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Generative Design of A 6-Axis Quadcopter Drone for Weight Optimization

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Abstract: Unmanned aerial vehicles (UAVs), known as drones, can be remotely operated using embedded technology and software-controlled flight plans. A six-axis drone's main problem is that its significant weight limits how much it can be used. As a result, the flexibility and endurance of the drone's design are necessary for excellent performance during altitude displacement. In order to create a body frame for the quadcopter, the project intends to solve the weight optimization problem via generative design. The three main steps of the optimization attempts utilizing generative design procedures are (a) abstraction, (b) initialization, and (c) interpretation. These are accomplished by employing the five generative design processes. The stress analysis and the generative design process were used to confirm that the generative design technique will help reduce the drone's weight. The drone using three (3) generative designs, was set to a total weight of less than 1kg. The results show that Generative Design 2 shows good optimization as follows, (a) 50.00% of parts of assembly optimized from eight parts to four parts, (b) 54.09% of the weight of the body frame optimized from 1.1565kg to 0.531kg, (c) 36.17% of the height of the body frame optimized from 94mm to 60mm, (d) 45.44% of stress analysis increased from 3.457MPa to 5.028MPa, (e) 83.00% reduction of displacement elongation from 3.918mm to 0.666mm and (f) 61.25% of production time optimized from 40 hours to 15.5 hours.

Keywords: Generative design, weight optimization, 6-axis quadcopter drone

1. Introduction

Unmanned aerial vehicles (UAVs) are multirotor flying machines that can be remotely piloted using embedded electronics and software-controlled flight plans. Multirotor flying vehicle is a generic term that includes all types of drones. A quadcopter is the simplest type of controllable multirotor flying vehicle in a UAV. The quadcopter uses four rotors arranged in an equal square pattern [1,2]. The quadrotor's inherent dynamic nature makes it good maneuverability. Quadcopters have four inputs: roll, pitch, yaw, and throttle, and six outputs to make it an underactuated system [3,4]. A few typical quadcopter applications are traffic monitoring, shipping delivery, geographic mapping, and search & rescue. In order to enhance feature matching and image perspective projection for agriculture, UAV has developed into an integrated instrument for monitoring and evaluating live green plants [5,6]. Association for Unmanned Vehicle System International (AUVSI) has reported that the most promising markets for UAVs are precision agriculture and public safety. To design a quadcopter, several design considerations must be considered, such as weight, payload, and supply of services. A drone has limited usage due to its heavy weight [7,8]. The manufacturing

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method of drone design is the main challenge following control targets, including production cost weight that can maintain both flexibility and fluidity required for creative design exploration [8].

In 1956, George E. Bothezat [9] designed a quadcopter converted from a wing model. However, early prototypes of the quadcopter suffered from poor performance, required extra pilot workload, poor stability augmentation, and limited control authority. The stability of these drones is controlled using electronic control systems and sensors. Tatale et al. [9] classified quadcopters into two categories: micro and mini air vehicles. Size and weight are the difference in classifying these types of quadcopters. Fig. 1 shows three types of dynamic parameters: the angle of pitch, roll, and yaw on a conventional quadrotor model. Each rotor is significant in creating thrust, torque, and direction, whereby the propellers create the thrust to the quadcopter [10-12]. Two of the thrust created clockwise act as pullers. The other two are anti-clockwise and act as pushers, resulting in zero torque. These rotors also determine the quadcopter's orientation around the center of mass to vary the speed and direction of the quadcopter. There are many parts to a quadcopter structure, which comprises the central part, a frame with four arms, as shown in Fig. 2. Other parts will be mounted to the frame in addition to the frame, including a battery, four brushless DC motors, a controller board, four propellers, and sensors. Therefore, the rigidity and weight of the frame must be prioritized to host all the components. The Axis of the drone is one of the foremost parameters to be considered in this research where it serves as the parameters of the weight optimization of the drone. A 3-axis drone is a UAV that can vertically lift during flight with only a gyroscope, which can only be stabilized by directly commanding the angular velocity. In comparison, the 6-Axis quadcopter drone is a UAV that can have an additional vertical lift, rolling, pitching, and yawing rotation during flight with a gyroscope and an accelerometer. Conventional engineering design entails iteratively analyzing and revising an initial notion until a workable solution is obtained [13]. The thrust force is necessary to guide correctly during flying in the desired direction.

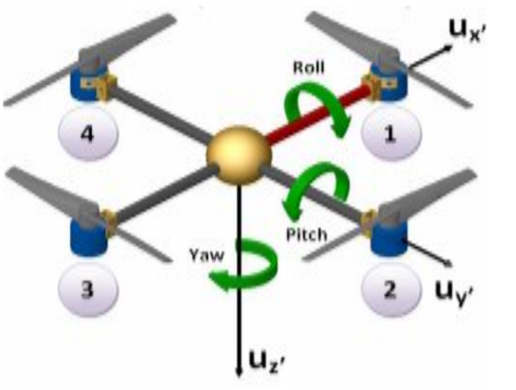


Fig. 1 - Yaw, pitch, and roll rotations of a conventional quadrotor [9]

Fig. 2 - Assembled Quadcopter Design [9]

