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Optimization of quadcopter frame using generative design and comparison with DJI F450 drone frame

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Abstract: This research accentuates to explore designing the drone frame using Generative design tools. A quadcopter is designed using Autodesk generative design embedded in Fusion 360. The simulation results such as static stress-strain, modal frequency and displacement results of additive manufactured quadcopter are compared with a DJI flame wheel F450 drone frame. The generative designed frame has minimum displacement compared to traditional designed drone frame. It is observed that generative designing technique along with additive manufactured frames yields better frames with improved resistance to fracture and minimum displacement compared to traditional designed DJI flame wheel F450 drone frame.

1. Introduction

The term "drone" characteristically stated to any unpiloted aircraft that can carry out a striking range of tasks, vacillating from military operations to package delivery. It can be as large as an aircraft or as small as the palm of your hand. Drones are classified based on the following factors- size, range, abilities, weight. According to aerial platforms, drones are of four types- single rotor, multi-rotor, fixed wing and fixed wing hybrid. This research is fixated on multi rotor drones, chiefly quadcopters. Few common classifications of quadcopters based on its frame size include true-X, square, hybrid X, H and stretched X. Generative design is an iterative design progression that proposes promising answers to a design issue. Design techniques such as topology optimization, lattice optimization etc., are focused on improving pre-existing models, contrasting generative design emphases solely on creating new possible designs with the limited constraints or parameters.

Generative designing is an iterative design exploration process, pioneered by Autodesk, uses artificial intelligence [AI] algorithms and high computing power of cloud to generate numerous design options emerging from one CAD design, done by defining certain parameters. Principally, by setting our advanced goals and its constraints, we will autonomously be able to generative thousands of design outcomes satisfying the desired requirements. The designer will not be able to evaluate all the design outcomes generated without cognitive catastrophe [1]. Few of the input parameters include the Design space consists of preserve and obstacle geometry; the design conditions include structural constraints and structural loads; design criteria include objective and manufacturing technique; and the material used for workpiece. Traditional optimization techniques focus on one variable whereas generative design is aimed at providing different design solutions and these design variants helps in meeting the demands for various other practical applications which will logically be difficult to describe mathematically [2].

Design problems in various technical fields are solved using generative design tools. Several researches have contributed in using generative design to obtain reasonable solution. Recently, the MaRS Innovation District in Toronto, Canada built an office environment, in which the floor plan was designed using generative designing. Similarly, Airbus uses generative designing to reimagine the central panels for the A320 Aircraft. Likewise, there has been a lot of research/ projects going on in these domains starting from the advances in generative designing [3] to the modeling and analysis of Quadcopter F450 Frame [4]. Harish Doraiswamy [5] proposed a catalogue-based framework where conceptual building design options of the interactive exploration can be enabled based on the adjustable view preferences. Authors compared different frames designed in generative designing to that of conventionally designed frames. The variability of the designs must be carefully controlled to advance various stimulating designs, such that the design generated will be comprehensible, unpredictable and most importantly desirable [6].

The conventionally designed DJI Flame Wheel F450 frame is compared with the design obtained from Generative designing drone frame. The Autodesk's Generative Design, hosted in Fusion 360 software is used to create model using the base parameters and structural constraints set by the user before generation is initiated. Simulation results were then compared including static stress-strain analysis, displacement and model frequency tests performed on the frames obtained from generative designing along with the results of DJI Flame Wheel F450 frame.

2. Dynamic Modeling and Calculations

The aerodynamic lift can be explained with the help of the Bernoulli's Conservation of Energy. This theory is also called as "Longer path" or "Equal transit theory". The equation for calculating lift (L) is given as,

$$L = \frac{1}{2} \times \rho \times V^2 \times A \times C_L \tag{1}$$

Where, ρ is air density, (~1.2 kg/m^3)

V is velocity, m/s

A is surface area of blades, m^2

C_L is coefficient of lift

Table 1. Consists of all the components along with its weight

Component	Number of individual components	Weight of individual component (in gm)	Net Weight of individual component (in gm)
RS2205S Motor	4	28.8	115.2
Pixhawk controller [a]	1	73	73
M8N GPS	1	32	32
5'' Propeller	4	4	16
BLHeli ESC	4	14	56
FC Hub PDB	1	8.5	8.5
Camera	1	12	12
Telemetry	1	15	15
iA6b Receiver	1	14.6	14.6
Lipo Battery 3S	1	200	200

[a] Including the controller and anti-vibration stand.

