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Topological Optimization applied towards the development of a small and lightweight MAV composite frame

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ABSTRACT

This paper proposes the design and manufacturing process of a lightweight MAV composite frame with high structural efficiency, applying the topology optimization by minimizing the structure compliance. The study presents a real MAV frame, designed to the 2018 IMAV indoor competition. Structural optimization is a frequently used discipline in aerospace applications, and the topology optimization is its the most recent branch, that is used to obtain the optimal material distribution in a predefined domain. The utilized formulation tries to maximize the stiffness of the MAV composite frame, with stress constraints, in order to achieve high payload-to-empty-weight ratio, and energetic efficiency improving the vehicle autonomy.

1 INTRODUCTION

Several international market researches are forecasting a huge grown of the drone market in the next decade, since drones are demonstrating to be extremely useful to many agricultural, commercial, military and industrial applications. The study of unmanned vehicle systems is fundamental to ensure optimal results and reduce human risks, looking for greater efficiency, control and maneuverability.

In the context of the development of UAVs, there is a gradual growth of the research areas related to the mechanical-structural development of a multi-rotor drone frame. In that way, using a topological optimization method on the center plate of a MAV is of main importance, as structural and energetic efficiency are main goals for the development of an indoor competition for MAVs. This method is widely used in aeronautics, and the objectives sought are similar: the balance between stiffness and structural weight. Thus, the context of the structural efficiency, 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.

The development and application of the methods explained here are centered on the participation of the AeroRio UAV Design team in the International competition of International Micro Air Vehicles (IMAV) 2018. This competition aims to develop autonomous drones capable of performing a series of tasks involving both intelligence and the *de facto* structure of the drone. Thus, due to the restrictions involving the tasks and the scores of the competition, the maximum dimensions of the frame were estimated, which would allow the execution of the tasks. The developed MAVs need to be optimized for structural efficiency taking into account static and modal analysis for optimized structure validation.

The flight score of the IMAV 2018 indoor competition is directly affected by two multiplier factors, the Mass factor (M) and Power factor (W). The Mass factor increases as the MAV mass decreases, and the power factor increases by reducing the power capacity of the batteries, challenging teams to seek for structural and energy efficiency. In order to allow the developed MAV to navigate autonomously by the indoor course, proper embedded electronics (sensors, cameras, flight controllers, computer modules, etc) should be selected, aiming at weight and power consumption minimization. Besides, the propulsion system (motors and propellers) should be as efficient and lightweight as possible.

Regarding energy efficiency, must be said that by having a defined motor-propeller system, it is necessary that the frame has a high structural efficiency for the least power consumption of the motors for the displacement of the drone. It should be noted that by increasing the overall weight of the frame structure, the capacity of the batteries should be increased as well, since the motors will be operating under more extreme conditions. Thus, in developing a light and rigid structure, it is possible to obtain lower power consumption, as well as improvements in control and dynamics of the drone, considering the defined motor-propeller system.

The design of the frame contributes to the development of a small, lightweight and low power MAV. However, reducing the weight of the frame might lead to a reduction of its stiff-

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ness, since there is a trade-off between stiffness and weight. The development of the drone frame follows the composite material selection and configuration, considering materials such as carbon fiber, plywood and Polylactic Acid (PLA). The maximum dimensions of the frame were estimated based on restrictions involving the tasks and the scores of the competition, aiming to ensure that it would be capable to execute all course elements.

In this paper, the adopted formulation for topology optimization seeks stiffness maximization by minimizing the structure compliance, for a given amount of material, in order to obtain a small and lightweight composite frame with high structural efficiency, providing improved control and stability. The developed MAV was optimized for structural efficiency, taking into account static and modal analysis for structural validation. The manufacturing procedure of the optimal structure will be also presented and discussed.

2 CONFIGURATION OF THE MAV

The indoor competition of IMAV 2018 highlights three main tasks which the drone must perform during the course: crossing windows of defined dimensions, crossing a maze of cylindrical obstacles and crossing hoops of restricted dimensions as well. Dimensional constraints are mainly generated by the smallest hoop present in the IMAV circuit, where it measures around 36 x 40 cm, so the MAV should have dimensions smaller than those. In addition, the MAV must be compact enough to accommodate the electronic and transmission system for carrying out the mentioned tasks. In this way, the MAV is restricted to lateral dimensions of less than 33 cm, as a safety factor. Thus, certain parameters must be chosen for the good performance of the drone. Among them, the configuration of the motor-propulsion system. Thus, after a series of tests the E-MAX MT1806 motor was chosen, since its mechanical dimensions were appropriate, besides allowing good possible thrust for the drone. The selection of the propeller was also restricted by the smaller hoop size, in which two were the most feasible to use, the 5” of diameter and the 6 ”. Thus, static thrust tests were performed to measure the effective thrust of the drone with the chosen motor-propulsion system. Thus, a maximum thrust of 270 g was obtained with the E-MAX MT1806 motor and the 5 ” three blade propeller.

