Vehicles (UAVs) encompasses various domains, including Combat, Reconnaissance, Logistics, Research and Development, Civilian and Commercial Applications. As UAV technology undergoes advancements, the transition to drones becomes increasingly evident in civilian and commercial sectors. While drones are technically a subset of UAVs, they are frequently associated with smaller, more accessible models designed for personal or professional use, such as aerial photography, delivery services and recreational flying. The affordability and ease of use of these devices has led to their integration into various sectors, transforming industries and aspects of everyday life [4]. Unmanned aerial vehicles (UAVs) can be categorized into three primary classifications as fixed-wing UAVs, single-rotor UAVs, and multi-rotor UAVs. These three categories are collectively referred to as 'drones'. Multi-rotor UAVs can be also further categorized into four-rotor UAVs, six-rotor UAVs, and eight-rotor UAVs. The drone that is most popular and recommended is the four-rotor drone, due to its simplicity, performance and budget [1,4,5].

In the academic literature and production sectors, computer-based tools have become indispensable for the design and analysis of structures. The use of solid modelling through CAD (Computer Aided Design) methodologies empowers designers to define components and assemblies, leveraging geometry for simulations, analyses and prototyping. CAE methods [6-9] facilitate virtual prototype simulations and static, kinematic and dynamic analyses, enhancing efficiency and accuracy in design and analysis processes.

Nowadays, topology and shape optimizations are vital tools in product design. They are used in many industries, including the automotive and aerospace sectors. Additive manufacturing technologies have expanded their applications. Topology optimization and additive manufacturing are closely linked. This link increases the efficiency of prototyping and decreases production times. Topology optimization is a technique for optimizing material distribution within a designated design space. It considers specific loads, boundary conditions, and constraints. The objective is clear: to reduce the weight of the structure while maintaining or improving its strength and natural frequencies. A key aim of optimization is determining the most appropriate material usage within the specified design area to achieve the desired structural performance. In the process, the designed volume is divided into smaller elements, a finite element analysis (FEA) model is created, and boundary conditions are applied to perform the FEA. During the analysis, the elements exhibit intermediate density values. These values approach 1 or 0 by employing penalization techniques such as the power law to penalize higher-density elements. This process ensures convergence towards solid and void regions to build the final structure. The optimization process uses an iterative updating of the material density by the optimization algorithm to converge to a solution, thereby achieving optimal performance and design volume. The final structure is determined by ensuring a smooth transition between solid and void regions.

Two common methods for determining the distribution of elements in topology optimization are Solid Isotropic Material Penalization (SIMP) and the Evolutionary Structural Optimization Technique (ESO). The general scheme of those two methods is shown in Figure 1 [10,11].

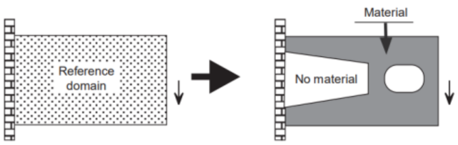


Fig. 1. The general scheme of SIMP and ESO

Haddad et al. conducted a comparison study of X, plus, and H types of drones. They applied FEA (finite element analysis), shape optimization and numerical analyses to compare their efficiency and structural stability. According to results, X-type drones had better performance for the parameters of efficiency, effectiveness, easy operating, movement capacity and stability [12].

Bendsøe et al. studied to create special method for shape optimization applicable for structures like drone frames. They improved and developed a meshing system to obtain better results from optimization and FEA studies [13].

Leon et al. conducted a structural optimization study for their frame. Their aim was to decrease the weight of the system to increase the flight time. They observed an important increase in the flight time with the optimization [14].

Costa et al. demonstrated the efficacy of the optimization process for UAV. They focused on enhancing flight performance by improving the shape optimization process to achieve not only energy efficiency but also a balance between overall weight and stiffness. This balance was critical for increasing the payload capacity and overall efficiency of the design [15].

Sreeramoju et al. conducted an optimization study with the comparison of 3 different materials. They aimed to provide a selection guide for material of the drone chassis with parameters of low weight and high endurance. They analyzed the structure for the materials of Aluminum A356 T6, aluminum 6061 and abs plastic. Their analyses results presented that 35% reduction was obtained with optimization works. They also provided material selection guidance with the parameters of cost, strength, weight, energy consumption and stability for the designers [16].