To assess the function of optimization in design and its interaction with conventional approaches, the design attributes are examined at each stage of the conventional design process and compared with the requirements. The conventional design process does not involve computer simulations of predicted energy performance, leading to poor performance and high costs operations. Recently, generative design methodologies have been used more and more in a variety of technical domains. The mechanical industry has used generative design, a technique that depends on the capabilities of contemporary CAD systems, to pursue performance-driven design [14-16]. They are able to elaborate and present a number of reasonable solutions for a design challenge to a human user by utilizing artificial intelligence capabilities. Several different configurations satisfy enforced design constraints and maximize a goal function supplied to the algorithm using the generative design process. The suggested alternatives are the outcome of an artificial intelligence-guided iterative exploration of the relevant optimal solution. The generative design process comprises three major stages: (a) abstraction, (b) initialization, and (c) interpretation. In the first stage, generative design generates ideas for design requirements and analyzes the problems; hence the genetic model will be initialized after all the rule algorithms have been identified. Then, the designer must judge the output and select the optimum solutions. A approach known as Design for Manufacturing Assembly (DFMA) is utilized when developing new products and improving existing ones in order to reduce manufacturing and assembly costs [17]. Design for Manufacturing (DFM) and Design for Assembly (DFA) are combined in a process known as DFMA (DFA). DFM is a method for producing parts that facilitate production, whereas DFA is a methodology for creating products that are simple to assemble to predict the assembly cost and time [18]. The products were improved thanks to the DFMA method in terms of quality, capability, and the reduction of manufacturing costs. DFMA also introduced optimization, reducing the amount of work, time, and money needed to put together for future advancement. The goal of DFMA is to reduce the number of parts used in an assembly, increase the usage of current manufacturing techniques, and identify product requirements prior to the creation of a product. For example, a part reduction is one of the parameters used in the DFMA method. A decrease in the number of parts per product and the number of part types will result in an optimization that reaches a minimum number of components. In this research, a six-axis drone has limited usage due to its heavy weight. Therefore, high performance in a drone's altitude displacement requires the drone design's flexibility and endurance. Therefore, the types of material used for drone design will give different mechanical properties, i.e., tensile strength, stiffness, impact strength, and flexural strength [19-21]. The primary concern on weight optimization is the structure design of the product; there are some issues with the structure design type, which is limited iteration solutions by achieving the weight optimization. Therefore, this research aims to solve the weight optimization problem using the generative design procedure for designing a body frame of the quadcopter by using Autodesk Inventor and Autodesk Fusion 360. The generative design procedure will assist in reducing the weight of the 6-Axis quadcopter drone body frame, whereby in this research, the design will be verified using the stress analysis and the displacement analysis to reduce the part of an assembly, production time, and height of the body frame.

2. Methodology

2.1 Generative Design Weight Optimization and Specifications

Weight Optimization is one of the techniques primarily used in the automobile industry recently to achieve the optimum weight of the desired part or product. Weight optimization aims to attain the 6-Axis quadcopter drone designs with lower weight, use less material for manufacturing, and ultimately reduce the cost of the design. Weight optimization aims to create a concept design with a lower weight than other designs. The 6-Axis quadcopter drone parameters maintained for weight optimization are material, manufacture method, length of the body frame, and width. The weight optimization specification goals are as follows: (a) parts of the assembly, (b) body frame size, (c) the weight of the body frame, (d) stress analysis, (e) displacement analysis, and (f) production time. Tables 1 and 2 show the specifications of the 6-Axis quadcopter drone that will be maintained and the targeted goals for weight optimization. Mechanical structural design is one of the significant components in this research, as it must be carefully designed according to the set objectives. Table 3 and Fig. 3 show the parameters of the design, which are the length (L), width (W), and height (H) of the 6-Axis quadcopter drone. These are critical parameters essential when designing the body frame of the quadcopter.

2.2 Specification Goals for Weight Optimization

In weight optimization, one of the critical factors in reducing weight is reducing the number of parts. The reduction of part numbers on assembly is significant for weight optimization. To get to a minimum number of components in a system, part of assembly reduction reduces the number of parts per product and the variety of part kinds. Table 4 shows the specifications of the DJI Phantom 2 Vision drone used as the benchmarking design in this research. The DJI Phantom 2 Vision weights at 1.215kg. The thrust to weight ratio for the DJI Phantom 2 Vision is 1.6. Table 5 shows the specifications of a conventional design. The mass and the thrust to weight ratio of the DJI Phantom 2 Vision and conventional design does not show significant difference, i.e.: 1.60kg and 1.75, respectively as shown in Table 4 and Table 5 since the two designs have similar weight, therefore the same motor (DJI PV-05 DJI 2212) and propeller are applied for the conventional design. The DJI PV-05 DJI 2212 motor with 920KV provides low-speed high torque motor rotation with specifications in Table 4.

Table 1 - Specifications maintained for weight optimization

No	Specification	Parameters Maintained
1.	Material	ABS Plastic
2.	Manufacture Method	Additive Manufacturing
3.	Length of Body Frame	500mm
4.	Width of Body Frame	200mm

Table 2 - Specifications goals for weight optimization

No	Specification	Goals
1.	Parts of Assembly	Reduced
2.	Height of Body Frame	Reduced
3.	Weight of Body Frame	Reduced
4.	Stress Analysis	Improved
5.	Displacement Analysis	Improved
6.	Production Time	Reduced

Table 3 - Parameters of the design

Parameters	Symbol
Length	L
Width	W
Height	H

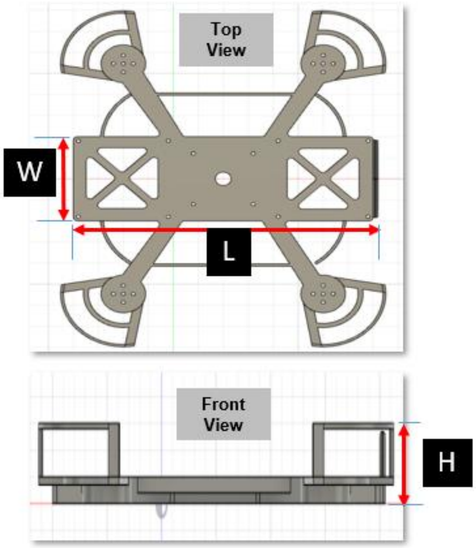


Fig. 3 - 6-Axis quadcopter drone design parameters

Table 4 - Specifications of DJI Phantom 2 Vision drone [22]

