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TOPOLOGICAL OPTIMIZATION AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES FOR DESIGNING DRONE STRUCTURES

Unmanned aerial vehicles (UAVs) have become an indispensable tool for solving a wide range of complex tasks. To improve and increase the efficiency of unmanned aerial vehicles, it is important to optimize their structural elements. Reducing weight and strategically distributing loads while maintaining structural strength and rigidity directly impacts flight endurance, stability, payload capacity, and overall airframe integrity. Integrating topological optimization with artificial intelligence enables the automated design of components tailored to specific operational requirements.

The application of an integrated approach to automate the design of small-type UAV structures and the combination of classical methods of topological optimization with artificial intelligence and additive manufacturing technologies were considered. A microdrone airframe, fabricated via 3D printing using carbon fiber-reinforced nylon (Nylon PA12 + CF15), was analyzed both before and after generative design optimization. The effectiveness of the optimization and the changes in the structure's rigidity and stability were assessed. Optimization resulted in an approximately 12% reduction in structural mass relative to the baseline model. Structural modeling and load simulations demonstrated that the maximum displacement of the optimized model does not exceed 3 mm, compared to 9 mm for the baseline structure. The results from virtual load simulations and physical testing of the printed models confirm that structural mass can be significantly reduced while preserving the integrity and core functional performance of the airframe. The study is based on simplified loading conditions and is limited to the number of experimental samples. Furthermore, dynamic and vibrational loads were not accounted for in the current study. Future research will focus on expanding the experimental framework and conducting an in-depth analysis of combined loading conditions that significantly affect the aerodynamic performance and real-world flight envelopes of drones.

Keywords: unmanned aerial vehicles, computer modelling, topological optimization, generative design, additive manufacturing technologies, 3D printing.

Introduction

The rapid advancement of unmanned aerial vehicle (UAV) technologies has fundamentally transformed their fields of application, ranging from environmental monitoring and cargo transportation to commercial and military operations. The development and fabrication of the first stable UAV prototypes were based on the trial-and-error approach [1], which required considerable time and additional financial resources. The methodology for designing aircraft of various types changed significantly in the mid-twentieth century with the introduction of electronic computing systems, theoretical foundations and fundamental methods of design and optimization, as well as computer-aided design (CAD) systems. These developments enabled engineers to create complex and accurate digital twins and subsequently apply the obtained results and methodologies for commercial purposes.

Analysis of Recent Research and Publications

Today, artificial intelligence (AI) technologies make it possible to achieve a new level of optimization for both individual structures and integrated systems [2]. Their widespread implementation, combined with additive manufacturing, is expected to facilitate the mass production of adaptive UAVs

whose characteristics can be modified directly at the deployment site without the need to redesign the entire system or prove large-scale manufacturing processes [3–6].

Machine learning (ML) enables systems to learn from large datasets and continuously improve their performance. Its application to the design and investigation of digital twins for aircraft has already become well established [7, 8]. Several studies have explored the possibility of using machine learning models, particularly artificial neural networks (ANNs), to predict structural and configuration changes in aircraft based on datasets containing the characteristics of selected experimental designs. During the design of the initial structure, a dataset is generated and subsequently used by the neural network to improve the performance characteristics of the original design [9, 10]. In addition, neural network-based systems are being developed that can analyse completed designs, identify errors, and provide recommendations during the design process for individual system components, including engines, wings, equipment mounts, stabilization systems, and overall control systems [1, 11–13].

Thus, most existing studies have been conducted for large-scale aircraft. However, the application of these technologies to small-class UAVs requires further investigation and comprehensive analysis, particularly in the areas of design optimization, structural analysis and modernization, as well as the evaluation and optimization of the performance of individual subsystems.

Purpose of the article

The main purpose of the study is to reduce the weight of the structure of a small-type UAV while maintaining the required strength and stiffness characteristics. To achieve this purpose, it is necessary to optimize the topology of the UAV frame while simultaneously ensuring the rational distribution of loads among the structural elements. The implementation and consideration of the specified parameters will contribute to improving the technical characteristics of the UAV, increasing energy efficiency, and expanding the possibilities of its application. The structure of the article reflects the stages of the conducted research: selection of the frame type, additive manufacturing in combination with generative design and comprehensive optimization methods (material selection, investigation of the original topology, optimization, investigation of the optimized topology), and comparison of the results.