Asif et al. designed and produced a drone structure frame using Fusion 360 software with pla plastic material. They also applied optimization and FEA studies to compare the strength of the structures. From the results they presented that 93% weight decrease was obtained with the optimization works [17].

Ali et al. investigated the durability and impact resistance properties of the drone structure they designed. They applied a topology optimization process to decrease the weight of the structure. They observed not only a 50% decrease in weight but also increase in the stiffness and endurance to weight ratio [18].

Specific calculations and numerical analyses are important to design an efficient drone structure and application of the topology optimization process. The mass sizing, thrust force, power requirement, flight duration calculations should be conducted. According to the results of those analyses and calculations, the component can be selected and placed properly into the structure. These processes also can create constraints of the topology optimization process [19,20].

In this study, a quadcopter structure type drone was designed and developed. All the parts and assembly models were created using Computer Aided Design tools. The thrust calculations were conducted for proper component selection and creation of the load sets in the engineering analysis and optimization processes. The electronic hardware (Rgb camera, raspberry pi, brushless motors, motor drivers, flight and power distribution boards.) were selected and integrated into the structure with proper mounting elements. FEA were conducted to confirm the strength and stability of the system. Topology optimization was applied in order to decrease the weight and energy consumption of the system. A drone power analysis tool was designed for the purpose of calculating and comparing the energy consumption of primary and optimized structures. When compared to existing literature, a useful drone power analysis tool was designed for the validation of the results of topology optimization studies with regard to aspects of energy consumption and power requirement. The tool has been created as a GUI (graphical user interface), enabling researchers to consider their results and optimized structure outputs with the parameters of power requirements and energy consumption. This approach is expected to enhance the efficiency of drone structure optimization studies.

II. MATERIAL AND METHOD

A. Design of the Robotic Structure

In this part of the project, quadcopter structure type drone was designed using Fusion 360 software. The thrust calculations were conducted to select and place the proper brushless dc motor and drivers of them. The weight of the frame was found in design environment. The weight of the frame was calculated as about 600 gr with the assigned abs plus material. 11.1 V 3S lipo battery was selected as energy supplier for the system. The weights of all the electronic hardware were found using their data sheets. These values were used for total weight and thrust force calculations (Equation 1).

$$W_{total} = W_{frame} + W_{battery} + W_{hardware} \tag{1}$$

The total weight of the system was calculated as about 2,000gr. By using this value and Newton's law of motion, the total thrust force requirement was calculated as about 19.5 N. Because of safety and efficiency reasons the brushless motors were selected with the thrust capacity of 8 N. The system has about 32 N thrust force with 4 pieces of motors. The equation of the flow momentum change (Equation 2) was used to confirm these thrust calculations and determination of the diameters of the propellers.

$$T = \frac{\pi}{8} D^2 \rho \Delta v^2 \tag{2}$$

T = thrust [N]
D = propeller diameter [m]
Δv = velocity of air accelerated by the propeller [m/s]
ρ = density of air

All the parts top and bottom frame connection elements of the hardware were created and assembled. The electronic hardware: rgb camera, raspberry pi, brushless motors, motor drivers, flight and power distribution boards selected properly and integrated into the structure.

The top and bottom frame material used as abs plus plastic. The mechanical properties of this material are given in Table 1.

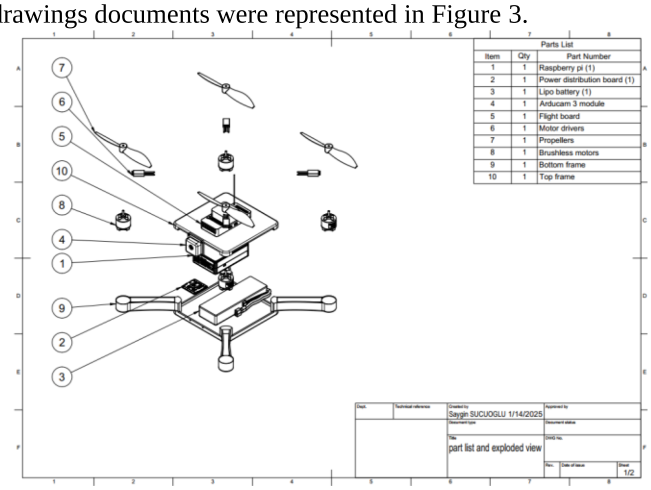
TABLE I
MECHANICAL PROPERTIES of
ABS PLUS PLASTIC MATERIAL [21]