No	Specification	Value
1.	Model Mass	1.215kg
2.	Propeller Dimension	228.6mm(diameter) x 114.3mm(pitch) (30g)
3.	Motor	DJI PV-05 DJI 2212 (920Kv)(53g)
4.	Thrust	(0.485kg)(4)(9.81) = 20N
5.	Thrust to Weight Ration	(0.485)(4)/(1.125) = 1.60

Table 5 - Specifications of conventional design

No	Specification	Value
1.	Model Weight	1.106kg
2.	Propeller Dimension	228.6mm(diameter) x 114.3mm(pitch) (30g)
3.	Motor	DJI PV-05 DJI 2212 (920Kv)(53g)
4.	Thrust	(0.485kg)(4)(9.81) = 20N
5.	Thrust to Weight Ration	(0.485)(4)/(1.125) = 1.75

2.3 Generative Design Procedures

There are five procedures in the generative design procedure, as depicted in Fig. 4. The generative design will be carried out entirely using Autodesk Fusion 360. The first procedure is selecting and defining the preserved geometry and preserving the generative design parameter. Next is to select the generative design's obstacles geometry and set the structural constraint on preserve geometry. Load case on preserving the geometry is then applied, and ultimately, the selection of the final generative design. The preserved geometry of generative design incorporates bodies in the final shape of the generative design. Fig. 5 shows the preserve geometry selected for generative design, which totals four parts of the assembly compared to the conventional design, with eight parts. The preserve geometry consists of the mounts for the motors, flight controller, and supports. The maintained geometry, shown in green, is where the loads and constraints are defined. These four parts of the assembly are the bodies that will not change during generation outcomes, and the area of the main body frame will maintain at 500mm x 200mm. The second procedure of the generative design will be defining the obstacle geometry. The obstacle geometry of generative design represents the empty spaces for generative design. Fig. 6 shows the obstacle geometry selected for generative design, which creates quadcopter shape spaces. The motors, flight controller, and supports mount holes are regarded as obstacle geometry. The red-colored obstruction is referred to as the outer boundary. The third generative design procedure will define the structural constraint on preserving geometry. The structure constraint on preserving the geometry of generative design defines interfaces between design and the surrounding environment. Fig. 7 shows the structural constraint on preserving geometry for the generative design that defines interfaces between the design and the surrounding environment. The motor mount holes are regarded as the fixed constraints according to how the fixed constraints are defined in static analysis. The fourth procedure of the generative design will be defining the load case to preserve the geometry of the generative design. The load case on preserve geometry of generative design defines the forces applied on that generative design should withstand. Fig. 8 shows the load case on preserve geometry for generative design, which defines the forces that the generative design should withstand. The load cases are applied to the preserved geometry. In load case 1, the component is weighed at 15.62N and applied downwardly to the top face of the preserved geometry. In load case 2, a 20N motor thrust is supplied to the motor mount's underside, pushing it upward. The fifth procedure, the final procedure of the generative design, will be a selection of the final solution of generative design. Multiple design iterations will help identify the optimal outcomes by exploring and filtering multiple iterations. Fig. 9 shows the selection of the final solution for generative design. The explore tab on the toolbar makes it possible to see the many design iterations. This study has several possible outcomes; the optimum outcome will be chosen using the optimized design with the highest stress and lowest weight.

