Major Project

Design, Fabrication and Control of an Ornithopter

Department of Mechanical Engineering
ME 4356

Under the Guidance of : **Prof. (Dr.) S. Pavitran**

VISHWAKARMA INSTITUTES

Group Members

Final Year Mechanical

Division & Roll No.	Name	Gr. No.
A-19	Dhiren Bhabad	11810572
C-22	Ojas Mandlecha	11810880
B-08	Sankalp Gharmalkar	11810519
A-68	Shreeya Gadgil	11810511

Objectives

1. To build an efficient mechanism that can perform motion similar to the motion of wings of bird.
2. To design a mechanism for the tail of the ornithopter to control direction during flight.
3. Designing wings of the ornithopter considering the lift force required.
4. To design the robot in Solidworks software with consideration of assembly and manufacturing.
5. To build two testing setups to measure the thrust provided and to check the flight stability of the ornithopter.

Introduction

- Biomimetics or biomimicry is the emulation of the models, systems, and elements of nature for the purpose of solving complex human problems.
- In simple words “**Biomimicry is the practice of looking to nature for inspiration to solve design problems in a regenerative way.**”
- To replicate the wing flapping mechanism of Buzzard.
- The ornithopter could be used for surveillance, traffic monitoring or wildlife surveys.

Fig.1. Wing of Buzzard

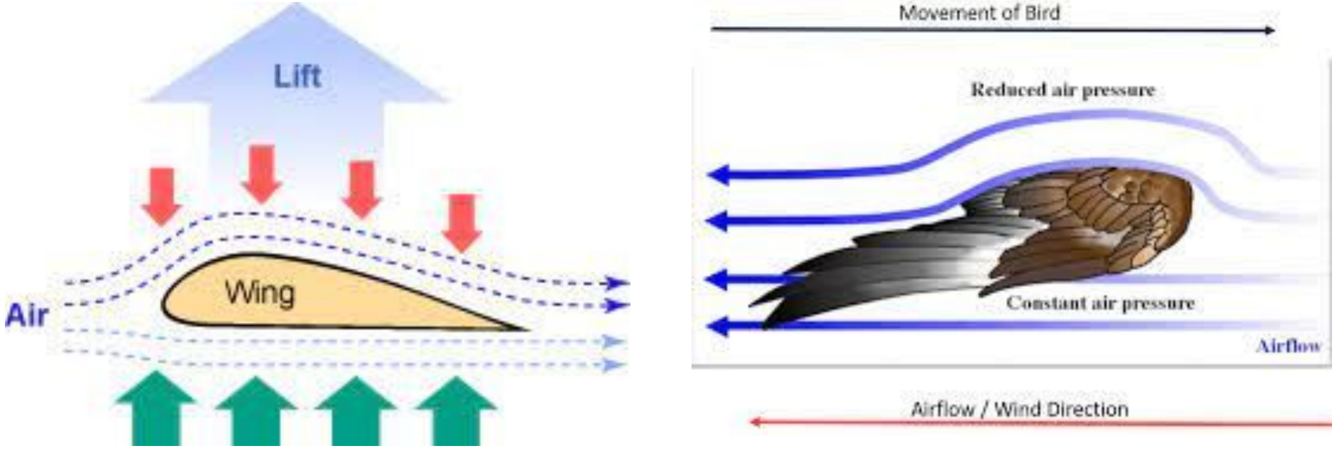


Fig.2. Flow of air over shape of wing

Literature Review

Sr. No.	Title and Author	Objective	Methodology	Result and Conclusion
1.	Design and Implementation of an Ornithopter Dan Sanderson, Jourdan McKenna, Brian Baggaley, Frederic Wight	1. The primary objective is to make a mechanical design. 2. Be able to transition from flapping to gliding and back to flapping with minimal disruption of flight pattern.	1. The model was based on the Robin bird. Accordingly, specifications were calculated. 2. Different types of wing designs were tried and tested. 3. Variation in flapping was tested on a setup with the ornithopter attached to a zipline. 4. A Vernier Force Sensor was used to measure the force during flapping.	1. The robot was able to transition from flipping to gliding with minimal flight pattern disruption. 2. Robot can achieve a velocity of 0.848 m/s on the zip line. 3. It was durable enough to withstand impacts while testing.

Literature Review

Sr. No.	Title and Author	Objective	Methodology	Result and Conclusion
2.	Aerodynamic modeling of a flapping membrane wing using motion tracking experiments. Dr. James E. Hubbard Jr.	1. To prepare an analytical model of flapping membrane wing aerodynamics using experimental data as an alternative to CFD.	1. Review of aerodynamic theory. 2. Vicon Motion tracking system has been employed 3. Data acquisition has been done by placing the sensors on the wings. 4. The results were compared with CFD results.	1. The importance of flexibility of wings has been explained. 2. The effect of flapping angle on lift force has been studied.
3.	Design and construction of an autonomous ornithopter Zachary John Jackowski	1. To design an ornithopter with maximum payload capacity and lightweight	1. Review of biomimetics and previous attempts to design ornithopters. 2. Manufacturing and testing different prototypes.	1. Lightweight and durable components ensure high performance of the ornithopter. 2. Design modifications have been made for repairability on field.

Methodology

Mechanism And Calculation	Design	Testing	Optimization	Final Results and Manufacturing
Finding mechanism for respective task and performing its corresponding calculations.	CAD modeling of the robot based on the calculations.	Measurement of acquired lift force and flight stability of prototypes.	Optimization or modification in design according to the results obtained from testing.	Finalizing the Model.

Determining the wing area

$$Wing\ Loading = \frac{Bird\,Weight}{Wing\ Area}$$

Wing Loading = 30

Bird weight = 7.35 N

Wing Area = 0.26 m^2

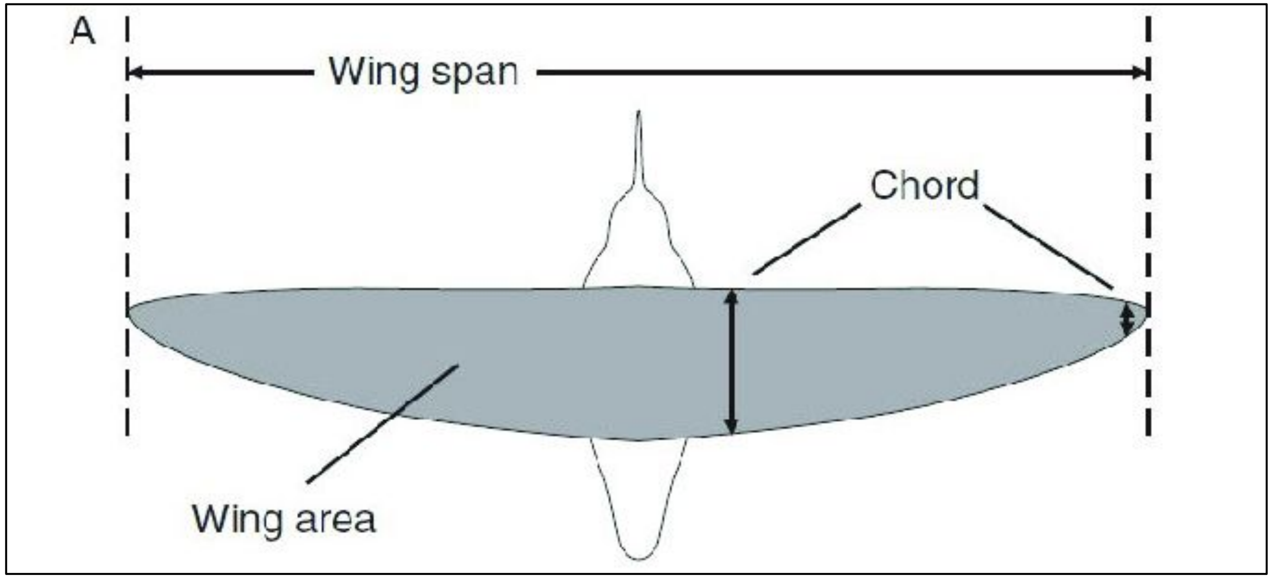


Fig 3: Bird Terminologies

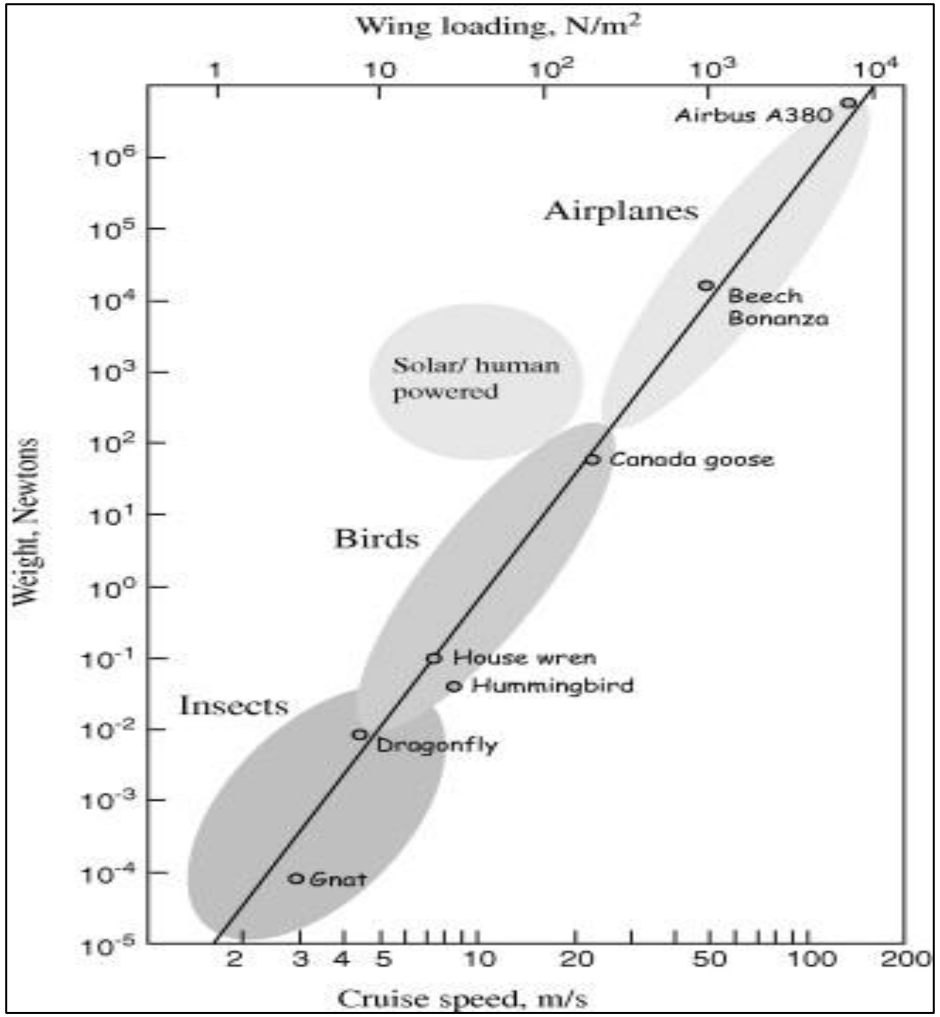


Fig 4: Weight Vs Wing Loading

Weight of Components

Components	Weight (grams)	Quantities	Total Weight (grams)
Main Body	75	1	75
Gear Box	165	-	165
BLDC Motor	80	1	80
Servo Motor	45	1	45
Shaft & Bearings	20	3	60
Electronics	100	-	100
Battery	85	1	85
Wings	40	2	80
Total Weight			**690**

Table No. 1 Weight Estimation

Wing Flexibility

- **Down stroke**
  - Lift force
  - Partial Thrust

- **Up stroke**
  - Partial Thrust

Fig 5: Wing positions of Ornithopter

When the ornithopter flaps its wings, the major forces acting on it will be drag force and its own weight.

