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Hybrid optimisation technique for enhancing weight reduction of quadcopter

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ABSTRACT

In every domain of product development, manufacturers deal with the common problem of weight reduction. Topology optimisation and lattice optimisation are widely used methods for reducing weight without compromising structural integrity or stiffness. Enhanced weight reduction of the quadcopter eventually leads to increasing payload carrying capacity and offers higher efficiency. The objective of this research is to analyse optimisation techniques for quadcopters. A 3-D model of a quadcopter has been designed in the CAD tool. Further, the hybrid optimisation technique, a part of topology optimisation followed by lattice optimisation, has been applied. The utilisation of the hybrid optimisation technique offers a significant weight reduction of the model of the quadcopter. The various properties have been validated by performing linear static analysis with similar loads in the FEA tool.

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KEYWORDS

Additive manufacturing;
hybrid optimisation; lattice
optimisation; quadcopter;
weight reduction

1. Introduction

A quadcopter is a compact four-rotor helicopter. With the advancement of additive manufacturing every day, intelligent machines are taking the place of humans in every industry. Amongst them are the logistics and defence sector, where the utility of unmanned aerial vehicles, specifically quadcopters overcome enormous growth in recent periods. This development raises the problem of designing a quadcopter that can replace the current, inefficient design and carry the maximum payload more efficiently. Quadcopter is mainly used in many applications, i.e. aerial photography, shipping and delivery, geographic mapping, disaster management, precision agriculture, search and rescue, military operations, weather forecasting, and wildlife monitoring. The recent scope of quadcopter product development is focused on manufacturing lightweight and structurally efficient components. Many studies concentrate primarily on increasing the quadcopter's efficiency, and a potential way to achieve this goal is by lowering the device's base material weight. Each quadcopter has its thrust-to-weight ratio (TWR). By increasing TWR, payload carrying capacity can increase along with the benefits of less power consumption and less material consumption, so the material cost will significantly reduce.

For achieving a greater TWR ratio in quadcopter, the main need is to get reduced the base material weight of the quadcopter by some sort of popular optimisation technique. Predominantly, material optimisation techniques, i.e. topology optimisation

and lattice optimisation can be applied to the conventional model by using the optimisation tool or software. The utilisation of both techniques is better for the weight reduction of the quadcopter. This strategy is so effective because it combines two approaches, i.e. lattice optimisation and topology optimisation. Our goal for this research is to create innovative methods for lowering component weight limits without compromising stiffness. With the aid of topology optimisation, a weight-optimised model is produced. This is then further improved by using the lattice optimisation technique, leading to the ultimate achievement of hybrid optimisation, which significantly reduces the weight of the quadcopter.

Various literature has been reviewed that has adapted the different optimisation techniques for the enhancement of weight reduction. In Tapp et al. (2004), weight optimisation was investigated using an effective topology optimisation technique to reduce the weight of sandwich constructions. The final optimisation model produced by topology optimisation had a weight reduction of only 25%. Using a genetic algorithm, a researcher has optimised the weight of hydrogen storage containers for quadcopters. Consequently, it was possible to reduce the weight in the algorithm iteration by 23.79% compared to the starting weight (Lee et al. 2020). The engine subframe mount, by utilising $AlSi_{10}Mg$ alloy material, which is produced by permanent mould casting and supports the engine. For the reduction of the weight of the engine subframe, topology optimisation was used by

defining the design space and using an extension of the SolidWorks software tool. The overall weight reduction is 20% from the original model (Merulla et al. 2019).

In (Kantareddy et al. 2016) the Lattice structure has been used which is a complex design that can maintain high stress and stiffness to enhance weight reduction. By using a lattice structure weight can easily be stored in a metallic structure. For metallic structures (Kantareddy et al. 2016), there have been many design challenges and the need for various higher-end tools. Designing metallic lattice structures for saving weight, using various commercial software, i.e. SolidWork, Formz, and SimpleWare. M.V. Aditya Topology optimisation procedure has been applied (Ma'arof et al. 2022) to reduce the weight of the Engine Mounting Bracket and concluded 15% weight saving. Naveen et al (Cascino, Meli, and Rindi 2024) have reduced the weight by topology optimisation alone engine mounting bracket by 40% with maintaining the strength and stiffness of that part. Calabrese et al (2017) has provided the technique for the optimisation of machining fixtures for aeronautical thin-walled components. Topology optimisation process that is used for minimise minimising the weighted compliance. Dongkai Xu et al (2012) performed the topology optimisation of die weight reduction for high-strength sheet metal stamping. By this topology optimisation, the weight of the blank holder is reduced by up to 28.1%. Shukla et al. (2010), using a finite element model of CASNUB, a three-piece freight bogie frame was presented. Bogie has modelled by using NX3, the UGS software. Transient analysis of the bogie frame was performed to calculate the fatigue strength. MATLAB software tool was used to reduce the weight of the bolster-fitted bottom centre bearing plate and the optimisation has resulted in approximately 7.6% reduction in weight of the bolster. In (Seppälä and Hupfer 2014), the topology optimisation in the structural design of a LP Turbine Guide Vane for weight reduction was performed, and as a result, a significant weight reduction of 19% with a rise in temperature gradients. The high-performance automotive chassis design by a topology optimisation-based approach has been given in (2011). Optimisation has been applied to the design process of a rear-central engine high-performance vehicle chassis for achieving weight reduction target topology, and size optimisations are coupled with FEM analyses and taken in cascade for reaching an optimum chassis configuration. Gauchia et al. (2010), performed weight optimisation of a real bus structure by genetic algorithms method and checked the structural analysis or FEA analysis by ANSYS software. The usage of topological optimisation tools for support bracket weight minimisation (Letsatsi Mt and Agarwal 2021) and heavy motor vehicle chassis using various methods have been