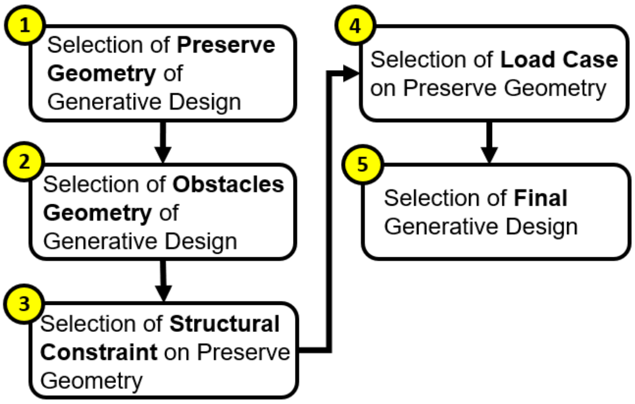


Fig. 4 - Defining preserve geometry for generative design

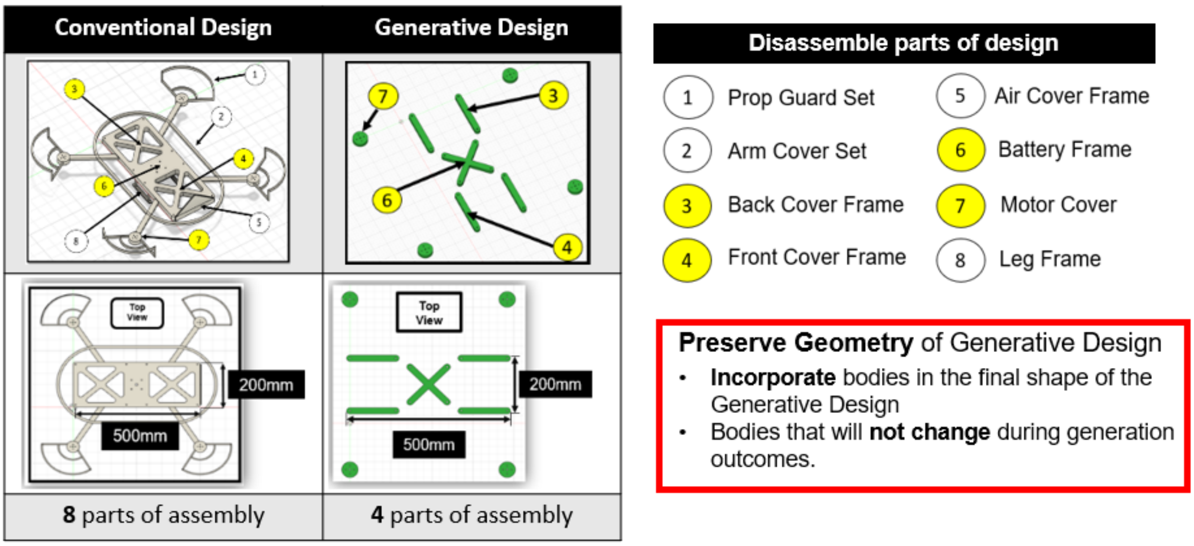


Fig. 5 - Defining preserve geometry for generative design

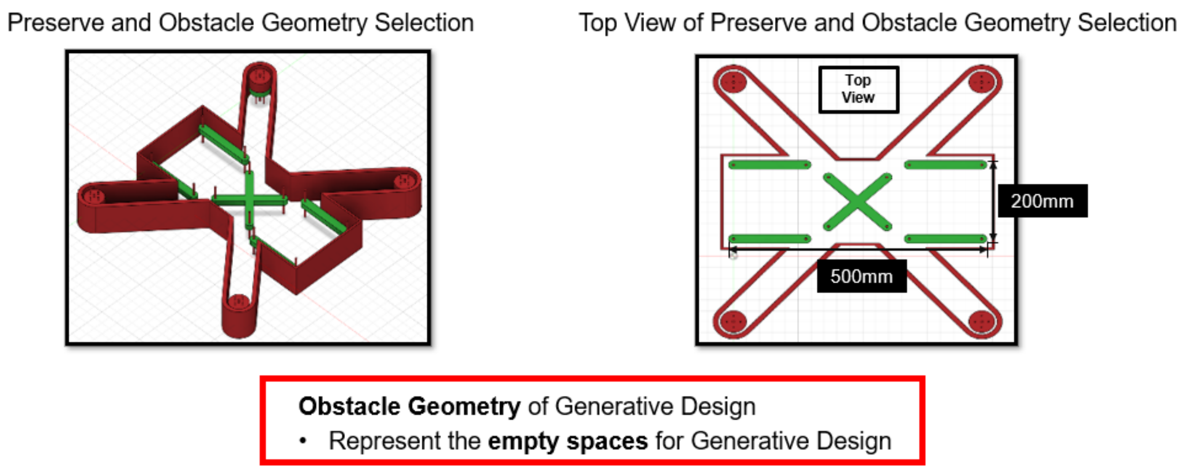


Fig. 6 - Defining obstacle geometry for generative design

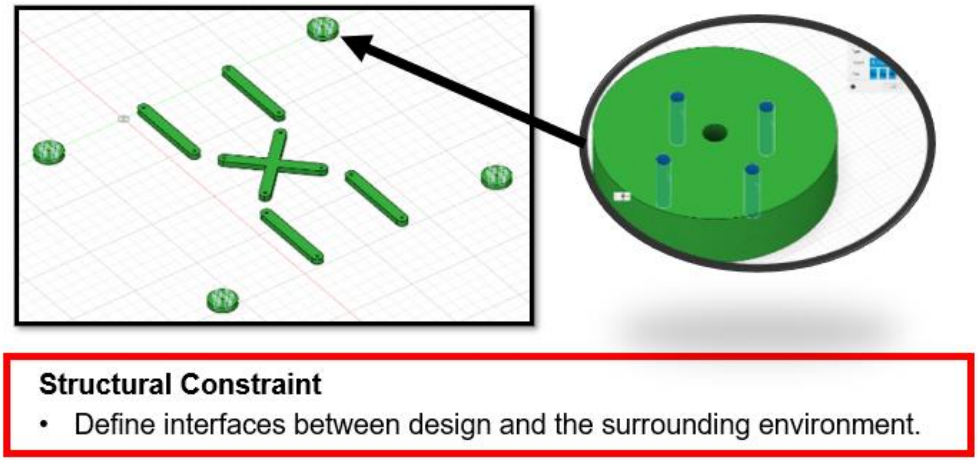


Fig. 7 - Defining structural constraint for generative design

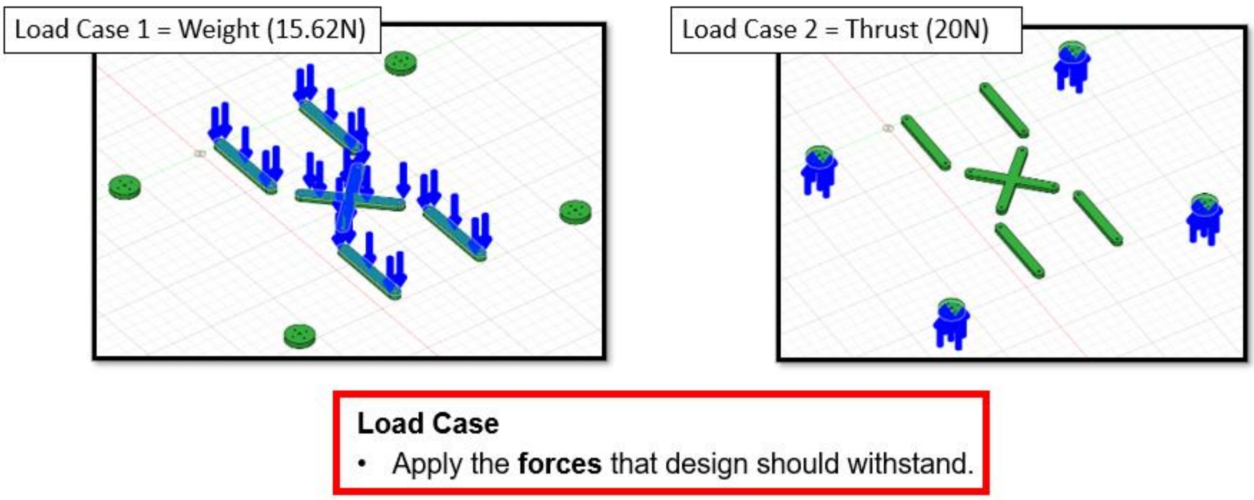


Fig. 8 - Defining load case on preserve geometry for generative design

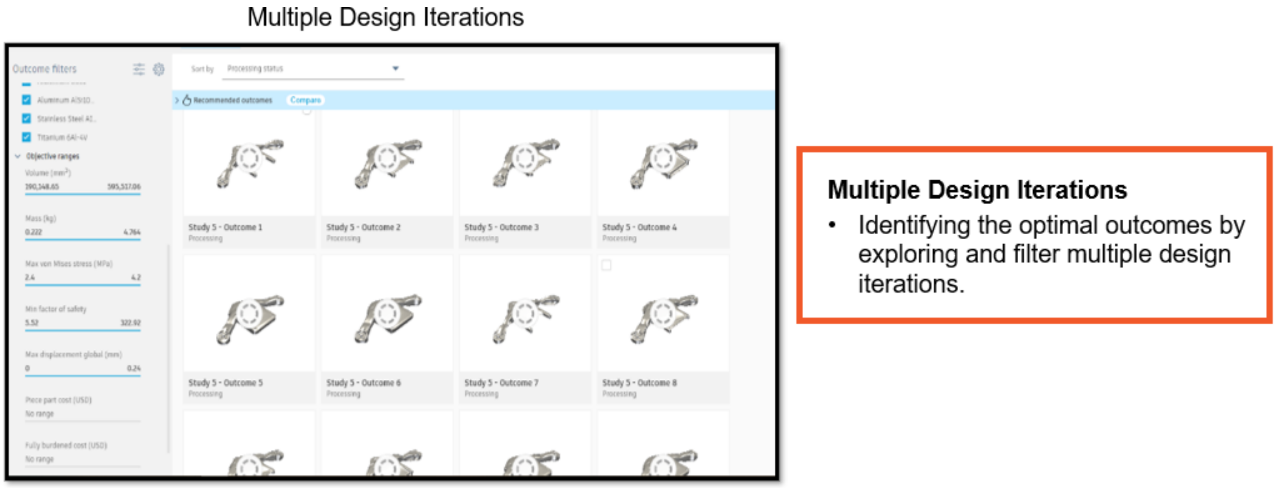


Fig. 9 - Selection of final solution for generative design

3. Results and Discussion

3.1 Stress and Displacement Analysis of Conventional Design

This section analyzes the deformation and stress in the model from structural loads and constraints in this section. The results are calculated based on the linear response to the stress assumption. Acrylonitrile Butadiene Styrene (ABS) plastic has been selected as the material chosen for the static stress analysis. Table 6 shows the material ABS properties. Fig. 10 shows the motor mounts of the conventional design when defining constraints. For this research, the motor mounts are regarded as the fixed restrictions. Four mounting holes are present, and a total of sixteen holes for four motors have been chosen for fixed limits. When creating a load case for model weight, Fig. 11 depicts the body frame of the traditional design. The estimated total weight of the parts, including the motors, battery, flight controller and receiver, and propellers, is 15.62N. On the model's upper face, the load case is applied in a downward direction. When defining the load case for motor thrust, Fig. 12 depicts the body frame of the standard design. This load enclosure is situated at the upward-facing bottom surface of the motor mount. The motor thrust of 20N is considered for this research.

Table 6 - ABS plastic properties

Properties	Value
Density	$1.06e^{-6}$ kg/(mm^3)
Young's Modulus	2240MPa
Poisson's Ratio	0.38
Yield Strength	20MPa
Ultimate Tensile Strength	29.6 MPa
Thermal Conductivity	$1.6e^{-4}$ W/ (mm.C)
Thermal Expansion Coefficient	8.57^{e-5} C
Specific Heat	1500 J / (kg.C)

