FULL LENGTH PAPER

CONCEPTUAL DESIGN AND STATIC STRUCTURAL ANALYSIS OF A QUADCOPTER FOR HEART MOBILITY IN BANGALORE CITY

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Abstract

The present work involves conceptual design and static structural analysis of a quadcopter which carries the human heart as a payload for heart transplantation operation between a donor hospital and a recipient hospital within Bangalore city. The payload for this mission was first estimated by choosing an appropriate container for the heart. Then, the range of the required quadrotor was determined taking into account the distance between various hospitals in the city which perform heart transplants. Thereafter, the propulsion system was selected. Finally, the different parts of the quadrotor were selected. The quadrotor was conceptually designed using the Catia software and the static structural analysis was carried out using Ansys software.

Introduction

In organ transplantation, the damaged or the missing organ of a recipient is replaced by a healthy organ from a donor. The organ donor may be living, brain dead or dead via circulatory death. Brain dead is typically defined as the irreversible loss of function of the brain and the brain stem. Circulatory death is defined as the irreversible loss of function of the heart and lungs. The recipient and the donor can be in the same hospital or in two different hospitals. If they are in two different hospitals then the organ needs to be transported from the donor hospital to the recipient hospital. A successful and timely transfer of an organ between the two hospitals can save the life of the recipient. Therefore, the problem of organ transport becomes an important engineering problem.

The popular modes of transportation of organs are known as the "green corridor" and the "air ambulance". In a green corridor, the traffic signals between the donor hospital and the recipient hospital are operated manually by the traffic police to avoid red signals. Moreover, efforts are made by the traffic police to maintain smooth traffic flow. The establishment of a green corridor is a tedious process due to the involvement of multiple stakeholders, need to select a suitable time for the transportation and requirement of many police personnel. To manage a green corridor in the mega-cities such as Bangalore, Delhi and Mumbai etc. is extremely difficult because of congestion in the roads and chaotic traffic.

In the air ambulance approach, a helicopter is used to transport the organ between the two hospitals. The air ambulance is appropriate when transportation is required between two cities. However, the high cost and large size discourages a full scale conventional helicopter from transporting organs within two hospitals in the city. Another drawback of this mode of transportation is that flying of full scale helicopters is not allowed near the hospitals due to high levels of noise. In many big cities, most of the populated places where hospitals are located restrict the flying of helicopters. Thus, the air ambulance is a restrictive option in many highly populated cities.

UAVs have a wide range of applications in the fields such as search and rescue [1], disaster monitoring [2, 3],

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industrial inspection [4], security surveillance, surveying and measuring [5], aerial video, agriculture [6] and health care sector [7,8].Thus, UAVs (also called drones) can be a good alternative for transporting organs compared to full scale helicopters.

In the healthcare sector, drones are used to supply blood [9], Automated External Defibrillators (AEDs) [10, 11], medicines [12], and organs [13]. While fixed wing drones have good range and endurance, they cannot hover, fly at low speeds, or land in a small space. Flapping wing drones have low payload capacity and cannot easily fly the distance between two hospitals. Furthermore, their control and airworthiness is more complicated compared to rotary wind drones such as the multi-copters. Rotary wing drones are one of the best options for organ mobility. The drawbacks of the green corridor and air ambulance can be overcome by using rotary wing drones. Rotary wing drones are capable of hovering and performing vertical take-off and landing, and low speed flight. By using such a drone, we can transport the organs relatively quickly between two hospitals in the city. For a patient awaiting an organ transplant in a hospital, every second is crucial and can make the difference between life and death. Normally, when the organ transplant is performed within an hour of harvesting the organ, the outcome is better. Therefore, drone based organ delivery can save human lives. However, commercial drones are often expensive and not specially designed for organ delivery.

The main focus of this paper is developing a drone for transporting the human heart inside a typical large city. The heart has a low tolerance and needs to be transplanted into the patient within four hours of harvesting the organ. Some other organs like kidney, liver and lungs have a higher tolerance and can be kept for 24 to 36 hrs, 12 hrs and 6-8 hrs, respectively [14]. Therefore, we focus on the human heart in this paper. In addition, the city of Bangalore has emerged as the city with the highest levels of traffic congestion in the world [15]. Therefore, we choose Bangalore as the city for this research work.

Payload Selection

Payload is the weight a drone or Unmanned Aerial Vehicle (UAV) can carry. It is usually counted outside of the weight of the droneitself and includes anything additional to the drone. The payload plays a vital role in designing the drone. In this paper, the payload is the human organ to be carried and the container in which the organ is placed. The payload should be as low as possible while satisfying the requirements for the problem. Therefore, the lowest weight organ transport container is selected after a search of the literature; this is the so-called "Life box" [16].

The "Life box" is a system that extends the preservation time of the organ, specifically the heart for now, and allows for increased travel time and distance, or in other words endurance and range. It was developed by research students Deval Karia, and Rohit S Nambiar and they were supervised by Prof B. Gurumoorthy and Prof Ashitava Ghosal of the Mechanical Engineering Department at the Indian Institute of Science, Bangalore. The objective of the "Life Box" was to significantly reduce the size and weight of the case in which live organs are carried. It is designed to maintain a steady temperature of 4-8 degrees Celsius, which is vital for the heart to survive for eight hours outside the body. Dry ice (solid carbon dioxide) is used as a refrigerant. A non-oxygenated cardioplegic solution is pumped through it to increase the life span. Cardioplegia is the deliberate stopping of the heart which is typically done to permit heart surgery. The cost of the device and the consumables required to transport the heart are much less compared to those currently in use.

The total weight of the "Life box" device is 4.5 kg. Among the different human organs, the heart is selected as a payload because it has a low tolerance and has to be transplanted within four hours from being taken out from the body. The payload will be the sum of the weight of the heart (310 gram) and the weight of the life box (4.5 kg). This leads to 4810 grams. We select 5 kg as the payload, after rounding upwards to the nearest integer value in kilograms. This permits some variation in the heart weight depending on the patient and some room for aleatory and epistemic uncertainties in the life box modelling and manufacturing process.

Range Determination

Range is the horizontal distance a drone can fly between take-off and landing. In this project, range is selected as the distance between two hospitals; that is from organ donor hospital to the organ recipient hospital. After due research, nine popular hospitals in Bangalore were selected, which perform heart transplantation. Then we calculated the distances between these hospitals. The 9 heart transplant hospitals in Bangalore considered in this study are:

- Narayana Institute of Cardiac Sciences, Bommasandra
- Manipal Hospital, HAL Airport Road
- Aster CMI Hospital, Sahakara Nagar
- Fortis Hospital, Bannerghatta Road
- MS Ramaiah Narayana Heart Centre, Mathikere
- Apollo Hospital, Bannerghatta Road
- Columbia Asia Hospital, Whitefield
- BGS Global Hospital, Kengeri
- Sri Jayadeva Institute of Cardiovascular Sciences and Research, Jayanagar

Table-1 gives the details of some of the heart transplants which were performed in Bangalore in the recent past. In these cases, a human heart was transported from the donor hospital to the recipient hospital. The distance between the hospitals is obtained using Google maps and ranges from a minimum of 4.5 km to 30.9 km. The normal driving time was also obtained using Google maps and ranges from 10 minutes to 1 hour 19 minutes.