The drag force is calculated by following formula

$$F_d = \frac{1}{2} \times C_d \times \rho \times A \times V^2$$

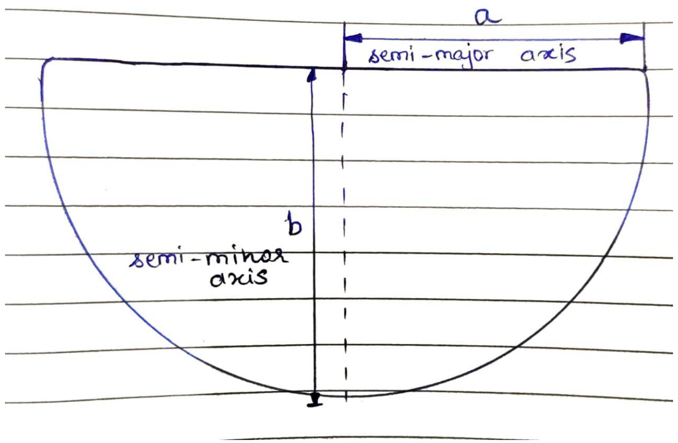
- $Area\ (A) = \frac{\pi ab}{4}$
- $Frequency\ (f) = 6$
- $\omega = f \times 60 \times 0.10472$
- $Radius\ (R) = Centroid\ of\ quater\ ellipse$
- $V = R \times \omega$

$Density\ of\ air = \rho = 1.225$

$Coefficient\ of\ drag = C_d = 1.05\ (Cube, flat\ surface)$

$Semi\ major\ axis = a = 0.5$

$Semi\ minor\ axis = b = 0.32$



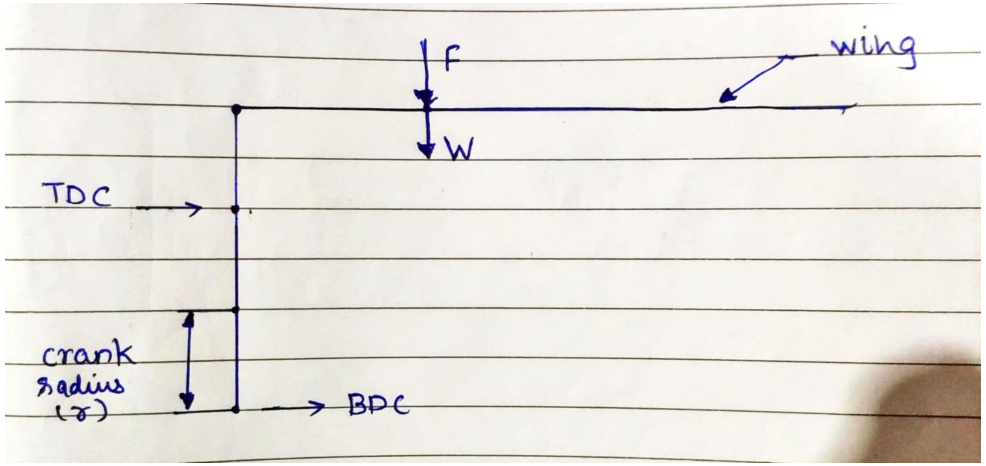


Fig 6: Forces acting on the wing

BLDC Motor Torque Calculations

$$Total\ drag\ (F_d) = 2\ \times F_d$$

$$Weight = W$$

$$Total\ force = \ F_d + W$$

$$Crank\ Radius = r$$

$$Torque = (F_d + W) \times r$$

All these values and formulas were calculated in excel sheet to narrow down the the reduction ratio and BLDC motor.

https://docs.google.com/spreadsheets/d/1AwN7oHJm2QgTFMpb154mPdjUXOrblMUWJqgVfvwyTiw/edit#gid=0

CAD model

1. BLDC Motor

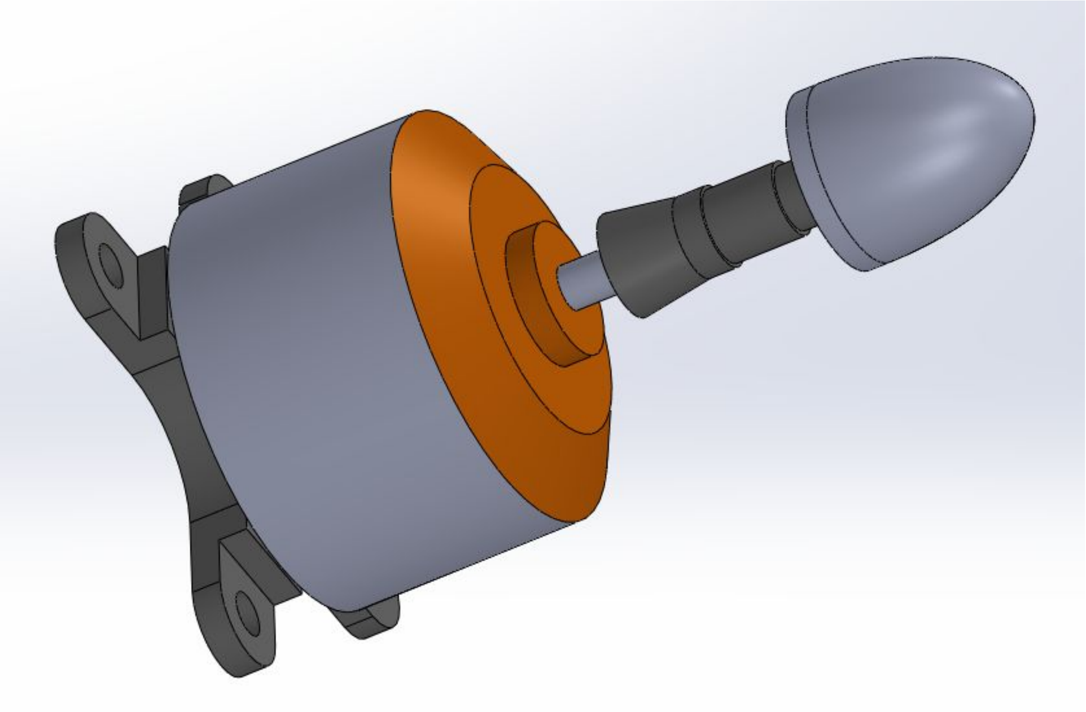


Fig 7: BLDC Motor CAD

Model	A2212 10T 13T
Motor KV (RPM/V)	1000
Current Handling Capacity (A)	12
No-Load Current (mA)	500
Max. Efficiency Current (A)	4 ~ 10
Compatible LiPO Batteries	2S ~ 3S
Shaft Diameter (mm)	3.17
Maximum Efficiency	80%
Length (mm)	27.5
Width (mm)	27
Weight (gm)	64
Shipment Weight	0.067 kg
Shipment Dimensions	12 × 6 × 5 cm

Fig 8: Motor Specs
Ref: https://robu.in/

CAD model

2. Gearbox

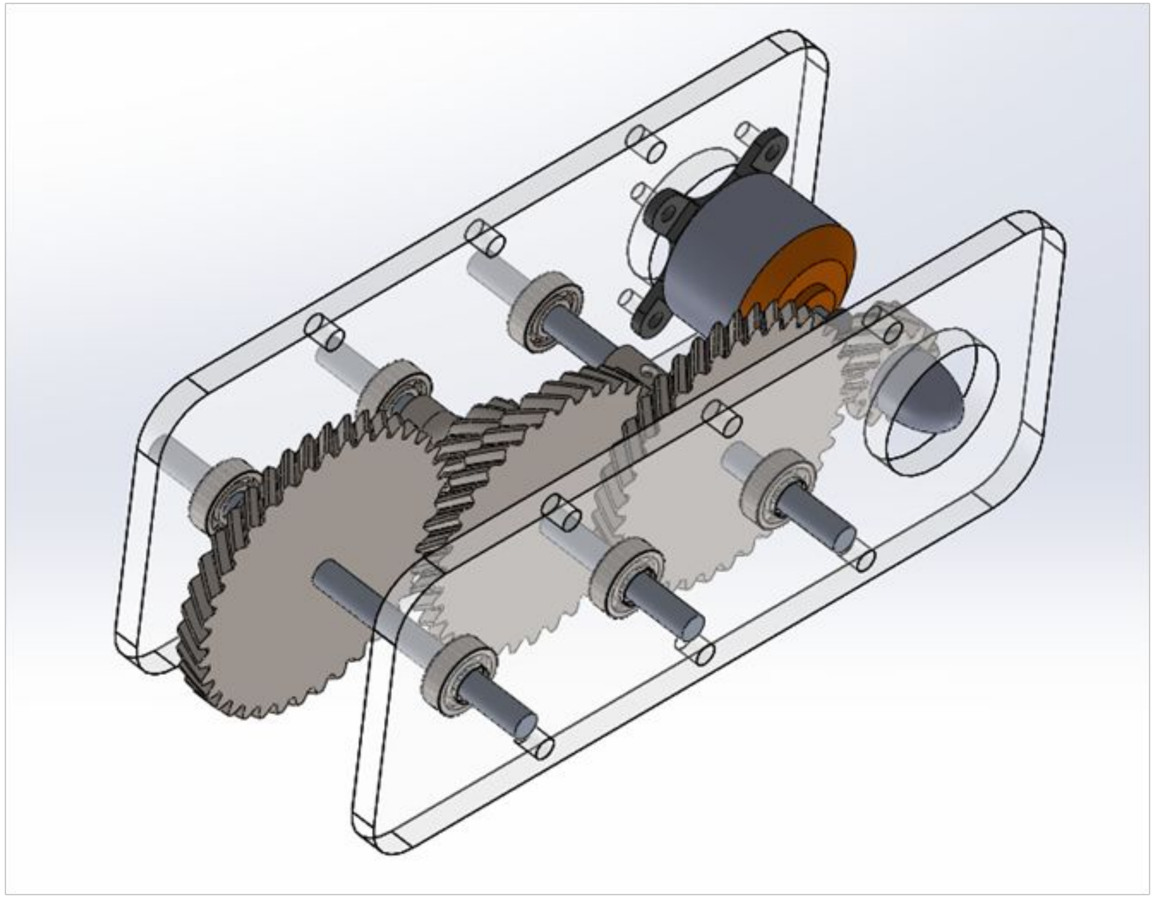


Fig 9: Gearbox with BLDC Motor

Calculations

Gearbox Reduction Calculation

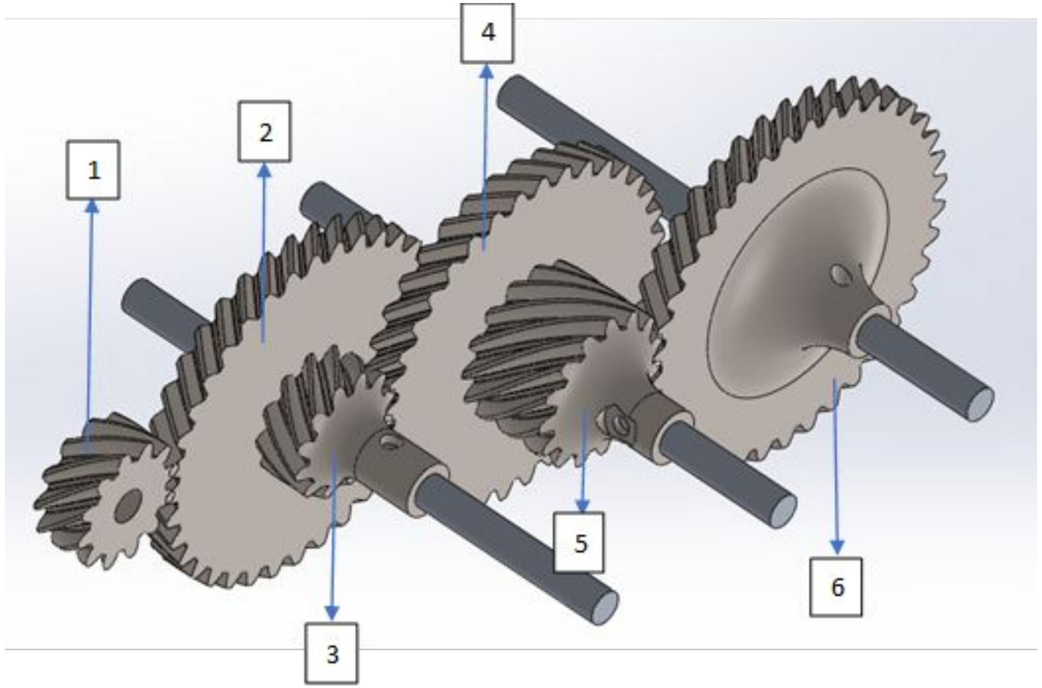


Fig 10: Gearbox

Type of Gear Train: Compound Gear Train
Type of gears used: Helical Gear

Gear No.	No. of teeth	Total Reduction achieved
1 (Input Gear)	12	0
2	36	36/12=3
3	12	3 (Compound Gear)
4	36	3 x (36/12) = 9
5	15	9 (Compound Gear)
6 (Output Gear)	38	9 x (38/15) = 22.8

Table No. 2 Gear reduction values

CAD model

3. Ornithopter Wing Front Pivot Mechanism

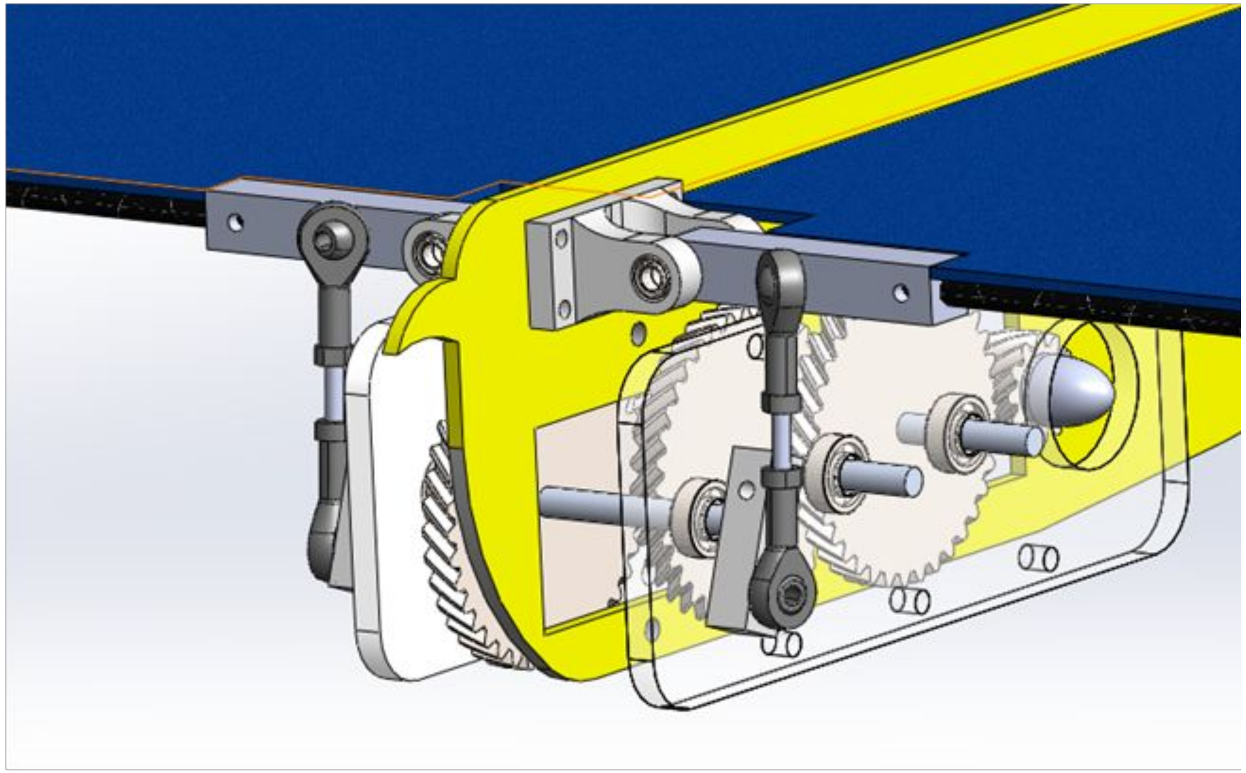


Fig 11: Wing Front Pivot

Front pivot mechanism calculations

- **Assumption:** We have assumed here, that when the crank is at the bottom dead center (lowest position) the wing would he horizontal.
- Considering this, geometrical relationship between the flapping angle of wing, crank radius, center distance between rod end bearings and distance between rod end bearing and frontal pivot was established.