discussed in (Agarwal and Mthembu 2021, 2022a, 2022) Traditionally, lattice structures and related types of complex structures can be manufactured via casting, sheet metal forming, or wire bonding processes and many other conventional manufacturing processes in (Wadley 2005). However, due to many limitations in the conventional manufacturing process for the fabrication of lattice structures, additive manufacturing technology (Koneri et al. 2020) is very essential to use. The design for the additive manufacturing principle provides successful approaches for 3D printing. With the help of additive manufacturing and various 3D printing processes, complex, porous, lattice-type, and lightweight structures can easily be manufactured. Additive manufacturing has given a new way to design and manufacture the product. A rapid growth in additive manufacturing in all sectors made it easy to print complex parts (Chen et al. 2017; Gao et al. 2015; Vartanian et al. 2016). There are many additive manufacturing processes used in the manufacturing industry recently. For printing the 3D modelled complex structure with the help of polymeric structured materials, the Stereolithography apparatus (SLA) shares a remarkable likeness to the manufacturing of photo-sensitive polymeric complex structures (Cooke et al. 2003). FDM is a wire-fed technology, where a small wire with a diameter (1.5 mm to 3 mm) is fused and turned into a paste-like form and that paste is injected through print heat to print layer-by-layer plastic material added to create the 3-D modelled part (Kumar, Verma, and Jeng 2020).

A concept of optimisation has been explored and applied to the application of different optimisation techniques on a single model in a defined order to achieve the research objective. Topology optimisation is the conventional optimisation technique that deals with the material distribution and the way the members within a structure are connected as shown in Figure 1. It treats the equivalent density of each element as a design variable. Under topology optimisation, the material density of each element should take a value of either 0 or 1, defining the element as being either void or solid, respectively. Hence, material removal takes place in the topology optimisation wherein the stress concentrations are less. Meanwhile, the lattice optimisation technique is the most recently developed technique which aims to replace the elements of intermediate densities, which occur during classical topology optimisation, with lattice cells. In topology optimisation, intermediate density elements are limited due to penalty factor P (element densities are closer to 0 or 1) which equals 2 or 3, and in lattice optimisation by default this parameter is 1 or 0. The penalty factor controls not only the intermediate densities, it also defines the stiffness of the topology element. Hence, both these

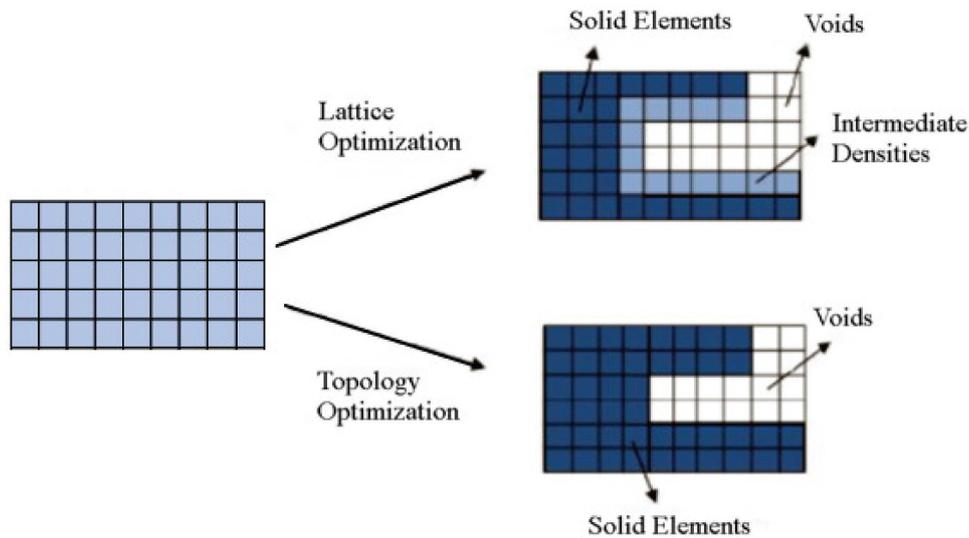


Figure 1. Element densities in lattice and topology optimisation.

methods in conjunction can eliminate the lowest and the intermediate densities elements which can enhance the elimination of the volume fraction of the model. In this paper, hybrid optimisation, i.e. topology and lattice optimisation techniques have been used together for the weight reduction of quadcopter.

In this paper, the 3-D solid model of quadcopter has been created using CAD software. The CAD model is imported into the CAE software for performing various optimisation techniques, i.e. the topology and lattice optimisation. Once the model has been imported into the CAE software, primarily geometry clean-up is performed on the model to remove the fillets and chamfers. Further, material is assigned to the model, specifically for this analysis Plastic (Nylon) has been used as the material for the structure of the quadcopter. Loads and boundary conditions were applied, these contain all the loads generated by the rotor such as thrust and rotational inertia loads. Also, the base of the quadcopter is constrained for all the degrees of freedom (DOF). All the steps of pre-processing have been performed and a solution has been created for topology optimisation and lattice optimisation individually. Various optimisation parameters are assigned in the solution for the optimisation techniques such as design variables, design responses, optimisation constraints, and optimisation objectives. Moreover, for the lattice optimisation, lattice parameters were defined additionally with these parameters. After assigning all these parameters, the solution setup has been completed for the model.

After obtaining the final optimised model, manufacturing that model is also a little challenging.

Because in the hybrid optimisation process, the model must perform with a lattice structure. So, in general, a lattice structure is a very complicated porous structure to get reduced weight. For manufacturing this complicated structure, conventional manufacturing processes, i.e. casting, welding, metal forming, and steel-metal working are very difficult to implement due to the complex and porous structure. To overcome the issue mentioned above, additive manufacturing or 3-D printing is the best approach for manufacturing complicated parts with high accuracy and surface finish (Kazemian et al. 2017). 3-D printing can also be called layered manufacturing because in that process material will go to add layer by layer approach. This hybrid-optimised quadcopter can easily be manufactured by an additive manufacturing process. The final optimised CAD model has been used for different processes of 3-D printing for rapid manufacturing.

