Weight optimization of fixed landing gear for medium range UAV

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Abstract: Weight reduction of Unmanned Aerial Vehicle (UAV) components and systems is one of the most essential factors for aviation. Take-off gross weight can be divided into crew weight, payload, fuel, and empty weight. The empty weight is divided into the structure, engine/s, landing gear, avionics and fixed equipment. Engine/s, landing gear, avionics and fixed equipment are selective items. Weight optimization can be made for structure and landing gear to minimize aircraft total weight.

The main objective of the present study is to optimize weight and reach safe landing for a medium range UAV landing gear. The reduced weight can be used to increase payload and/or fuel to increase range or endurance of the UAV.

In the present study, ANSYS shape (Topology) optimization tool is used to get a proposed shape for the UAV landing gear. Then parametric size optimization of the shape proposed was done. Design of experiment (DOE) technique is used in order to get the minimum weight for the landing gear at a specified stress limit.

Aluminum alloy 7075-T61 and bi-directional carbon fiber which are the most common used materials in UAVs landing gear were used, It was found that using topology weight optimization technique reduces Aluminum Alloy landing gear weight by (30.4 %) changing the material to be bi-directional carbon fiber without optimization reduce landing gear weight with additional value (27.9 %). Optimizing bi-directional carbon fiber landing gear reduces the weight with additional value (4 %) to be the total weight ratio by (62.3 %).

The optimization technique for weight optimization is a guide to optimize any other type of landing / part to minimize the total weight for the Unmanned Aerial Vehicle.

Keywords: Weight reduction, Shape optimization, Size optimization, Optimization Design Parameters

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1. Introduction

Due to the importance of weight reduction in aviation field [1] structural optimization methods started in aerospace industry in by the end of 1950. Aerospace manufacturing industry increases applications of optimization methods for the optimum design to minimize aircraft structural components weight [2].A few of these studies are referenced in this section to provide some background information in the field. In 1960s, Brandt and Wasiutynski[3] reviewed the state of art in the field of optimal design of structures. In addition, survey papers by Schmit [4] and Vanderplaats [5] offered numerous and important references on the theory and applications of structural optimization. Analytical work was done on component optimization, of which the work presented by Shanley [6] is a typical example. Dantzig [7] developed linear programming techniques, and with the advent of computer technology, these techniques were applied to the design of frame and beam structures. Schmit [8], offered a comprehensive study on the application of mathematical programming techniques to solve different types of nonlinear and inequality-constrained problems concerned with the design of elastic structures under a variety of loading conditions. Schmit and Farshi [9] published the concept of using approximation techniques for structural synthesis. These techniques resurrected the use of mathematical programming for structural optimization. Starnes, Jr. and Haftka [10] overcame the difficulties in using approximation techniques for some constraints such as buckling, by introducing the concept of conservative constraint approximations.

2. Optimization

Optimization is a problem in which design values are needed to be determined to reach best objective function under certain constraints [11].

Optimization can be classified into two main types: Structural Optimization and Shape and Size Optimization. The differences between them are shown in Figure-1.

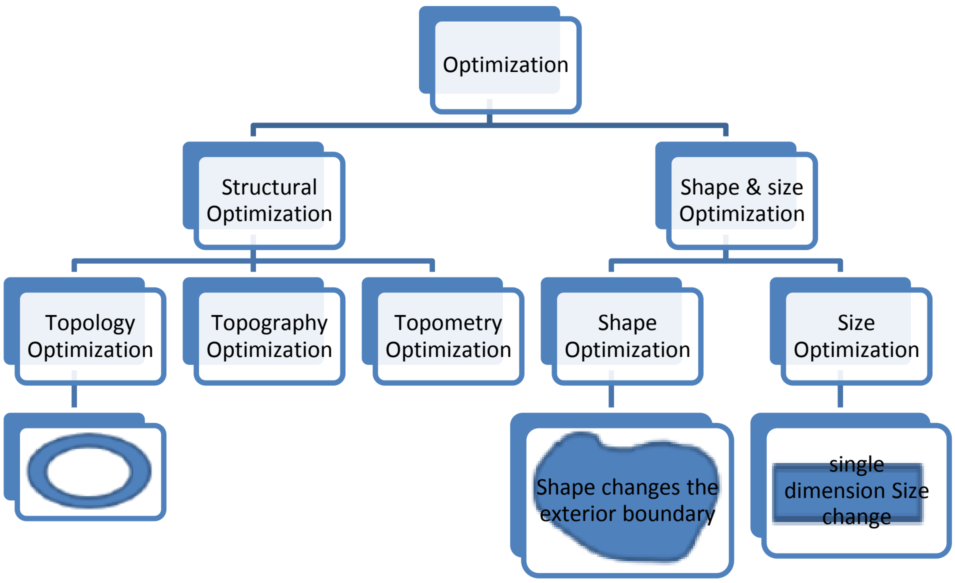

Figure-1: Optimization techniques [12].

In order to improve the obtained results optimization problem has to be formulated. An objective function, design variables and state variables needs to be introduced. The objective function (f) represents an objective that could either be minimized/maximized. Volume of a structure or stiffness could be the objective. Some structural design domain and state variables associated to the objective function, needs to be defined. [13]

The design variables (x) describes the design features of the structure, it may represent the geometry. The state variable (y) represents the structural response which can be, for example be recognized as stress, strain or displacement. The state variables depend on the design variables, y(x). The objective function is subjected to the design and state variable constraints to steer the optimization to a required solution [13].

$$\begin{cases} \boldsymbol{Min\ x} & \boldsymbol{f(x, y(x))} \\ \boldsymbol{Subject\ to} & \begin{cases} \boldsymbol{design\ constraint\ on\ x} \\ \boldsymbol{state\ constraint\ on\ y(x)} \\ \boldsymbol{equilibrium\ constraint} \end{cases} \end{cases} \tag{1}$$

For an example a displacement in a direction, function G(y) that represents the state variables can be introduced. This state function can be incorporated as a constraint to the optimization task, where it is usually formulated such that $G(y) \leq 0$. Consider the case where G(y) is represented by a displacement vector G(u(x)) in a discrete finite element problem. To establish the state function, this requires that nodal displacement is solved for: [13].

$$\boldsymbol{u(x) = K(x)^{-1} f(x)} \tag{2}$$

Where “K” is a Global stiffness matrix and “f” is a Global load vector.

