UAV Airframe Topology Optimization

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Topology optimization of a UAV airframe

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Abstract The development of advanced UAV airframes is currently one of the challenges for the aeronautical industry. An accurate mechanical-structural design analysis provides optimal design solutions. A structural optimization process includes the selection of geometry via topological optimization, the selection of materials by finite elements method and the study of the processes related to the main structures of an UAV. A robust and lightweight UAV airframe allows to increase the flight time and the carrying capacity of the system. This paper deals with the topology optimization of an airframe for an unnamed aerial vehicle (UAV) type quadcopter. The material selection process of the UAV airframe has been achieved through CES Edupack database, taking into account the function, objectives, constraints, free variables and other considerations during the process of structural optimization. The structural-mechanical optimization of the UAV airframe has been performed using a generative design algorithm through SolidWorks topology optimization method. Also, an estimation of the carrying capacity of the UAV airframe has been realized analytically.

Keywords Topology optimization, UAV design, Generative design, Structural design, CAD design.

1. Introduction

Nowadays, the study of small-sized unmanned vehicle systems (UAVs) is fundamental to ensure optimal results and reduce human risks, looking for efficiency, control and maneuverability. UAV systems represent a suitable alternative for monitoring, ground mapping, agricultural and environmental preservation practices, fire detection, transmission power line infrared supervision, etc. [1-3]. The use of modern manufacturing capabilities and element base, the availability of new composite materials led to production of aerial vehicles with lightweight and robust frames, the development of micro-electronic components, such as microcontrollers, sensors, receivers, drivers, miniature-type cameras, etc. helped to create high-precision navigating and flight stabilization systems for aerial vehicles, as well as digital data transmission over long distances [4-6].

There is an important field related to the mechanical-structural design of small-sized UAV systems, the main goal of which is to implement a fast and accurate design analysis tools to find optimal design solutions, including complex knowledge from different disciplines. Thus, for optimal design results of UAVs it is fundamental to go through a process of iterations related to three main aspects: the selection of geometry via topological optimization, the selection of materials by finite elements method and the study of the processes related to the main structures of the drone [7-9].

2. Statement of the problem

Currently, there is a large number of UAV systems, however it has not been possible to improve their flight time and carrying capacity. Since to increase the flight time it is necessary to increase its power source and this generates the increase of the weight of the UAV, and therefore its carry capacity decreases. This study is focused on the development of a lightweight and robust UAV airframe using topology optimization concept based on a generative algorithm [9-11]. According to the outlined objectives, some guidelines have been observed: reviewing the previous related articles/works and performing a topology optimization by several existing methods based on UAV mechanical-structural analysis design concept [9, 11-13]. In this paper the selected optimization process consists of three aspects: the selection of geometry via topological optimization, the selection of materials and the processes related to the analysis by finite elements method for validating the results. [9, 14]. This paper is organized as follows: Section 3 presents a description of the material selection process using the software CES Edupack [15]; Section 4 presents the topology optimization process using a generative algorithm of Solidworks; Section 5 presents a study of the efficiency of the designed UAV airframe; Section 5 concludes this purpose, such as some notes about further work.

3. UAV airframe material selection process

The design and construction of any UAV airframe is driven by consideration of a range of failure modes, such as elastic deformation, yielding, buckling, fracture, fatigue, corrosion, etc. The airframe of the UAV must be lightweight but strong to withstand all forces acting on it, however its cost should be reasonable. The material selection process for a UAV airframe involves attempt to find the best match between the property profiles of the materials required by the design [15]. In accordance with high design requirements to the modern UAV systems, composite materials especially polymer matrix composites reinforced with continues fibers are the most suitable choice [16]. In this paper we considered the use of the software CES Edupack as tool for material selection process of the UAV airframe [15, 17]. This software makes possible to find out the best material for any project taking into account four main boundary conditions: function, objectives, constraints, free variables, the main propose of which is to optimize the material performance index. The performance *P* of a component/structure can be expressed as follows:

$$P = f\,(F,G.M) = f1(F)\cdot f2(G)\cdot f3(M) \tag{1}$$

where F – functional requirements, G – geometry, M – material properties

The performance is optimized by maximizing *f3(M)* and is called performance index *M*. Hence, the performance index is a combination of materials properties that characterize the performance of a material in a given application [15].