The components and its weight used for modeling are given in table 1. The total weight of the component obtained is 542.3 g. Therefore, considering the frame weight to be 250 g approximately and by adding 20% buffer on component mass, the total load [M] got to be 1000 g. G is the gravitational constant calculated by the gravitational effects of the law of universal gravitation, which is 9.8 m/s^2 precisely.

$$M = 1000\ g = 1\ kg \tag{2}$$

$$F = M \times G = 10\ N \tag{3}$$

Therefore, for a quadcopter the thrust of each motor is equivalent to 10 N. Propeller design is one of the most imperative criteria to be studied to analyze the performance of the quadcopters, which is expressed as

$$\eta = \frac{P_{out}}{P_{in}} \tag{4}$$

where, η is the efficiency of the propeller

P_{out} is the output power, that's the ability of the propeller to yield the given thrust (N) at the given airspeed (m/s).

P_{in} is the input power, that's the power given by the motor. In other words, the input power of the propeller is the output power of the motor.

Generally, a 2-blade propeller yields two pressure pulses and a 3-blade propeller will yield three pressure pulses per revolt. Therefore, a 3-blade propeller will be intrinsically smoother and quieter than a 2-blade propeller, making 3-blade propeller comparatively efficient than a 2-blade propeller.

3. Generative designing and selection of quadcopter frames

The human computer interaction targeting the generative design process can be divided into three dynamic phases- **Define; Generate** and **Explore**. Define is principally the phase we find our problem and convey it to the computer via fixing the goals and constraints. Generate is the place where the computer will look into the design and constraints defined by the user and works through those options in various different angles. Explore is where the computer will show the user, the options the computer devised using the conditions defined in the Explore phase. Explore phase is a decision making and interaction phase between the computer and the user. The generative design process is done as said with the help of AI algorithms including convolutional neural networks, Generative adversarial networks [GANs] including Conditional GANs [CGANs], Conditional Wasserstein GANs [CWGANs], Boundary Equilibrium GANs [BEGANs] and so on. Ivan Sosnovik [7] familiarized convolutional encoder-decoder architecture and stated the issues with image segmentation tasks. Similarly, Hongbo Sun [8] explained and studied four different typical exploration approaches of Reinforcement Learning [RL] converging on the development of Solid isotropic microstructure with penalization [SIMP] and Bi-directional evolutionary optimization [BESO] for structure-based topology optimization difficulties. Sangeun [9] proposed a framework consisting of iterative design exploration and design evaluation parts. YI Ji-jun [10] developed an element self-governing nodal density method for topology optimization, which is a part of generative designing.