This means that the optimization task can be expressed in a so-called nested formulation where the equilibrium constraint is taken care of by the state function formulation [13].

$$\begin{cases} \boldsymbol{Min\ x} & \boldsymbol{F(x, y(x))} \\ \boldsymbol{Subject\ to} & \mathbf{G(u(x)) \leq 0} \end{cases} \tag{3}$$

The optimization task presented in equation is called simultaneous formulation in comparison. Equation (3) is usually solved by evaluating derivatives of f and G with respect to x. In this context, x will represent a geometrical feature.

Constraints can be divided into two main different types[14]:

1. ***Geometric constraints.***
    a. **Frozen areas:** Part of the body constrained with a relative density.
    b. **Symmetry conditions:** in entire design part of the design space may be specified as symmetric.
    c. **Production conditions:** one of the most important geometric constraint, designed to counter that make the part possible to be produce with conventional production methods.
    d. **Member size:** Specifying upper and lower limits for any member size to assures that no cross section is too big or small.
    e. **Fixation constraints:** If the part is fixed with other part, fixation area or holes must be considered

2. ***Performance constraints:*** design responses after defining the objective.

Optimization starts from CAD design and ends with final geometry as shown in Figure 2 [15].

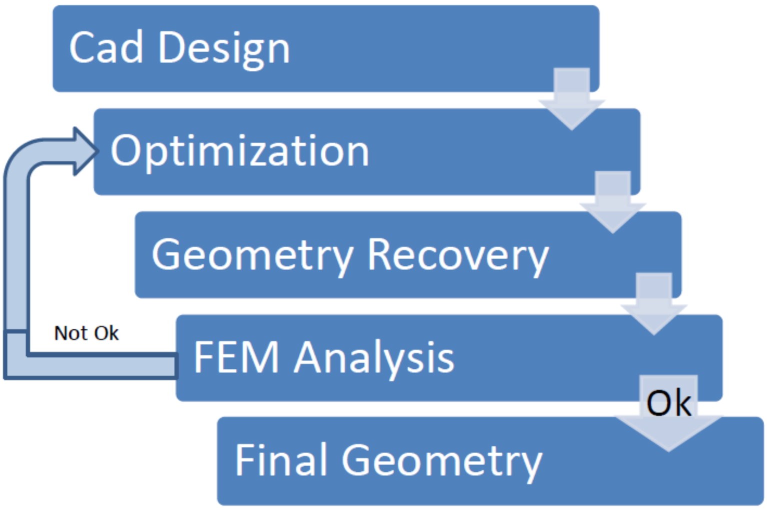

Figure 2: Steps For Optimization

2.1 Parameter study steps

ANSYS design optimization algorithms drive Workbench to find improved designs automatically. These algorithms can search the design space with direct solves or use the response surface. The relationships between multiple objectives, constraints and parameter can be taken and define them in the interface as follows:

Step 1: Parameters:In this step , Input and out parameters are defined,[16].

Step 2: Design of experiment: In this step Simulations with several design points are performed. The design points are chosen according to method of design of experiment, [16].

Step 3: Response surface: In this step the design points are their response values are used to best-fit mathematic functions. The functions are called response surfaces. Each response value (output parameter) has a response surface [16].

Step 4: Optimization: In this step, the constraint of each output parameter is specified [16].

The main objective of this study is optimizing weight and reach safe landing for a medium range Unmanned Aerial Vehicle (UAV) Landing gear.

3. Preliminary UAV Design calculation

For a steady state flight, there are four type of forces affecting an airplane in order to fly straight and leveled, all the forces are in equilibrium. The produced lift is balanced with its weight and the thrust produced by its engine is balanced with the drag force.
This balance of forces changes as the airplane rises and descends, as it speeds up and slows down, and as it turns. All of them are interrelated and changing one force affects the others[17].
During landing an airplane pilot needs to reduce thrust and increases drag, Therefor, the lift is reduced in an organized way until it becomes lesser than the airplane weight. As a result for this difference between lift and weight airplane descends. Finally, the airplane touches down and land on the runway. The landing gears absorb the impact of the touch down. To study the stresses on the landing gear, the impact force has to be calculated [18] .

3.1 Airplane Take-off Weight

Airplane take-off gross weight is the total weight of the aircraft according to its designed mission [19]. Take-off gross weight can be broken into crew, payload (or passenger.), fuel, and empty weights. The empty weight is divided into the structure, engine/s, landing gear, avionics and fixed equipment. Take-off weight buildup can be summarized in the following equation:

$$\boldsymbol{W_{T.O} = W_{crew} + W_{payload} + W_{fuel} + W_{empty}} \quad (4)$$

Where:

$W_{T.O.}$ = *Take-off weight (kg)*
W_{crew} = *Crew weight (kg)*
$W_{payload}$ = *payload weight (kg)*
W_{fuel} = *Fuel weight (kg)*
W_e = *Empty weight (kg)*

Empty-weight fractions vary from about 0.3 to 0.7 of the total weight. Type of aircraft also has a strong effect on empty-weight fractions. The empty weight fraction is estimated using improved statistical equations [23] as follow:

$$\frac{W_e}{W_{T.O}} = a + bW_{T.O}^{C1}A^{C2}(hp/W_{T.O})^{C3}(W_{T.O}/S)^{C4}V_{max}^{C5} \quad (5)$$

Where:

A,a,b,C1,C2,C3,C4,C5 Constants change according to Airplane type
hp = Engine horse power (hp)
S = Airplane wing area (m^2)
V_{max} = Maximum airplane speed (Km/hr.)