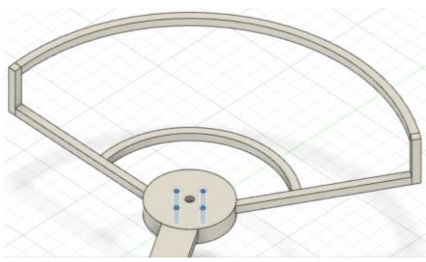


Fig. 10 - Defining constraint motor mounts

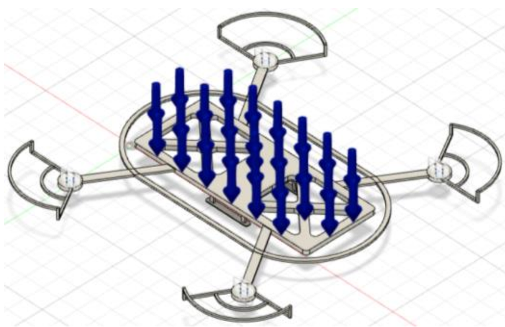


Fig. 11 - Defining load case for model weight

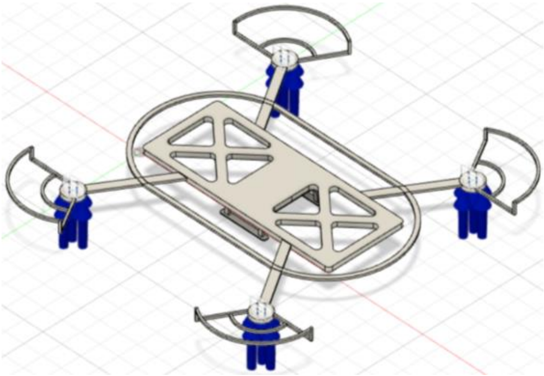


Fig. 12 - Defining load case for motor thrust

3.2 Generative Design Iteration Based On Weight Optimization

After the generative design process has been selected, there are more than 30 design iterations outcomes based on the specifications of weight optimization. In this research, three generative designs (Design 1, Design 2, and Design 3) are selected for comparison from the multiple iterations. Fig. 13 compares the weight of the body frame, design view, and linkage between the cover frame and battery frame. The linkage between the cover and battery frames differentiates the physical appearance of the three generative designs. Generative Design 1 has the most significant gap between the cover and battery frames. Generative Design 2 has the smallest gap but is more prominent than generative Design 3. From Fig. 13, Generative Design 2 has the lowest weight on the body frame, which is 0.531kg, while Generative Design 3 has the highest body frame, 1.5kg. Fig. 14 shows the comparison in terms of the height of the body frame. The conventional design has the highest height of the body frame, 94mm, compared to Generative Design 1, which has a height of the body frame, which is 80mm. Generative Design 3 has the lowest height, 42mm, but higher than Generative Design 2, 60mm. Fig. 15 compares the three generative designs in terms of part of an assembly. The conventional design has the highest part of an assembly, eight parts, compared to Design 1, 2, and 3, i.e., four parts. From the analysis, the generative design procedure reduced the parts from eight to four compared to the conventional design. The total four assembly parts in generative design are the battery frame, motor cover frame, back cover frame, and front cover frame.

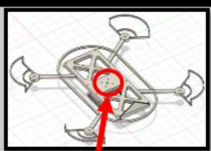
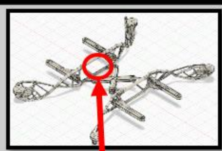
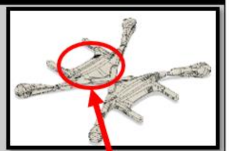
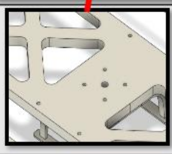
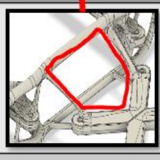
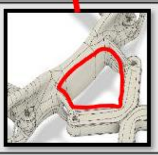
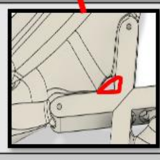
Design	Conventional Design	Generative Design 1	Generative Design 2	Generative Design 3
Design View				
Linkage in between Cover Frames and Battery Frame				
Weight of Body Frame	1.156kg	0.597kg	**0.531kg**	1.5kg

Fig. 13 - Comparison of weight of body frame, design view and linkage in between cover frame and battery frame