Table-2 gives the distance between the hospitals, obtained from Google maps. We want to ensure that the drone is able to operate between most of the hospitals. So, we selected 30 km as the range for our drone as it covers most of the hospitals in the city. A few cases are too far apart and are ignored as outliers here in the interest of costs. We therefore need to design a drone which has a range of 30 km and a payload of 5 kg. Given the wide use and familiarity of the quadcopter configuration, we have selected this type of vehicle for our problem.

Table-1 : Previous Heart Transplants Performed in Bangalore

Sl. No.	Year	Donor Hospital	Recipient Hospital	Driving Distance (Km)	Normal Driving Time	Method for Organ Mobility (Time taken if known)
1	3 Apr 2010	Manipal	Narayana Health	22.9	48 minutes	Green Corridor
2	11 Sep 2014	BGS Global	Narayana Health	31	51 minutes	Green Corridor
3	24 Aug 2015	Sagar	Narayana Health	23	51 minutes	Green Corridor (20 minutes)
4	24 Jun 2016	Apollo	Manipal	13.3	38 minutes	Green Corridor
5	31 Dec 2016	Manipal	Jayadeva	12	33 minutes	Green Corridor (11 minutes)
6	27 Feb 2017	Apollo	MS Ramaiah	19.3	1 hour	Air Ambulance (7 minutes)
7	29 Aug 2017	Aster CMI	Narayana Health	33.1	1 hour 12 minutes	Green Corridor
8	1 Mar 2018	Apollo	MS Ramaiah	19.3	1 hour	Green Corridor
9	14 Mar 2018	BGS Hospital	Narayana Health	31	51 minutes	Green Corridor (26 minutes)
10	14 Mar 2018	Columbia Asia	Narayana Health	30.8	1 hour 19 minutes	Green Corridor (29 minutes)
11	20 Mar 2018	BGS Hospital	Narayana Health	31	51 minutes	Green Corridor (28 minutes)
12	17 Apr 2018	Aster CMI	Jayadeva	18.8	1 hour	Green Corridor (21 minutes)
13	4 Jul 2018	Sparsh	MS Ramaiah	4.5	10 minutes	Green Corridor
14	20 Mar 2017	Apollo	MS Ramaiah	19.3	1 hour	Green Corridor (33 minutes)

Table-2 : Distance Between the Hospitals (Km)

Hospitals	Narayana	Manipal	Aster CMI	Fortis	MS Ramaiah	Apollo	Columbia	BGS	Jayadeva
Narayana	0	22.9	33.1	19.4	30.7	19.6	30.8	31	18.2
Manipal	22.9	0	19.4	13.1	15.9	13.3	10.7	22.5	12
Aster CMI	33.1	19.4	0	21.4	8.5	21.5	25.8	27.4	18.8
Fortis	19.4	13.1	21.4	0	19.8	0.3	21.9	16.5	3.7
MS Ramaiah	30.7	15.9	8.5	19.8	0	19.3	28.8	24.4	16.6
Apollo	19.6	13.3	21.5	0.3	19.3	0	21.7	14.7	2.9
Columbia	30.8	10.7	25.8	21.9	28.8	21.7	0	48.5	20.7
BGS	31	22.5	27.4	16.5	24.4	14.7	48.5	0	12.6
Jayadeva	18.2	12	18.8	3.7	16.6	2.9	20.7	12.6	0

Propulsion System

Propulsion system plays a vital role in the design of a drone. Two key points should be considered while selecting the propulsion system. The first is the application and requirement of the drone. The second involves the payload, range, endurance, speed, and flight altitude of the drone.

The propulsion system selected for our quadcopter is the series hybrid propulsion system. The hybrid-electric propulsion system is defined as the combination of an electric motor and an internal combustion engine within one power plant [17]. The three main configurations in the hybrid propulsion system are the series configuration, the parallel configuration and the series-parallel configuration. In the series configuration, one power unit propels the aircraft and the energy storage is hybridized. The advantages of the hybrid propulsion system are: high energy density compared to battery propulsion system, longer flight time and range, high payload capacity, higher reliability and speed, and no need of replacing and re-charging the batteries.

Series Hybrid Configuration

In a series hybrid configuration, as shown in Fig.1, the propeller is only driven by the electric motor. The mechanical power generated by the internal combustion engine is converted into electric power by a generator. The electric power is used either to directly provide power to the electric motor or to charge the battery.

The advantage of the series configuration is that the combustion engine is completely decoupled from the thrust generation and can therefore constantly run at its optimum operating point. It is easy to control the propulsion system. As a disadvantage, the electric motor needs to provide the complete propulsion power alone, so that it needs to be dimensioned for the maximum power phase and thus is heavy.

Parts Selection and Weight Estimation

The baseline quadcopter for our project is the Carrier H4 Hybrid. In this section, the overall weight estimation and different parts selection of the quadcopter is mentioned.

Parts Selection

The main parts of hybrid quadcopter are:

- Frame
- IC Engine
- DC Generator
- Fuel Tank
- Battery
- Electronic Speed Controller

- Propeller
- Fuel and Motor

These parts are discussed below.

Motor: To get the drone airborne, we need the right amount of thrust from its motor. The following steps are carried out to calculate the required amount of thrust [18].

Step1: Determine the weight of the drone and double its weight in order to calculate the required amount of thrust which is required from a motor. Weight of the drone is equal to 26 kg and therefore double the weight of the drone is 52 kg.

Step2: Add 20 percent to this doubled weight to ensure that the drone will be able to hover. Now, twenty percent of the doubled drone weight is 0.2 (52) =10.4 kg. Thus, the total thrust is 52 + 10.4 = 62.4 kg.

Step3: Divide the total thrust by the number of rotors the drone possesses. In our drone, there are four rotors as it is a quadcopter. Thus, the thrust carried by each rotor is 62.4 / 4 = 15.6 kg. The thrust required by one motor is 15.6 kg.

Step4: Browse the motors online or in a store. The thrust produced by the motor will be mentioned by the manufacturer. The thrust number must match or exceed the number obtained in Step 3.