AP = Center distance between rod end bearings (d)
BP = Crank Diameter (2r)
OA = Distance between rod end bearing and frontal pivot (x)
∠NOM = Flapping angle of wing (θ)

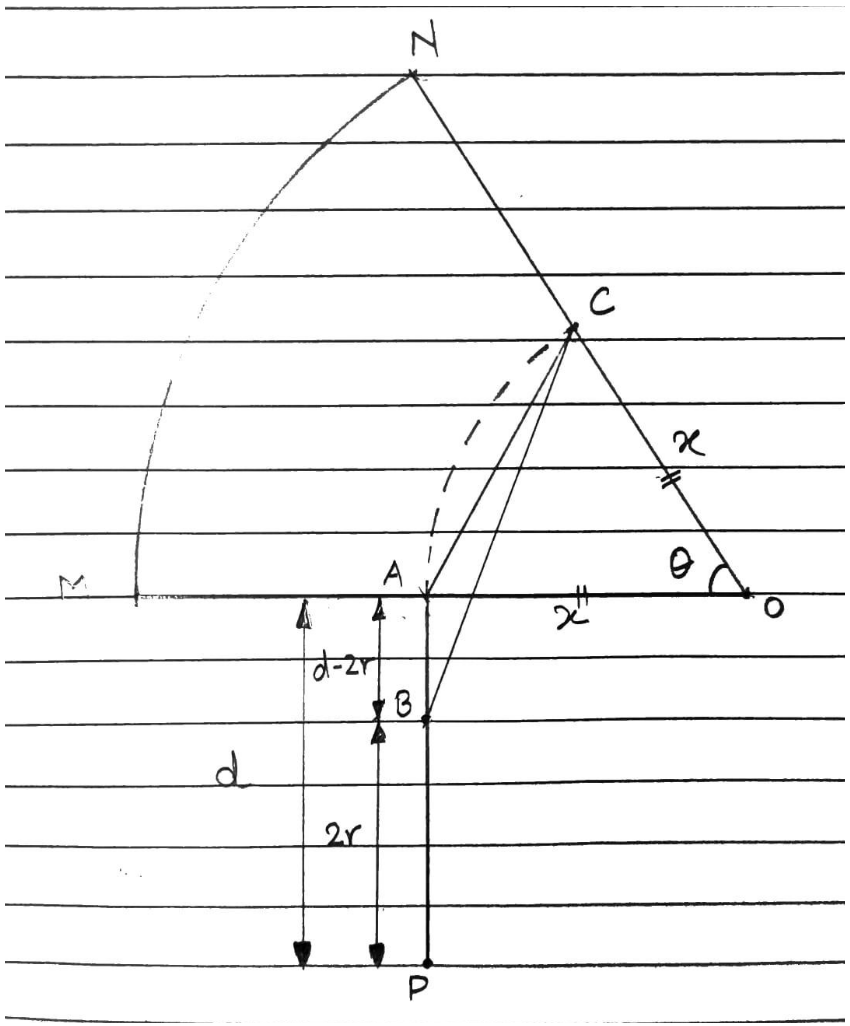
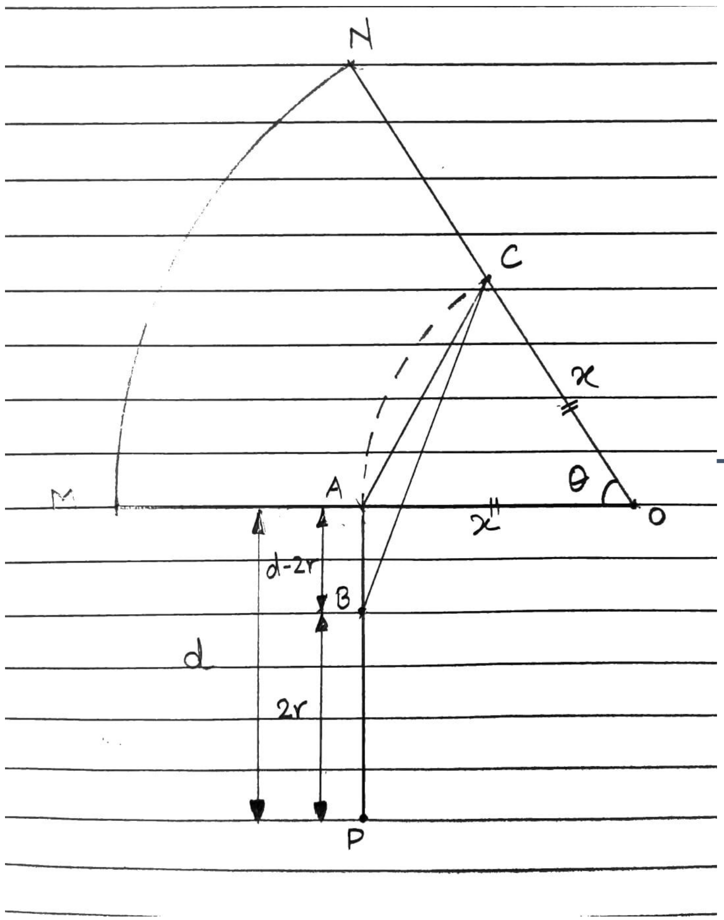


Fig.12: 2D representation of front pivot mechanism (front view)

Front pivot mechanism calculations



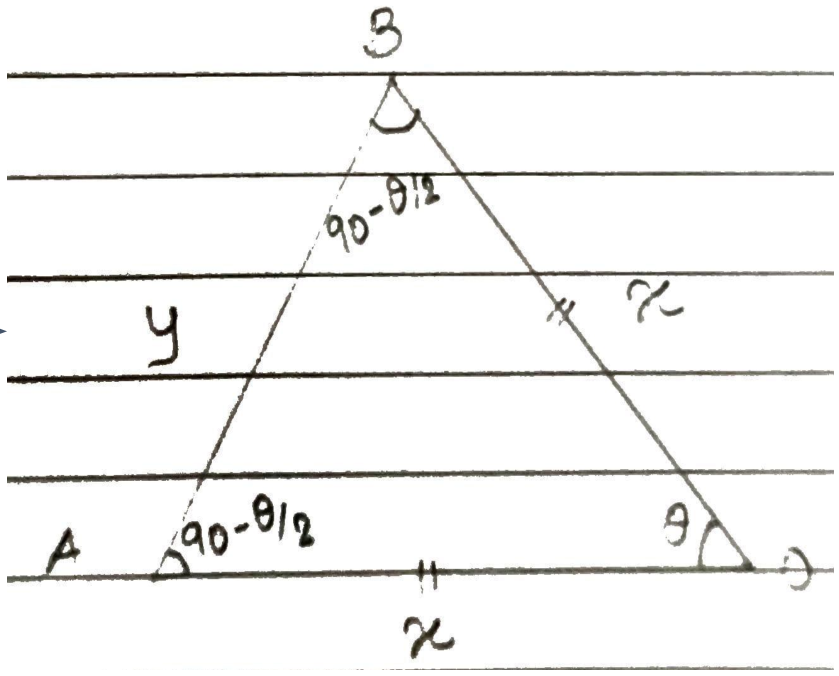


Fig 13: 2D representation of front pivot mechanism (front view)

OA = OB (Radius)

Applying sine rule to ΔOAB

$$\frac{\sin\theta}{y} = \frac{\sin(90 - \frac{\theta}{2})}{x}$$

$$y = x\frac{\sin\theta}{\cos\frac{\theta}{2}}$$

Assume flapping angle **θ**, we can calculate **y** (AB).

Considering the design dimensions,

x was assumed 23 mm

Front pivot mechanism calculations

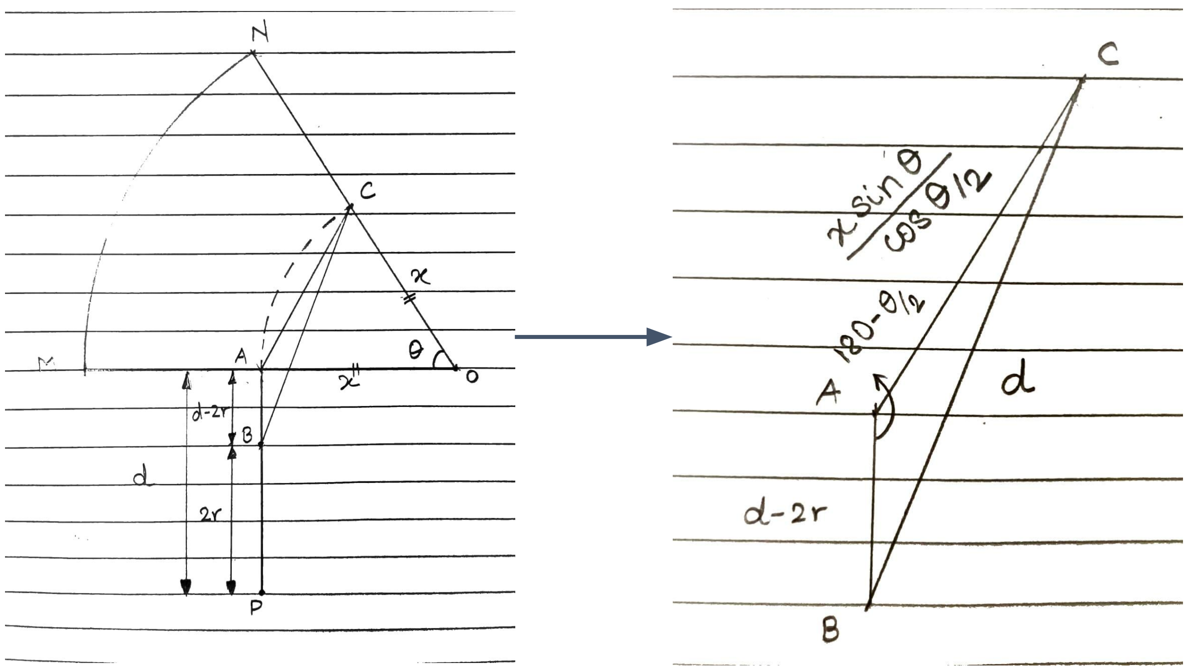


Fig 14: 2D representation of front pivot mechanism (front view)