In this study we will consider the following boundary conditions (see Table 1) based on the material selection algorithm used in the CES Edupack program with a general level 3 database, which contains around 3900 materials for selection, as shown in Figure. 1.

Table 1. Boundary conditions for the UAV airframe material selection process

Boundary conditions	**Description**
Function	UAV support module, high resistance to deformation and dampening impact on take-off and landing.
Constraint	Resistance to bending, buckling, dampening impact
Objective	Minimum weight, maximum strength
Free variable	Material, area and shape
Other considerations	Simple construction, workplace temperature +/- 40ºC, low dilation coefficient to avoid thermal deformations, reasonable manufacturing cost

Our study is divided into 4 stages. In the first stage of our study, taking into account the area and geometry of the airframe as free variables and the length of the construction as constant variable, and also the stiffness as constraint, and weight as constraints, it is necessary to minimize the performance index as follows:

$$M_1 = \rho/(\gamma/E) \tag{2}$$

where, ρ – density [kg/m^3], γ – shape factor, *E* – Young modulus [GPa]

In the second stage of our study, taking into account the same free and constant variables, and the strength to compression as constraint, it is necessary to minimize the performance index as follows:

$$M_2=\rho/(\gamma^{1/2}/\sigma_c) \tag{3}$$

where, ρ – density [kg/m3], γ – shape factor, σ_c – compression strength [GPa]

In the third stage of our study, taking into account the same free and constant variables, and the resistance to buckling as constraint, it is necessary to minimize the performance index as follows:

$$M_3=\rho/(\gamma/E)^{1/2} \tag{4}$$

where, ρ – density [kg/m^3], γ – shape factor, E – Young modulus [GPa]

In the fourth stage of our study, taking into account the same free and constant variables, and the yield strength as constraint, it is necessary to minimize the performance index as follows:

$$M_4=\rho/(\gamma^{1/2}/\sigma_y)^{2/3} \tag{5}$$

where, ρ – density [kg/m^3], γ – shape factor, σ_y – yield strength [MPa]

Then, the first results obtained from the CES Edupack database about the most suitable materials for a UAV airframe are represented on the logarithmic scale as shown in Figure 1.

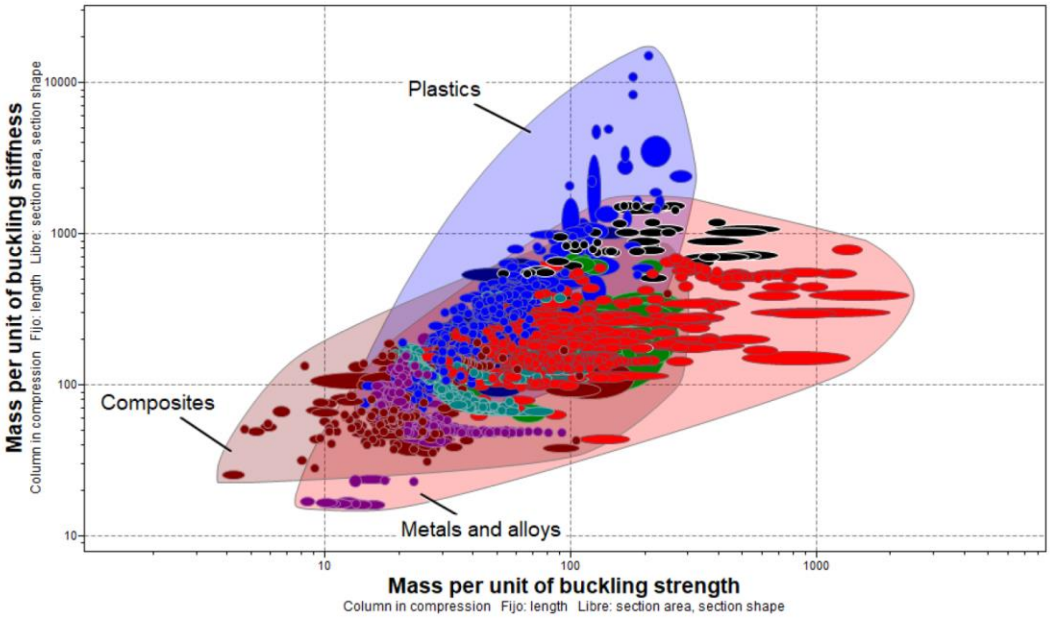

Fig. 1. Suitable materials for a UAV airframe

Thus, composites, plastics, metals and alloys families of materials are shown as a suitable option for the selection of materials for a UAV airframe. According to the results, the list of possible materials for our UAV airframe has been reduced and it consists of 328 materials. One of the main goals of our study is to reduce the weight of the construction, the further filtering work will be driven to the study of suitable composite materials.