Engine/s, landing gear, avionics and fixed equipment are selective items. Weight optimization can be made for structure and landing gear to minimize aircraft total weight.

From equation no. (5), The Constants A,a,b,C1,C2,C3,C4,C5 for the proposed UAV will be selected as listed in Table 1 [23]

Table 1: Constants for the proposed UAV

A	a	b	C1	C2	C3	C4	C5
0.99	0	0.59	0.1	0.05	0.1	0.05	0.17

With the assumption for maximum airplane speed (Vmax=110 km/hr.), engine horse power 32 hp and wing area (S=8 m^2)

$$\frac{W_e}{W_{T.O}} = 0.588 \qquad W_{T.O} = \frac{W_e}{0.588}$$

3.2 Airworthiness Requirements (AWR):

The airworthiness of an aircraft is concerned with safety standards combined during all phases of its construction. Structure strength range assures safety in event of a crash landing, and includes design requirements relating to aerodynamics, performance, hydraulic systems and electrical systems [20].

The choice of minimum safety standards is mainly the concern of the 'National and International' airworthiness authorities, which are official requirements handbooks. AWR handbooks include design data, operational requirements, safety requirements,….etc. [20].

For this study Federal Aviation Regulations (FAR) part 23 will be the reference to calculate the landing force to assure safety landing. According to FAR (part 23): [21]

- Factor of safety of 1.5 must be used.
- The landing weight 95 percent of the maximum weight.
- Wings lift not exceeding two-third of the weight of the airplane.

4. Problem Definition:

For medium take-off weight fixed landing gear is used. For large take-off weight retractable landing gear with shock absorber is used in both take-off and landing.

As a case study, a medium range UAV with maximum take-off weight ($W_{T.O}$) **150 kg**, landing weight (W_L) can be calculated according to FAR(23):

$$\boldsymbol{W_L = 0.95\, W_{T.O.}} \tag{6}$$

$$\boxed{W_L = 142.5\ kg}$$

$$\boldsymbol{L_{landing} < \frac{2}{3} x 9.81\, W_L} \tag{7}$$

$$\boxed{L_{landing} < 932\ N \qquad L_{landing} = 908\ N}$$

$$\boldsymbol{W_F = W_L - \frac{L_{landing}}{9.81}} \tag{8}$$

$$\boxed{W_F = 490\ N \qquad m_F = 50\ KG}$$

The falling force, will be calculated like a falling ball, [22]. The dynamic energy in a moving object will be calculated for a falling body from an altitude 0.5 m. From calculations and FAR23 constraints the total landing force will be 3678.75 N. This force will be divided into two equal forces. Each is 1850 N acting on the left and the right gear contacts

There are two main constructions constraints which should be considered during the selection of UAV fixed landing gear shape and dimension:

1. Fixation of landing gear to the UAV fuselage. Fuselage size is calculated in preliminary design. Dimension of fuselage and way of fixation make constrain in landing gear dimension [23].
2. Fixation of wheel to landing gear. Wheel base and tire size are calculated in the preliminary design. Wheel base distance from fuselage to the ground make another dimension constrain in landing gear [23].

From pervious constrains landing gear will be divided into three main parts as shown in **Figure 3**:

1- Part-1: Wheel fixation part which appears with a green color. Size of this part is calculated from tire size.

2- Part-2: Landing gear fixation part which appears with a yellow. Size of this part is calculated from fuselage size.

3- Part-3: Shock absorption part which will be designed and optimized. This part appears with a red color. Size of this part is calculated from wheel base dimension and distance between fuselage and ground.

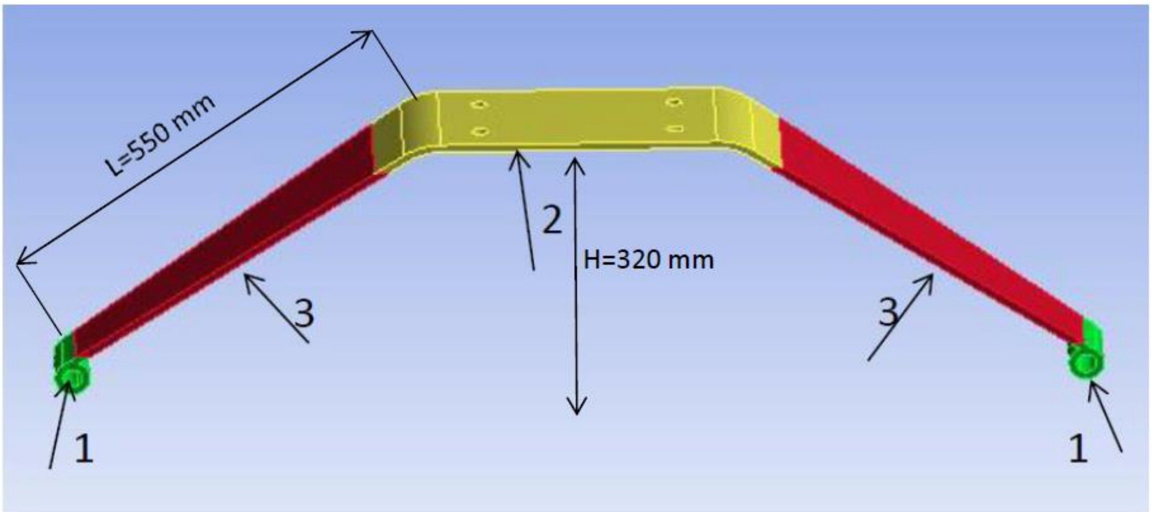

Figure 3: UAV Landing gear main parts

Dimension of shock absorption part can be changed according to calculation and optimization. Dimension of the other two parts are related to other dimensions.

From Figure **3**, the altitude of Part-2 from centroid of part-1 (wheel fixation point) is “h” mm. The total length of each leg of part-3 is “L” mm.