Presentation of the main material

Selection of the frame type of a small-class UAV. The development of an intelligent algorithm for automating the process of generating the structure of a small-class UAV requires a comprehensive approach, which begins with the formation of a set of structural data in separate information databases. For this purpose, it is necessary to determine the types of drones and frames for conducting the research [14, 15].

Commercial drones, in particular quadcopters, dominate the market of small-class unmanned aerial vehicles. They employ four motors and the corresponding equipment for flight stabilization.

During the design of a quadcopter frame, lightweight but rigid structural elements capable of supporting the elements, components, and sensors required for the operation of the system are usually used (Fig. 1).



Fig. 1. Types of quadcopter frames: (a) Plus-shaped; (b) H-shaped; (c) X-shaped

The most common frame of this type of UAV is the X-shaped frame (Fig. 1, c) with motors located at the ends of the structural elements. At the same time, it is necessary to use specialized sensors, in particular, a gyroscope for analysing the position in space and controlling the individual motors, changing the speed and direction of rotor rotation. A frame of this type is easier to manufacture, but it requires additional equipment for controlling the aircraft as a whole [16, 17]. Its advantage is the possibility of easily adjusting the main characteristics, while its drawback is the mutual exclusion of manoeuvrability and flight stability. To achieve greater stability, it is necessary to sacrifice turning directions and the speed with which one or another direction of movement can be changed. Such a system is more suitable for economical drones intended for territory inspection using sensors or cameras and for planned movement along a predefined automated trajectory.

An analogue with some additional parameters is the Plus-type frame (Fig. 1, a). Here, the structural beams are positioned perpendicular to each other. This makes it possible to find a compromise between manoeuvrability and flight stability [18]. At the same time, the possibility of frame damage as a result of a collision increases, since most of the impact is absorbed by one of the structural members of the unmanned aerial vehicle. However, for economical drones, this is not of significant importance.

The structural members in the H-shaped frame (Fig. 1, b) are arranged parallel to each other and connected by a central member, which serves as the base for the electronics and sensors. This type of frame is used mainly in

specialized unmanned aerial vehicles. The H-shaped frame has greater strength and, in most cases, when a collision or accident occurs, the main impact is distributed to the overall structure or simultaneously to two structural members, which increases the stability of the system. Such a structure is rather bulky compared to other frame types; therefore, it is used mainly in cargo and specialized drones, for example, agricultural drones or delivery drones [19].

An equally important characteristic of the frame is its aerodynamics. Usually, small-class unmanned aerial vehicles have rather poor aerodynamic characteristics because their structure does not allow the system components to be enclosed beneath an aerodynamic fairing [20]. However, even with additional means in the form of separate aerodynamic fairings or structures for improving flight characteristics, individual sections of the quadcopter are subjected to high air resistance. The aerodynamic drag force is described by the following formula:

$$F_d = \frac{1}{2} C_d \rho A v^2 \quad (1)$$

where C_d is the drag coefficient of the shape, which depends on the selected frame type; A is the effective surface area perpendicular to the flow; ρ is the air density ($\sim 1.22 \text{ kg/m}^3$); v is the air flow velocity relative to the component.

Based on Eq. (1), a basic analysis of different frame types can be performed, and the optimal type can be selected for further generation and optimization. Table 1 presents the drag characteristics for individual frame types.

Table 1

Description of technical characteristics for individual frame types

Frame type	Shape description	Drag coefficient, C_d	Aerodynamic features	Total drag force at an air flow velocity of 15 m/s
X-shaped	Classical cross-shaped form	0.8–1.1	Moderate drag, a balance between stability and manoeuvrability	2.5–3.2
Plus shaped	Structural members arranged perpendicular to each other	1–1.2	Significant frontal drag due to the interaction of the front structural member with the air	3.2–3.5
H-shaped	Structural members arranged parallel to each other	0.9–1.1	High stability, but vortices occur between the beams during high-speed flight	3.6–4.2

Considering the presented data, it can be concluded that the X-shaped structure has the best technical characteristics for a small- and medium-class quadcopter (Fig. 2). This type of frame makes it possible to simplify the execution of individual manoeuvres and the overall control of the vehicle, which expands its application in the most common types of quadcopters today – FPV (first person view) drones [21].