Then, our filtering work will be focused on some considerations like the workplace temperature, the geometry of the UAV airframe and the manufacturing process (filament winding) [18]. With the use of the established filters, the list of possible materials for the UAV airframe is reduced to 10 elements.

According to the obtained results from CES Edupack database, the characteristics for the development of a lightweight and robust UAV airframe will be the following: tubular profile with constant circular section along the length of the profile made of composite material epoxy resin thermoset polymeric matrix with a pre-impregned aramid fiber reinforcement by filament winding procedure. The main properties of the selected material are shown in Table 2.

Table 2. Main properties of the selected material for the UAV airframe design

Property	Value
Density	1380 kg/m^3
Young modulus	60 GPa
Poissons ratio	0,34
Compressive strength	234 MPa

4. UAV airframe topology optimization

The design of the 3D model of the UAV airframe was carried out using the software SolidWorks with the help of topology optimizations tools based on a generative design algorithm. During the design process all the geometric characteristics, shape and dimensions, selected material, etc. were taken into account with the aim to reduce the mass and increase the stiffness and strength of the designed airframe.

Since the geometry of the UAV airframe is symmetric, a solid cube (540x540x90 mm) is considered for the initial design. A slot is provided for mounting electronic devices and batteries and four slots are provided for the motors (see Fig. 2a). Then using the SolidWorks topology optimization tool, it becomes possible to get a first approximation of the optimal design of the UAV airframe based on the selected contact points on the solid cube (see Fig. 2b). In our study we apply a force of 30 N to each slot provided for the motors and a fix the central slot provided for mounting all the electronic devices and batteries. After some iterations we obtain the optimized UAV airframe, which in terms of weight and strength by the use of a generative algorithm with elements of intellectual design its possible to obtain.

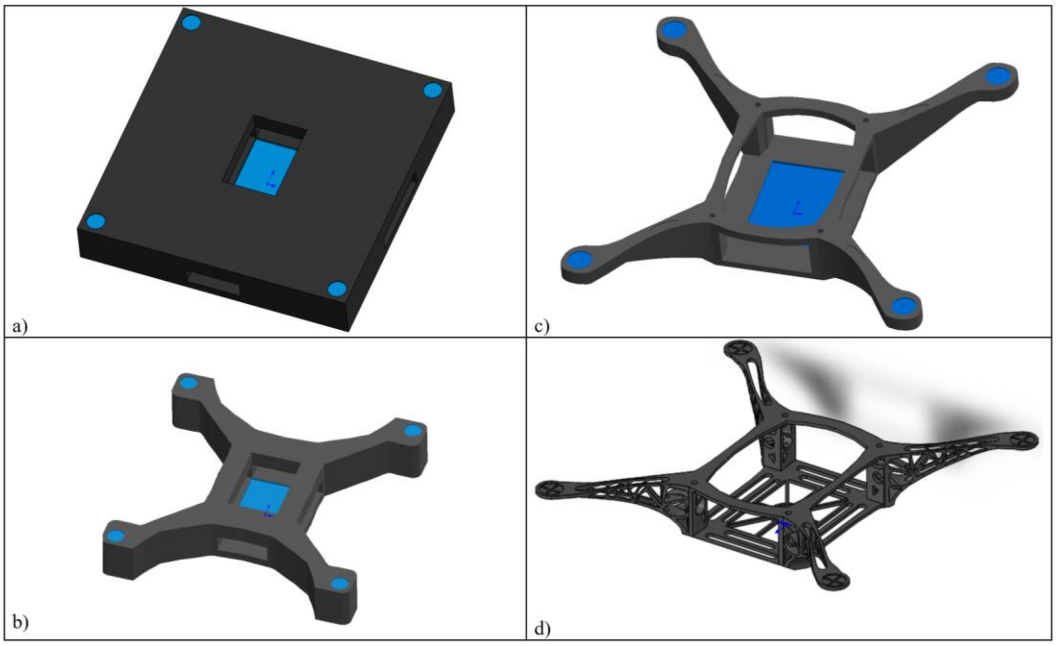

Fig. 2. Topology optimization SoildWorks: (a) initial design; (b) 2nd iteration; (c) 3th iteration; (d) optimized UAV airframe