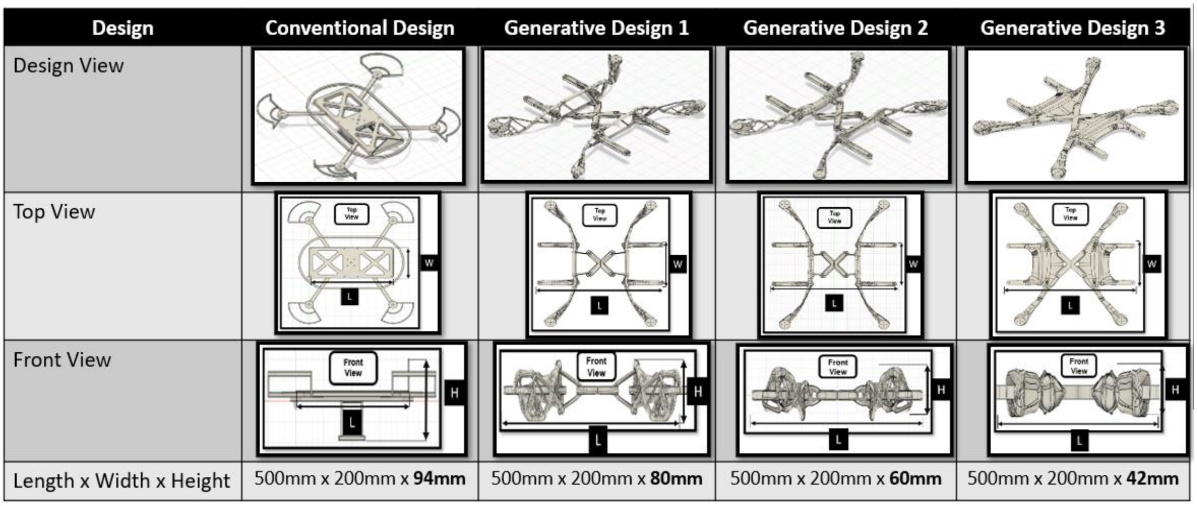


Fig. 14 - Comparison of height of body frame

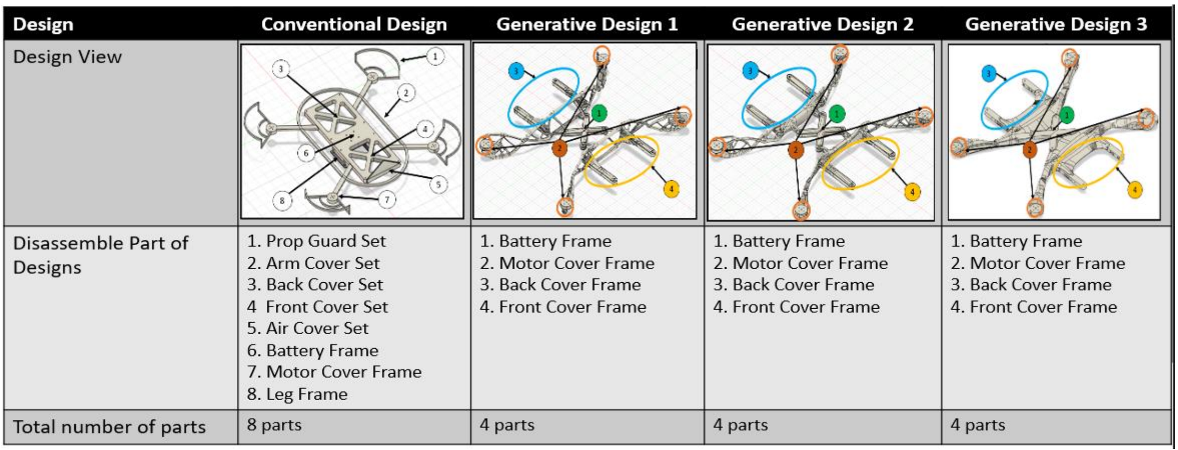


Fig. 15 - Comparison of part of assembly

3.3 Stress and Displacement Analysis

Fig. 16 compares generative designs in terms of stress and displacement. Stress analysis analyzes the maximum value for stress used to determine whether a given material will yield or fracture. Generative Design 2 has the maximum value for stress analysis which is 5.028MPa compared to the Conventional Design and the other two generative designs. The displacement elongation analysis analyzes the value of the displacement on material when the force is applied. Generative Design 3 has the lowest maximum displacement, 0.2538mm, among all the designs. Fig. 17 shows the comparison between generative designs in terms of production time. The additive manufacturing method is conducted using the Ender 5 Plus device, and the material will be fixed as ABS Plastic. The conventional design has the longest total production time, 40 hours. Generative Design 2 has the shortest value for production time, which is 15.5 hours.

3.4 Comparison of Conventional Design and Generative Design

Table 7 shows the comparison between conventional design and the three generative designs in terms of part of an assembly, the height of the body frame, weight of the body frame, stress analysis, displacement analysis, and production time. The results tabulated in Table 7 and Fig. 18 display the analysis of weight optimization of different designs. All three generative designs have the same lowest parts of the assembly, four, in contra to the conventional design, which has eight parts. Reduction in the total parts of assembly used helps save the costs such as the amount of labor required and the usage of material to enhance higher efficiency of production. For the weight of the body frame, Generative Design 2 indicated the lowest weight at 0.531kg. The reduction in the total weight of the body frame brings benefits in saving battery life as the downward force that needs to be overcome has been reduced. Fused Deposition Modelling (FDM) is selected for simulation in manufacturing additive manufacturing. The 3D printer model is Ender 5 Plus with a 0.4mm nozzle, 20% infill, and 0.2mm layer height. Generative Design 2 showed the shortest production time among all designs by using FDM manufacturing which is 15.5 hours. In the height of the body frame, Generative Design 3 showed the shortest height among all designs, 42mm. Low height will reduce the center of gravity which helps increase balance and stability. In stress analysis, Generative Design 2 showed the most potent stress among the designs, 5.028MPa, which will enhance the body frame's strength to withstand the forces during flight. For the displacement analysis, Generative Design 3 showed the shortest displacement or low elongation among the designs, 0.2538mm. This low value of elasticity enhances the strength of the body frame to withstand the forces during flight and improve the robustness of the design. In summary, based on Table 7 and Fig. 18, Generative Design 2 was selected as the best solution for weight optimization. Although Generative Design 3 showed the shortest height of the body frame and displacement analysis, its weight exceeds 1kg, which is 1.5kg.