After performing this task, the selected motor is the U12II KV120. This motor has the following properties:

Thrust = 20 kg
Weight = 778 gm
Price = $369.9
Motor service life = 1500 flights (40mins/ flight)
Idle current (24V) = 1.5A
Rated voltage (Lipo) = 10-14S
Peak current (180S) = 95A
Maximum power = 4560W

The selected motor is shown in Fig.2 [19].

Electronic Speed Controller (ESC) and Propeller: The ESC and propeller details are given as follows. The ESC chosen is the Flame 180A HV. It has the following specifications:

Price = $259.99
Continuous current = 180A
Peak current = 220A
Weight = 279 gm
Dimensions =112.2*50.5*35.5 mm
LIPO = 6-14s [20]

The propeller chosen is the G 30*10.5 propeller.

The propeller specifications are as follows:

Price = $ 335.9 (2pcs/pair)
Dimensions = 762*266.7 mm
Weight (Single propeller) = 132 gm
Material = CF+Epoxy
Optimum RPM = 1300-3000 rpm/min
Thrust limitations = 33 kg [21]

The ESC and propeller are shown in Fig.3 and Fig.4 respectively.

Battery: The battery selected is the Tattu 22.2V 25C 6S 22000mAh Lipo battery with the AS150 + XT150 plug. The specifications of the battery are as follows:

Price = $ 461.89
Weight = 2490 gm
Capacity = 22000mAh
Voltage = 22.2V/6S
Discharge Rate = 25C
Size = 195 x 91 x 64mm [22]

The battery is shown in Fig.5.

Generator: The selected generator is the "H2400generator" [23] which supplies 2400W of power continuously. The specifications of the H2400 generator are:

Weight = 4.2 kg without accessories/5.6 kg total
Total Power = 2.4 kW continuous
Dimensions L x W x H) = 355 x 319 x 251 mm
Output voltage = DC 12S (49V)
Fuel consumption = 750 g/kwh
(hovering 2.5 Liter/hour
Service Temperature = -20 ~ 40°C
Altitude (above sea) = 2000m
Starting = Electrical starter
Fuel = Automobile #95 or above gasoline

The H2400 generator is shown in Fig.6.

Weight Estimation

The weight estimation of all the components is shown in Table-3.

Cost Analysis of Proposed Design

We now calculate the cost to build the quadcopter (without considering the payload), as shown in Table-4. The overall cost to build this Hybrid Quadcopter is $ 9268.95 / Rs 6,58,955.248 (assuming $1=71.09 rupees).

Design of the Hybrid Quadcopter

The different parts of a hybrid quadcopter were incorporated and assembled in computer aided engineering software CatiaV5. The payload box is also designed and placed on the top of the quadcopter. Fig.7 shows the isometric view of the quadcopter. Fig.8 shows the drafting of the quadcopter; all the four views are shown in a single sheet by reducing their size.

Analysis of the Hybrid Quadcopter

Static structural analysis is carried out using the finite element analysis software ANSYS 16.0. The steps followed in this analysis are: engineering data, geometry, model (setup and solution) and finally the results and discussions. These steps are mentioned in detail below.

Table-3 : Weight Estimation of the Drone

Sl. No.	Components	Weight of Individual Component	No.of Compo-nents	Total Weight of Components
1	Motor	778 gm	4	3.112 Kg
2	ESC	279 gm	4	1.116 Kg
3	Propeller	132 gm	4	528 gm
4	Battery	2.49 Kg	1	2.49 Kg
5	Frame	4 Kg	1	4 Kg
6	Payload	5 Kg	1	5 Kg
7	Generator	5.6 Kg	1	5.6 Kg
8	Fuel Tank	800 gm	1	800 gm
9	Fuel	2.7 L ~ 2.5 Kg	1	2.5 Kg
10	Others	1 Kg	1	1 Kg
			Total Weight of Drone	**26.146 Kg**

Engineering Data

In this step, materials are selected for different parts of the drone, as shown in Table-5.

DC motors have permanent magnets made from iron and cobalt alloys. So, we assigned iron and cobalt alloy for the motor [24]. Aluminium is a light weight material which relatively easy to work with. It is inexpensive as well as readily accessible. So, we selected aluminium for the frame [25] [26].

Different parts of the generator are made up of different material. For example, the stator frame is made up of cast aluminium, cast iron or fabricated steel plates. The armature ring is made up of special magnetic iron or silicon steel. The frame holding the armature is made up of cast steel [27]. We designed a generator as a single component; we cannot assign these many materials for a generator. So, in general we assigned stainless steel material for the generator. Stainless steel and aluminium are the inbuilt materials in the Ansys software. Cobalt-iron alloy is not there in the software; hence we need to add this material before carrying out the analysis. Material properties of Cobalt-Iron Alloy are:

Density = 8.6 g/cm^3

Poisson's ratio = 0.29

Tensile strength = 870 Mpa (ultimate) 400 Mpa (yield)

Young's modulus = 230 Gpa [28]

Table-4 : Cost Estimation of the Drone

Sl. No.	Components	Price of Individual Component	Quantity	Total
1	Motor	$ 369.9	4	$ 1479.6
2	ESC	$ 259.99	4	$ 1039.96
3	Propellers	$ 335.9	4	$1343.6
4	Battery	$ 461.89	1	$ 461.89
6	Generator	$ 4,779	1	$ 4,779
7	Fuel Tank	$ 12.66	1	$ 12.66
8	Fuel	$ 1.04 (1L)	2.5 L	$ 2.6
9	Others	$ 150	1	$ 150
			Total	**$ 9,269.31**

Table-5 : Materials Used for Different Parts of the Drone

Drone Parts	Materials
Motor	Cobalt-Iron Alloy
Generator	StainSteel
Frame and Propeller	Aluminium

Geometry

After selecting the materials, the model which is in CAT part format is converted into the stp file and this file is uploaded onto Ansys.

Model

In this step, materials, meshing, loads and boundary conditions are applied to the model and then the problem is solved. First the model is setup in ANSYS and then the solution is performed.

Setup: As mentioned above, the selected materials are assigned for the respective parts of the drone.

Connections: In this step, the following settings are given:

Behaviour = Symmetric
Formulation = Pure penalty
Pinball radius = 1mm

These settings are shown in Fig.9.

Mesh: A coarse mesh is first carried out and the other details of the mesh are shown in Table-6 and Table-7. The meshing file is shown in Fig.10.

Loads: The horizontal part of the landing gear is fixed, a 153 N of load is applied on the motor mount and a 50 N load is applied on the upper plate as shown in Fig.11. There is 153 N in thrust force acting upward. Also the 50 N force is the weight of the payload acting downward.

Solution

The following entities are solved for in this step: Total deformation, equivalent stress, equivalent strain, maximum principal stress and shear stress. These response parameters provide an indication about the structural safety of the drone.