Now consider ΔABC,

Applying sine and cosine rule to ΔOAB,

$$\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c}$$

$$\frac{\sin(180-\frac{\theta}{2})}{d} = \frac{\sin B}{x\frac{\sin\theta}{\cos\frac{\theta}{2}}} = \frac{\sin C}{d-2r}$$

$$a = \sqrt{b^2 + c^2 - 2.b.c.\cos A}$$

Here,

$$d = \sqrt{y^2 + (d-2r)^2 - 2.y.(d-2r).\cos(180-\frac{\theta}{2})}$$

where, $y = x\frac{\sin\theta}{\cos\frac{\theta}{2}}$

By assuming flapping angle and d or (d-2r) we can find rest all of the values

Front pivot mechanism calculations

By using these formulas, these are assumed and obtained values,

Parameter	Value
θ	60^0
x	23 mm
d	51.5 mm
r	11 mm

Table No. 3 Pivot geometric values

CAD model

4. Ornithopter Wing Back Pivot Mechanism

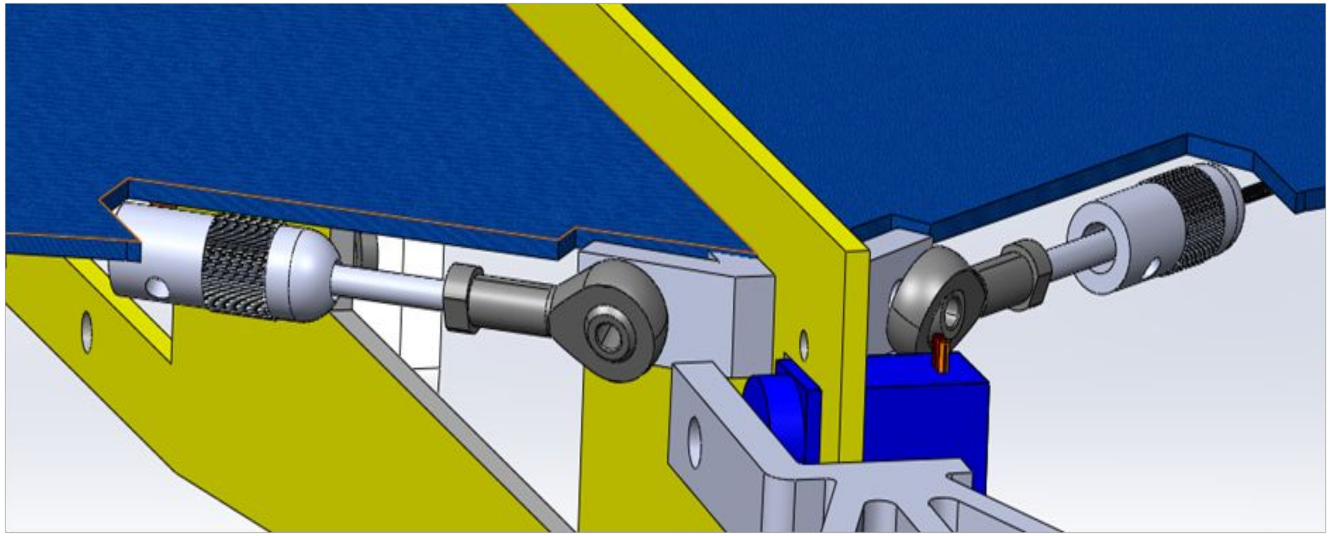


Fig 15: Wingback Pivot

Servo Motor Torque Calculations

- Torque calculated for servo motor will be in the same way as BLDC motor.
- Here the area will be of the tail wing (isosceles triangle)

$$F_d = \frac{1}{2} \times C_d \times \rho \times A \times V^2$$

- $Area\ (A) = \frac{bh}{2}$
- $\omega = Rated\ speed\ of\ Servo$
- $Radius\ (R) = Centroid\ of\ isoceles\ triangle$
- $V = R \times \omega$

$$Torque = (F_d + W) \times R$$

$Density\ of\ air = \rho = 1.225$

$Coefficient\ of\ drag = C_d = 1.05\ (Cube, flat\ surface)$

$base = b = 0.22$

$height = h = 0.24$

$Weight = W = 0.05$

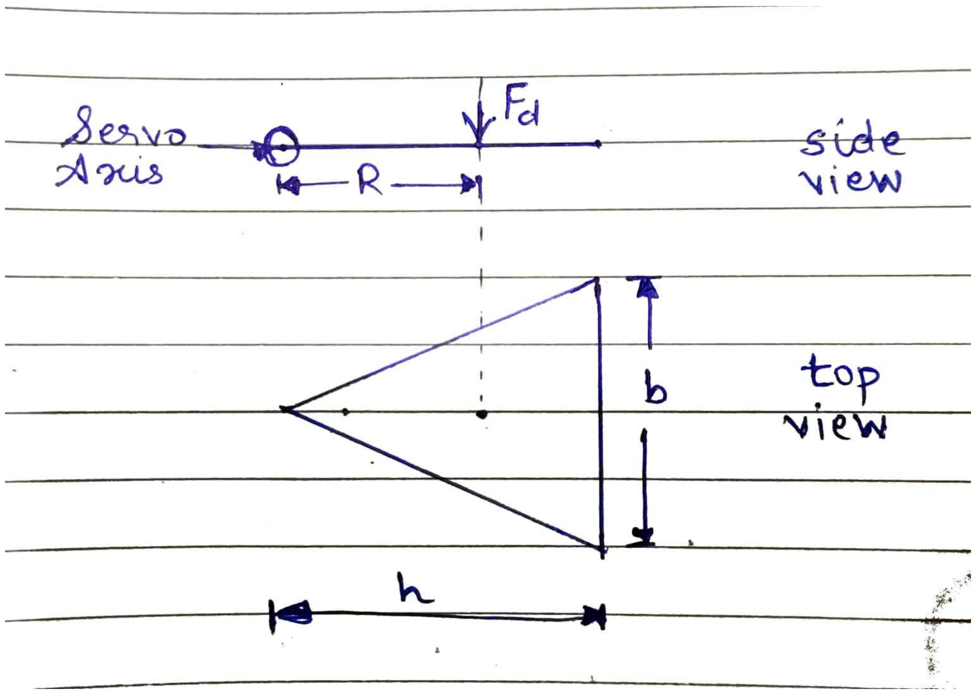


Fig 16: Location of the force acting on the tail

- Similarly, excel sheet was for this calculation to narrow down the servo motor

https://docs.google.com/spreadsheets/d/1AwN7oHJm2QgTFMpb154mPdjUXOrblMUWJqgVfvwyTiw/edit#gid=673182568