Two different materials will be used to solve this model, Aluminum alloy 7075-T61 with Ultimate Strength (σ_u) 572 MPa and Yield Strength (σ_y) 503 MPa, bi-directional carbon fiber of thickness (0.1 mm) with Ultimate Compression Strength (σ_C) 437 MPa and Ultimate Tensile Strength (σ_T) 513 MPa.

5. Stress Analysis for initial Model

The model used to solve non-optimized model is shown in Figure 4. Landing gear is fixed by 4 bolts to UAV. The landing gear structure is 80 layer carbon fiber bi-directional composite material with a stacking $(45_5,0_{30},\ 45_5)_S$ with thickness 0.1 mm for each layer. 96% of the meshed cells are in the excellent zone. This result shows that the used mesh is in excellent zone.

In initial shape model, landing gear is fixed to UAV by four points of fixation to fix it from directional motion and/or rotation. This fixation is shown in Figure 4. Load is divided into two equal forces. Each is 1850 N in Z-direction acting on left and right gears contact.

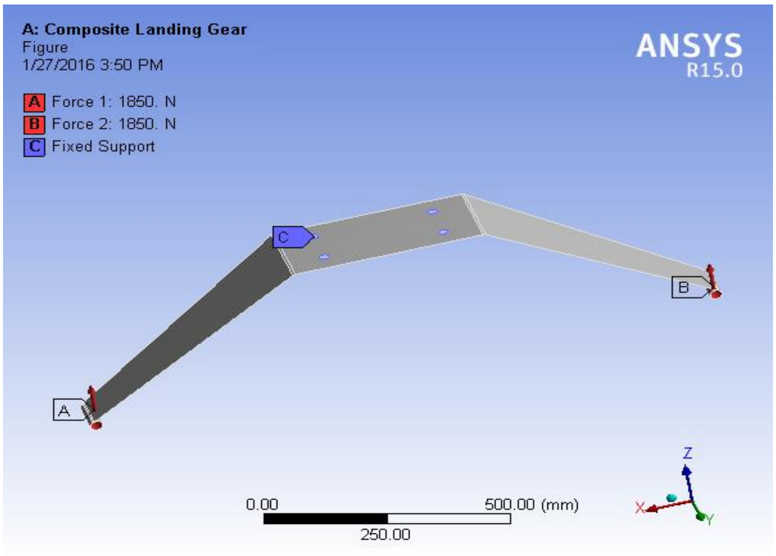

Figure 4: Non-optimized shape load and fixation

ANSYS-15 workbench (Static Structure module) program is used to solve flat model to find the Equivalent stresses (Von Mises) for Entire Section. The output results of the model solution are shown in Figure 5:

Table 2: Carbon fiber Flat Shape results

Maximum Stress (MPa)	Minimum Stress (MPa)	Weight (Kg)
410.63	*0*	2.9782

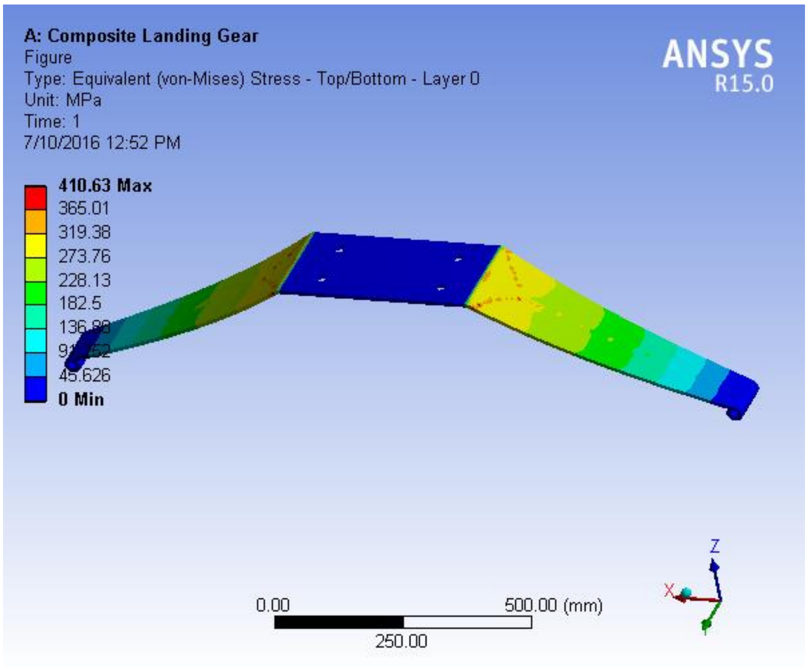

Figure 5: Flat Entire Section Equivalent stresses

6. Stress analysis for shape optimization model

Aluminum alloy flat shape with weight 7.14 Kg is solved by ANSYS workbench (Shape Optimization module) program version 15 to find the optimum shape. The result is shown in Figure-6

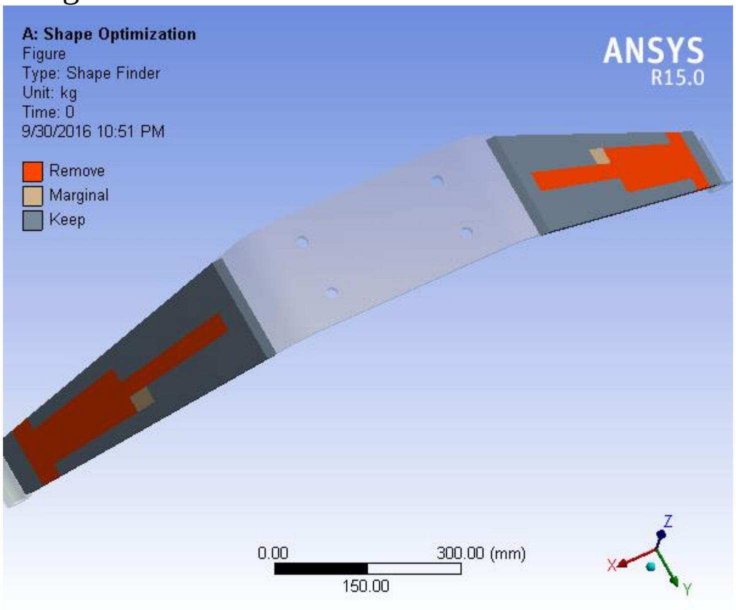

Figure-6: Shape optimization result for Flat shape

It can be seen from the shown figure that the shaded part in the design space is suggested to be removed from the landing gear. This shape was modified for production purposes and is shown in Figure 7.