2. The flow of design optimisation process

In the paper, a CAD model of quadcopter has been designed, and the hybrid optimisation technique has been introduced to minimise the weight of the model. The detailed Process flow of this technique is explained.

2.1. A CAD model of quadcopter

Various designs of quadcopters were studied to be best suited for the objective of carrying first-aid kits, Infrared search and track cameras, and grenades for defence applications. Figure 2 shows the three-dimensional solid model of quadcopter and it has been designed in the CAD Software using Siemens NX 12.0 and Dassault Systems SolidWorks 18.

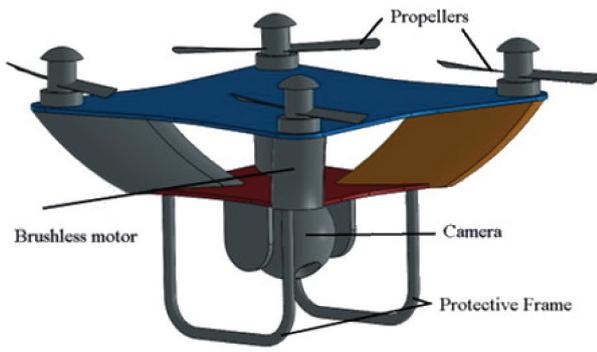


Figure 2. A CAD model of the quadcopter design.

2.2. Loads and boundary conditions

The most primitive step of pre-processing is to assign material properties to the model. The material used for the Quadcopter is Plastic (Nylon), and various properties of this material are discussed in Table 1. Since a linear static analysis has been performed on the given model, so all six degrees of freedom must be constrained. For propulsion, 4 numbers, for turning 2730 brushless motors with a 10 A maximum current is used along with APC style $6 \times 4E$ propellers of 0.1524 m diameter. The maximum thrust that can be produced by all motors is 3N at 10,000 rpm. Also, due to the rotational motion of the propellers, a calculated rotational inertial force of 3 N is generated at the hinges. Finally, the mass of 3 kg has been applied 100 mm below the quadcopter which can be assumed as a payload.

3. Topology optimisation

For performing topology optimisation on the quadcopter, the Altair Inspire software tool is used. This software solves topological optimisation problems using the density method, also known as the solid isotropic material with penalisation method (SIMP) in the research community. The material density of each element in the density method is directly used as the design variable and varies continuously between 0 and 1; these indicate the state of void and solid, respectively. The material young modulus at each element varies continuously as the material's relative density varies in conjunction. The relation between the ratio of elemental young modulus (E) to material young modulus (E_0) and relative density factor (ρ_e) is shown in Figure 3 (Zhao et al. 2021).

As the element's material elastic modulus reduces, element stiffness is also reduced. According to the SIMP method, the global stiffness is modulated according to the equation shown in Equation 1, where K_e is the element stiffness matrix, ρ_{min} is the minimum relative density, ρ_e is the element's relative density, p is the penalty factor, and N is the number of elements in the design domain.

$$K_{SIMP(\rho)} = \sum_{e=1}^N [\rho_{min} + (1 - \rho_{min})\rho_e^p] K_e \quad (1)$$

The topology optimisation solution is carried out in a systematic way in the Altair Inspire and the flow process is explained in Figure 4. According to the flowchart, the required parameters were initially

Table 1. Material properties of Plastic (Nylon) of the quadcopter.

Youngs Modulus(E)	Poisson's Ratio(μ)	Density(ρ)	Yield Stress	Coefficient of Thermal Expansion
2.910E+3 MPa	0.410	1.230E +3 kg/m ³	75.000E + 0 MPa	72.000E - 06/K

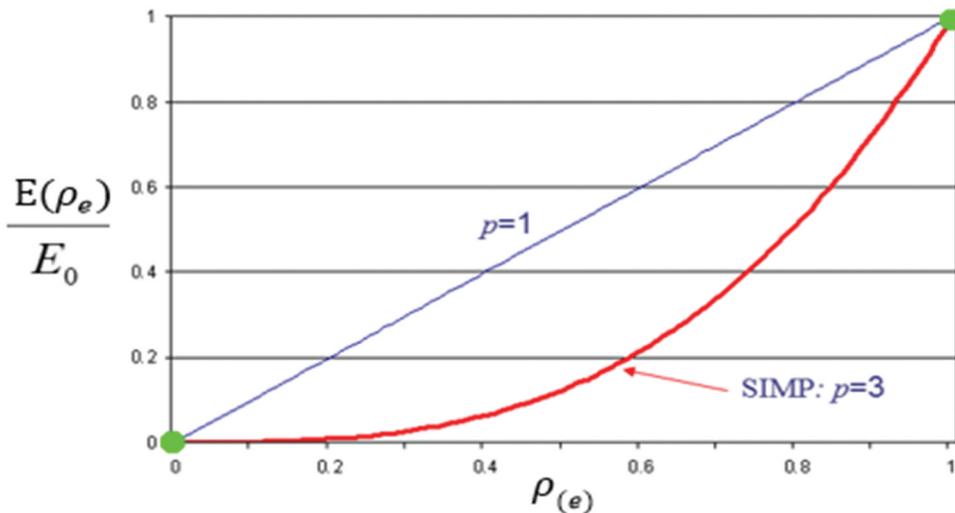


Figure 3. The plot depicts the relation between E/E_0 vs ρ_e (Gao et al. 2015).