CAD model

5. Ornithopter Tail Mechanism

- Servo motor SG90 has been used because of ease of position control

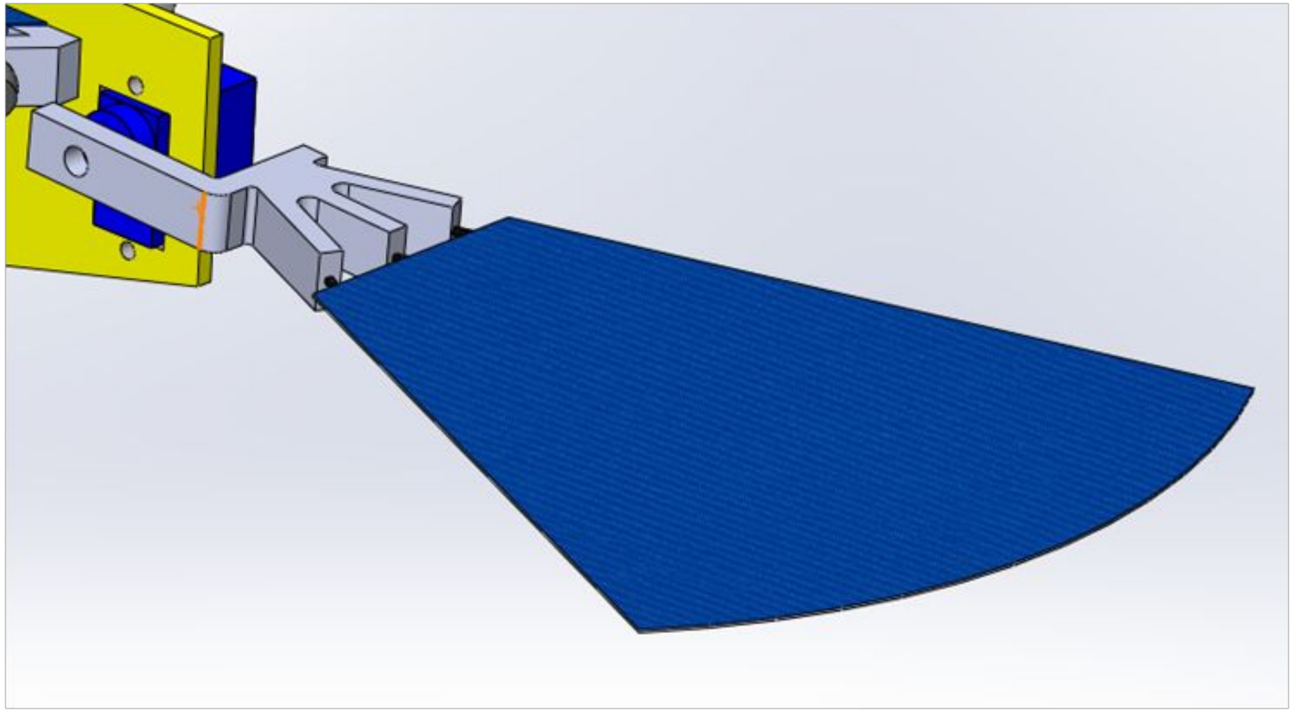


Fig.17. Tail mechanism

CAD model

5. Final CAD

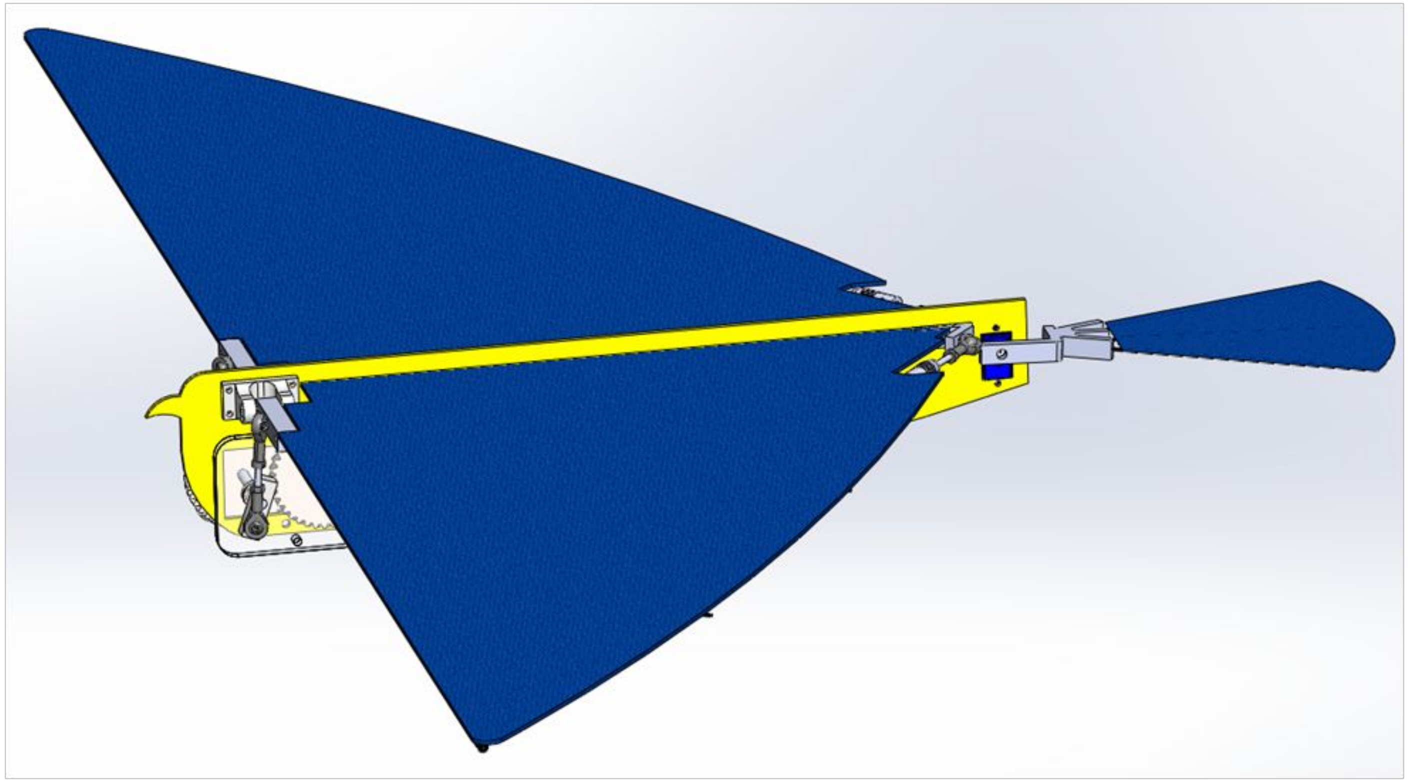


Fig.18: Final CAD

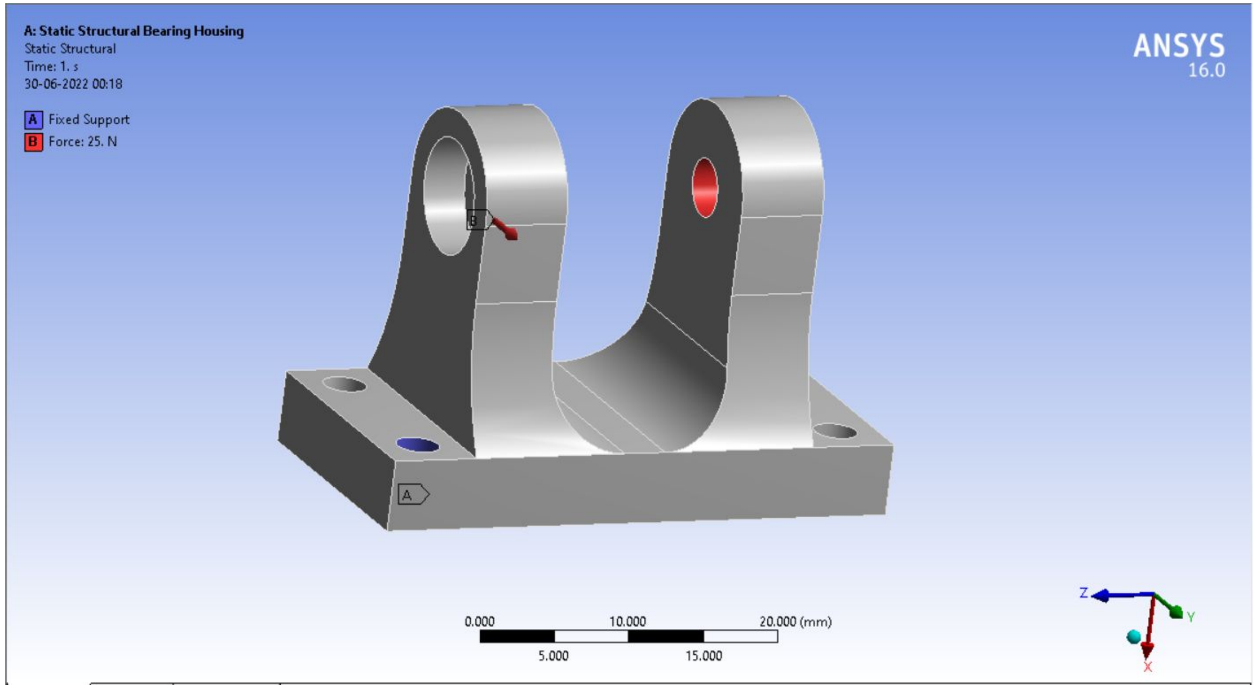
Analysis(1/4):Bearing Housing

Material Properties

Properties of Outline Row 3: ABS

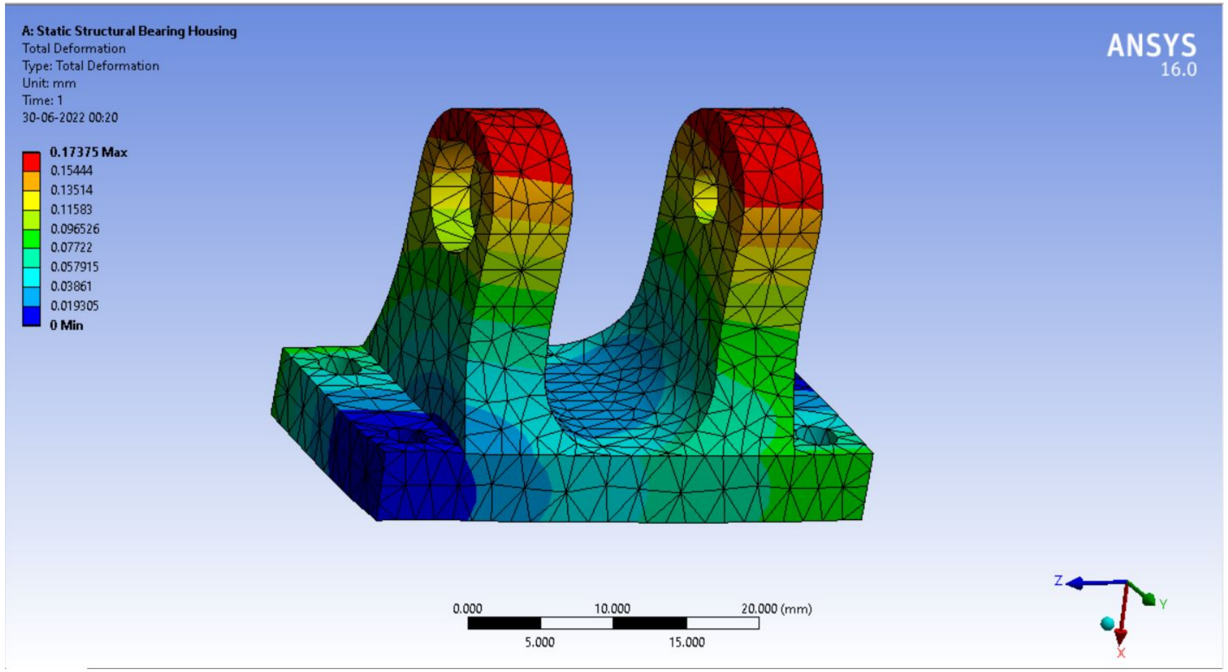
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	1141	kg m^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Mod...			
5	Young's Modulus	1.19E+09	Pa		
6	Poisson's Ratio	0.29			
7	Bulk Modulus	9.4444E+08	Pa		
8	Shear Modulus	4.6124E+08	Pa		
9	Field Variables				
13	Tensile Yield Strength	1.85E+07	Pa		
14	Tensile Ultimate Strength	2.76E+07	Pa		

Boundary Conditions

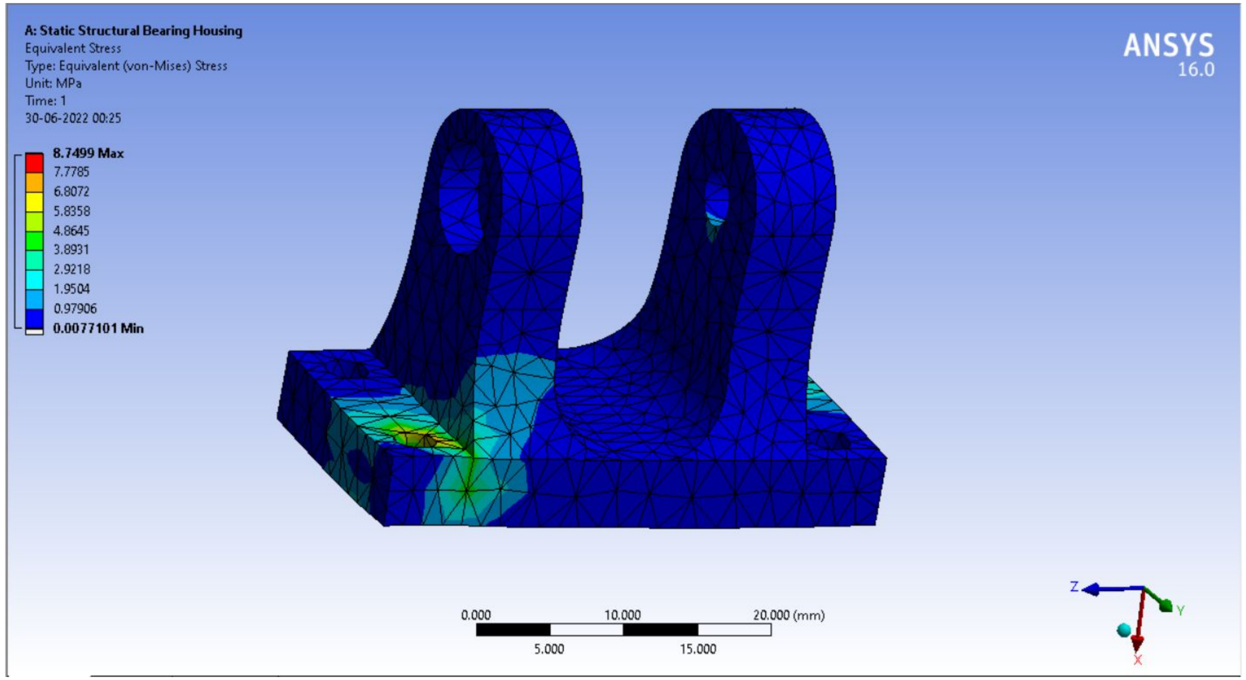


Analysis(1/4):Bearing Housing

Total Deformation



Equivalent Stress



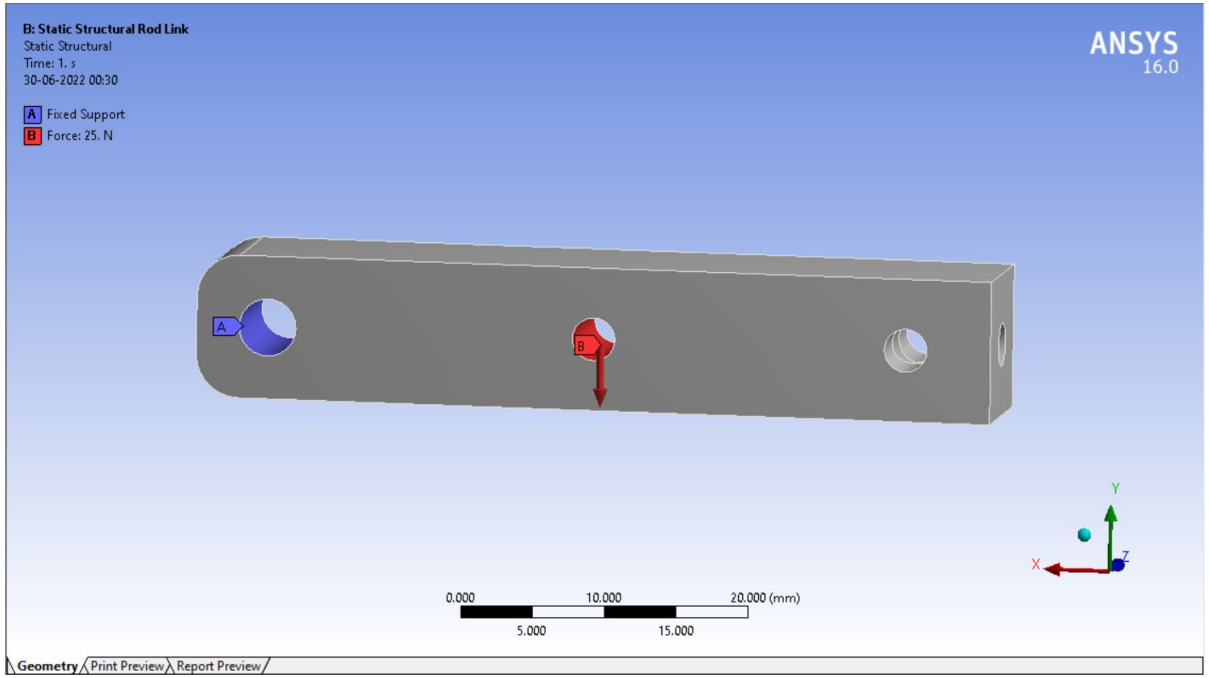
Analysis(2/4):Rod Connecting link

Material Properties

Properties of Outline Row 4: ABS 2

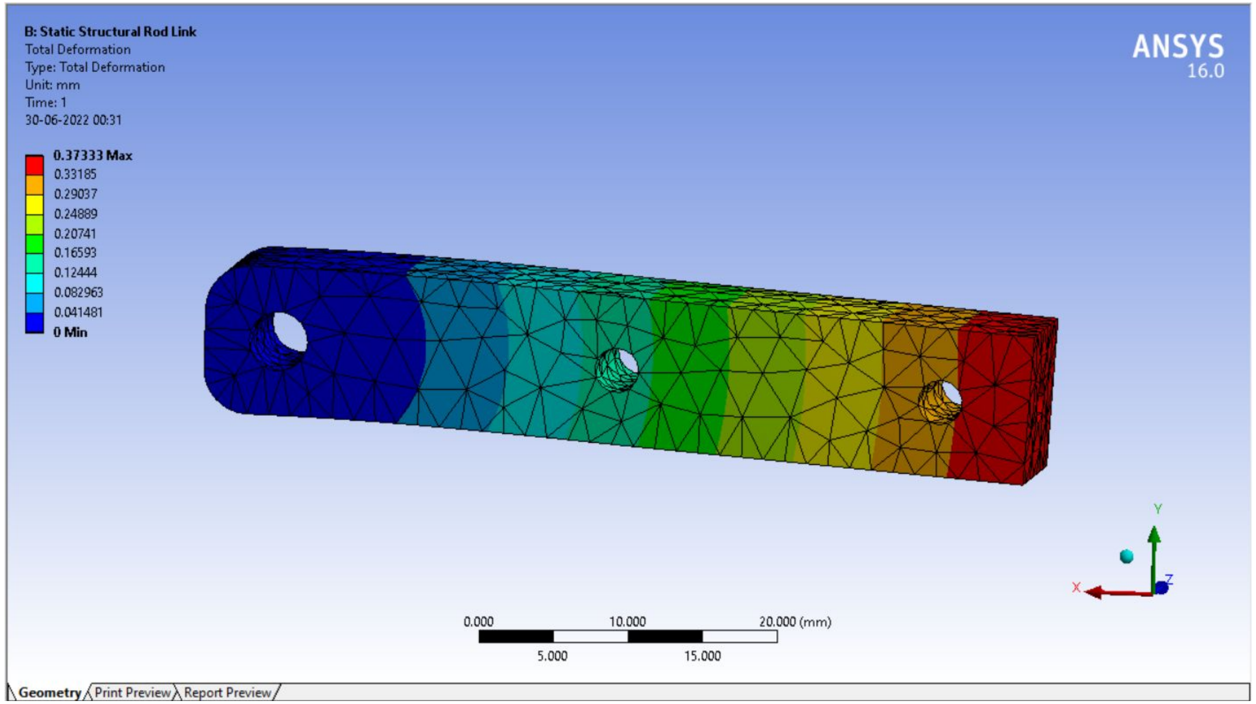
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	900	kg m^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Mod...			
5	Young's Modulus	1.19E+09	Pa		
6	Poisson's Ratio	0.29			
7	Bulk Modulus	9.4444E+08	Pa		
8	Shear Modulus	4.6124E+08	Pa		
9	Field Variables				
13	Tensile Yield Strength	1.85E+07	Pa		
14	Tensile Ultimate Strength	2.76E+07	Pa		