Usually, they are manufactured in large quantities using subtractive technologies, that is, by removing material from a workpiece or cutting a finished frame from a sheet of material. However, additive technologies are becoming increasingly widespread, as they make it possible to manufacture the required frame directly at the place of drone operation without the need to order it from a manufacturer [22]. This contributes to its rapid adaptation to the required set of components and sensors, as well as the correction of structural errors without the need for modification of large batches of ordered frames from the manufacturer [23].

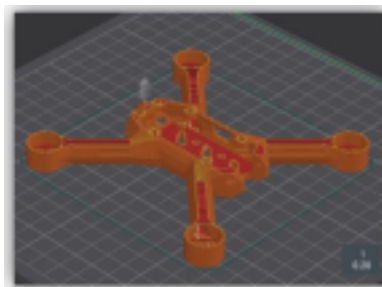


Fig. 2. Example of a UAV frame

Additive manufacturing combined with generative design and comprehensive optimization methods. An available method for creating lightweight structures is additive manufacturing or 3D printing. The FDM (Fused Deposition Modelling) technology of layer-by-layer deposition of specialized filament is the most common and cost-effective method for manufacturing complex components. To create a physical UAV prototype, nylon (Nylon PA12) with carbon fiber elements (CF15) was selected. The main material characteristics are presented in Table 2.

Table 2

Comparison of the characteristics of pure nylon (Nylon PA12)
and nylon with carbon fiber (Nylon PA12 + CF15)

Parameter	Nylon PA12	Nylon PA12 + CF15
Printing temperature, °C	255–270 °C	260–280 °C
Bed temperature, °C	~100 °C	50–70 °C
Shrinkage after cooling	1–5%	1–2%
Elastic modulus, σ_t	~1400 MPa	~7500 MPa
Compressive strength limit, σ_c	40–55 MPa	70–110 MPa
Elongation at break, %	50%	2–5%

The melting temperature of this filament is within the range available for commonly used 3D printers. Its advantages include low weight, high stiffness, and printing stability (provided that the printing technology requirements are followed). However, printing with this material requires additional modifications, in particular, a hardened steel nozzle and the installation of an all-metal heat break. Due to its hygroscopic properties, the use of a drying chamber with filament drying systems is required since the presence of moisture significantly deteriorates its characteristics. The UAV frame prototype (Fig. 3) was manufactured using a widely available 3D printer model – Ender V3 Se.

The investigation of the frame prototype will make it possible to practically evaluate the optimality of the selected settings and confirm the possibility of printing optimized models under the specified technological process parameters.



Fig. 3. UAV frame manufactured by 3D printing

At the next stage, a computer model was developed, and the material properties were investigated using load simulation methods. For design and computer simulation, the CAD (Computer-Aided Design) system Autodesk Fusion 360 was used. The system provides tools for fine adjustment of the final model topology. The load simulation was performed using the FreeCAD and Gmsh software packages. During UAV operation, bending loads caused by the weight and thrust of the motors are predominant. At the same time, under certain conditions and with additional loading, the motor thrust is not uniform, while the UAV power source creates an additional uniaxial load on the frame. For simulation purposes, the basic force parameters were applied to the front part of the quadcopter, and four constraint points were defined at the mounts of the rear motors (Fig. 4).