The MAV must be capable of carrying a battery that provides enough power to the motors and sufficient current for the electronic image processing and control system. Thus, taking into account the choice of the propulsion system, a 2S of 5200 mAh was chosen, allowing around 300 g of thrust. Thus, it should be noted that stiffness involves both the manufacture of a frame that is bending moments resistant and having the first high frequency modes, away from the approximately 150 Hz generated by the motors. The bending strength is fundamental to allow higher efficiency of the motors, as these will lose less power for the deformation of the frame.

3 OPTIMIZATION

The Topology Optimization Method have been widely employed for sizing and shape optimization of aerospace structures [1], since it can adapt the structural configuration for its restrictions by redistributing the material layout and accordingly the load carrying paths. This technique has been developed since the Bendsøe and Kikuchi [2], specially for least-weight and performance design.

For this project, in order to achieve high payload-to-empty-weight ratio, a 2D frame with fixed thickness was optimized utilizing the Topology optimization tool in ANSYS Mechanical, in order to minimize the structure compliance. The compliance basic formulation is presented on the following equation (1) based on [3], which maximize the stiffness of the MAV frame.

$$\left\{\begin{array}{rl}\min\limits_{x}: & c(x) = U^T K U = \sum_{e=1}^{N} (x_e)^p u_e^T k_0 u_e \\ \text{subject to}: & \frac{V(x)}{V_0} = f \\ : & KU = F \\ : & 0 < x_{min} \leq x \leq 1 \end{array}\right. \tag{1}$$

From the equations we have that, **F** and **U** are respectively the global force and displacement vectors, **K** is the global stiffness matrix, u_e and k_e are the element displacement vector and stiffness matrix, respectively, **x** is the vector of design variables, $x_m in$ is a vector of minimum relative densities (non-zero to avoid singularity). Also, **p** is the penalization power, $V(x)$ and V_0 is the material volume and design domain volume, respectively and **f** is the prescribed volume fraction.

The initial domain dimensions of the frame and the position of the motors were defined respectively by the smallest hoop present in the IMAV circuit, and the propeller size required for the desired thrust. In order to optimize the computational effort, forces and moments were applied to half frame due to symmetry, as shown in Figure 1 where the free body diagram is presented.

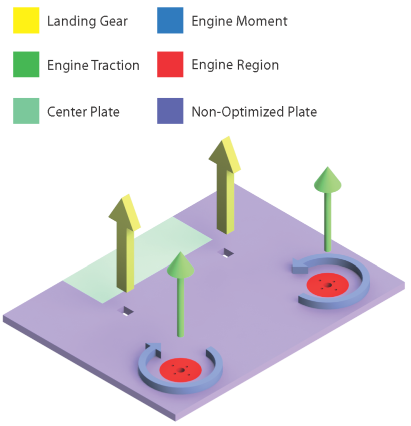

Figure 1: Free body diagram for optimization

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In order to obtain the optimal structure, the Static Structural analysis were realized with the frame fixed support being the center plate, subjected to several steps and combinations of loads, mainly due to the motor and the landing gear of the drone as presented in Table 1. magnitude of the loads were determined by the selected propulsion configuration of the Drone.

Structure	**Type**	**Loads**
MOtor	Max Thrust	3.0 N
	Max Moment	0.5 N.m
Landing Gear	Landing impact	4.5 N

Table 1: Main Loads for Static Structural ANSYS analysis

The regions excluded from the optimization domain are in red, and were defined by the Boundary Conditions of the Static Structural analysis, as can be seen on Figure 2

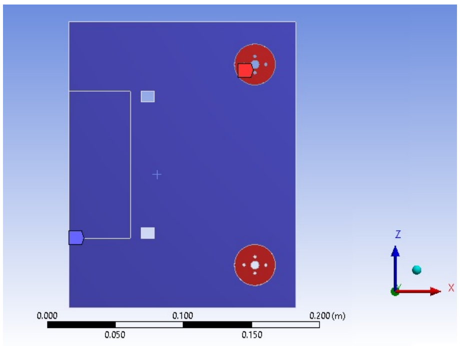

Figure 2: Optimization Region

The Topology Optimization was realized with the parameters tabulated on the following Table 2. The result obtained from the optimization is on Figure 3 and was used as model for the design of the frame that will be validated on the next section.