With the aim to validate the optimized obtained conception of the UAV airframe through topology analysis of SolidWorks a finite element analysis has been performed to ensure that stress, deformation, displacement and safety coefficient of the construction are withing acceptable limits. The analysis is carried out with the same load and boundary conditions used during the optimization process. (see Fig. 3).

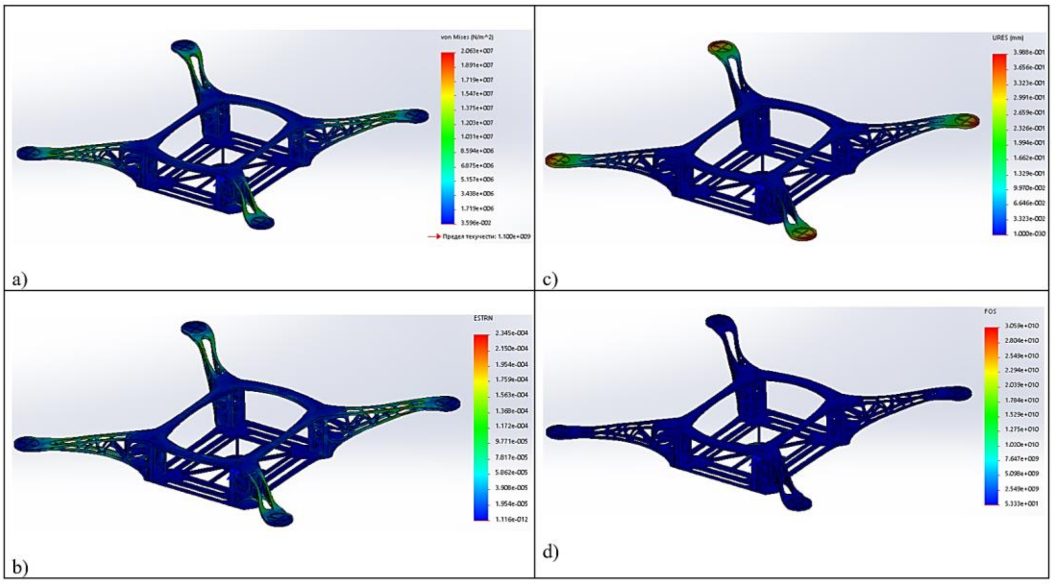

Fig. 3. Finite element analysis: (a) Von-Misses stress; (b) maximum deformation; (c) displacement; (d) safety coefficient

Based on the results obtained by finite element analysis, it becomes possible to evaluate the main characteristics of the optimized UAV airframe (see Table 3). The optimized UAV airframe has a final weight of 0.4 kg and has a safety coefficient equivalent to 53. Thus, it is possible to assume that this UAV airframe is capable of bearing an equivalent weight of up to 21,2 kg.

Table 3. Finite element analysis results

Analysis	Value
Maximum stress	20, 63 MPa
Maximum deformation	0,235 mm
Maximum displacement	0,38 mm
Safety coefficient	53

5. Carrying capacity estimation

After the topology optimization of the UAV airframe has been carried out, it is necessary to consider the whole element base of every UAV system, such as its electromechanical and electronic devices, batteries, and also its payload capacity, taking into account the objectives of the task, which the drone is developed for.

For an electrically powered UAV system the concept of total weight W_{total} may be written as follows [19, 20]:

$$W_{total}=W_{airframe}+W_{batteries}+W_{motors}+W_{sensors}+W_{payload} \quad (6)$$

where, $W_{airframe}$ – airframe weight, $W_{batteries}$ – batteries weight, W_{motors} – motors weight, $W_{sensors}$ – sensors weight, $W_{payload}$ – payload weight.

One of the important parameters to take into account is the relationship between the payload weight $W_{payload}$ and W_{total}. According to the reviewed literature and related works [11,12-15] this relationship it is possible to estimate as follows:

$$W_{payload}=0.4 \cdot W_{total} \quad (7)$$

where, $W_{payload}$ – payload weight, W_{total} – UAV total weight.