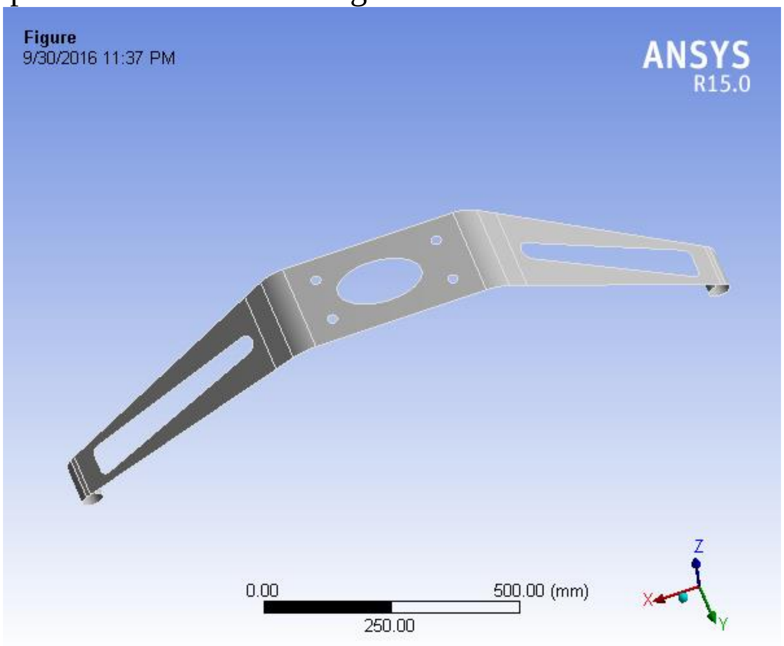

Figure 7: Shape Optimization model

For the shape shown in Figure 7 one can define 6 input parameters as shown in Figure 8 to be used in shape optimization analysis with the weight as an objective function. Maximum stress will be used as constraint.

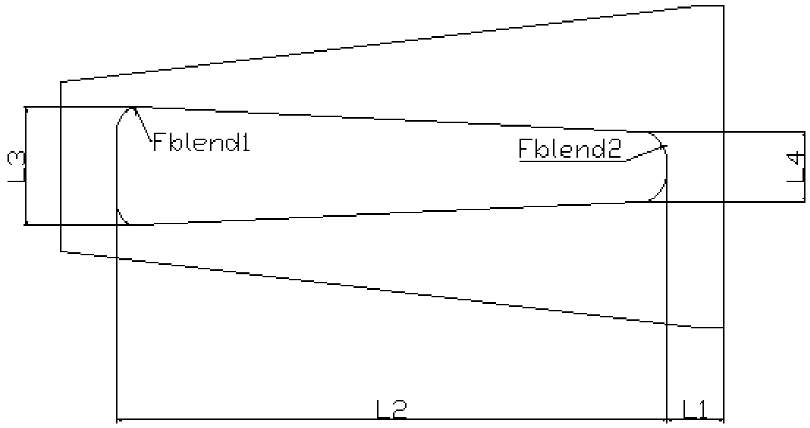

Figure 8 : Input parameters for parametric size optimization.

There are six input parameters, one output parameter, and one constraint. In design of experiment for our case a total of 45 design points (include current design) are chosen.

Response Surface Optimization was used to analyses the input parameters with output parameters. Output parameter has a response surface as shown in Figure **10** to predict output values. Output constrain has a response surface as shown Figure 9 to monitor stress.