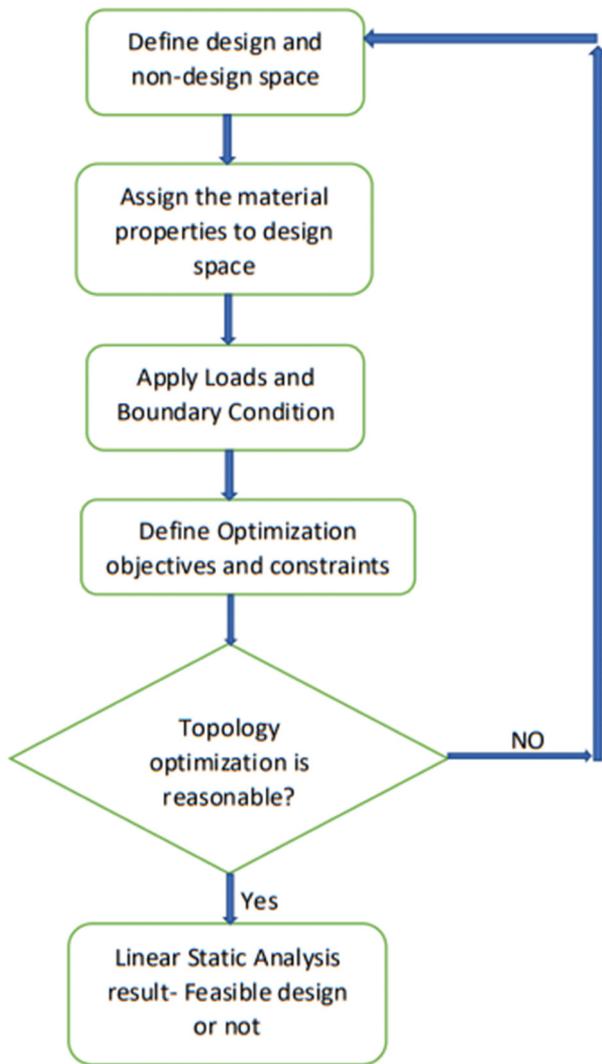


Figure 4. Flow chart process of topology optimisation in Altair Inspire software tool.

initialised, material properties were assigned, loads were applied, and objective functions were applied. The primary objective of performing topology optimisation on any component is to reduce the weight significantly while intact the structural properties.

Excessive weight can lead to various issues such as higher manufacturing costs and reduced efficiency (Hu, Gadipudi, and Salem 2019). Often, geometry obtained because of performing topology optimisation is quite complex and may not contain symmetric elements. A geometry must be further optimised and linear static analysis needs to be performed on the final design as shown in Figure 5 to conclude whether the design is feasible or not.

4. Lattice optimisation

In the hybrid optimisation process, lattice optimisation is a successive step to be performed after topology optimisation. Due to penalty factor P (element densities are closer to 0 or 1) which equals 2 or 3, limited intermediate density elements exist in topology optimisation, whereas this parameter by default is 1.0 in lattice optimisation. The penalty factor defines the stiffness of the topology element, it also controls the intermediate densities. Equation 2, is used to correlate the density of a topology element to its stiffness (Natarajan et al. 2019).

$$E = E_0 \rho^P \quad (2)$$

where E is the optimum stiffness of the topology element for the density ρ , E_0 is the stiffness of the initial design space material (actual material data), ρ is the density (or volume fraction) of a topology element, and P is the penalty applied to the density to control the generation of intermediate-density elements.

4.1. Design space

In lattice optimisation, design space is the user-defined space in the model which transforms into the final lattice structure after optimisation. While setting mass constraints, targeted mass is calculated concerning the percentage of total design space

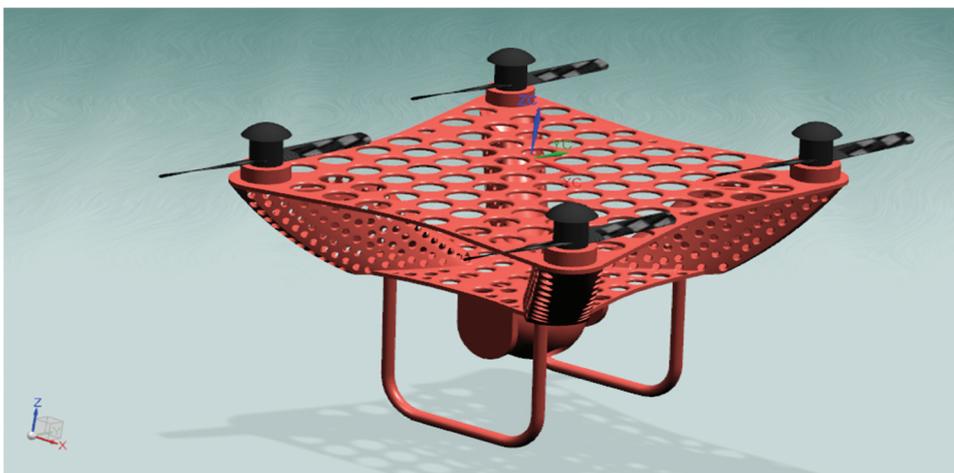


Figure 5. Topological optimised design of the quadcopter.