Element Type	Hexahedrons
Number of Elements	18450
Element Order	Quadratic
Max Number of Iterations	500
Convergence Accuracy	0.1%
Penalty Factor	3
Objective	Minimize Compliance
Response Constraint	Volume
Percent to Retain	30%
Member Min. Size	0.015 m

Table 2: Topology Optimization parameters

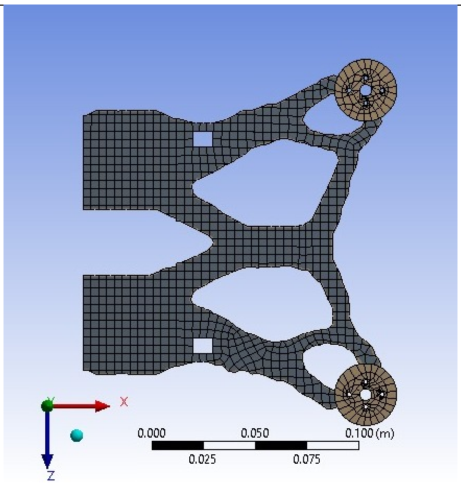

Figure 3: Topology Optimization result

4 MATERIAL SELECTION

Following the topological optimization, the materials were chosen considering the mechanical properties and the manufacturing processes to develop the frame. Several materials were considered, but some were highlighted because of the wide knowledge of their manufacturing techniques and applications in the aeronautical engineering. The materials, therefore, must follow the maximum design constraint: increased structural efficiency. Thus, materials highlighted and analyzed should be light and easy to manufacture, allowing to obtain geometries with smaller tolerances and to validate results of the optimization. In addition, they should confer high strength-to-specific-mass ratios. A good choice is composite materials, which allow the combination of diverse mechanical properties and the possibility of conformation to obtain the optimized geometry.

Thus, by choosing composite materials, there is the need to make two effective choices: the core and the reinforcement materials. The reinforcement is the component of the composite material that will suffer the major loads of the structure in question. The reinforcement must, therefore, possess such mechanical properties as high tensile and compressive strength, ie, mechanical properties related to the stresses suffered by the structure, in this case, the MAV frame. In that way the reinforcement must have a high mechanical resistance, combined with a low density, therefore following the maximum of a high specific resistance to the traction, fundamental in the case analyzed here.

Table 3 presents the mechanical properties of materials widely used in aeronautical industry that can be applied in structures such as the frame.

Carbon fiber has a high specific tensile strength giving important properties such as rigidity and resistance to loads. It must be considered that the model of the frame to be constructed must possess a fundamental characteristic that is the manufacturability. Carbon fiber has lamination methods that

Property	Unit	CFRP	PLA
Tensile Strength	MPa	600	46.8
Compressive Strength	MPa	570	46.8
Young Modulus	GPa	70	600
In-Plane Shear Strength	MPa	90	-
In-Plane Shear Modulus	MPa	5000	3350
Density	kg/m^3	1600	1290

Table 3: Mechanical Properties of the analyzed structural materials

allow the fabrication of complex geometry structures, but with certain constraints. Thus, the PLA presents fundamental characteristics related to the manufacturability, and can be applied in 3D printing processes, which allows the construction of structures with more complex geometries that can be efficient, yet has a high specific weight and not confers a high resistance like CFRP, but depending on the structure, the PLA can bring rigidity to it.

The core, in turn, assumes the role of increasing the cross-section of the frame structure as a whole. Thus, by applying a core that is capable of significantly increasing the cross-section and increasing the moment of inertia [4] of the same, allowing better performance of the structure, in addition to being able to withstand greater loads. In addition, the core, despite supporting significantly smaller efforts than those undergone by the reinforcement, should be made of a material with high shear strength, allowing to accommodate this property, to the characteristics already presented by the reinforcement. The core also allows a greater facility for the laminate to have more favorable geometric characteristics, as is the case of the mentioned cross section.

Property	Unit	H80 Foam	lite ply
Tensile Strength	MPa	2.5	31.05
Compressive Strength	MPa	1.4	36.2
Young Modulus	GPa	0.09	9.3
In-Plane Shear Strength	MPa	1.15	1.90
In-Plane Shear Modulus	MPa	27	318.9
Density	kg/m^3	80	500

Table 4: Mechanical Properties of the analyzed structural materials

Among the materials analyzed, the manufacturability of the material must be reconsidered, as well as the necessary characteristics for the design of the MAV, which needs to be light and compact. PVC H80 foam clearly has a much lower specific weight and is also easy to manufacture. The H80 foam also allows high stiffness due to its mechanical properties. lite ply also gives high rigidity when laminated with CFRP, however, because it is commercialized in boards with a limited thickness of 3 mm, it does not have high versatility when designing and constructing frames with more complex geometries, as in the case of laminated H80 foam with CFRP.