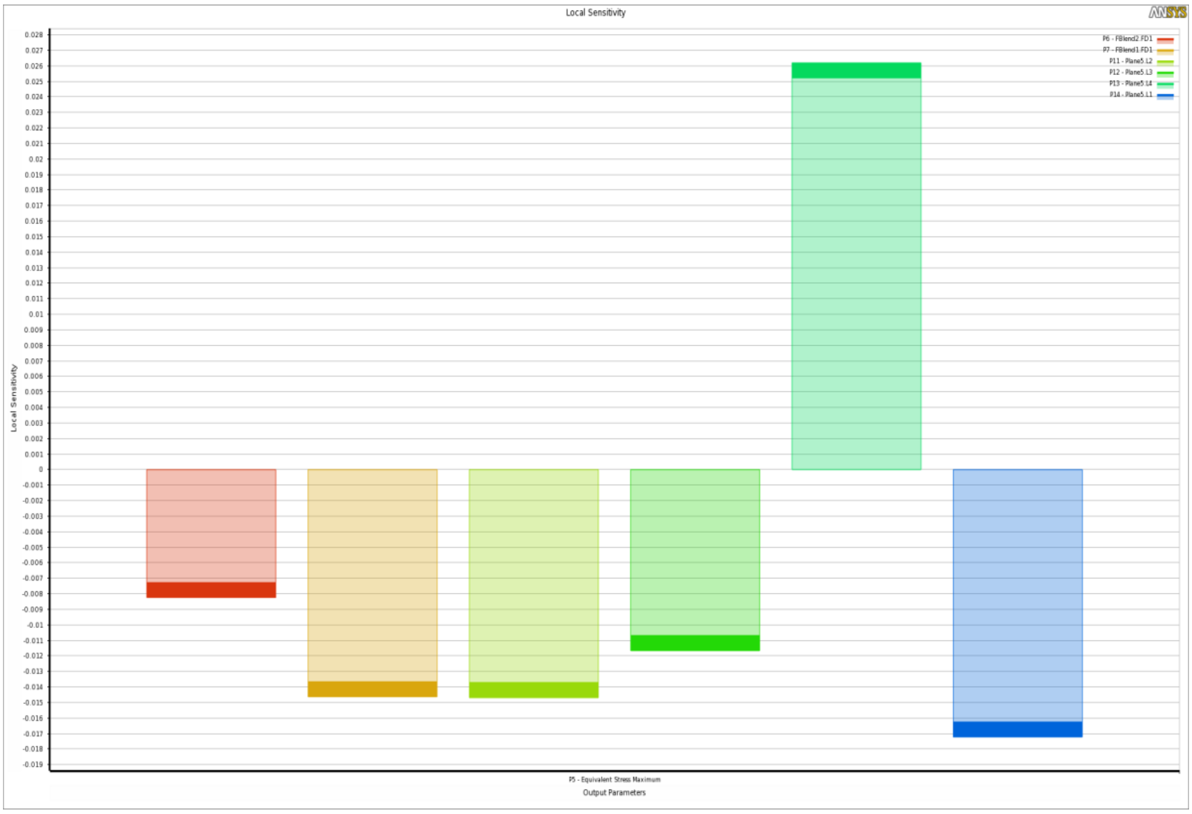

Figure 9: Sensitivity of maximum stress to design parameters

Figure 10: Sensitivity of weight to input parameters

From studing Figure 9 and Figure **10** we can conclude:

- Fblend1 & Fblend2 have no effect on weight but they can be used to reduce the stress
- L2 & L3 have the major effect on reducing weight and stress
- L4 reduce the weight with an increase in the stress
- L1 has no effect on weight but can be used to reduce the stress

From the previous conclusions, changing L2 and L3 with weight can be shown in Figure **11**, and with the maximum stress is shown in Figure 12

For the sensitivity of the input parameters shown in Figure 8 with maximum stress and weight, Response surface optimization of ANSYS-17 a 45 design points are created. Summary of the results is shown in Table 3 showing the output values for minimum weight. The values will be approximated to new selected values which can be used in production. These selected values will be used to start calculation of stress and weight.

The model used to solve shape optimization is the same model shown in Figure 7 with the dimensions shown in Table 3. This model is solved using the materials aluminum Alloy (7075-T61) with a thickness 9 mm and carbon fiber bi-directional composite material