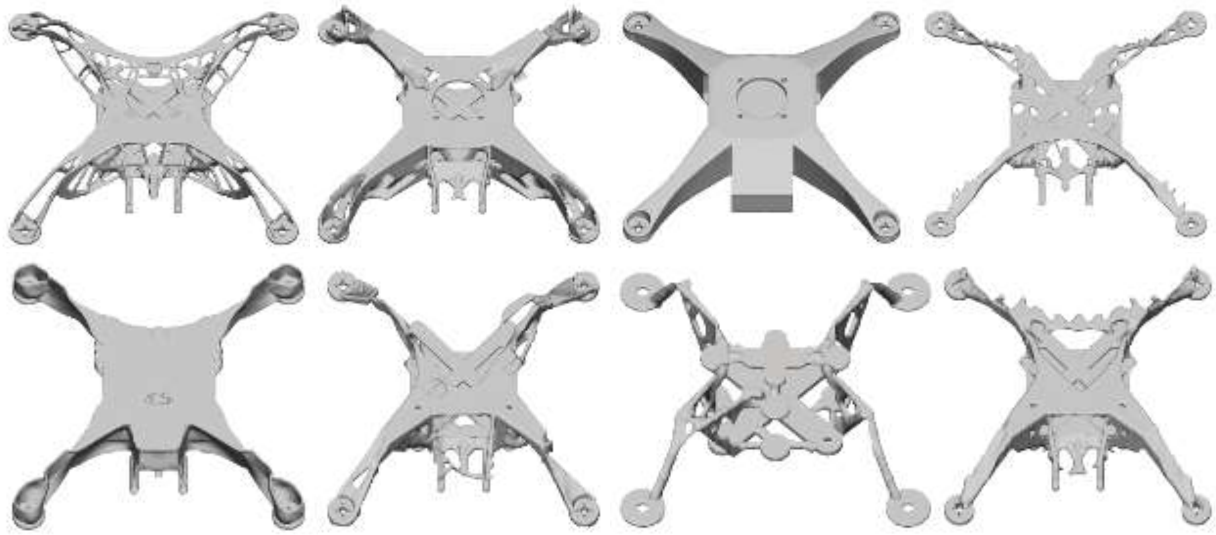


Figure 1. The various outcomes created when generative design was applied.

A quadcopters model is created using the specifications given in table 1 and generative design is applied to the model. In generative design, after various iterations, 74 designs where unconventionally generated and out of which 8 design outcomes have considered being the most suitable and pertinent based on our requirements and those 8 designs are shown in figure 1. The stress-strain, vibration, total weight of the frame, minimum factor of safety, etc. factors are considered to select the best outcome. In every iteration, the edifice of the CAD model will be tested and then, the AI algorithm will learn from the testing done in each and every step and will apply the changes at the subsequent iterations thus producing optimistic design which ultimately meets the desired expectations of the user [11]. Most of the CAD systems rely on the core constraints and measure to paradigm the geometry of the CAD model, though the procedural aspect of the constructional geometry is hidden from the user [12].

One key advantage to be noticed in these designs is that generative design slowly chips away material from a huge block, which implies that however complex the geometry of the CAD design, singularity of the design is maintained, in other words, a design is produced as a single part. The iterative process starts with an optimal block mass considering the hole and obstacle boundary implemented while fixing the design parameters. The Algorithm is designed in such a way that the removal of mass is done in a streamlined way ensuring maximum materialistic properties. The cloud-based system simultaneously processes multiple designs with unique topologies and properties. The design after generative designing checks if the structure is as per the requirements specified as goal via the parameter and structural constraints failing which the design will be discarded [13]. Figure 2 depicts the most effectual iterative design attained among various other design outcomes; hence these designs are used to compare with the DJI F450 frame considering factors such as processing status, study, visual similarity, material, piece part cost, fully burdened cost, volume, mass, maximum Von-Mises stress, minimum factor of safety and maximum displacement global [14].

(a) Frame 1 (b) Frame 2

Figure 2 Optimal design outcome obtained from generative design

Study 8 - Outcome 1, Iteration 6 (final)		new study (5) - Outcome 1, Iteration 48 (final)	
Properties		**Properties**	
Status	Completed	Status	Converged
Material	ABS Plastic	Material	ABS Plastic
Orientation	-	Orientation	X+
Manufacturing method	Unrestricted	Manufacturing method	Additive
Visual similarity	Group 4	Visual similarity	Unique
Production volume (pcs.)	2500	Production volume (pcs.)	2500
Piece part cost		Piece part cost	
Range (USD)	303 - 624	Range (USD)	272 - 524
Median (USD)	418	Median (USD)	348
Fully burdened cost		Fully burdened cost	
Range (USD)	303 - 624	Range (USD)	272 - 524
Median (USD)	418	Median (USD)	348
Volume (mm³)	214,162.43	Volume (mm³)	260,586.4
Mass (kg)	0.227	Mass (kg)	0.276
Max von Mises stress (MPa)	1.5	Max von Mises stress (MPa)	0.1
Factor of safety limit	2	Factor of safety limit	2
Min factor of safety	13.3	Min factor of safety	137.63
Max displacement global (mm)	6.22	Max displacement global (mm)	0.01