Boundary Conditions

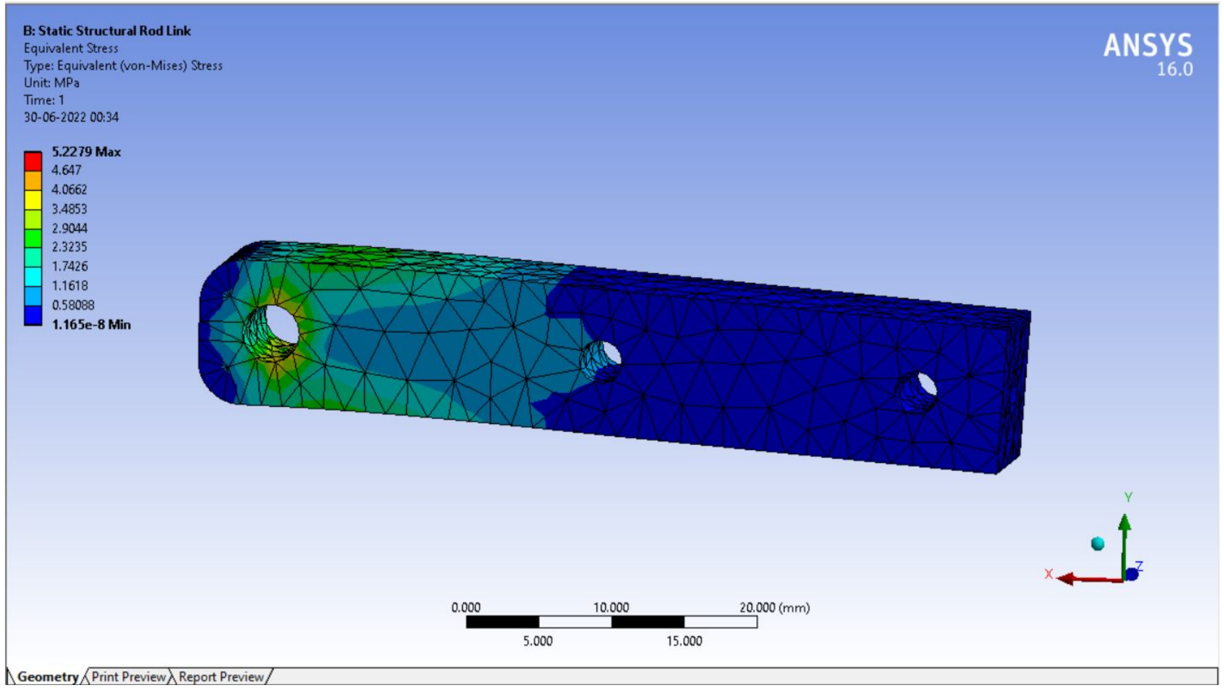


Analysis(2/4): Rod Connecting Link

Total Deformation



Equivalent Stress



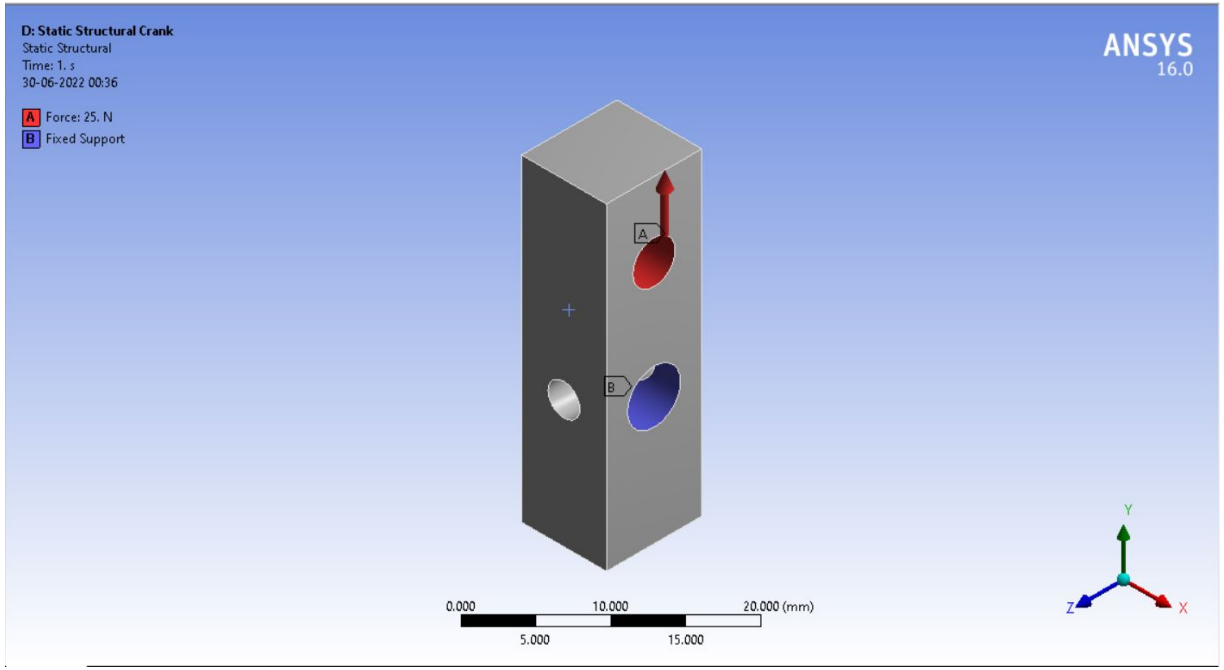
Analysis(3/4): Crank

Material Properties

Properties of Outline Row 5: ABS 3

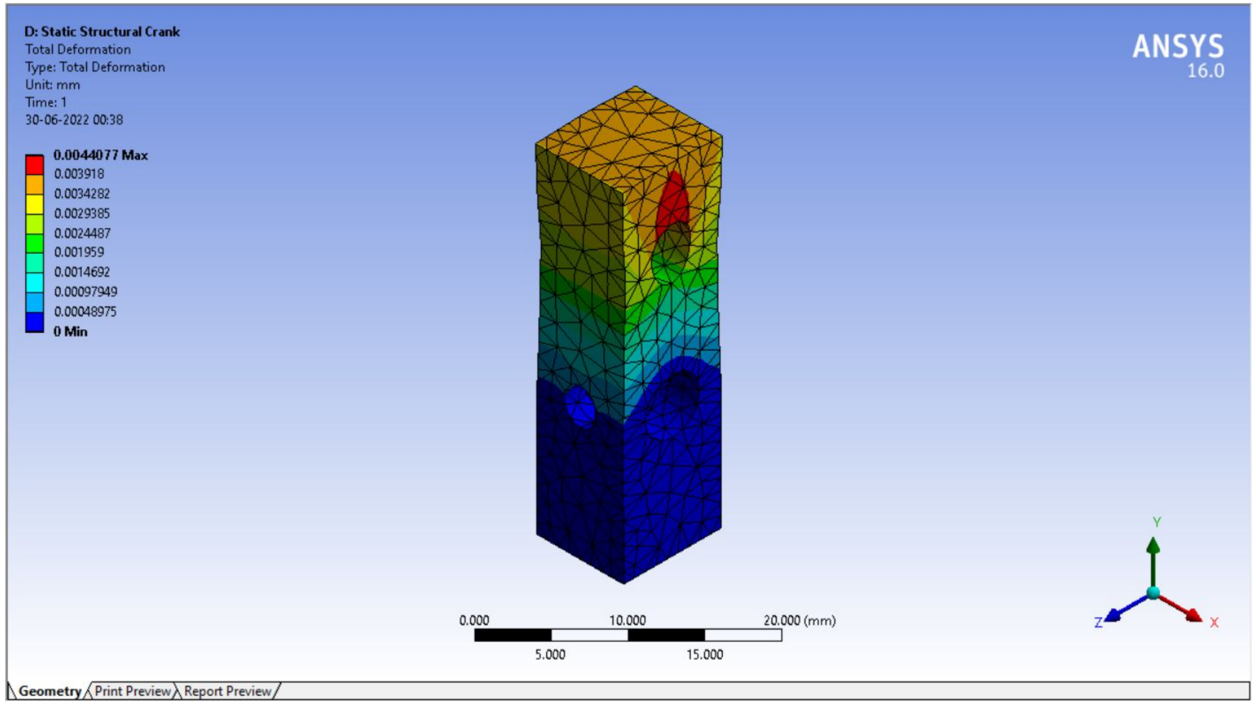
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	960	kg m^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Mod...			
5	Young's Modulus	1.19E+09	Pa		
6	Poisson's Ratio	0.29			
7	Bulk Modulus	9.4444E+08	Pa		
8	Shear Modulus	4.6124E+08	Pa		
9	Field Variables				
13	Tensile Yield Strength	1.85E+07	Pa		
14	Tensile Ultimate Strength	2.76E+07	Pa		