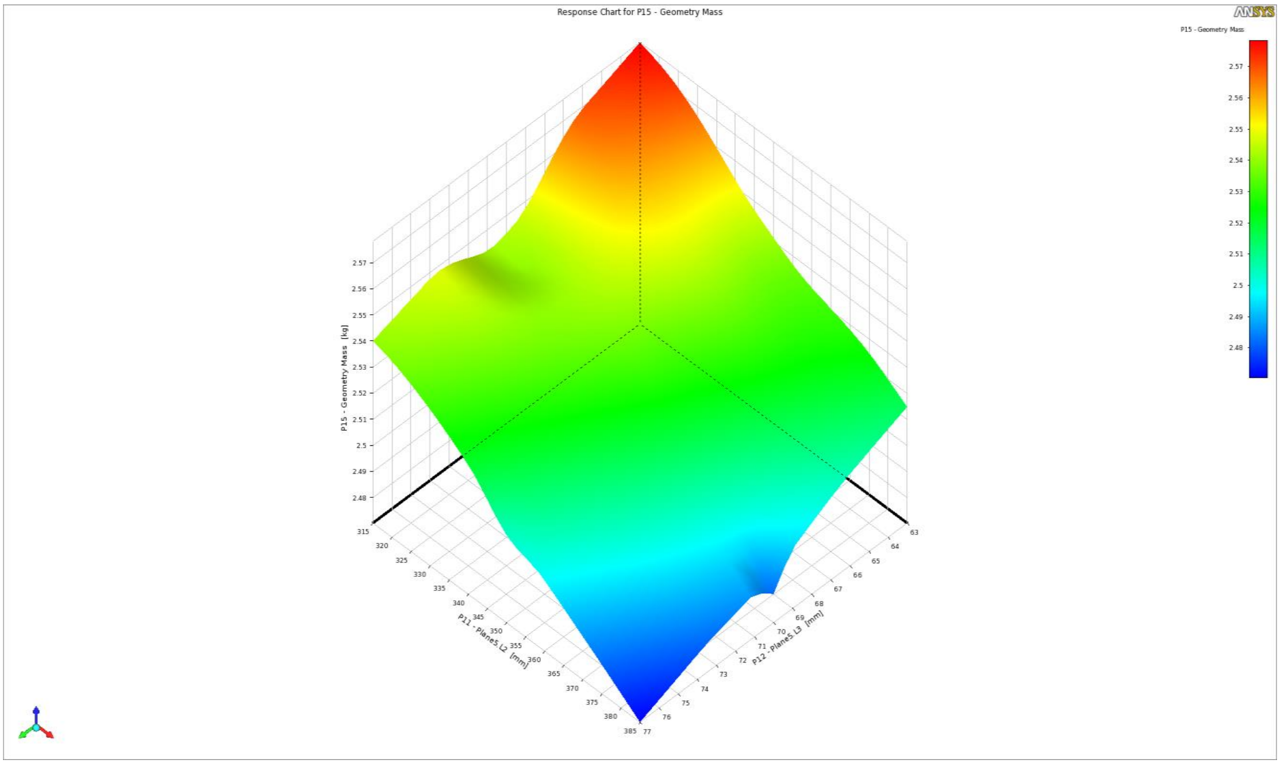

Figure 11: Effect of L2, L3 changes on weight

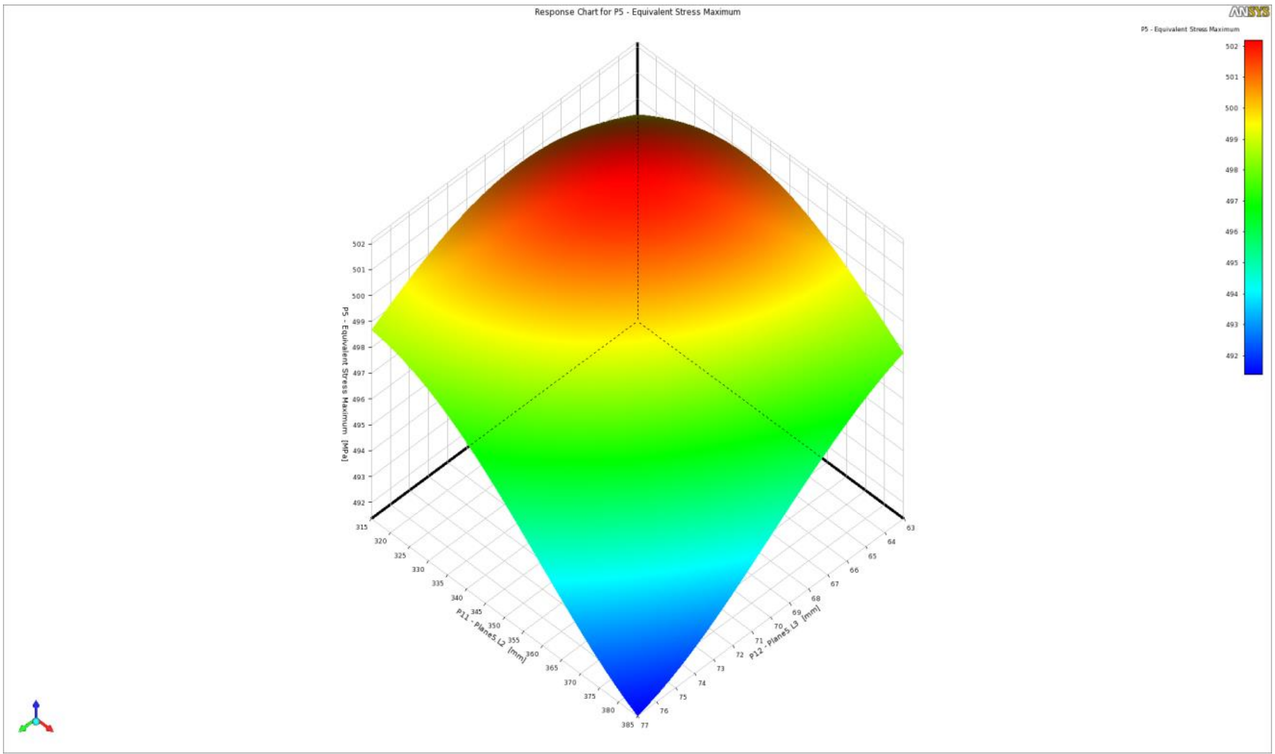

Figure 12: Effect of L2, L3 changes on maximum stress

Table 3: Summary of surface optimization for input parameters

	Parameter	Initial Value	Upper limit	Lower Limit	Output point	Selected value
Input Parameters	Fblend1 (mm)	30	33	27	28.26	28
	Fblend2 (mm)	20	22	18	18.84	19
	L1 (mm)	85	93.5	76.5	89.913	90
	L2 (mm)	350	385	315	370.23	370
	L3 (mm)	70	77	63	74.05	74
	L4 (mm)	50	55	45	52.89	53
Output Parameters	Stress (MPa)	500.85	503	---	501.26	---
	Weight (Kg)	5.065	---	---	4.94	---

6.1 Size Optimization Results for Aluminum Alloy

Mesh skewness ranges is used to measure mesh quality. 60.986% of the meshed cells are in the excellent zone. This result shows that the used mesh skewness is in excellent zone.

In Al-Alloy Shape Optimization model, the landing gear is fixed to UAV by four points of fixation to fix it from directional motion and/or rotation as shown in Figure 4. According to load calculation, load is divided into two equal forces. Each is 1850 N in Z-direction acting on left and right gears contact.

ANSYS workbench (Static Structure module) program was used to solve Al-Alloy shape optimization model to find Equivalent stresses (Von Mises) for Entire Section. Results for Al-Alloy Shape Optimization model are automatically calculated by the program. Results are shown in Figure 13 and its details are:

Table 4: Aluminum alloy optimized Shape results

Maximum Stress (MPa)	Minimum Stress (MPa)	Weight (Kg)
500.59	4.8843×10^{-7}	4.97

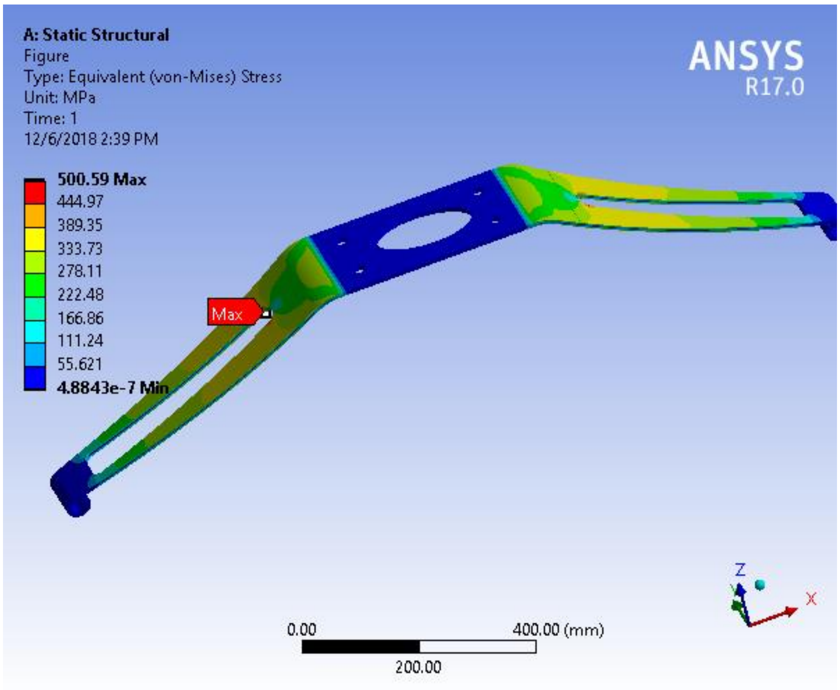

Figure 13: AL-Alloy shape optimization Equivalent Stress

6.2 Size Optimization Results for Carbon fiber bi-directional composite material

The landing gear structure is 90 layer carbon fiber bi-directional composite material with a stacking $(45_5,0_{35},45_5)_S$ with thickness 0.1 mm for each layer.