Table-6 : Details of Mesh

Details of "Mesh"	
Display	
Display Style	Body Colour
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	5.0 mm
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	7.6193e-003 mm
Inflation	
Patch Conforming Options	
Patch Independent Options	
Advanced	
Defeaturing	
Statistics	

Table-7 : Meshing Parameters

Parameters	Values
Element Size	3 mm
Nodes	929889
Elements	360805

Structural Analysis Results

Total Deformation: From Fig.12, we can say that the maximum deformation takes place at the front part of the drone that is at the two propellers which is indicated in red colour. The minimum deformation is at the landing gear which is indicated in blue colour.

Equivalent Strain: Fig.13 shows the equivalent strain distribution on the drone. The maximum strain produced in the drone is 0.017.

Equivalent Stress: Fig.14 shows the equivalent stress distribution on the drone. The maximum stress produced on the drone is at the frame below the motor that is 1076Mpa.

Principal Stress: Maximum principal stress produced on the drone is 1480 Mpa and minimum principal stress produced is 559Mpa as shown in Fig.15 and Fig.16, respectively.

Safety Factor: The safety factor distribution of a drone is shown in the Fig.17. The minimum factor of safety is 0.225 which is on the frame below the motor; this region can easily undergo the plastic deformation and can even crack under work. The area whose safety factor is less than 10 is about 10%. The maximum safety factor is 15.

Conclusion

A conceptual design and preliminary structural design of a quadcopter drone for heart transportation between two hospitals in Bangalore city is conducted. We have selected the "Life box" as the organ transporter box to carry the heart from donor hospital to the recipient hospital. The range of our drone is 30 km which is based on a study of the main hospitals conducting heart transplant operations in Bangalore city. After studying the different propulsion systems, we have selected the series hybrid propulsion system for our drone. Then according to the requirements, we selected the motor, ESC, propeller, battery and generator. Weight and cost analysis is then carried out. Next is the design and analysis of the drone. The sizing of the drone was conducted in Catia V5. The static structural analysis is performed in Ansys 16. The following points are observed from the static structural analysis: The maximum deformation takes place at the front part of the drone that is at two propellers. The maximum equivalent stress produced on the drone is at the frame below the motor that is 1076 Mpa and safety factor in this place is 0.225. This region can undergo the plastic deformation and crack can appear under work. To overcome this failure we can change the material used in these regions or we can increase the thickness of the module; by doing either of these changes we can obtain the safe design. Further studies need be conducted to strengthen and to prototype this drone.

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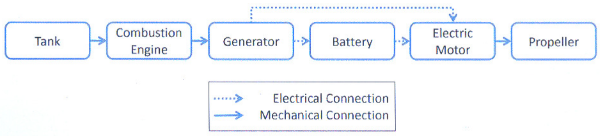