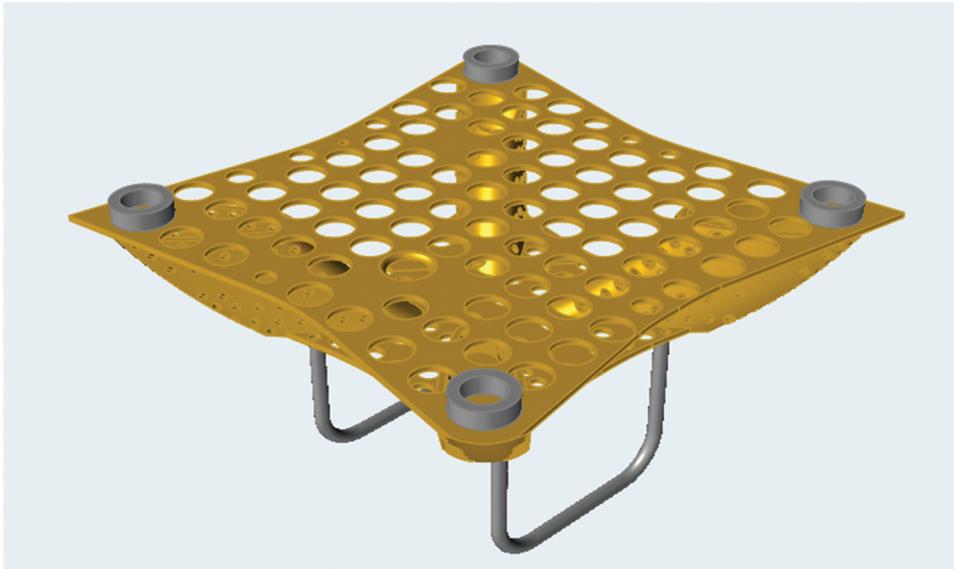


Figure 6. Design space (orange) and non-design space (grey) of the quadcopter.

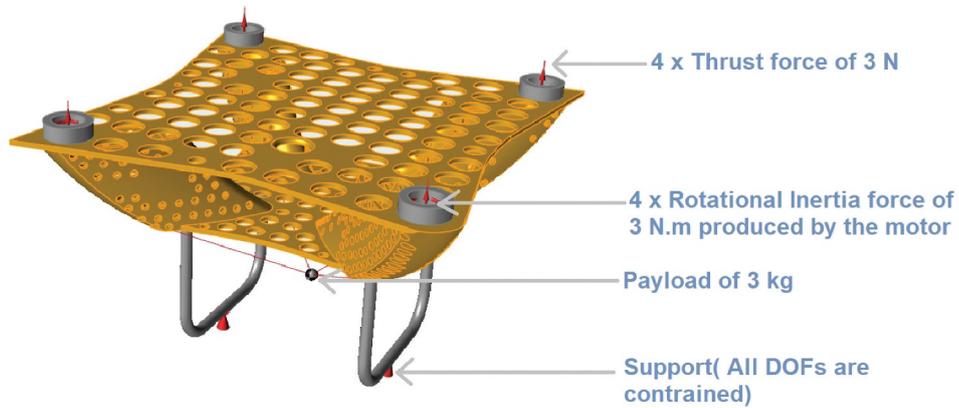


Figure 7. Loads and boundary conditions applied on the quadcopter.

volume. In general, the best practice is to not apply any loads and boundary conditions to the design space which could be applied to the non-design space. In Figure 6, design space and non-design space are highlighted with orange and grey colours, respectively.

4.2. Loads and boundary conditions

Loads and boundary conditions are the same for lattice optimisation as the topology optimisation and are discussed in detail in the above section. These similarities in the parameters for both optimisation techniques are due to the same experimental setup and the

optimisation objectives. Figure 7 represents the loads and boundary conditions applied on the Quadcopter.

4.3. Lattice parameters

While running a lattice optimisation solution, the lattice is created inside a design space based on the lattice parameters input given by the designer. Various properties can be assigned to a lattice as given in Table 2.

The target length denotes the edge length of the parent solid elements. The minimum and maximum diameters of the lattice beams correspond to the range in which diameters of the lattice beams can be generated. Both the practicalities of the geometry and the capabilities of the intended manufacturing process should be considered while assigning the properties to the lattice beams. By selecting fill with 100% lattice, complete design space is converted into the fully optimised lattice structure which is intuitive, and

Table 2. Lattice beam parameters.

Parameter	Value
Target Length	5 mm
Minimum Diameter	0.5 mm
Maximum Diameter	1 mm
Fill With	100% lattice

Table 3. Optimisation constraints.

Constraint	Value
Percent of Total Design Space Volume	35
Frequency Constraint	50 Hz (Minimum)

aesthetically pleasing results with clean transitions between design and non-design regions.

4.4. Optimisation constraints

Constraints define the target value for the optimisation response. Optimisation responses are the result parameters that need to be analysed after performing lattice optimisation, as these are the parameters that are optimised in the process of optimisation. The values of these responses need to be constrained to obtain a feasible solution. In this paper, two main constraints are applied and mentioned in Table 3.

The percentage of total design space volume defines the mass target or mass constraint, where a certain percentage of mass is kept intact. In the parameter setup, a 35% mass target is specified, then 65% of the material is carved away from the design space, leaving 35% of the original material. Typically, the value of the percentage of total design space volume ranges between 25 and 50. It is understood lower the percentage is more difficult it would be for a solver to predict the accurate result. Frequency constraint is used to control the frequency at which an optimised part vibrates. In Altair, Inspire minimum frequencies can be specified for the given load cases and the design space. In this paper, a natural frequency has been constrained which is found to be greater than or equal to 50 Hz. This frequency is greater than the surrounding frequencies of other parts so resonance can be avoided, which increases the overall life of the part.