Mesh skewness ranges is used to measure mesh quality. 97.43% of the meshed cells are in the excellent zone. This result show that the used mesh skewness is in excellent zone.

In C.F. Shape Optimizationmodel, landing gear is fixed to UAV by four points of fixation to fix it from directional motion and/or rotation as shown in Figure 4. According to the load calculations, load is divided into two equal forces. Each is 1850 N in Z-direction acting on the left and the right gears contacts.

Ansys workbench (Static Structure module) program was used to solve C.F. Shape Optimization model to find the Equivalent stresses (Von Mises) for Entire Section. Results for C.F. Shape Optimization model are automatically calculated by the program. Results are shown in
Figure **14** and its details are:

Table 5: Carbon fiber optimized Shape results

Maximum Stress (MPa)	Minimum Stress (MPa)	Weight (Kg)
435.04	$3.31x10^{-3}$	2.69

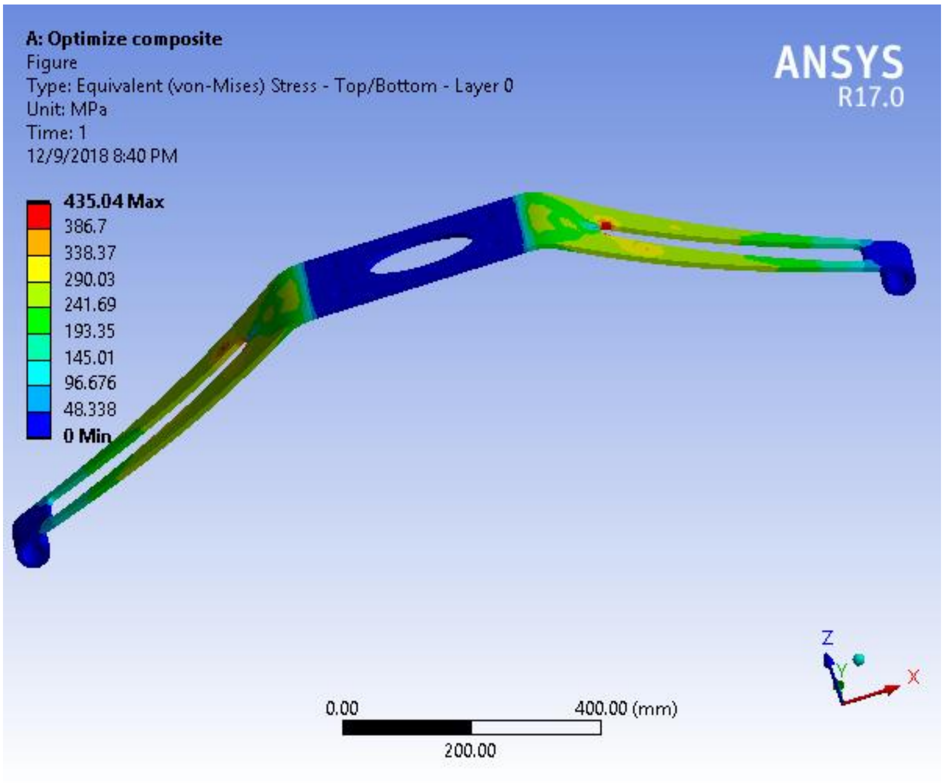

Figure 14: C.F. shape optimization Equivalent Stress (Entire Section)

7. Discussion and Conclusion:

Optimization is used to minimize the UAV landing gear weight. Table 6 shows the result analysis between the non-optimized shape and the optimized shapes using Aluminum Alloy (7075-T61) and carbon fiber bi-directional composite material.

Table 6: Weight ratio between non-optimized & optimized models

Shape	Weight (kg)	Weight reduction (kg)	Weight reduction ratio
Non Optimized (Aluminum Alloy)	7.14	0	0%
Optimized model (Aluminum Alloy)	4.97	2.17	30.4%
Non Optimized (carbon fiber)	2.98	4.16	58.3%
Optimized model (carbon fiber)	2.69	4.45	62.3%

Weight reduction of components and systems is important as one of the most essential factors for aviation. Take-off gross weight can be broken into crew, payload, fuel, and empty weights.

The empty weight is divided into the structure, engine/s, landing gear, avionics and fixed equipment. Engine/s, landing gear, avionics and fixed equipment are selective items. Weight optimization can be made for structure and landing gear to minimize aircraft total weight.

The reduced weight can be used to increase payload and the fuel weight to increase either the range or the endurance.

Final conclusions can be summarized as:

1- A comparison between different materials for optimized shape and non-optimized shape is made to calculate weight reduction for optimized shape.
2- The reduction in landing gear weight with (4.45 kg) with a ratio (62.3 %)
3- The reduction in landing gear weight with (4.45 kg) can make a reduction in UAV total weight by (7.57 kg) with a ratio (5.05 %)
4- The optimization technique for weight optimization is a guide to optimize any other type of landing / part to minimize the total weight for the Unmanned Aerial Vehicle.
5- **Future work:** In this study, a single parameter is used as output objective with maximum stress as constrain. In the future other parameters such as strain and deformation will be used to be a multi-output problem.

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