Fig.1 The Series Hybrid-Electric Configuration

Fig.2 The U12II KV 120 Motor

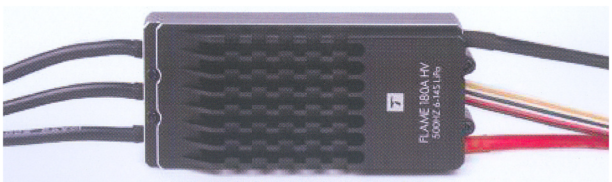

Fig.3 Flame 180A HV

*Fig.4 G 30*10.5 Propellers*

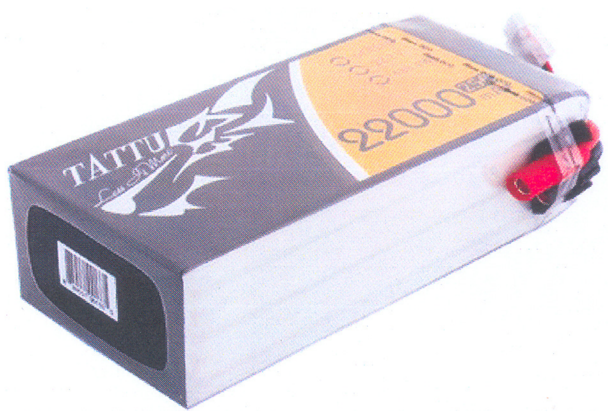

Fig.5 Tattu 22.2V 25C 6S 22000mAh Lipo Battery