4.5. Optimisation objective

Defining the objective is the most important step in the optimisation work process. Objectives are the results that one can achieve from the optimisation. The objective is to maximise the overall stiffness of the design space or minimise its compliance under a given amount of mass removal. Compliance is the reciprocal of the stiffness and measures the overall flexibility or softness of the structure. Hence, minimising the global compliance (C) is equivalent to maximising the global stiffness. Global compliance is minimised by using Equation 3, where u_e is the nodal displacement vector of the element e , K_e is the stiffness of the element e , and vector ρ contains the elements' relative densities ρ_e . During each

optimisation iteration, required functional constraints and target mass constraints must satisfy Equation 4, where v_e is the element volume, and M_{target} is the target mass of the optimisation. Also, equation 5, must be satisfied, where $K\{\rho\}$ is the global stiffness matrix modulated by the vector of relative densities, u is the displacement vector, and F is the external force vector. Further, design response constraints must also be satisfied which holds as shown in Equation 6, which limits various parameters such as stresses, displacements, eigenfrequencies, mass fraction, volume fraction, etc. Certainly, the stiffness of the optimised part would not be greater than the original part, but as our objective is to maximise stiffness, so software will optimise the design in such a way that resulted design achieves the maximum possible stiffness while mass constraints are also being satisfied.

$$\min C(\{\rho\}) = \sum_{e=1}^N (\rho_e)^p [u_e]^T [k_e] [u_e] \quad (3)$$

$$\sum_{e=1}^N \{v_e\}^T \rho_e \leq M_{target} \quad (4)$$

$$[K\{\rho\}]\{u\} = \{F\} \quad (5)$$

$$\theta(\{\rho\}_1\{u\})_1 \subseteq \theta_1^*, \theta(\{\rho\}_1\{u\})_2 \leq \theta_2, \dots \quad (6)$$

Equation depicts the global compliance, minimum global compliance, mass constraint, global force-stiffness equilibrium, and design response constraint.

5. Analysis of the proposed technique

Topology and hybrid optimisation were performed in Altair Inspire software and an optimised model was obtained which accomplished all the defined optimisation objectives specified. Further, linear static analysis was performed on the optimised model in Altair Inspire. The loads and boundary conditions defined were the same as for the optimisation solution. Altair Inspire generates mesh automatically using its meshing algorithms. The user just has to specify the mesh size in the run parameter setup. In this paper, a mesh size of 3 mm for both the topological optimised model as well as the lattice optimised model is defined. Additionally, the gravity effect was activated and its value was specified as $9.81m/s^2$. Also, contact definitions were added and defined as sliding contacts only.

Figure 8 shows the linear static analysis results for the topological optimised quadcopter model, Figure 8(a) displacement, Figure 8(b) von mises stress and Figure 8(c) factor of safety contour plots are shown.

The displayed model is viewed in the maximum deformed state for the assigned loads and boundary

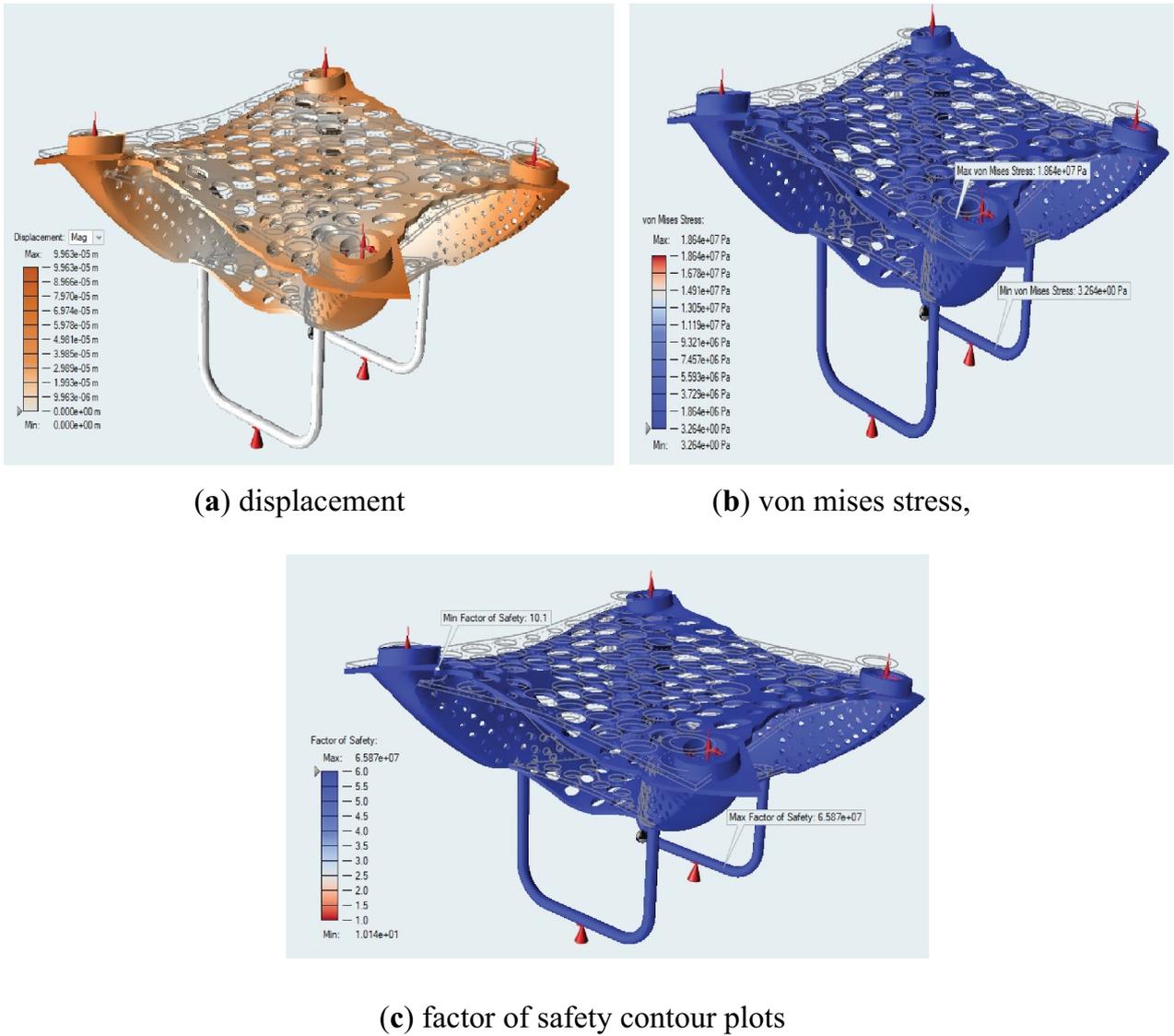


Figure 8. Linear static analysis results for various parameters: (a) displacement, (b) von mises stress, and (c) factor of safety contour plots.

conditions. Compared to the more complex non-linear static analysis, linear static analysis may be the better approach for examining the structural characteristics of the supplied quadcopter model because the model's deformations are within acceptable bounds.