(a) Frame1 (b) Frame2

Figure 3. Properties logged when Generative design was implemented

In this study, the quadcopter frames designed are 450mm in size, also termed as the wheelbase which refers to the diagonal motor-motor distance. The size is particularly chosen, as the DJI frame is of the same wheelbase, which brings in a legit comparison between design specifically in terms of weight and load capabilities. Figure 3 depicts the snapshot of properties logged during generative designing. The user is facilitated in the execution of all the steps by a simplified GUI that proposes the steps in a chronological order [15]. For engineering design optimization and exploration, supervised learning is very operative making mapping out viable regions quite simpler [16]. After finishing the initial design space exploration, the node-geometry was refined for additive manufacturing using multi-stage structural optimization [17].

Table 2. Comparison of generative design frame with DJI F450 drone frame

Factors	**Frame 1**	**Frame 2**	**DJI F450 frame**
Weight of the frame (g)	227	267	330
Minimum factor of Safety	13.3	133	3.301
Manufacturing Method	Additive Manufacturing [b]	Additive Manufacturing [b]	Advanced manufacturing
Maximum von Mises Stress (MPa)	1.5	17.11	21.33
Maximum Displacement global (mm)	6.22	0.01	4.016
Material used	ABS Plastic [a]	ABS Plastic [a]	Polyamide Nylon
Filament spent (mass, length)	2 g, 0.7 m [b]	1 g, 0.21 m [b]	Not available

[a] Choosing the material is most crucial part of design as it withstand the weight of components exerted on the frame, resistance against impact etc. ABS material is chosen, due to its high rigidity, impact resistance, and tensile strength. Dark color ABS will be prefered as other light colors will degrade over time.

[b] The filament used while 3D printing is obtained from CURA software, where the length and weight of the filament used includes the supports structures generated.

[c] Additive manufacturing technique retrieves data from the CAD file converting it into STL file which will then be sliced in softwares like CURA generating G-Codes used for 3d printing. Slicing will ultimately encompass the information of each and every layer to be printed in form of triangles [18]

4. Analysis on generative design and DJI F450 drone frame - comparison

In this section, the influence of factors given in table 2 is analyzed. Von Mises criterion is principled on von Mises-Hencky theory, which is also known as shearing energy theory or the maximum distortion energy theory [19]. Theory emphasizes that when Von Mises Stress equals or exceeds the effort limit, a ductile material shows weaknesses in some parts of its structure [20].