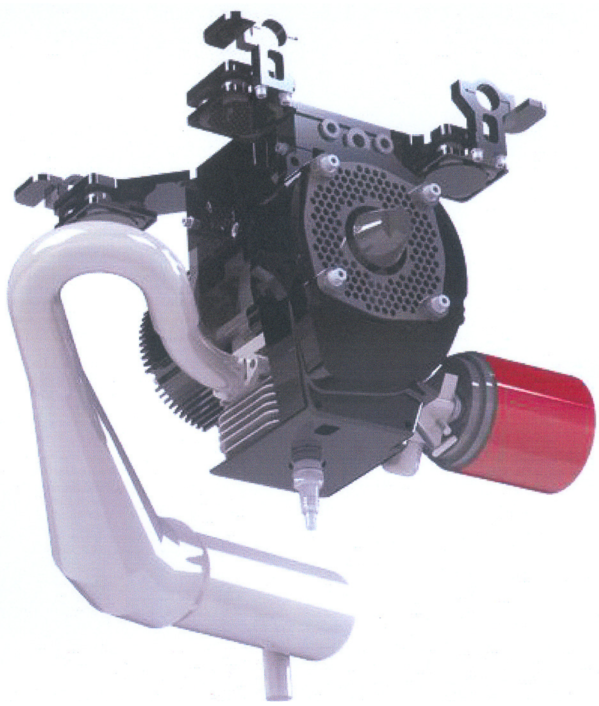

Fig.6 H2400 Generator

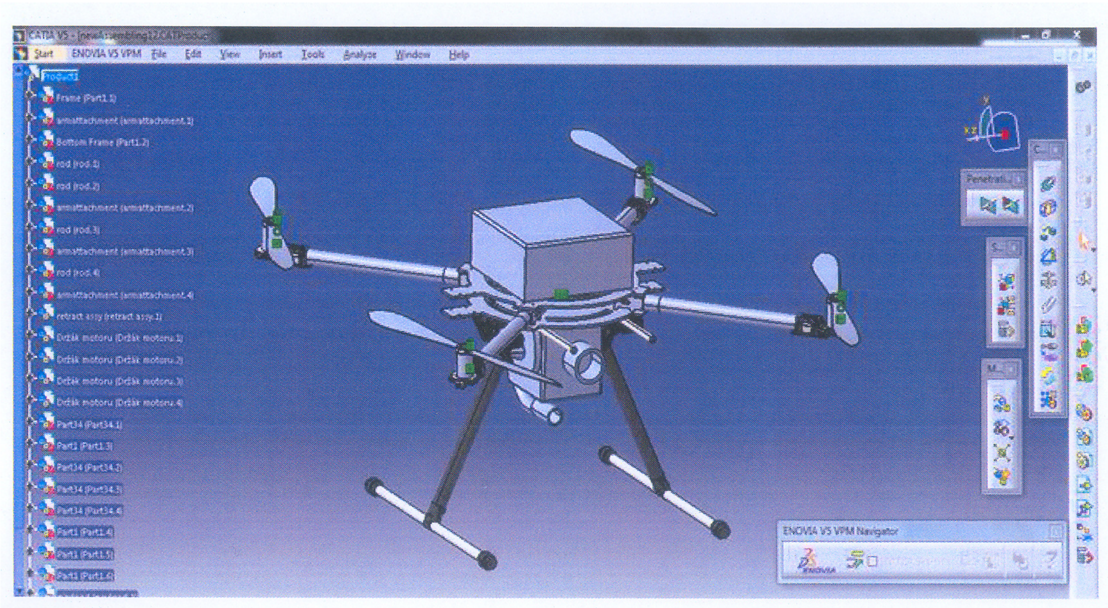

Fig.7 Isometric View of the Quadcopter Drone

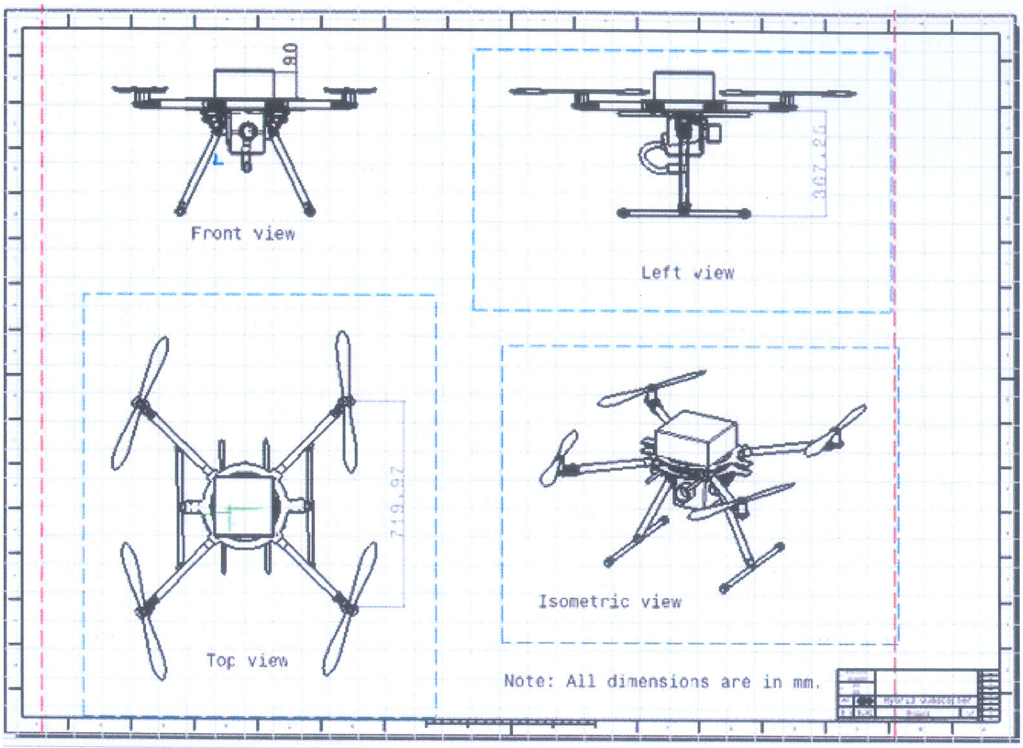

Fig.8 Drafting of the Quadcopter Drone

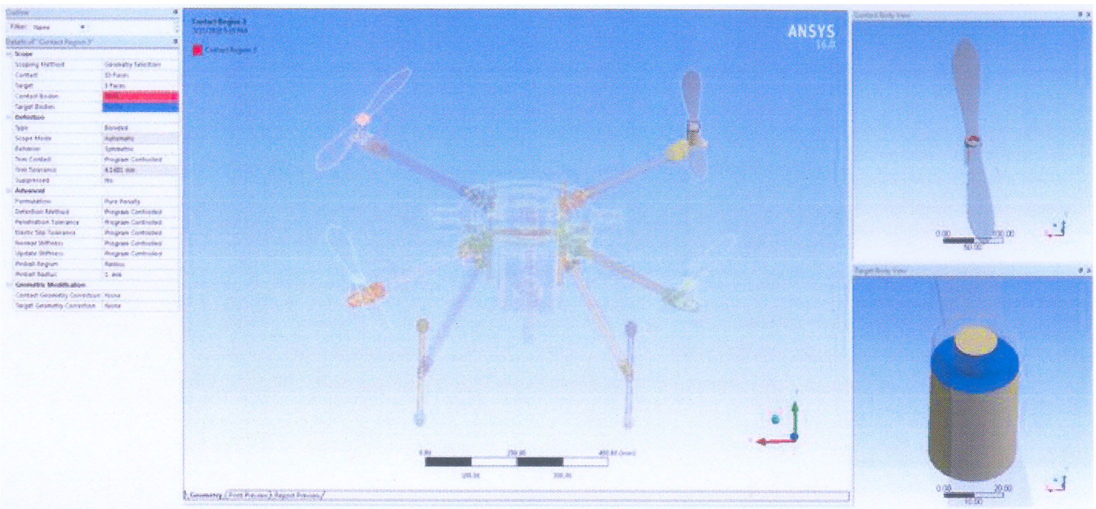