Name of the property	Value
Elastic modulus (GPa)	2.5
Ultimate tensile strength (MPa)	110
Density (g/cm^3)	1.04
Poisson ratio	0.1

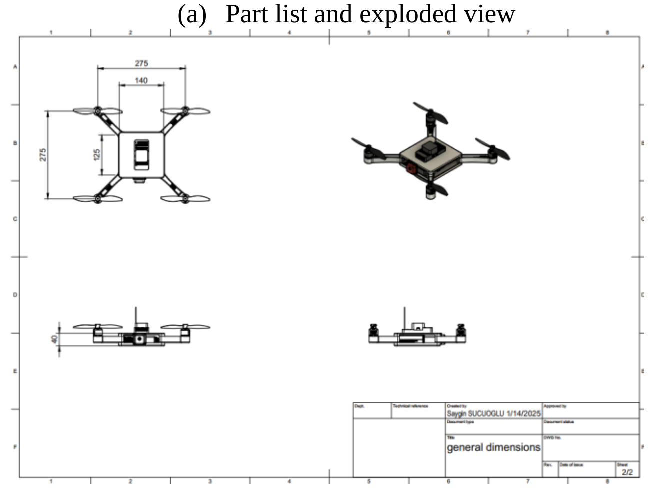
The assembled structure of the quadcopter structure type drone was shown in Figure 2.

Fig. 2. Assembly model of quadcopter structure type drone

After the 3d design process, the part list and exploded view and engineering drawings were created as useful documents for hardware selection and placements. The selected brushless dc motors with the specs of calculated values were mounted properly. 11.1 V 3S lipo battery, rgb camera, raspberry pi, motor drivers, flight and power distribution boards were integrated into designed places using proper connection elements. The part list and exploded view and engineering drawings documents were represented in Figure 3.



(a) Part list and exploded view



(b) Engineering drawings

Fig. 3. Part list and exploded view and engineering drawings of system

B. Engineering Analyses of Primary Structure

Engineering analyses were conducted using the finite element method (FEA) to assess the structural integrity and stability of the mechanical system. The primary objective of the FEA was to ascertain the viability of implementing topology optimization for this purpose, the material of the top and bottom frames was designated as ABS plus. The loads resulting from the thrusts of the motors and the weights of the elements 32 and 20 N, respectively, were applied to calculate the factor of safety and stress values. The engineering analyses were conducted in Ansys Workbench 2024 Static Structural Environment (Figure 4).

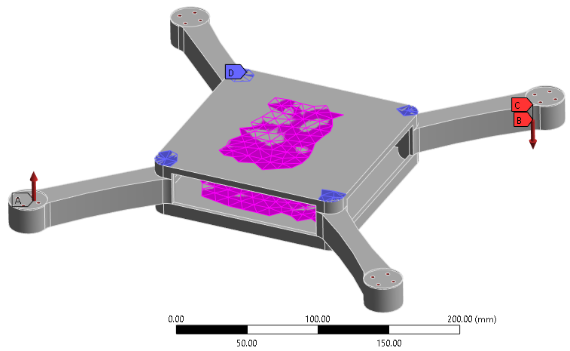


Fig. 4. Analysis set in Ansys Workbench 2024 Static Structural Environment

C. Topology Optimization Process

Topology optimization processes were conducted using the ESO (Evolutionary Structural Optimization Technique) in the Ansys Structural Optimization environment. The stress based ESO method, typically employs von Mises stress for removal process. Firstly, a piece of material large enough to cover the area of the final design is divided into a fine mesh of finite elements. Loads and boundary conditions are applied, and a stress analysis is carried out using a finite element program.

The same settings with the engineering analysis of primary structure were applied. The optimization type was defined as topology density. Threshold value of the optimization was used as 50% to decrease the weight of the chassis. Mounting places were defined as preserved areas to exclude from the optimization to create more realistic and efficient optimized structure. New optimized structure recommendations of the Ansys analysis environment were obtained (Figure 5).