Through the selected materials, various configurations were analyzed as the composite materials are able to bring different mechanical properties depending on the composition and arrangement of the core and reinforcement. Thus, different configurations for the drone structure were studied. Figure 4 shows four configurations that were studied. The materials arrangements of each configuration are shown in Table 5.

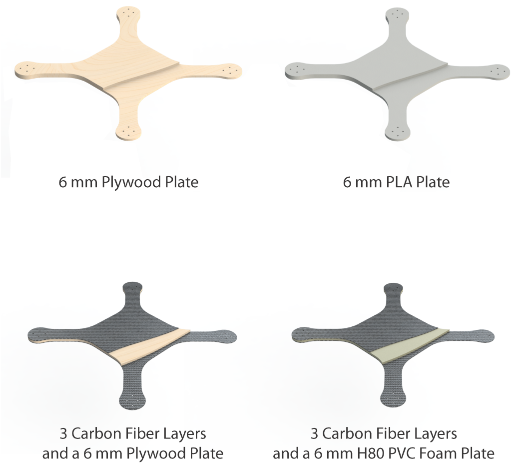

Figure 4: Possible Material Composition of the Frame

Configuration	Core Material	Reinforcement Material
1	H80	CFRP
2	Lite ply	CFRP
3	-	Lite ply
4	-	PLA

Table 5: Material of the frames analysed

5 SIMULATION

To evaluate the performance of the four configurations, all types were modeled in Solidwoks and both static and dynamic finite element analysis (FEA) were performed for each one. All analysis were made using Solidworks simulation tool, tetrahedral elements were used during mesh creation. Thus, An adaptive mesh was also used during meshing for better results. Each simulation was repeated, by increasing the number of elements until the convergence.

To ensure good stability and control of the MAV, the frame must withstand the flight loads without large displacements. The FEA static analysis was made in order to evaluate the maximum displacement of the frame under the design loads shown in Table 1. The boundary condition defined for this analysis was the center plate as a fixed area, representing the local of the heavier components. Loads, as motor forces and landing impact, were defined in the proper position. The displacements of configuration 1 are shown in Figure 5.

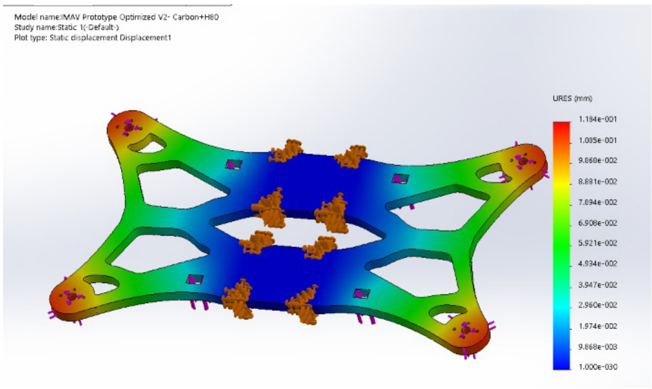

Figure 5: Static Analysis in Configuration 1

A modal analysis was made to estimate the natural frequency of the first mode. The final design should has its first natural frequency greater than $150Hz$, for dynamic stability of the structure during flight. To perform the analysis some assumptions were defined. First, the frame was considered in free vibration, then, no boundary condition constraints were defined, which simulates the flight condition. MAV components were simplified as concentrated masses in their position on the frame. Figure 6 presents the first elastic mode shape of configuration 1.

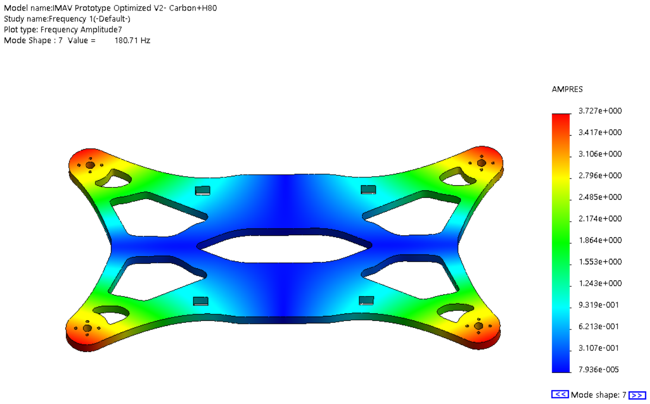

Figure 6: First elastic mode shape of configuration 1

The maximum static displacement, first natural frequency and weight were estimated and compared for each configuration. Thus, in the Table 6 are the data of the finite element simulations, which indicate the optimal configuration that combines all the aspects analyzed here.