Fig.9 Connections

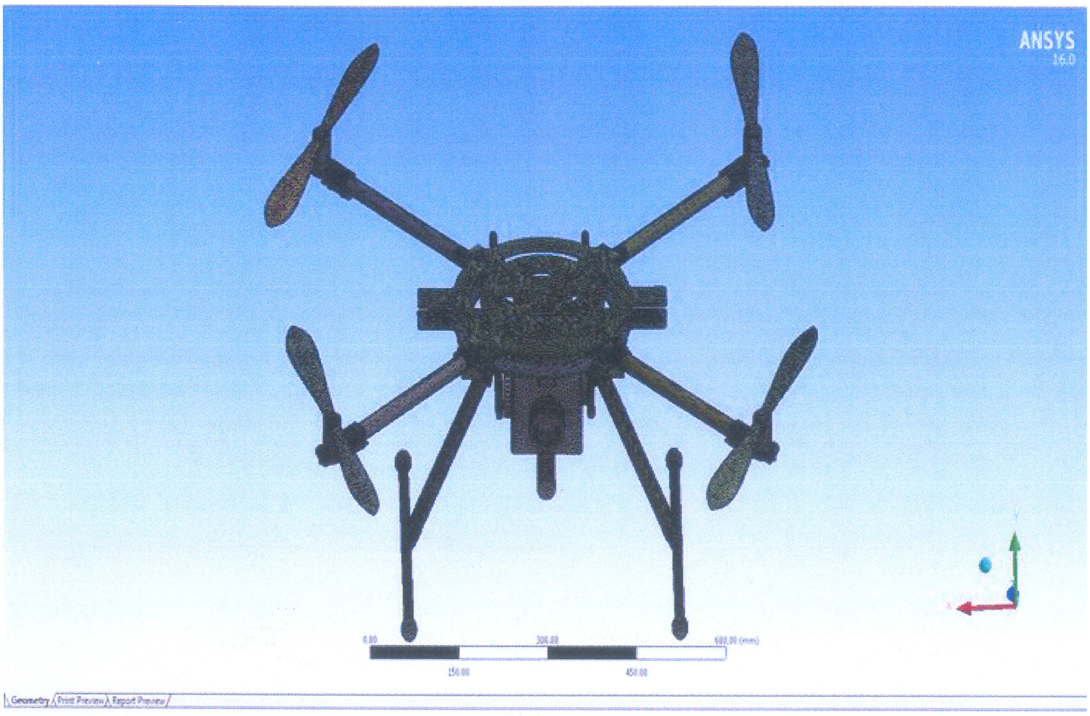

Fig.10 Meshing

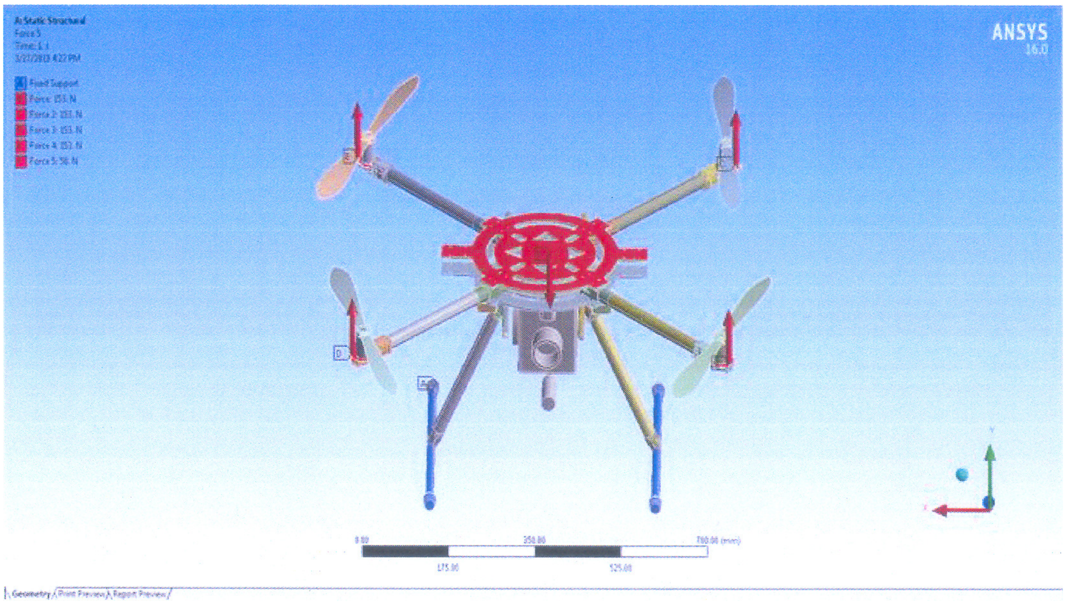

Fig.11 Loads

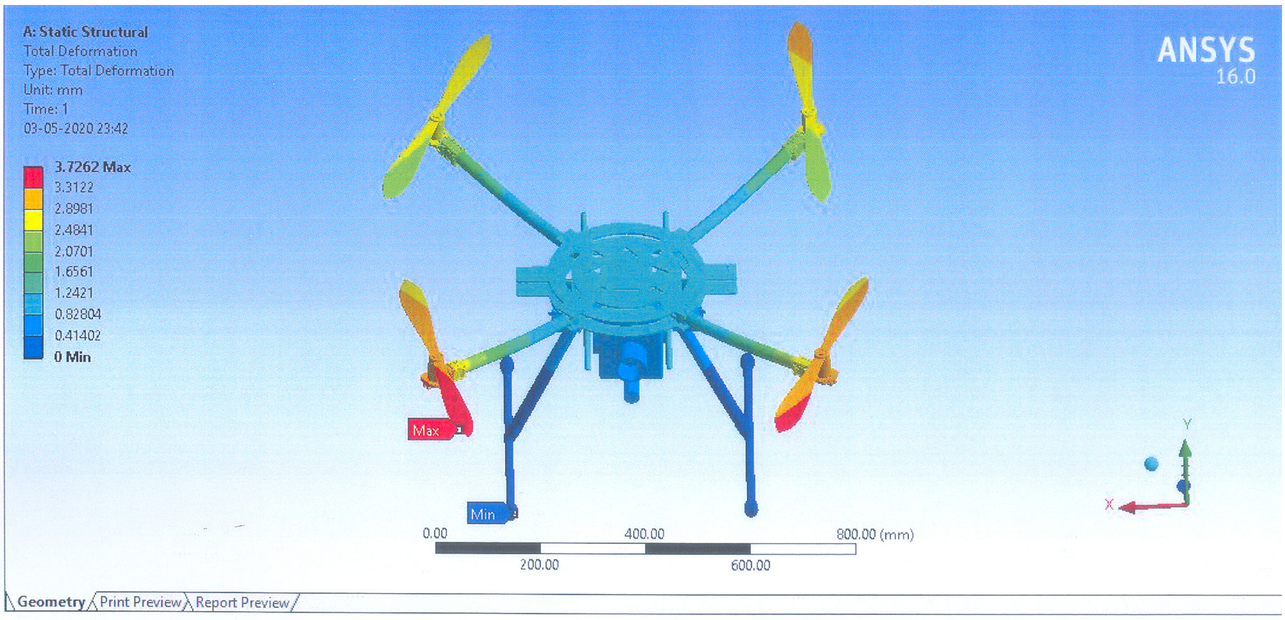

Fig.12 Total Deformation

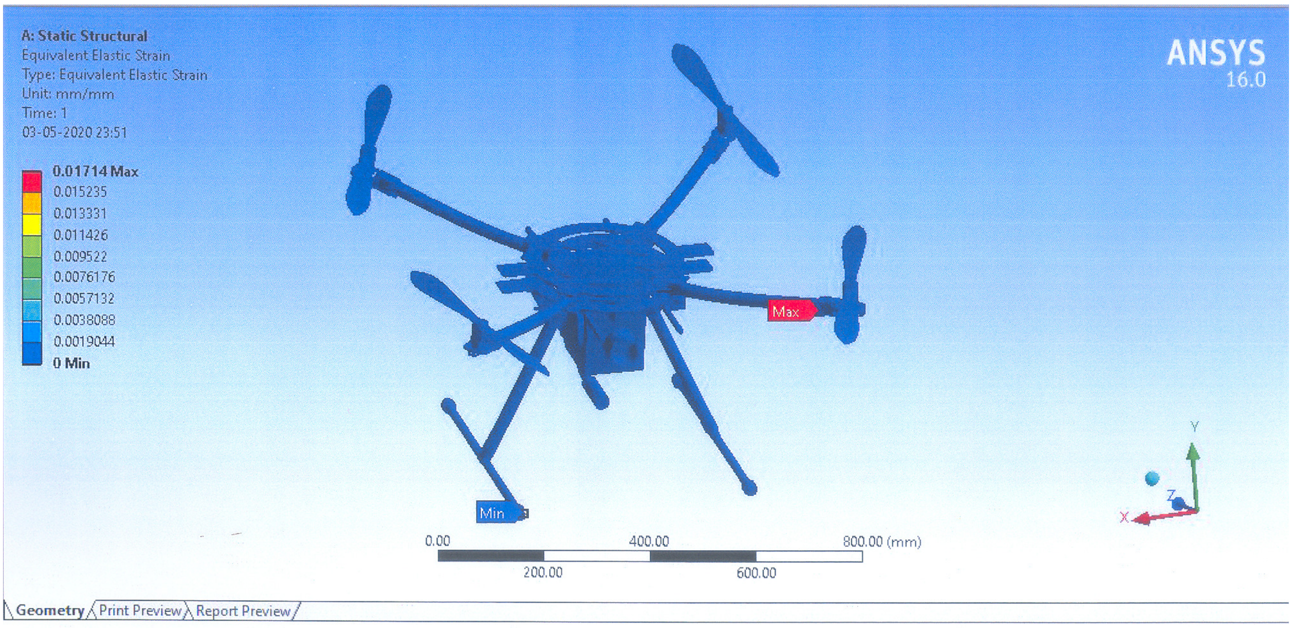

Fig.13 Equivalent Strain