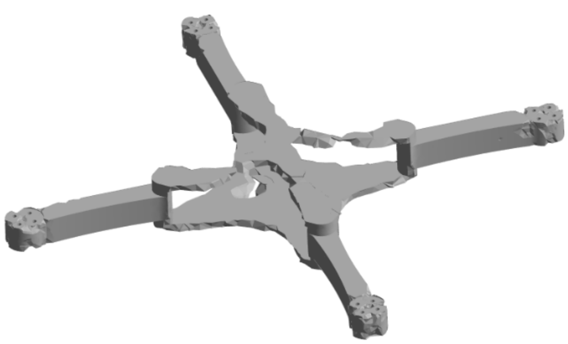


Fig. 5. Frame optimization recommendations

By using these recommended files outputs, a new optimized structure frame was designed (Figure 6).

Fig. 6. Optimized frame

The weight chassis decreased from 600 to 350 gr with the gain rate of 42%. This lightening was considered as reasonable for lower energy consumption. Engineering analyses were conducted with the same load cases of primary structure to confirm strength and usability of the newly created frame.

D. Drone Power Analysis Tool

The drone power analysis tool was designed for the purpose of calculation of energy consumption and weight analysis of quadcopter type drone system. By using the Python tkinter library, this tool was aimed at creating a graphical user interface (GUI) for improved user usage. The application was employed to do power analysis of quadcopter type drone structure, processing part list, detailed components such as brushless dc motor, battery, and frame material (Figure 7).

GUI can provide features to users to put specifications of components including voltage, current, quantity, and weight, directly from the part list data. Each component entry is appended to a cumulative list to create comprehensive analyses. The tool can dynamically calculate energy consumption and aggregate weight, thereby supporting real-time design evaluation and optimization. An important feature of this tool is its visualization capability to allow users to upload and display component images directly within the GUI. This property can improve the clarity of component selection and aid in correlating visual representations with numerical analysis.

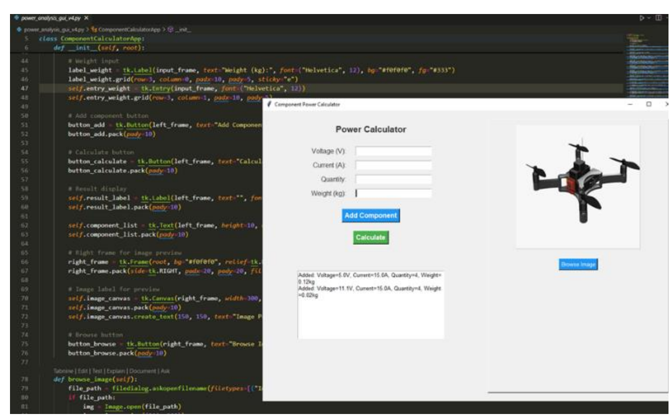


Fig. 7. Structure of power analysis tool

This analysis tool is significantly important for early-stage design, prototyping, and comparative analysis of quadcopter type drone system, as fast assessment of power and weight characteristics is crucial for informed decision-making and performance optimization (Figure 8).