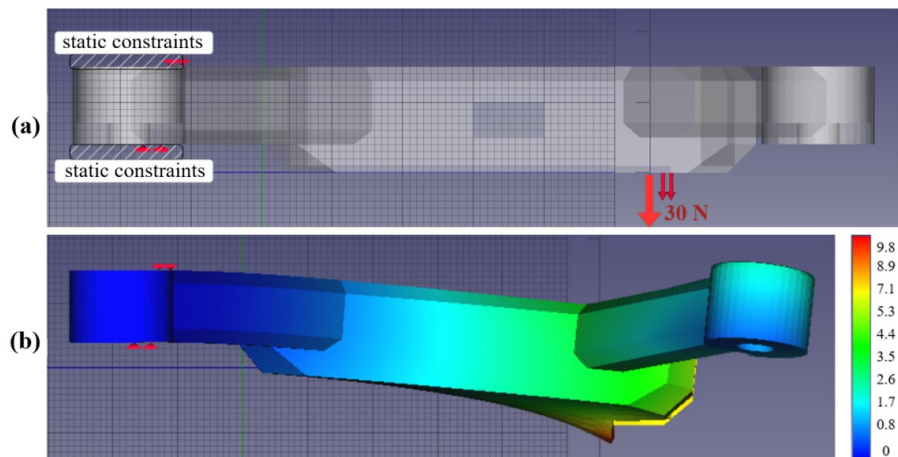


Fig. 4. Computer simulation of bending load of the UAV frame: a) load scheme; b) simulation results presented as displacement of the initial topology under load (wall thickness 4 mm; displacement diagram legend in mm)

According to the simulation results, the maximum displacement under a load of 30 N does not exceed 10 mm. Therefore, Nylon PA12 + CF15, according to its technical characteristics, meets the requirements for a UAV structural material and can serve as a basis for further modelling and topology optimization (generative design) of the aircraft frame.

The optimization of the frame consists of basic settings and several implementation steps. The first step before starting the generation process is to specify the preservation regions, i.e., areas that will be maximally restricted from optimization to maintain structural integrity and ensure the possibility of installing quadcopter components. These regions are usually divided into several groups, including mounting holes for cameras and motors, as well as through-holes for attaching additional components required for system operation. The next stage required for configuring generative design is the creation of loads acting on the frame structure. For this purpose, it is necessary to define the exact loads and forces that will affect the UAV during operation. It is also necessary to consider the safety factor - the minimum distance, wall thickness, or thickness of individual system elements after which optimization is stopped within the selected area (Fig. 5). Increasing the safety factor reduces the optimization threshold but increases the structural integrity. In this study, a safety factor of 2 was selected, as it is considered optimal for a quadcopter manufactured using 3D printing technology.

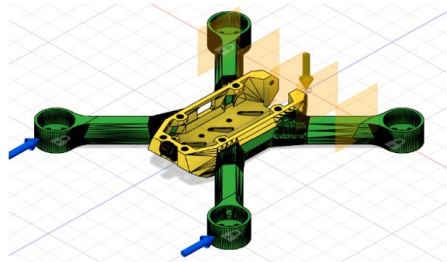


Fig. 5. Creation of zones for limiting generative design

In addition to classical optimization, an approach combining generative design and topology analysis with machine learning methods was applied [24]. Generative design, which is based on artificial intelligence technologies, uses new geometric shapes of the body based on specified input parameters, such as minimum mass, maximum stiffness, or allowable stresses. In such a system, optimization is modelled as the search for optimal parameters of the objective function:

$$\min_x = w_1 M(x) + w_2 D(x), \quad (2)$$

where $M(x)$ is the mass of the structure; $D(x)$ is the maximum deformation; w_1 , w_2 are weighting coefficients that characterize the importance of each criterion.

The use of neural networks in combination with genetic algorithms makes it possible to automate the process of selecting the best parameters of the objective function (2), and consequently, the structure itself. In this case, the neural network is trained on a given dataset containing information about geometry, loads, and boundary conditions, as well as the results of previous simulations. The optimal generative design results (Fig. 6) must be converted into a specialized topology, which will then be used for bending load simulation.



Fig. 6. Result of body geometry optimization

Research results discussion

After generating the optimal result, the previous model based on the optimized variant was simplified and converted into a format required for investigation using load simulation. To verify the simulation results, two physical samples were manufactured (Fig. 7). Comparison of their physical parameters, in particular weight, showed that the optimized model is approximately 12% lighter compared to the initial structure. The original model weighs approximately 25 g, while the weight of the optimized version does not exceed 20 g.