Also, a relationship between $W_{airframe}$ and W_{total} has been stablished [11,12-15], and it can be estimated using the following formula:

$$W_{airframe}=0.466 \cdot W_{total}^{-0.22} \tag{8}$$

where, $W_{airframe}$ – airframe weight, W_{total} – UAV total weight.

Then, it becomes possible to estimate the carry capacity of the UAV using the following expression:

$$W_{carry}=\frac{W_{payload}}{W_{total}} \tag{9}$$

where, W_{carry} – carrying capacity, W_{total} – UAV total weight, $W_{payload}$ – payload weight

For modelling the behavior of the expressed relationships in (8) and (9) we have considered different UAV systems with a rate of total weight equivalent to 0.5 – 10 kg. (see Figs.4-5).

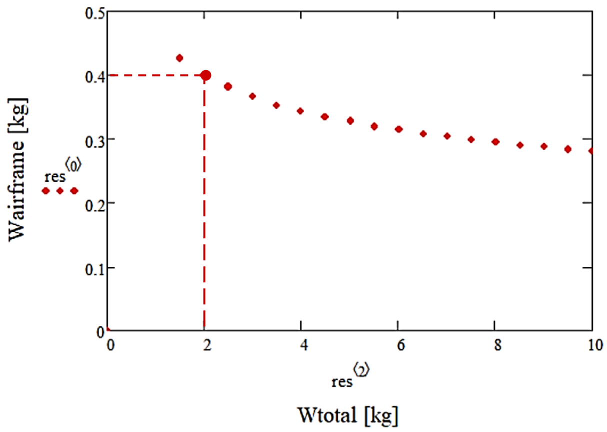

Fig. 7. UAV airframe weight characteristics against total weight

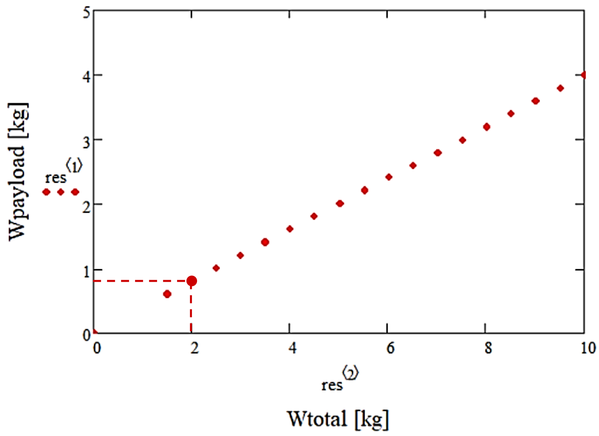

Fig. 8. UAV payload characteristics against total weight

Hence, taking into account the obtained results from the topological optimization process, and after the analytical modelling process for the estimation of the carrying capacity of the UAV, the desired total weight of the UAV type quadcopter should be 2 kilograms for an optimal performance, taking into account the electromechanical and electronical devices, etc., as part of the devices located onboard.

According to the carrying capacity characteristics of the developed UAV airframe against the total weight of the construction has a linear incrementing behavior. Since the optimal weight of the UAV airframe makes up 0.4 kg, the carrying capacity of the developed quadcopter is equal to 0.9 kg.

6. Conclusions

In this paper a topology optimization of an airframe four an unmanned aerial vehicle UAV type quadcopter has been carried out. The material selection process of the UAV airframe has been achieved through CES Edupack database, taking into account the function, objectives, constraints, free variables and other considerations. The structural-mechanical optimization of the UAV airframe has been performed using a generative design algorithm through SolidWorks topology optimization method. As result of the topology optimization has been obtained a robust and lightweight UAV airframe. Also, the designed UAV airframe has been tested through SolidWorks a finite element analysis tools to ensure that the construction has a good behavior to resistance to elastic deformation, yielding, buckling, fracture, fatigue, etc. Also, an estimation of the carrying capacity of the UAV airframe has been realized analytically, as result of this study the developed UAV airframe is capable to carry at least 0.9 kg. Further, will be calculated and optimized the relationships between the total weight of the construction and the electromechanical and electronical devices located on board the UAV for the selection process of the device element base to obtain better results in terms of carrying and flight time capabilities, etc.

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