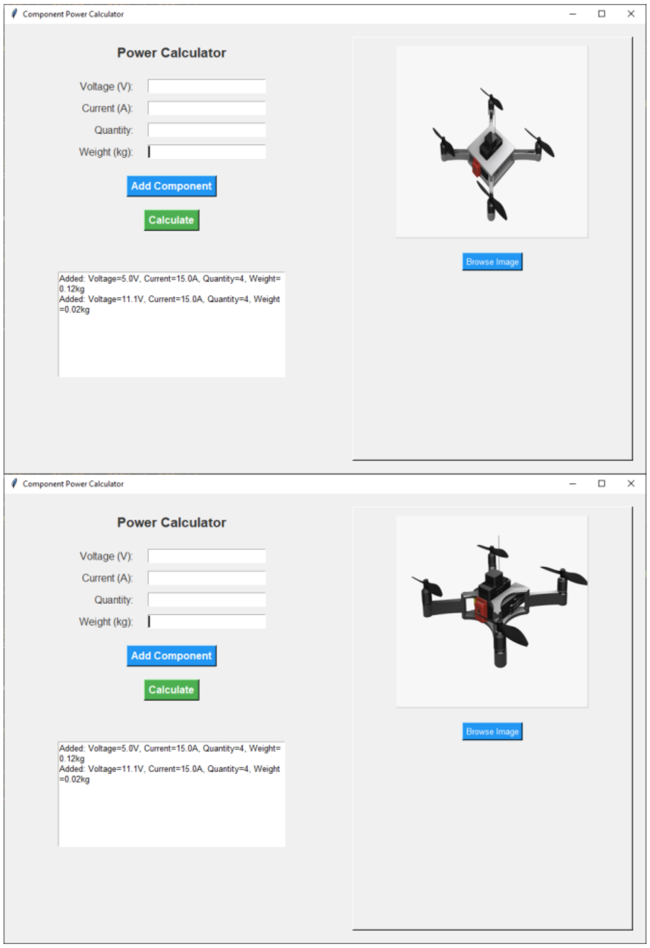


Fig. 8. Calculations with drone power analysis tool

D. Optimized Structure of Quadcopter Type Drone System

A new assembly model of drone structure was designed using optimized frame. The new structure was presented in Figure 9. As the mounting regions and places of the electronic hardware preserved from the optimization process, the new structure could be designed and assembled properly. The new structure frame was placed in design environment, the places of the hardware were determined. The new system was constructed using designed sub-assemblies and made ready for power analysis.

Fig. 9. New optimized structure

III. RESULTS AND DISCUSSION

A. Engineering Analyses Results of Primary Frame

The results of the FEA of the primary structure frame were observed to determine the necessity of the topology optimization process. It was obtained from the results that the weight of the frame and entire structure were about 600 and 2,000 gr respectively with abs plus frame material. The FOS (Factor of safety) value was found 12. This was considered as much more than the limits of safety. The von Misses stresses were calculated about 10 MPa (Figure 10). When those obtained results were considered, it was determined that the optimization process was feasible for decreased weight of the chassis, improved flying time and decreased energy consumption.

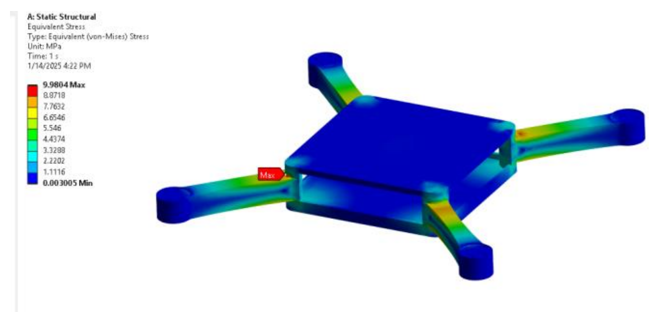
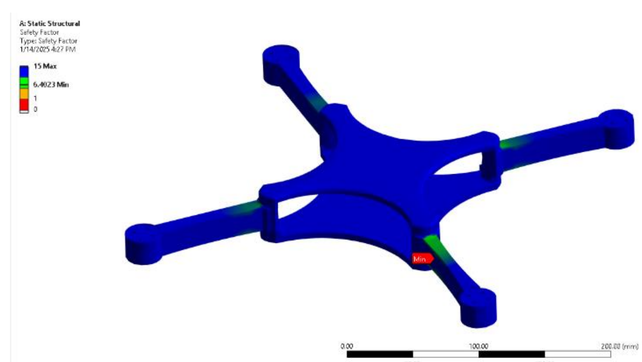


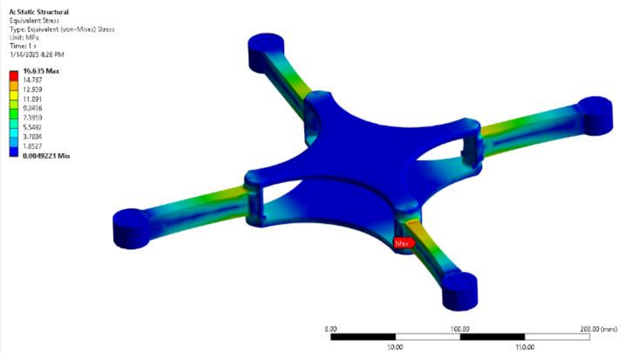
Fig. 10. FEA results of primary frame structure

B. Engineering Analyses Results of Optimized Frame

FEA results of the new optimized frame structure were represented in Figure 11. It resulted from these engineering analyses that FOS and occurred stresses were about 6 and 16 MPa. By considering those numbers, it could be interpreted that the structure is strong enough under the loads caused from brushless motor thrusts and weight of the components. Therefore, that was concluded that the new quad-copter drone structure with optimized-lightened frame, lower energy consumption and improved flight time was designed and constructed.