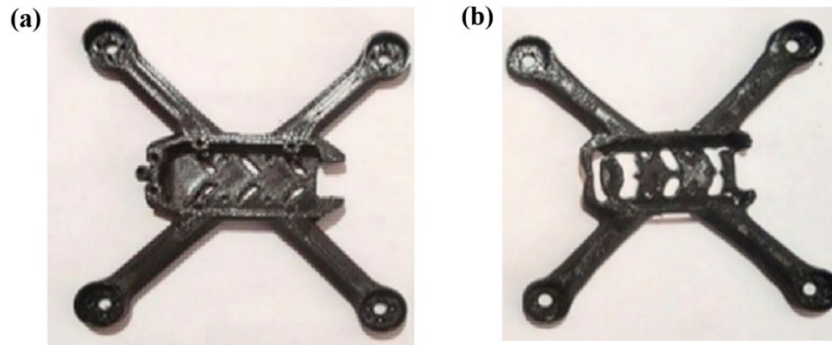


Fig. 7. Body models manufactured using additive technologies: original (a) and optimized (b) bodies

To evaluate the technical characteristics of the optimized structure, a load simulation was also performed with parameters analogous to those used for the load simulation of the original body (Fig. 8). The obtained results make it possible to compare the degree of displacement of the optimized geometry under the same load level, which characterizes the influence of topology optimization on the stiffness and stability of the structure. To verify the optimality of the generated model, the displacements obtained during experimental tests were compared (Fig. 9). The comparison diagram reflects the dependence of structural displacement on the applied load and makes it possible to evaluate the effectiveness of the optimization and the reliability of the behaviour of the optimized structure.

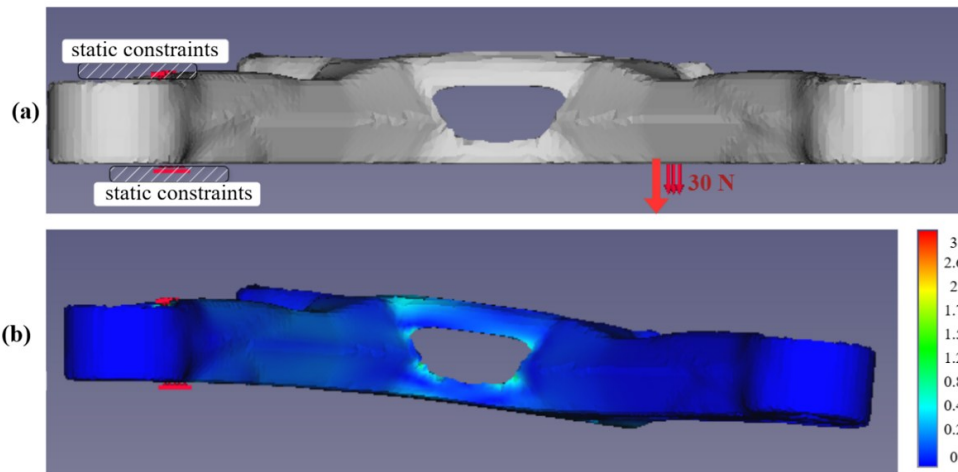


Fig. 8. Computer simulation of bending load of the optimized UAV body: a) load scheme; b) simulation results in the form of displacement of the initial topology under the action of load (wall thickness 4 mm; displacement diagram legend in mm)

The displacement graph in Fig. 9 represents the level of structural deformation. As the distance from the point of maximum load application increases, the displacement and deformation of the body structure decrease. The deformation of the optimized model has an almost linear character, indicating an even distribution of the load across the entire body, and therefore the maximum deformation distance is reduced and does not exceed 3 mm. The original model is characterized by nonlinear displacement, which indicates a less uniform load distribution and a greater deviation at the point of direct loading, amounting to approximately 9 mm.