Table 3 CAD design, obstacles and preserved boundaries of generative designs

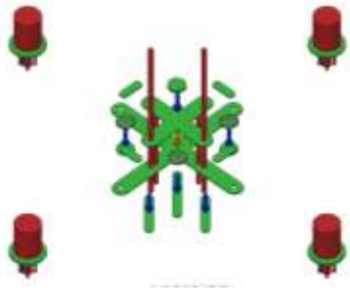
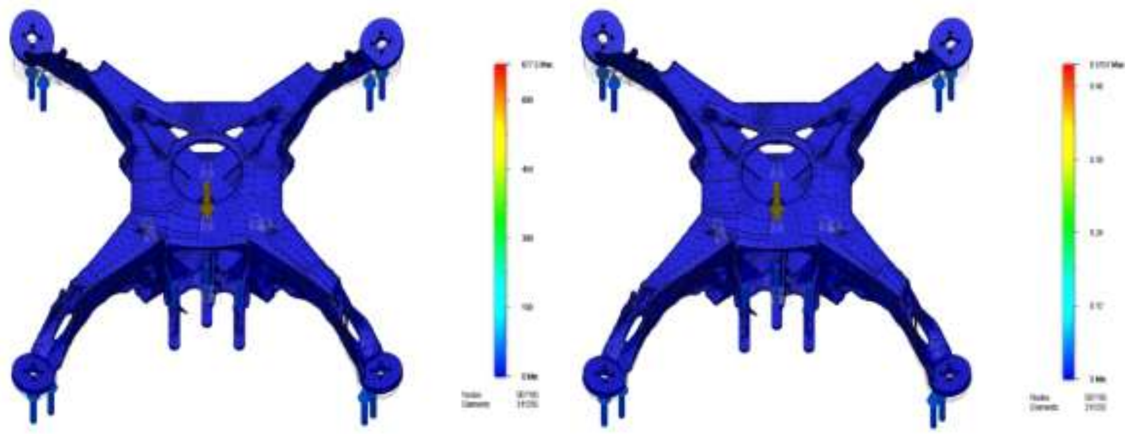
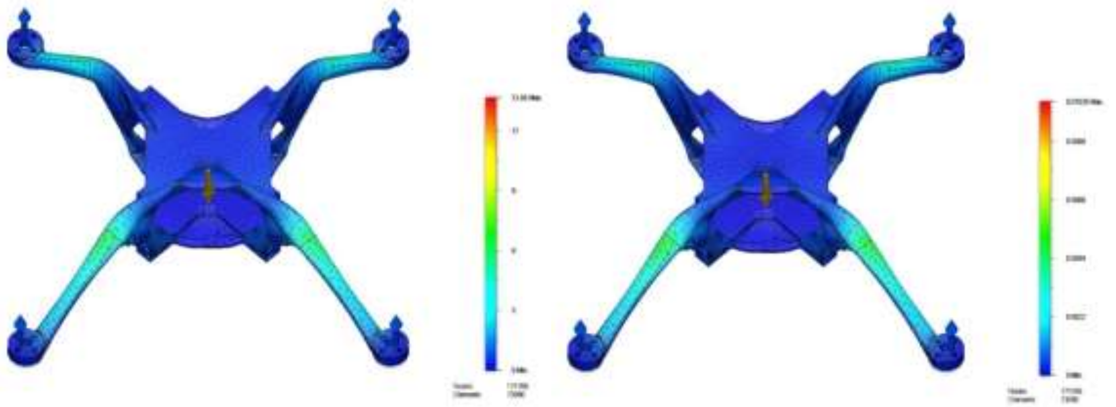
	Frame 1	**Frame 2**
CAD Design		
Obstacle and preserved boundaries		

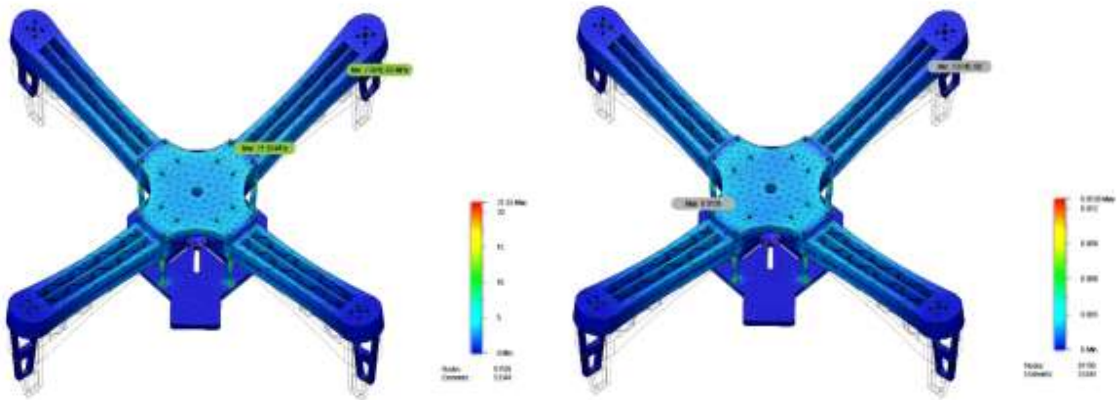
Figure 4. The schematic representation of DJI F450 drone frame [21]