(a) Factor of safety



(b) von Misses stresses

Fig. 11. FEA results of optimized structure

C. Power Analysis Results

Power analyses of the quadcopter drone were carried out to evaluate and to compare the energy efficiency and performance of the primary and optimized structures. It was intended to measure the improvements of the topology optimization process which focused on weight reduction and energy efficiency

Applied power analysis utilized electrical energy calculation equations. These were:

a. Power (P) = Voltage (V) Current (I)
b. Total Energy (E) = Power (P) Time (t)
c. Total Power Consumption = ∑ (Power consumption of individual components)
d. Weight comparison = ∑ (weights of all components in each design)

Key factors of the analysis could be listed as:

a. The standard lipo battery voltage was set at 11.1V (3S configuration).
b. Brushless motors were assumed to operate at 12V with a nominal current of 12A per motor.
c. RGB camera consumed 500mA at 5V.
d. The Raspberry Pi, motor controllers, flight and power distribution boards required 1A at 5V.

The comparison between the primary and optimized structures proved that significant improvements in energy efficiency were obtained with the topology optimization process. The data of the power analyses is given in Table 1.

TABLE 2
DATA SUMMARIZATION OF POWER ANALYSIS

Name of Component	Primary	Optimized	Remarks
Frame weight (gr)	600	350	The optimized frame was lighter.
Total weight (gr)	2,000	1,750	The structure was lighter.
Power for motion	0.88	0.5	Optimized frame required less power
Total power requirement (W)	667	533	Optimized design required less power.
Energy consumption per Hour (Wh)	667	533	Lower energy demands for same duration.

The findings of the research study demonstrated that the optimized design achieved a 41% reduction in frame weight. This lightening could directly contribute to decrease in energy consumption and to increase in operational efficiency

The total energy consumption of the optimized drone structure was 134 W lower than the primary. The decrease in weight with the application of the topology optimization process, lowering the loads on the brushless motors. This enhancement extends the flying time of the system.

Furthermore, the lowered energy consumption of the optimized design suggests that it might be possible to operate with energy units with smaller battery modules without compromising operational time. It can also help to decrease the cost of the system. The power analysis results validated the effectiveness of topology optimization in enhancing energy efficiency and operational capacity, as the optimized design not only achieved a 41% weight reduction but also demonstrated a 20% decrease in energy consumption.

This study has yielded optimization studies that can serve as a model for designers and researchers, especially in the domain of drone design and development. A drone power analysis module has been designed to validate the design, analysis and optimization studies. A review of drone design and optimization studies in the literature was conducted, and these studies were found to be valuable in terms of design, analysis and optimization. However, it is imperative to investigate the lightweighting processes employed with optimization in terms of energy consumption efficiency. In this study, a user program and interface that can assist in drone energy efficiency verifications have been designed, and an attempt has been made to contribute to the existing literature in this manner.

IV. CONCLUSION

In this research, development, topology optimization and power analysis studies of the quadcopter type drone structure were carried out. All the parts, sub-assemblies and assembly model were created using CAD tools. The engineering analyses were applied not only to check the structural strength but also to confirm the feasibility of the topology optimization process. Once, the necessity of topology optimization was determined, the new structure with the optimized frame was constructed. Power analysis tool was designed and utilized for comparison of the energy efficiency and power requirements of primary and optimized structures dynamically. All these studies and results can be concluded:

a. The frame of drone the structure was lightened with an important ration of 41%
b. The new optimized frame was structurally strong enough with the factor of safety value of 6
c. The power requirement of the structure decreased 20%
d. The design of a useful power analysis tool has enabled researchers to validate their structural and topology optimization studies
e. The necessary hardware components, namely lipo battery, rgb camera, raspberry pi, motor drivers, flight and power distribution boards, were selected and integrated into the structure in a satisfactory manner
f. A quadcopter type drone structure with the features of less weight and improved energy efficiency compared to the primary structure was designed and developed

REFERENCES

[1] S. M. Islam, "Drones on the Rise: Exploring the Current and Future Potential of UAVs.", 2023.arXiv preprint arXiv:2304.13702.

[2] M. Kahveci, N. Can "İnsansiz Hava Araçlari: Tarihçesi, Tanimi, Dünyada Ve Türkiye'deki Yasal Durumu", Selçuk Üniversitesi Mühendislik, Bilim Ve Teknoloji Dergisi, 5(4),2017, 511-535.