Boundary Conditions

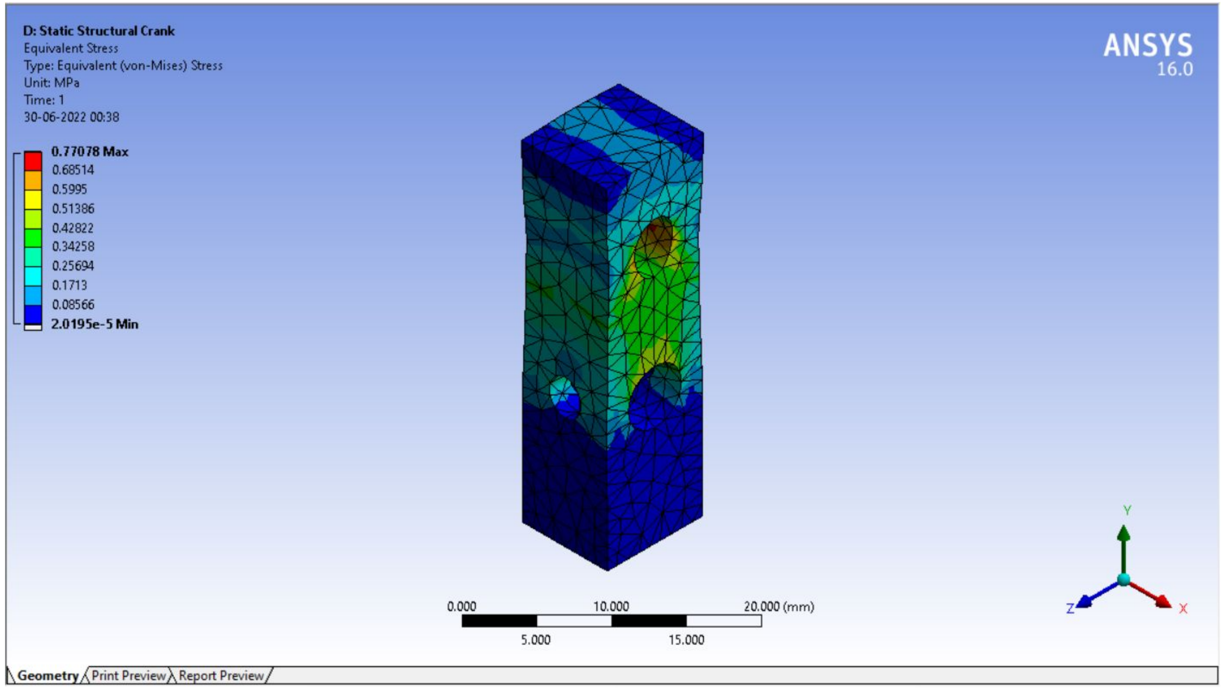


Analysis(3/4): Crank

Total Deformation



Equivalent Stress



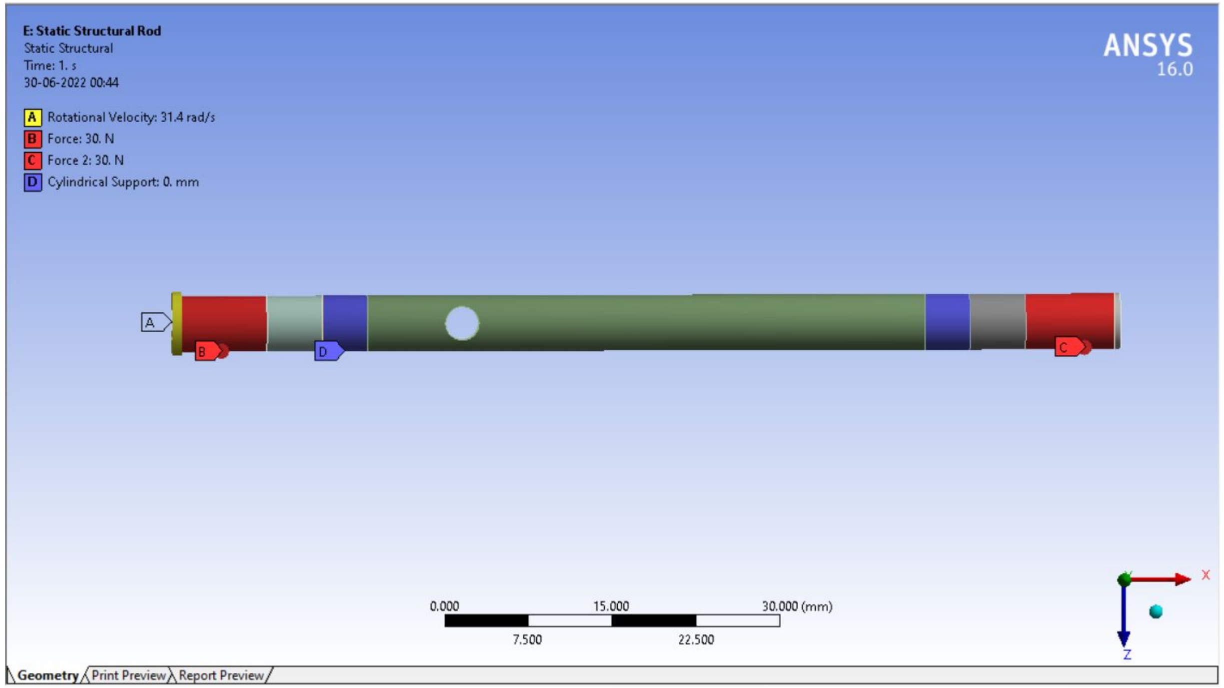
Analysis(4/4): Rod

Material Properties

Properties of Outline Row 4: Stainless Steel

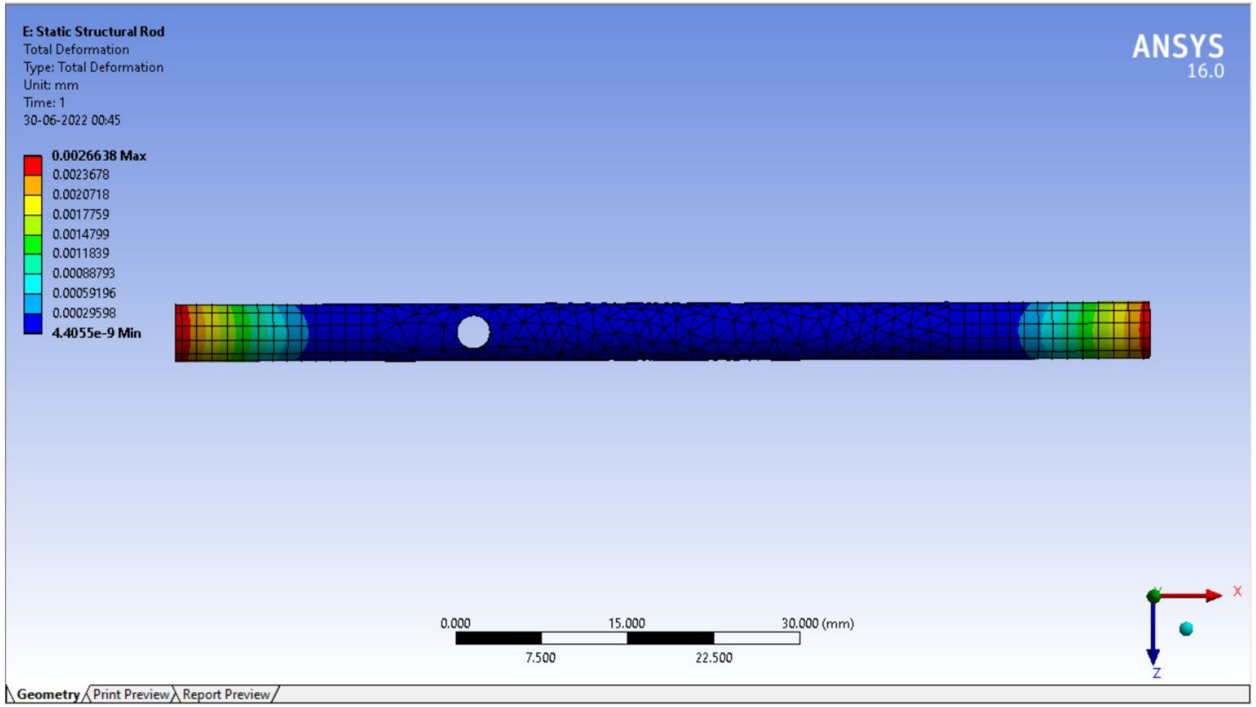
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7750	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
4	Coefficient of Thermal Expansion	1.7E-05	C^-1		
5	Reference Temperature	22	C		
6	Isotropic Elasticity				
7	Derive from	Young's Mod...			
8	Young's Modulus	1.93E+11	Pa		
9	Poisson's Ratio	0.31			
10	Bulk Modulus	1.693E+11	Pa		
11	Shear Modulus	7.3664E+10	Pa		
12	Field Variables				
16	Tensile Yield Strength	2.07E+08	Pa		
17	Compressive Yield Strength	2.07E+08	Pa		
18	Tensile Ultimate Strength	5.86E+08	Pa		

Boundary Conditions

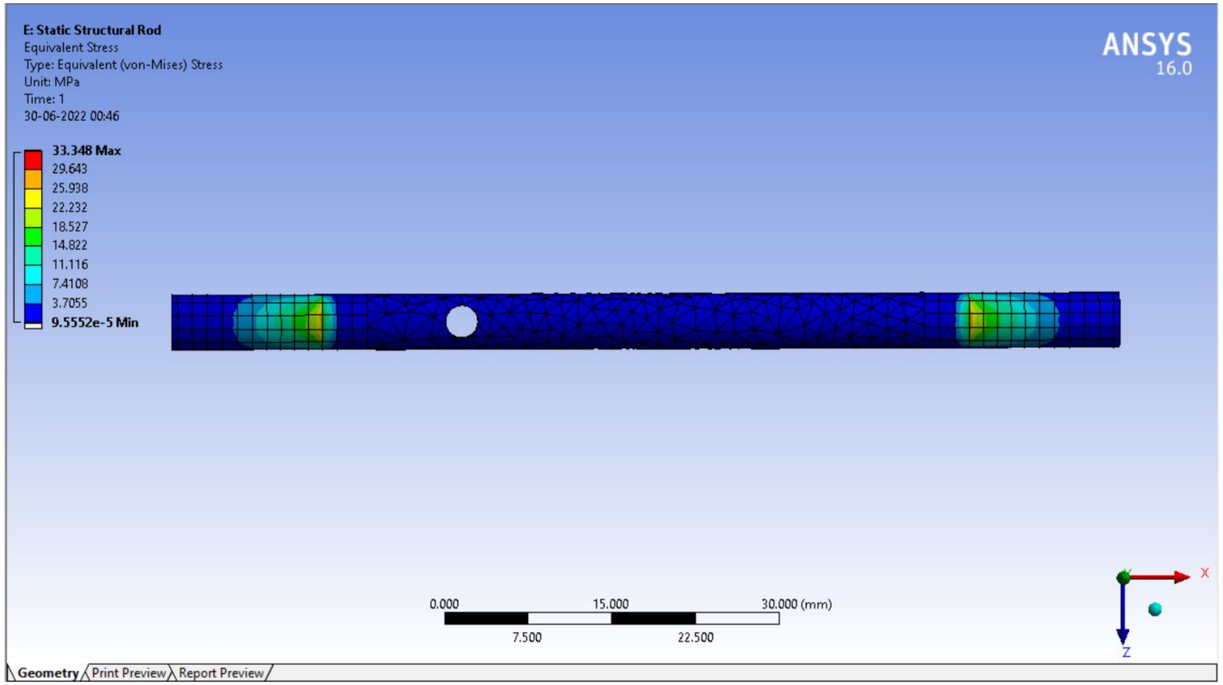


Analysis(4/4): Rod

Total Deformation



Equivalent Stress



Materials & manufacturing processes

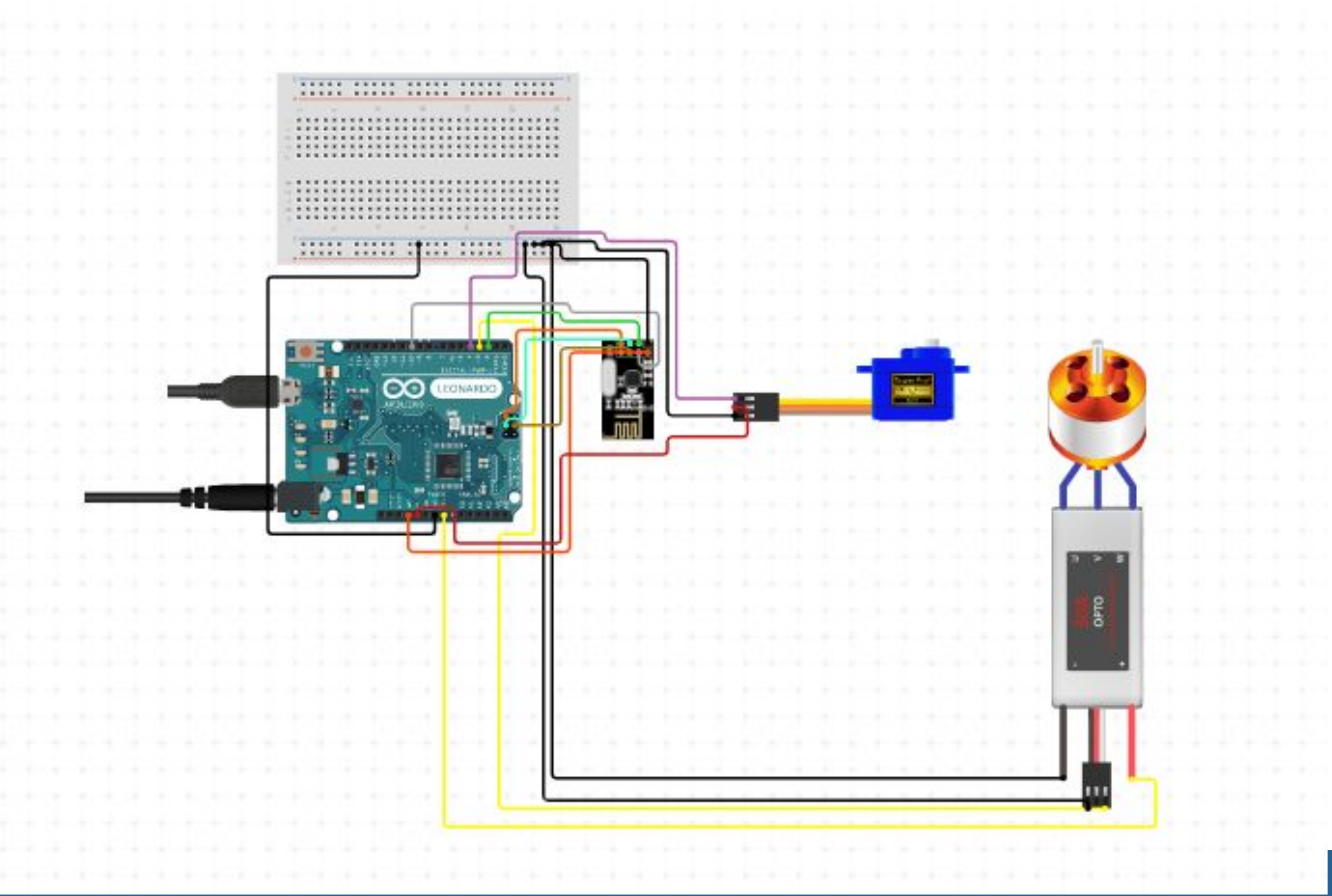
- It was essential to have the weight of the ornithopter as minimum as possible.
- Gears are 3d printed of ABS material.
- The main body is made up of fiberglass and is cut to required profile by waterjet cutting.
- The skeleton of the wings is made up of carbon fiber rods
- The wings have been made up of nylon fiber.