Conf.	**Max. Static Displacement (mm)**	**First Mode Frequency (Hz)**	**Structure Mass (g)**
1	0.1184	180.71	66
2	0.0442	285.08	130
3	0.3125	106.55	76
4	1.031	52.40	197

Table 6: Configurations Analysis

6 MANUFACTURING

A vacuum bagging lay-up technique is used to manufacture CFRP. The technique removes the excess of resin, which is mostly applied to achieve higher carbon fiber concentrations and, consequently, higher mechanical properties.

A PVC H80 foam was chosen as the structure sandwich core. The propose process aims at improving the moment of inertia of the drone arms, by increasing the distance between bottom and top carbon fiber layers. The lay-up is made directly on a square foam core, on both sides of the plate, which eliminates the need and machining of hard material molds.

During the lay-up, an epoxy resin of the same weight of carbon fiber is mixed to wet the fabric. Besides, a breather and a perforated film are used between the vacuum bag and the fabric to absorb excess of epoxy. The result of this process is a 8 mm carbon-foam sandwich plate with 1 mm CFRP laminate with approximately 35% of epoxy resin and 65% of carbon fiber in weight, at a vacuum of $-600mmHg$. Figure 7 shows the first step of the lay-up procedure.

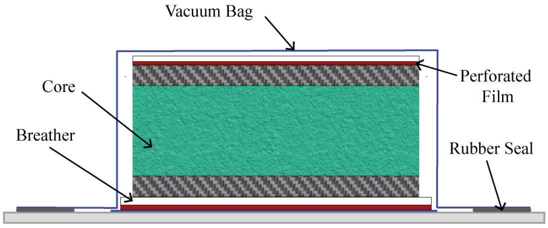

Figure 7: Lay-up technique of the composite frame

After the lay-up process, a CNC (Computer Numerical Control) milling machine is used to mill the sandwich plate to the desired design. A CNC machine is important to precisely achieve the layout optimized by the methodology, which insures the expected weight relief. Besides, the selected materials allow a small machine time and the durability of the milling tool.

7 RESULTS

After the results of the topological optimization, finite element simulations and material selection, it was possible to obtain complete analysis of the frames in the previously mentioned configurations. The simulation results obtained for configuration 1 are highlighted in Figures 6 and 5.

As shown above, the frames modeled with the geometry indicated by the topological optimization, show how the frames behave to the conditions originally established by the optimization. The PLA frame clearly exhibits poor overall performance compared to the other configurations shown and has a very high overall weight for the limited thrust of the motors. However, the lite ply frame only has a low total structural weight and is relatively interesting for the considered dimensions, however, the static simulations indicate that the maximum deformation of the frame is still very high when compared to the composite sandwich frames. Within composite frames, there are two analyzes that can be done. The configuration model 1 presents good resistance results, however, in the frequency analysis simulation, it ended up not having a rigidity, due to the foam in the core. However, the model of Configuration 2 represents the one that best behaves statically and in the analysis of frequencies, to the weight of 136 g which is significantly high considering that the sum of the masses of the electronic components chosen turns around 350 g. Thus, the model of Configuration 1 represents the ideal model, since it presents high structural efficiency and stiffness. Configuration 2 would be ideal considering a selection of a different propulsion system that supports a larger structural weight.

Figure 8: Final result of the MAV frame

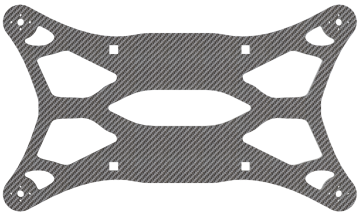

Figure 9: Top view of the optimized geometry

8 CONCLUSION

In this paper, authors present the development of a optimized MAV frame, which involves several aspects. In the context of the IMAV 2018 indoor competition, the development of light and compact frames involves structural characteristics such as strength and stiffness. Thus, the topological optimization allowed the study of complex geometries, reaching improved structural properties. By minimizing compliance, it was possible to obtain an optimized geometry for the loads considered here. Through the analysis of materials, four different frame combinations were performed by FEA simulations, combining materials such as CFRP, PVC foam and Lite ply. These analysis were focused on static and modal simulations and aimed at validating the geometry obtained in the topological optimization. Through the results, an final configuration was obtained considering the disposition of materials and also their manufacturing process. The designed frame of $66g$ follows the defined constraints parameters, as displacement and first natural frequency, allowing a high score in the mass multiplier parameter in the competition.

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