(a) Frame 1

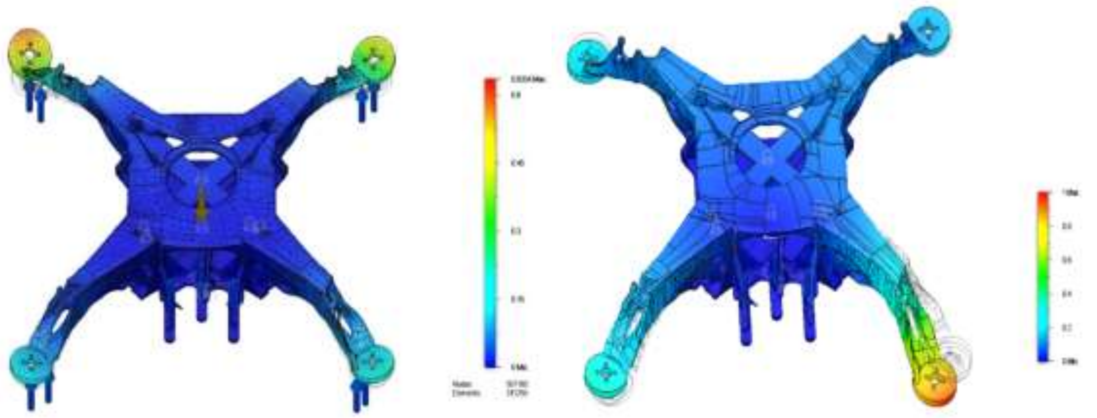


(b) Frame 2

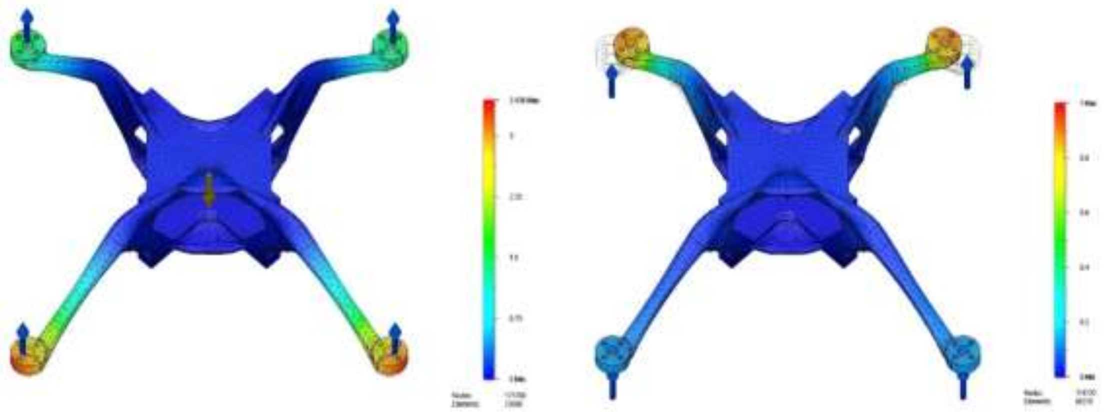


(c) DJI F450 frame

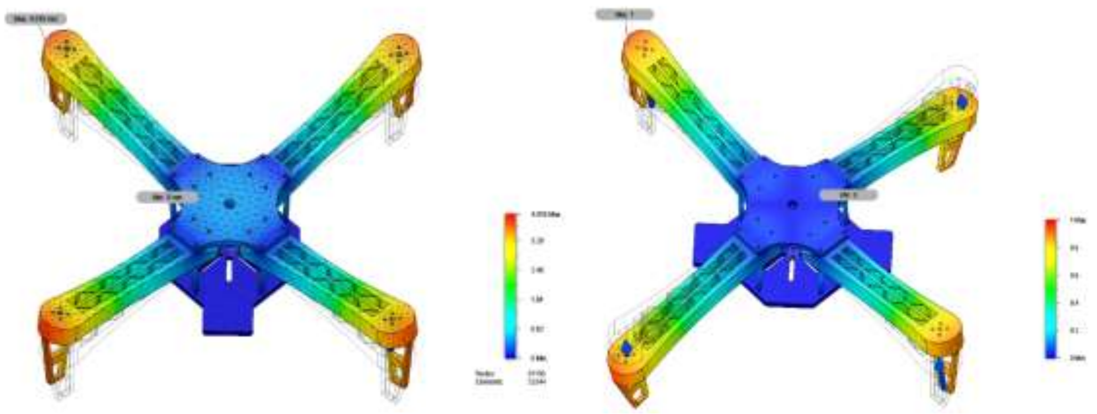
Figure 5. Comparison of stress-strain analysis between different frames