[3] M. Hassanalian, A. Abdelkefi,, "Classifications, applications, and design challenges of drones: A review." Progress in Aerospace sciences, 2017, 91, 99-131.

[4] M. H., Sabour, P. Jafary, S. Nematiyan. "Applications and classifications of unmanned aerial vehicles: A literature review with focus on multi-rotors." The Aeronautical Journal 127.1309, 2023: 466-490.

[5] J. Qu, Y. Dong, X. Gu, S. He, "Integrated frame topology optimization design of small quadrotor uav." In *Journal of Physics: Conference Series* Vol. 2292, No. 1, p. 012016, 2022, IOP Publishing.

[6] H.S. Sucuoglu, I. Bogrekci, P. Demircioglu, O. Turhanlar, "Design & FEA and Multi Body System Analysis of Human Rescue Robot Arm", Advanced Mechatronics Solutions Springer International Publishing, 2016, pp. 651-656, 2020.

[7] N. Demir, H.S. Sucuoglu, I. Bogrekci, P. Demircioglu, "Topology optimization of mobile transportation robot", International Journal of 3D Printing Technologies and Digital Industry, 2021, 210-9.

[8] N. Demir, H.S. Sucuoglu, I. Bogrekci, P. Demircioglu, "Structural & dynamic analyses and simulation of mobile transportation robot", International Journal of 3D Printing Technologies and Digital Industry, 2021, 5(3):pp.587-595, 2021.

[9] H. S. Sucuoglu,"Development of a robotic system with hybrid locomotion for both indoor and outdoor fire detection operations", 2020.

[10] H. Yurdem, A. Degirmencioglu, E. Cakir, E. Gulsoylu, "Measurement of strains induced on a three-bottom moldboard plough under load and comparisons with finite element simulations, Measurement", 2019,pp.594-602.

[11] J. H. Zhu, W. H. Zhang, L. Xia, "Topology optimization in aircraft and aerospace structures design, Archives of computational methods in engineering", 2016,Vol. 23, pp. 595-622.

[12] L. A. Al-Haddad, A. A. Jaber, W. Giernacki, Z. H. Khan, K. M. Ali, M. A. Tawafik, A. J. Humaidi, "Quadcopter Unmanned Aerial Vehicle Structural Design Using an Integrated Approach of Topology Optimization and Additive Manufacturing",2024 Designs, 8(3), 58.

[13] M. P. Bendsøe, N. Kikuchi, " Generating optimal topologies in structural design using a homogenization method", Computer methods in applied mechanics and engineering, 1988,71(2), 197-224.

[14] A. M. Leon, A. N. Rukavitsyn, S. F. Jatsun, "Topology optimization of a UAV airframe", In 6 th International Conference on Industrial Engineering ICIE 2020,,2020, pp. 338-346.

[15] T. R. Costa,,M. P. Caldas, P. M. N. Araujo, E. C. Silva, "Topological Optimization applied towards the development of a small and lightweight MAV composite frame".

[16] S. Sreeramoju, M. S. Rao, "Design and Analysis of Quad Copter Chassis Using Shape Optimization Technique", International journal for research in applied science and engineering technology, 2023,11(3).

[17] S. H. Asif, K. Hasan, N. R. Dhar, "Topology optimization and 3D printing of a unibody quadcopter airframe", In IOP Conference Series: Materials Science and Engineering Vol. 1305, No. 1, p. 012021, 2024, IOP Publishing.

[18] K. M. Ali, M. A. Tawafik, A. A. Jaber, "Quadcopter topology optimization based on impact analysis", In AIP Conference Proceedings Vol. 2977, No. 1,2023, AIP Publishing.

[19] J. H. Zhu, W. H. Zhang, L. Xia, "Topology optimization in aircraft and aerospace structures design, Archives of computational methods in engineering", 2016,Vol. 23, pp. 595-622.

[20] F. M. Özkal, H. Uysal, "General Aspects of Evolutionary Structural Optimization: A Review", Pamukkale University Journal of Engineering Sciences, 2009, 15(3).

[21] A. Martinetti, M. Margaryan, L. Van Dongen, "Simulating mechanical stress on a micro Unmanned Aerial Vehicle (UAV) body frame for selecting maintenance actions", Procedia manufacturing, 2018, 16, 61-66.