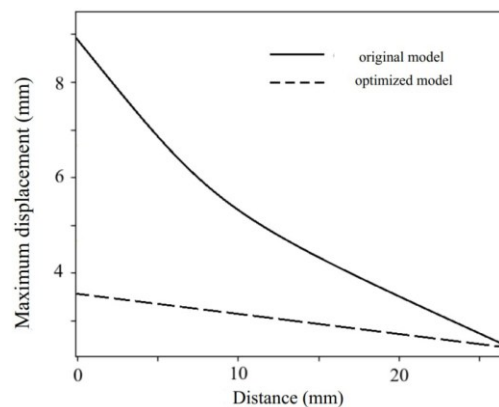


Fig. 9. Maximum displacement obtained during experimental tests for two models

Conclusions

The obtained results make it possible to quantitatively evaluate the effectiveness of the performed optimization and its impact on the stiffness and stability of the structure. The weight of the final structure was reduced by approximately 12% compared to the initial model. Modelling and load simulation showed that the maximum displacement of the optimized model does not exceed 3 mm, while for the original structure it is approximately 9 mm. The optimization of the body improved load distribution and increased the overall stiffness of the structure.

The performed study is based on simplified loading conditions and is limited by the number of experimental samples. In addition, the influence of dynamic and vibration loads on the aircraft was not considered. Further research will be aimed at expanding the experimental base and conducting an in-depth analysis of possible types of loads that significantly affect the aerodynamic parameters and actual flight modes of UAVs.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

Conceptualization, O.S.; methodology, O.S.; validation, N.M.; formal analysis, O.S.; investigation, N.M.; writing-original draft preparation, N.M.; writing-review and editing, O.S.; visualization, N.M.; supervision, O.S. All authors have read and agreed to the published version of the manuscript.

DECLARATION ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

In preparing this work, the authors used Grammarly for grammar and spelling checks. After using these tools/services, the authors reviewed and edited the text and took full responsibility for the content of this publication.

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ТОПОЛОГІЧНА ОПТИМІЗАЦІЯ ТА ТЕХНОЛОГІЇ ШТУЧНОГО ІНТЕЛЕКТУ ДЛЯ ПРОЄКТУВАННЯ КОНСТРУКЦІЙ ДРОНІВ

Безпілотні літальні апарати (БПЛА) стали незамінним інструментом для вирішення широкого кола складних завдань. Для поліпшення та підвищення ефективності БПЛА важливо оптимізувати їхні конструктивні елементи. Зменшення ваги та стратегічний розподіл навантажень за збереження при цьому міцності і жорсткості конструкції безпосередньо впливають на тривалість польоту, стійкість, вантажопідйомність і загальну цілісність планера. Інтеграція топологічної оптимізації зі штучним інтелектом дає змогу автоматизувати проектування компонентів, адаптованих до конкретних експлуатаційних вимог.

Розглянуто застосування комплексного підходу до автоматизації проектування конструкцій малогабаритних БПЛА шляхом поєднання класичних методів топологічної оптимізації зі штучним інтелектом і технологіями адитивного виробництва. Планер мікродрона, виготовлений за допомогою 3D-друку з використанням нейлону, армованого вуглецевим волокном (Nylon PA12 + CF15), проаналізовано як до, так і після оптимізації генеративного проектування. Оцінено ефективність оптимізації та зміни жорсткості і стійкості конструкції. Оптимізація призвела до зменшення конструктивної маси приблизно на 12% порівняно з базовою моделлю. Структурне моделювання та симуляції навантаження показали, що максимальне переміщення оптимізованої моделі не перевищує 3 мм, порівняно з 9 мм для базової конструкції. Результати віртуального моделювання навантаження та фізичних випробувань друкованих моделей підтверджують, що структурну масу можна значно зменшити, зберігаючи при цьому цілісність і основні функціональні характеристики планера. Дослідження базується на спрощених умовах навантаження та обмежене кількістю експериментальних зразків. Тут не вивчали динамічні та вібраційні навантаження. Подальші дослідження будуть зосереджені на розширенні експериментальної бази та проведенні поглибленого аналізу комбінованих умов навантаження, які суттєво впливають на аеродинамічні характеристики та реальні діапазони польоту дронів.

Ключові слова: безпілотні літальні апарати, комп'ютерне моделювання, топологічна оптимізація, генеративний дизайн, адитивні технології виробництва, 3D-друк.