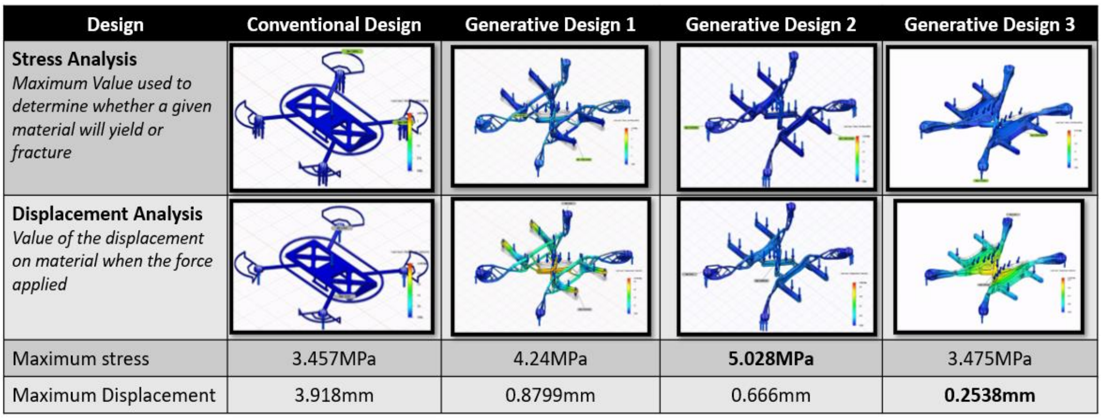


Fig. 16 - Comparison of stress and displacement analysis

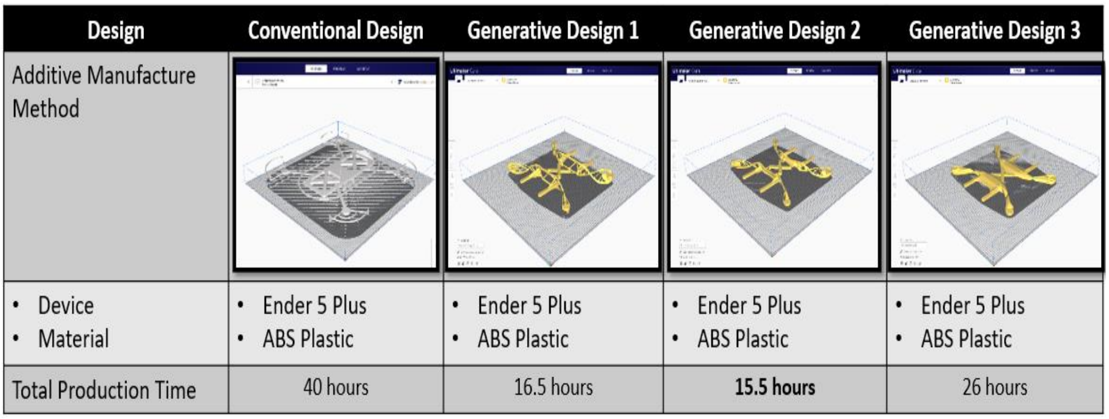


Fig. 17 - Comparison of production time

Table 7 - Comparison in between conventional design and generative design

No	Design	Conventional Design	Generative Design 1	Generative Design 2	Generative Design 3
1.	Parts of Assembly	8	4	4	4
2.	Height of Body Frame	94	80	60	42
3.	Weight of Body Frame	1.156kg	0.597kg	0.531kg	1.5kg
4.	Stress Analysis	3.457MPa	4.24MPa	5.028MPa	3.475MPa
5.	Displacement Analysis	3.918mm	0.8799mm	0.666mm	0.2538mm
6.	Production Time	40 hours	16.5 hours	15.5 hours	26 hours

4. Conclusion and Future Work

In conclusion, this research presents comprehensive works on the generative design of a 6-Axis quadcopter drone for weight optimization. There were multiple different explorations carried out using five procedures of generative design procedures. Three generative designs were selected for comparison with the conventional design using Autodesk Inventor and Autodesk Fusion 360. Six parameters of the 6-axis quadcopter drone are part of the assembly, the weight of the body frame, height of the body frame, stress analysis, displacement analysis, and production have been analyzed using Design of Manufacturing and Assembly (DFMA). Generative Design 2 was selected to optimize the weight optimization solution by implementing the generative design procedures. Generative Design 2 shows that (a) 50.00% of parts of assembly optimized from eight parts to four parts, (b) 54.09% of the weight of the body frame optimized from

1.1565kg to 0.531kg, (c) 36.17% of the height of the body frame optimized from 94mm to 60mm, (d) 45.44% of stress analysis increased from 3.457MPa to 5.028MPa, (e) 83.00% reduction of displacement elongation from 3.918mm to 0.666mm and (f) 61.25% of production time optimized from 40 hours to 15.5 hours. Based on Generative design 2, a 6-Axis quadcopter drone prototype has been optimized using Selective Laser Sintering (SLS) for weight optimization. All in all, this research concludes that the generative design procedure significantly improves the weight optimization process. Future works include applying other parameters such as type of material and complexity of lattice structure can be stimulated to obtain higher weight optimization. Further work includes fabricating and testing the prototype capability and performance on altitude displacement.

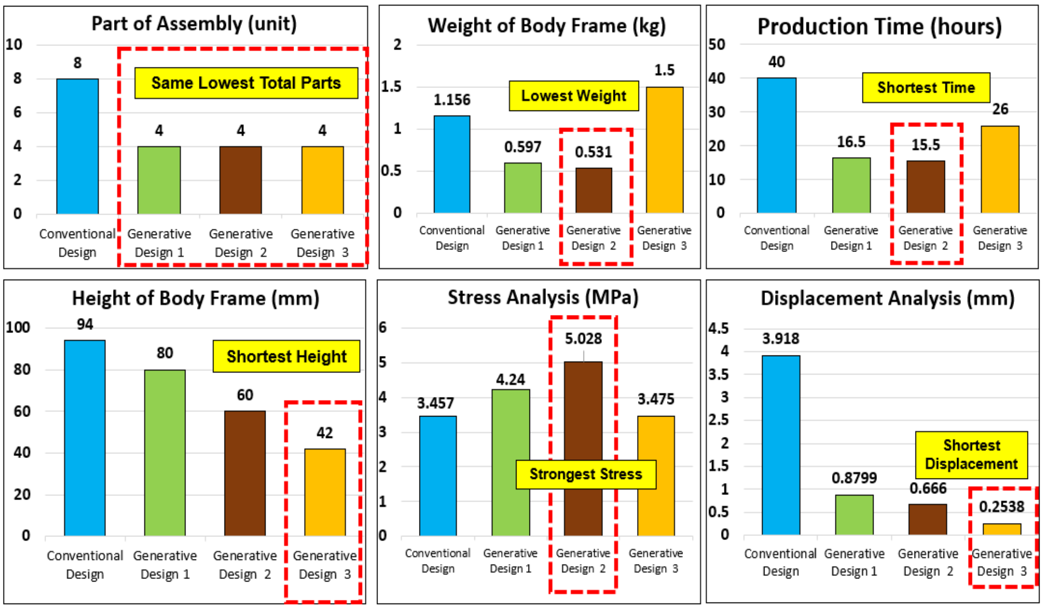


Fig. 18 - Weight optimization on conventional and generative design

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