A hybrid optimised quadcopter model is also analysed for the linear static analysis and the results for displacement as shown in Figure 9(a), a factor of safety in Figure 9(b), von mises stress in Figure 9(c), and lattice diameter contour plots is shown in Figure 9(d). Here, the lattice diameter is the diameter of the lattice beam in the quadcopter hybrid optimised model. As seen in the figure varying lattice diameters are present in the model for the entire range of lattice beams. This needs the utilisation of additive manufacturing techniques for the manufacturing of the hybrid optimised model. Conventional manufacturing techniques could also be used in a hybrid manner in conjunction with additive manufacturing techniques.

6. Results and discussions

This paper aims to propose a design of a quadcopter with minimal weight. This was achieved by adopting the hybrid optimisation technique over the conventional technique. The benefit of performing topology optimisation followed by lattice optimisation is the elimination of the lowest and the intermediate density elements in the model. Elimination of these elements does not significantly affect the structural properties while the weight of the model is reduced significantly.

6.1. Lattice optimisation on the quadcopter model

A lattice optimisation was performed on the original quadcopter model with the specified optimisation run parameters and objective. To achieve the aim of weight reduction, the weight of the model

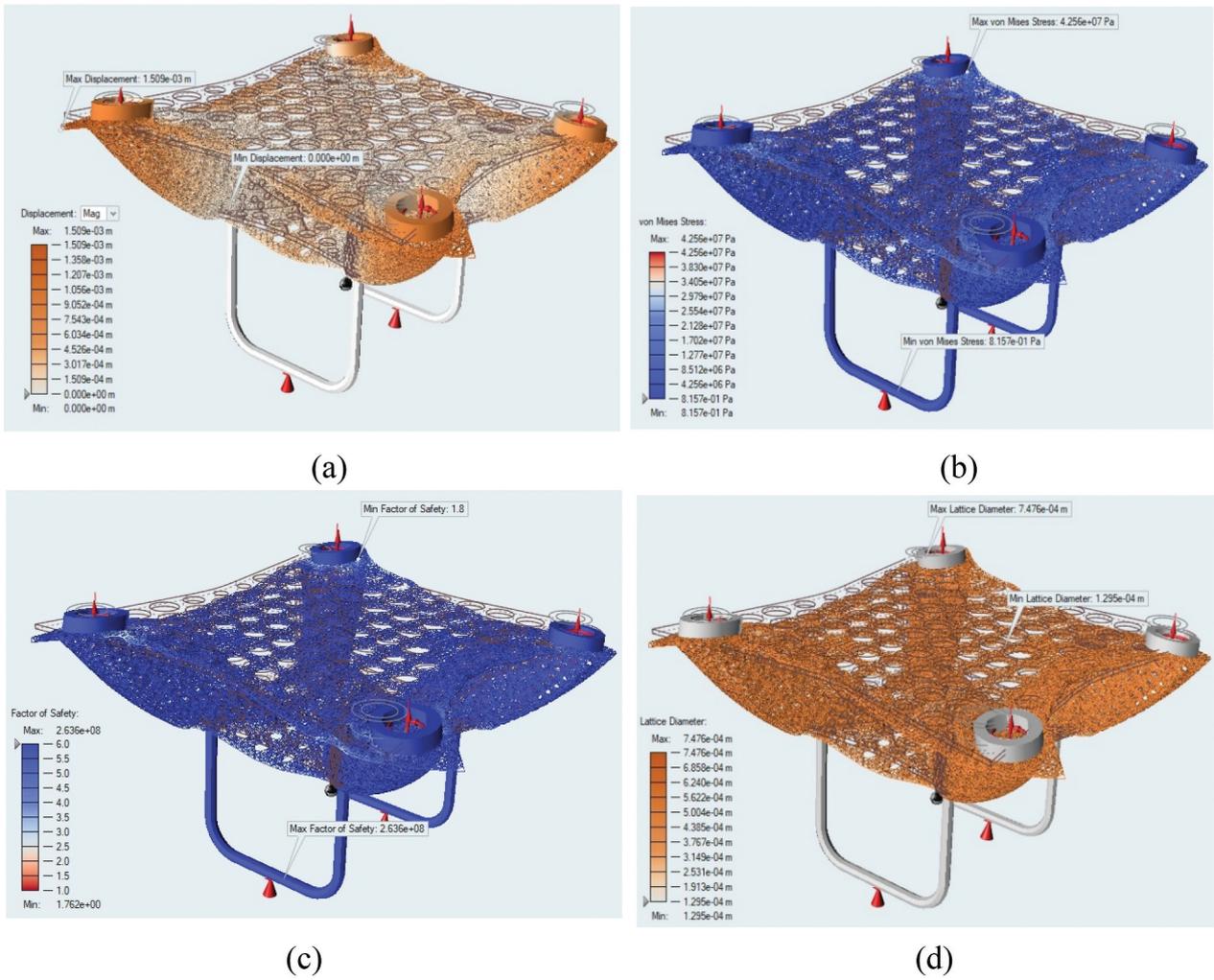


Figure 9. Linear static analysis result for a hybrid optimised model for various analyses: (a) displacement, (b) von mises stress, (c) factor of safety, and (d) lattice diameter contour plots.