(a) Frame 1



(b) Frame 2



(c) DJI F450 frame

Figure 6. Comparison of displacement and modular frequency between different frames

By studying the designs of frame 1, frame 2 and DJI frame that's figure 4, various shift in criterions has been observed and reflected in the following contexts. One factor to reminisce is that all the three designs where in safe range, that's the framework is safe to apply the load stated while simulating and thus the frame will not fail in static load conditions as per the structural load constraints in designing.

The traditionally designed figure 4 has severe stress points in the standoff region caused due to the axial loading at the end of the drone arm. The critical point on the standoff on repeated loading may fail in due course of time. While the generatively designed frames have no critical points of failures, it can ultimately withhold repetitive and cyclic loads. Generative design automatically iterates the mass distribution in such a way that there are no/less critical points of failure while decreasing maximum mass from the design while optimising its mechanical properties. The symmetric nature is also optimizing the centre of mass to be exactly in the centre of the frame which is a major factor to be considered while designing a drone. The major mass is distributed in the standoff section connecting the centre region and drone arm, this is majorly observed in all the designs computed throughout the experiment. The mass in the standoff section is to counter the turning moment caused by the thrust and the load couple. And also, additional overhanging structures were also created to counter the stress in that region. Another perceptible factor is the trend of the mass distribution in the standoff region, mass of the frame and factor of safety, more the mass in the region increases the factor of safety of the frame but in turn increasing the mass of the frame. More the number of overhangs less is the mass in the standoff region, less is the factor of safety when compared to a generatively designed drone frame with a solid mass in the standoff structure. The traditional F450 frame has a lot of mass reduction features incorporated as triangles has multiple critical points of failure despite the fact the mass is significantly greater than the generatively designed drone frames.

The overall performance of the drone frame designed via generative designing method has three notable factors healthier than the traditionally designed F450 drone frame. Starting with the factor of safety, Frame 2 has a factor of safety of almost 40 times that of figure 4. From the data and material parameters it can be inferred that the probability of failure of figure 4, that's the DJI frame is higher than the other drone frames designed using generative design. Secondly, Von Mises stress governs if a material given will yield or fracture in time. The Von mises stress value of figure 4 is 11.4 times greater than frame1 thus concluding the resistance of yield or fracture is more for frame 1 when compared to a traditionally designed drone frame. Finally, the maximum displacement under the load condition for frame 2 is just 0.01 mm which is approximately 400 times as compared to figure 4 which indeed proves the ability to resist deformation of the generatively designed drone frame. There is also reduction of weight when compared to the DJI frame. The weight of frame 1 is 227gms the wispiest of the 3 designs, followed by frame 2 with 267gms and then the DJI frame with 330gms. Thus, are numerous data logged and studied via various experiments and analysis.

5. Conclusion

In brief, generative design is a beautiful symbiosis between man and computer that imitates natural worlds evolutionary progression with the help of the computing power of the cloud to provide thousands of solutions to one engineering problem rather than applying them retrospectively. As a result of this computational processes, innumerable remarkable diverse structures that looks very organic in design are created. An immaculate analysis is done, between the traditional designing method and generative designing technique, comparing with two generative designed drone frames [Frame1 and Frame2] alongside a DJI Flame Wheel F450 frame [figure 4]. Thus, from the analysis and simulation data logged, it is proven with the help of these frames that the outcomes attained by generative design technique is much better in many aspects when compared to other traditional designing.

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