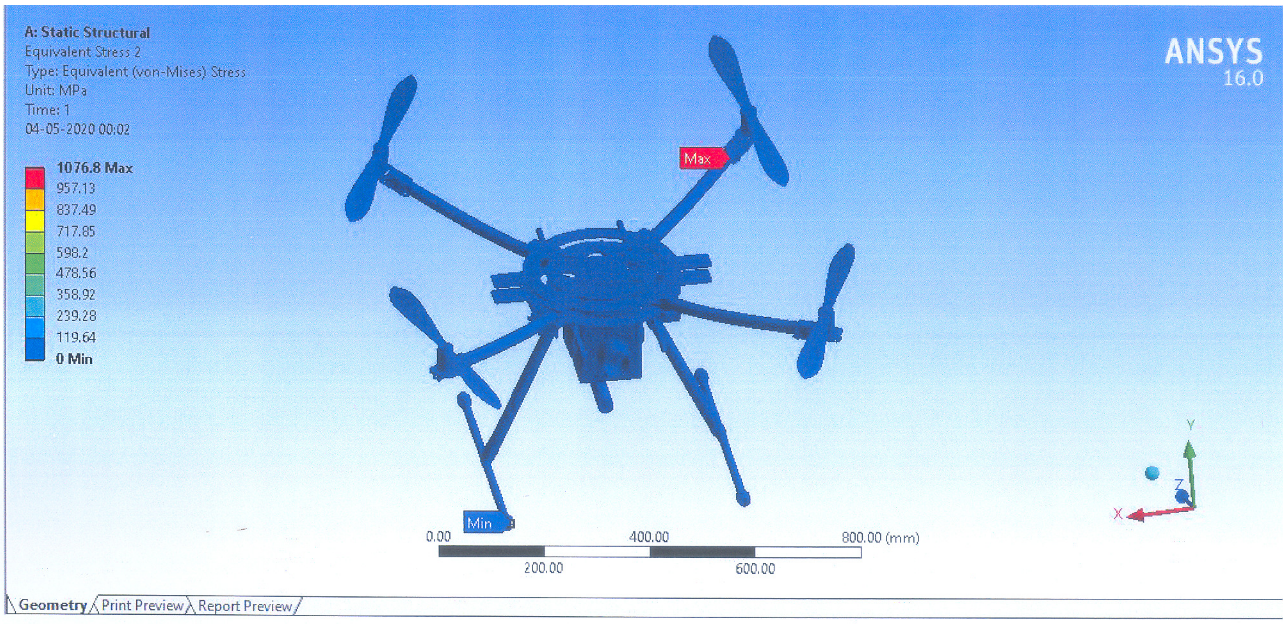

Fig.14 Equivalent Stress

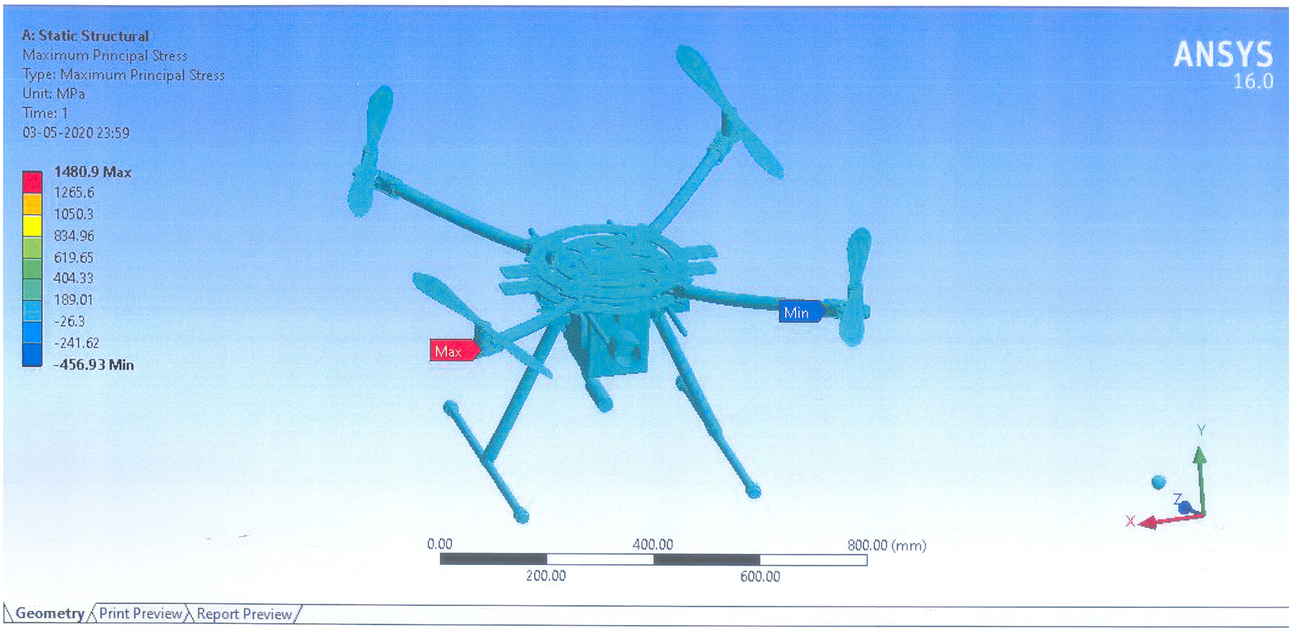

Fig.15 Maximum Principal Stress

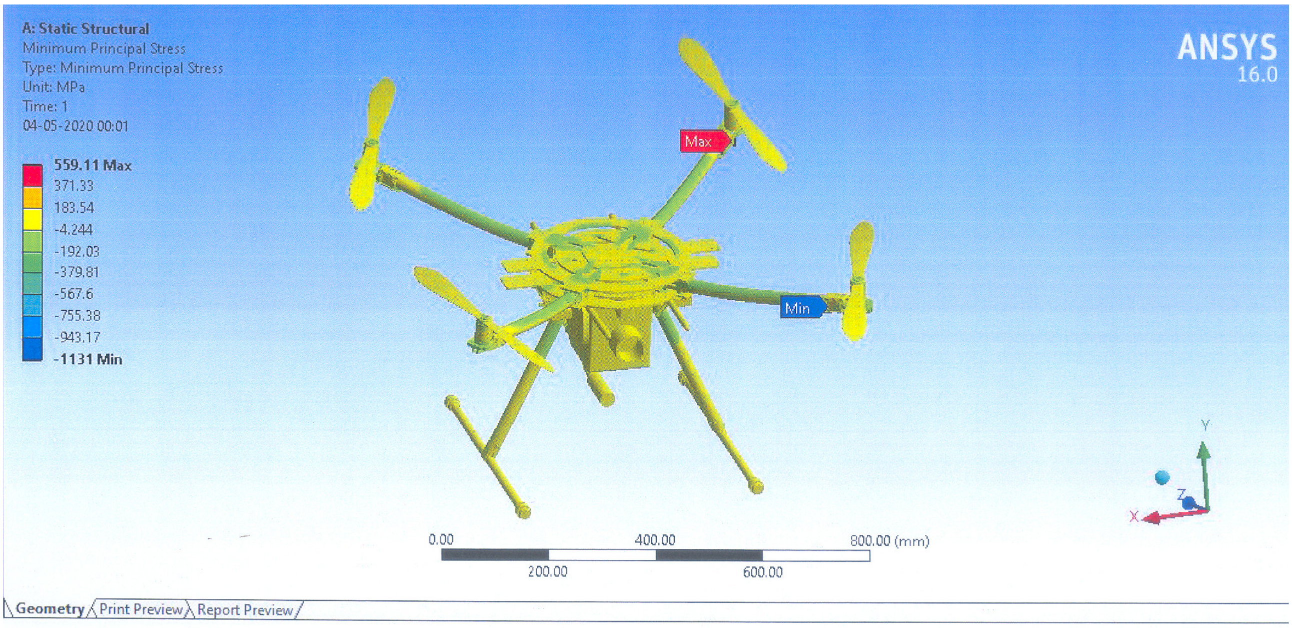

Fig.16 Minimum Principal Stress

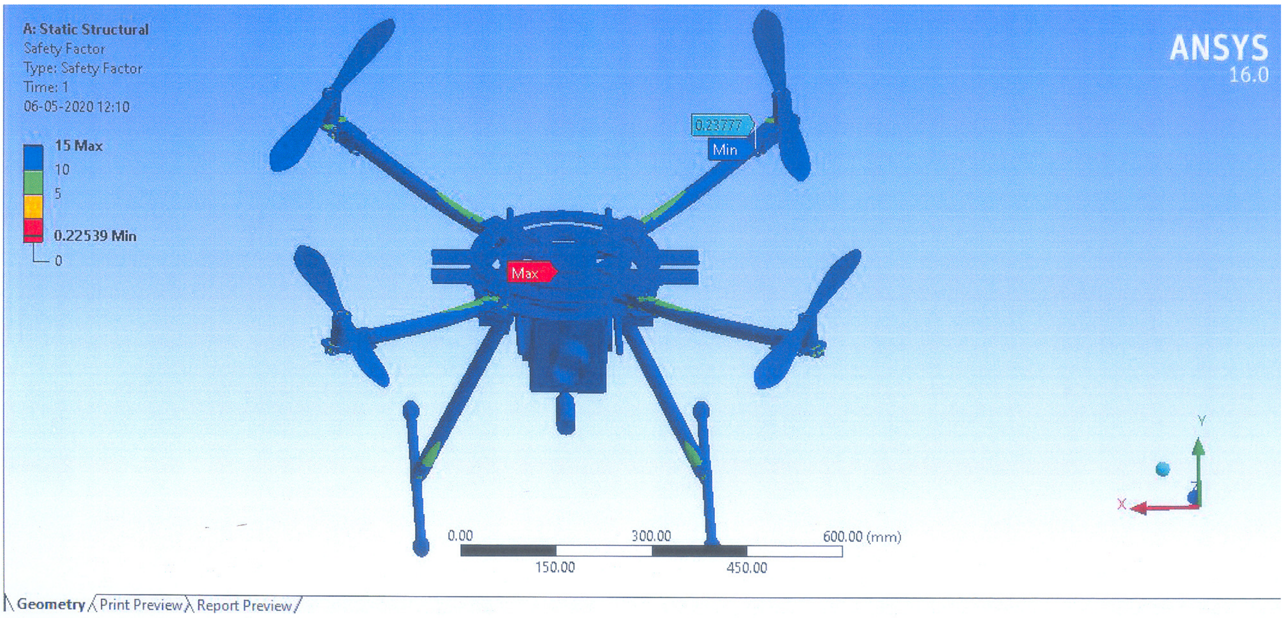

Fig.17 Safety Factor