Electronics

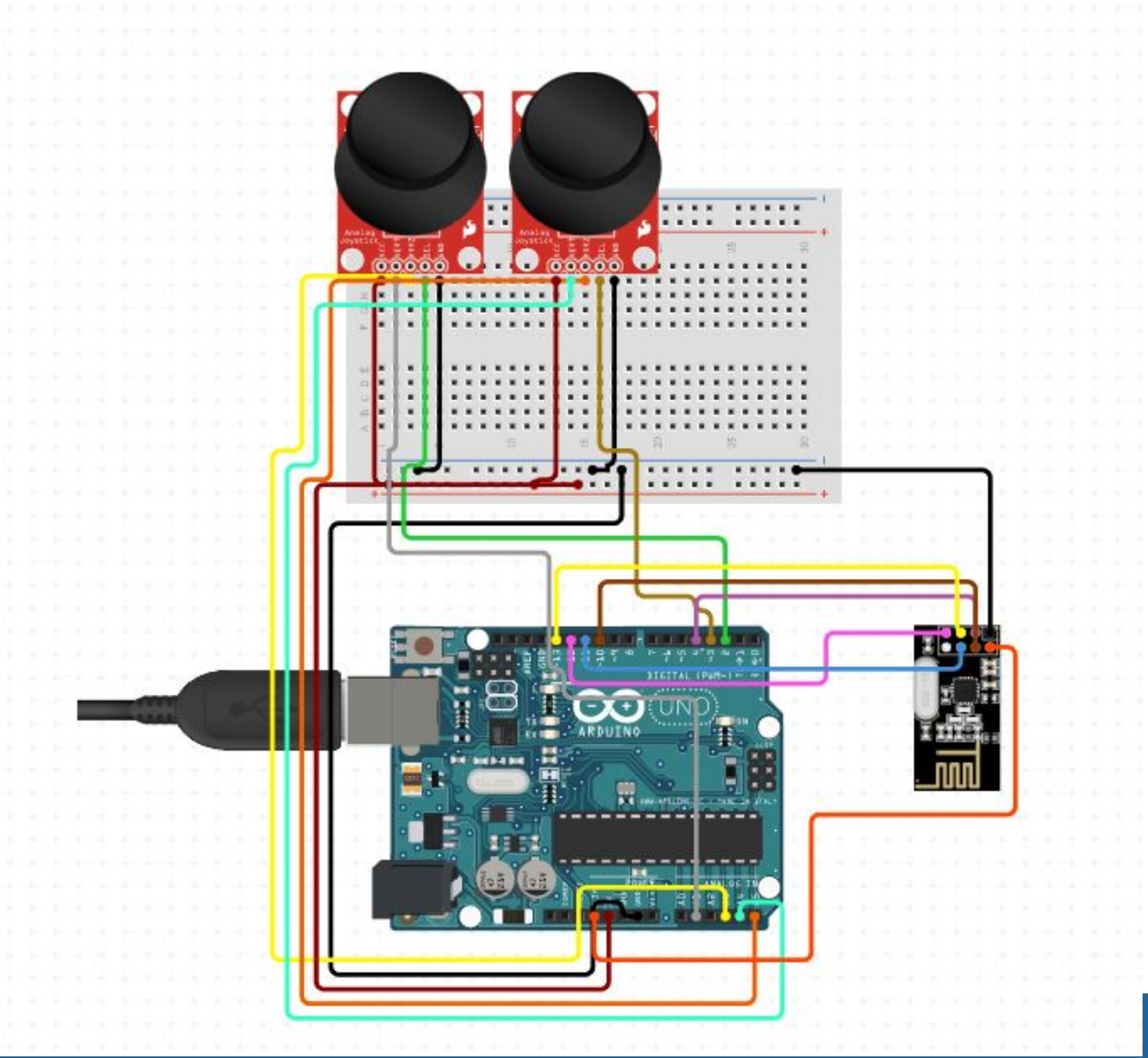
Components

- Electronic Speed Controller
- Radio frequency modules (2.4 GHz)
- Arduino UNO
- Joystick module

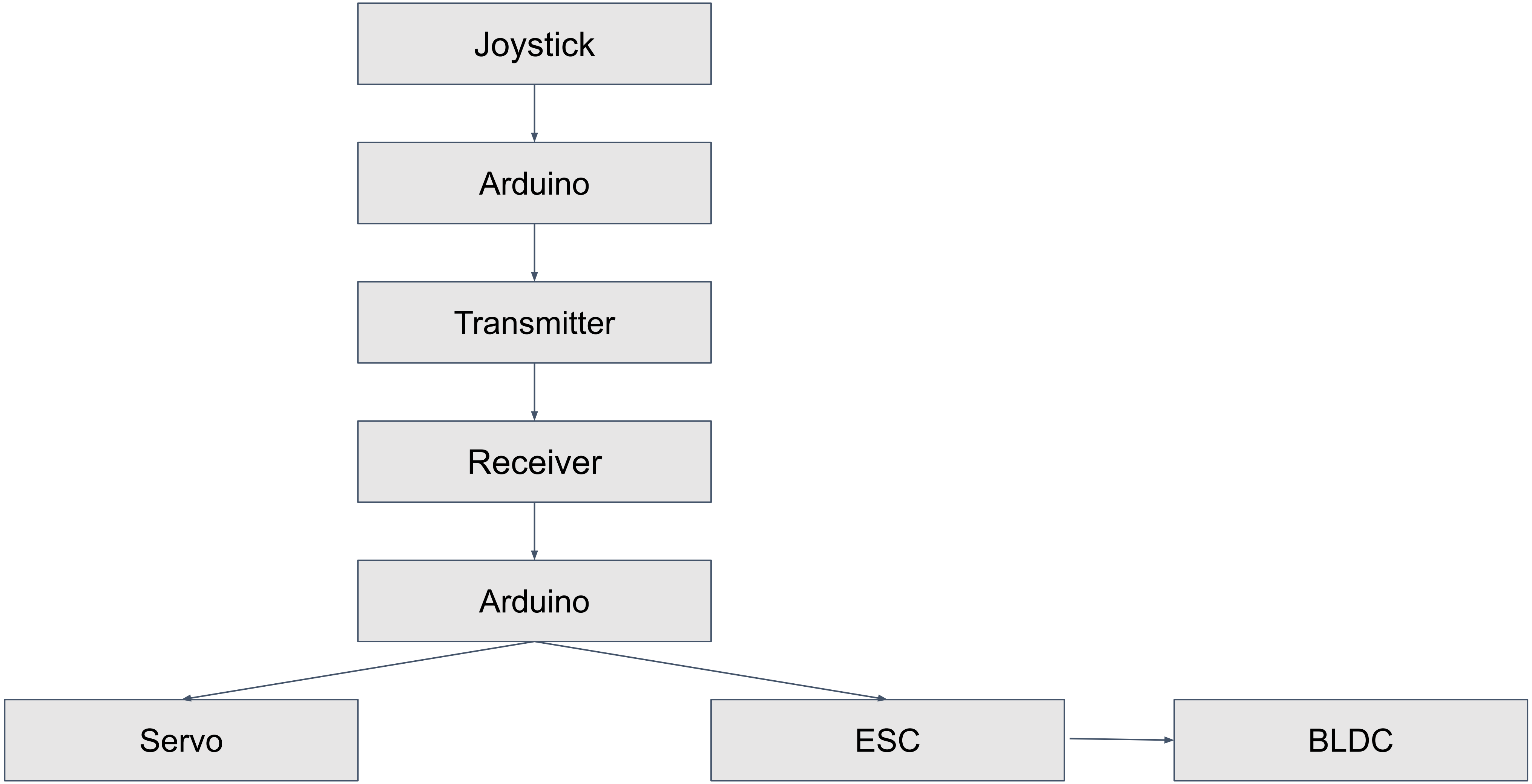
Electronic Circuit



Electronic circuit for the Controller



Electronics



Test Setup

- Based on the principle of balancing of moments

$$F_{Lift} * r = F_d * r$$

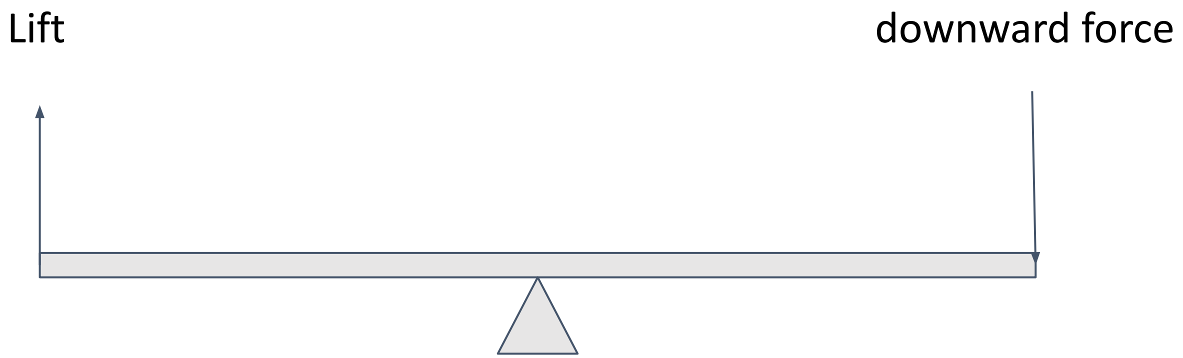


Fig 18: Moment balance on the test setup

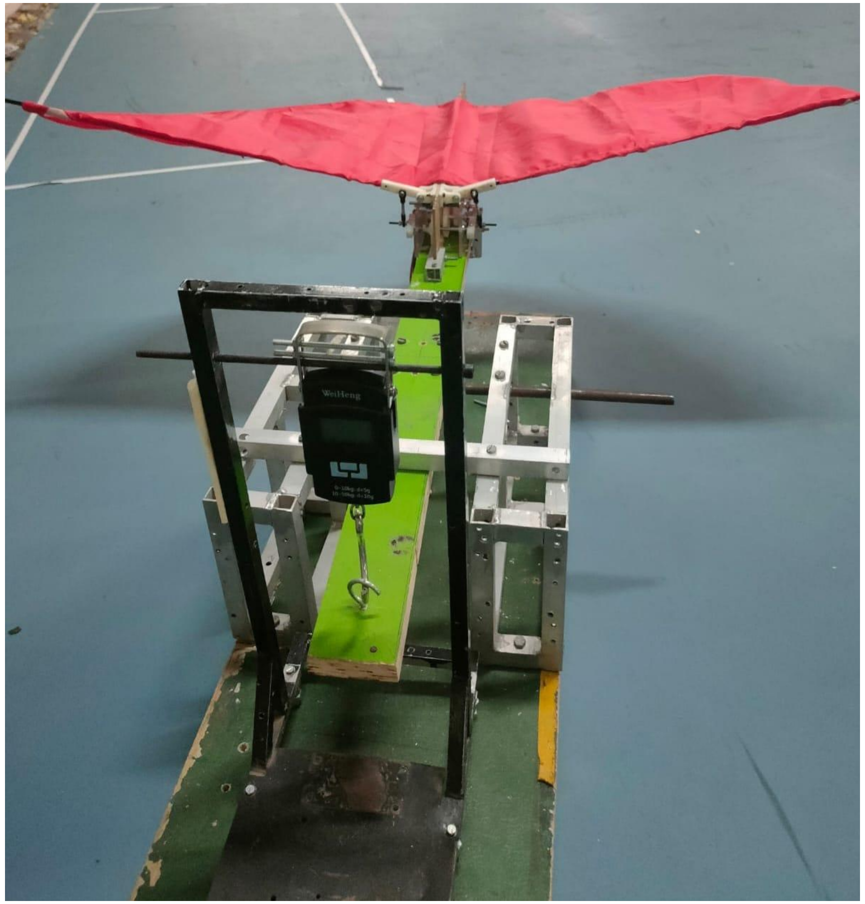


Fig.19. Test setup for lift measurement

Test Setup

- The ornithopter was suspended from a rope and actuated
- A slack has been observed in rope which indicated generation of lift force
- The ornithopter also followed a circular path indicating that it has a forward thrust.

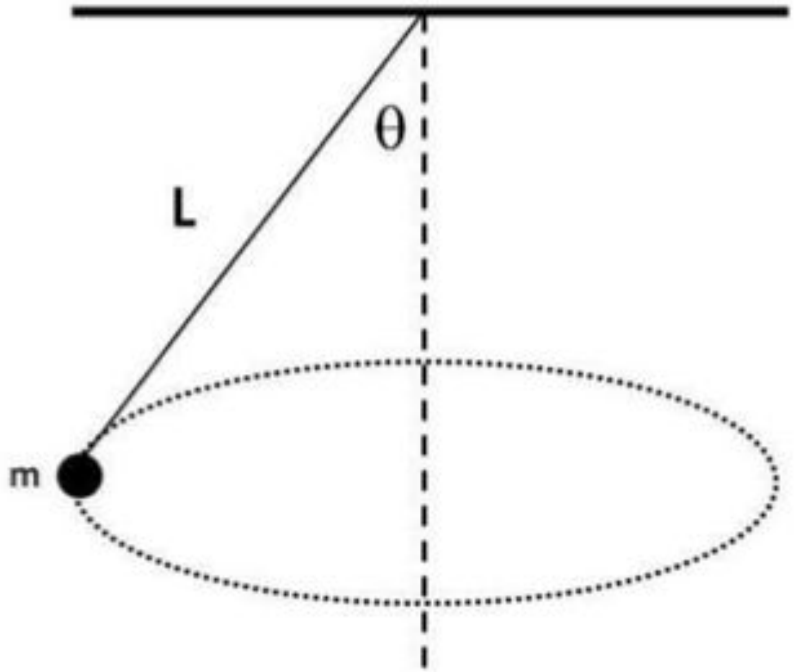


Fig 20: Representation of the test setup

Challenges

- Finding the required materials and components.
- Most of the manufacturing processes employed were time consuming which increased the project duration
- 3d printed spur gears weared out quickly which were later replaced by helical gears.
- It is a dynamic system hence it was difficult to do the calculations and the analysis.
- It was difficult to troubleshoot the problems related to electronics components.
- In the first test setup, the weight measuring device was unable to measure the dynamic readings.

Conclusion

- A suitable wing flapping mechanism has been chosen to mimic the flapping action of birds.
- The wing area has been calculated based on the approximate weight and the concept of wing loading.
- Suitable BLDC motor and gear ratio value has been selected based on the force required for flapping and the flapping frequency
- The ornithopter has been designed based on these inputs. Structural analysis of required parts has been carried out.
- Two test setups have been designed to verify the lift force and the forward thrust achieved by the ornithopter.
- The ornithopter has been wirelessly controlled with the help of radio frequency module.

Thank You!