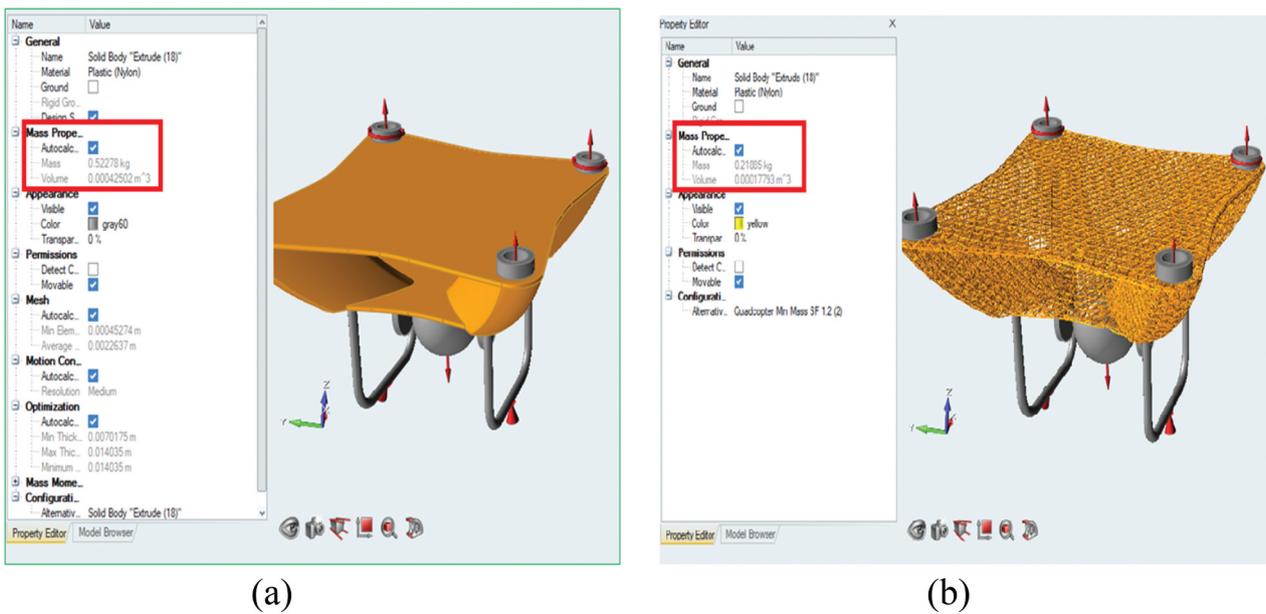


Figure 10. Weight of different quadcopter models, (a) original, (b) lattice optimisation.

Table 4. Comparison between original and lattice-optimised quadcopter model.

Original CAD model	Lattice optimised model	Percentage weight reduction
0.52278 kg	0.21885 kg	(1) %

Table 5. Comparison between original and hybrid optimised quadcopter model.

Original CAD model	Hybrid optimised model	Percent in weight reduction
0.52278 kg	0.083931 kg	83.9452%

**Figure 11.** Hybrid optimised quadcopter model.

before and after the optimisation is compared and analysed. In this regard, the weight of the original and the Lattice optimised model, is shown in [Figure 10](#). For better understanding, percentage reduction in the weight is mentioned in [Table 4](#).

6.2. Hybrid optimisation technique on quadcopter model

As mentioned above, the hybrid optimisation technique involves topology optimisation followed by lattice optimisation for enhanced weight reduction. [Table 5](#) contains the amount of weight reduction when compared with the lattice-optimised model.

The weight of the hybrid optimised quadcopter model is shown in [Figure 11](#).

Hence, comparing the lattice optimisation results with the hybrid optimisation results, it is evident that the hybrid optimisation technique enhanced the weight reduction of the Quadcopter model by 30.74% as compared to the lattice optimisation technique applied directly to the original quadcopter model.

7. Linear static analysis for all quadcopter models

Comparing the linear static analysis results obtained for the topologically optimised versus the hybrid optimised quadcopter model, one can assume parameters defining the structural properties of the model such as von mises stresses and displacement, and for the hybrid optimised model these values are slightly

Table 6. Linear static analysis results for the various analysis.

Analysis Type	Topology optimised model	Hybrid optimised model	Lattice optimised model
Factor of Safety (Minimum)	10.14	1.762	3.268
Displacement (Maximum)	0.09963 mm	1.509 mm	2.010 mm
Von Mises Stress (Maximum)	18.64 MPa	42.56 MPa	22.95 MPa

higher as compared to the topological optimised model as shown in Table 6. Hence, the model obtained after performing hybrid optimisation is the correct balance between the weight and the structural rigidity, neither of the two is compromised in the process. So, the optimum design for the defined optimisation objectives in each analysis is expected.

8. Conclusion

Various optimisation techniques were incorporated into the quadcopter model. The hybrid optimisation technique resulted in the highest weight reduction of 83.94% compared to the original quadcopter model. The model was designed by considering the requirements of defence forces for first aid, logistics, and attack purposes. To accomplish those objectives, payload carrying capacity of the quadcopter has been enhanced. Further, linear static analysis has been carried out for these optimised components to determine the various parameters and verify the functionality of the newly optimised components. The results obtained in the hybrid optimisation technique have been compared with the conventional method. The existing work can be further expanded to perform free size optimisation on the hybrid optimised model to reduce the weight of the model combined with a multi-model optimisation technique which could also find various applications in the commercial sector for logistics and courier purposes.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Kahaan Patel finished his bachelor's degree in Mechanical Engineering from Vellore Institute of Technology, Vellore, India, in 2018 and his M. Sc. Degree in Mechanical Engineering Design, from the University of Manchester, Manchester, M13 9PL, United Kingdom in 2023. His research area includes the design of CAD models using various software and analysis.

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Data availability statement

The data that support the findings of this paper are available from the corresponding author upon reasonable request.

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