Capstone Project Design Report on

Design and Development of a Test Rig for measuring propeller performance

Department of Mechanical Engineering
Punjab Engineering College (PEC), Chandigarh

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Project Guide
(Dr. V.P Singh)

DECLARATION

We hereby certify that the work which is being presented in the major project entitled **Design, Analysis and Fabrication of Propeller for Low Advance Ratios** in the partial fulfilment of the requirements for the award of the **Bachelor of Engineering** and submitted in the **Department of Mechanical Engineering** of the PEC University of Technology, Chandigarh, is an authentic record of our own work carried out during the period from **Aug 2019** to **Nov 2019** under the Supervision of Dr. V. P. Singh, Department of Mechanical Engineering.

Date: 23 October 2019

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ACKNOWLEDGEMENT

We deem it a pleasure to acknowledge our sense of gratitude to our project guide Dr. V. P. Singh under whom we have carried out the project work. His incisive and objective guidance and timely advice encouraged us with constant flow of energy to continue the work.

We shall remain grateful to Dr. Dheeraj Sanghi, Director, Punjab Engineering College, for providing us with a strong academic atmosphere by enforcing strict discipline to do the project work with utmost concentration and dedication.

We would like to express my sincere gratitude to the group members with whom fruitful discussions resulted in the successful completion of the project.

Finally, we must say that no height is ever achieved without some sacrifices made at some end and it is here where we owe our special debt to our parents and friends for showing their generous love and care throughout the entire period of time.

Contents

Literature Review

INTRODUCTION

The use of unmanned aerial vehicles (UAVs) for various purposes like transportation, military and civilian surveillance has increased manifold over the last couple of years. The most common configuration used for all these functions is the quadcopter configuration in which there are 4 rotors which support the payload in the middle. The main aim of aerospace industry involved in the design and development of quadcopters has been to increase the endurance, that is the time of operation for a single UAV on a single charge as most of the UAVs are battery operated. This increase in the endurance can be achieved significantly by optimizing the propulsion system. The overall efficiency can be enhanced to a great extent by enhancing the aerodynamic characteristics of the propellers used, without compromising with their structural characteristics.

PROPELLER AERODYNAMICS

Propellers are rotating devices which generate a net force in their axial direction. They have been used for powering various aircrafts since the advent of the first manned flight. Propellers are till date the most energy efficient propulsion devices and have not lost their significance even after the invention of gas turbine-based jet engines. For small aircrafts and UAVs, propellers are the only viable option to be used in the propulsion system because of their high efficiency at low operational speeds.

AIRFOIL

It is a characteristic shape which generates pressure difference between its lower and upper surface when subjected to an incident fluid velocity. This generates two components of force:

1. Lift: It is directed perpendicular to the fluid velocity.
2. Drag: It is directed parallel to the fluid velocity.

Airfoils are widely used in two aerodynamic structures namely wings (to generate lift) and propellers (to generated thrust).

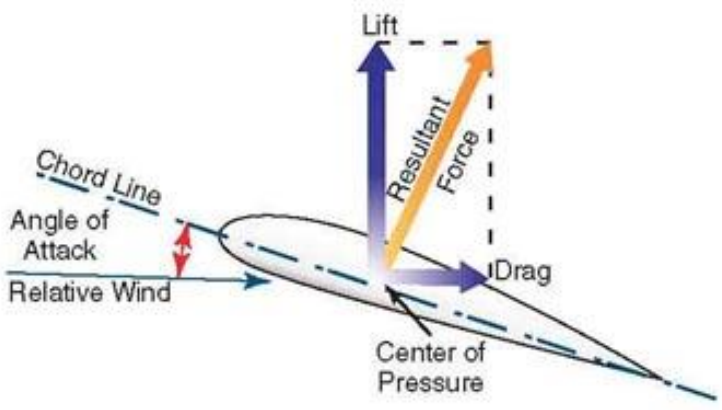

FIG 1: Forces generated by placing airfoil in a fluid flow.

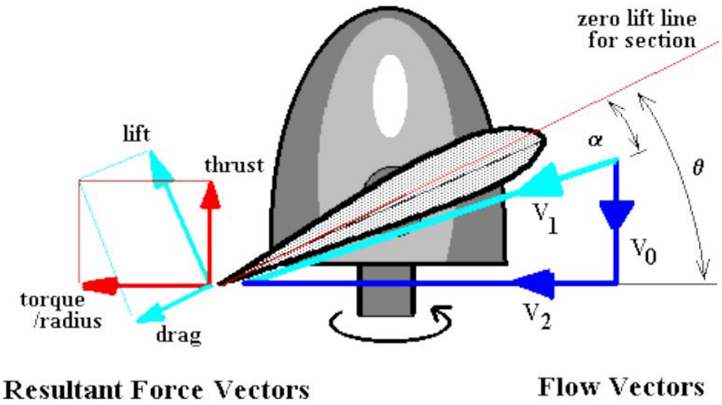

FIG 2: Thrust and torque generated by airfoil when subjected to rotation in fluid flow

The generation of thrust and torque has been shown in Fig 2, which shows that in order to generate a particular thrust T, we need to overcome a generated resisting torque (Q) which opposes the propeller rotation. This is where battery or fuel power is required to run the propeller by overcoming the resisting torque. The power required to run the propeller at a given angular velocity ω for generated torque Q is given by:

$$\textbf{Power} = \mathbf{Q \times \boldsymbol{\omega}}$$

Thereby, for a given operation, we can minimize the required power by either reducing the angular velocity of operation for the same thrust or by reducing the resisting torque, both of which depend upon the characteristics of the airfoil shape which has been used.

Minimisation of power required helps in increasing the overall efficiency and thereby the endurance (time of uninterrupted operation) for a UAV.

ADVANCE RATIO

It is a dimensionless coefficient which related the linear velocity (V m/s) of the propeller (diameter D) to its rotational velocity (n rotations/sec) as follows:

$$\mathbf{J} = \frac{\boldsymbol{V}}{\boldsymbol{nD}}$$

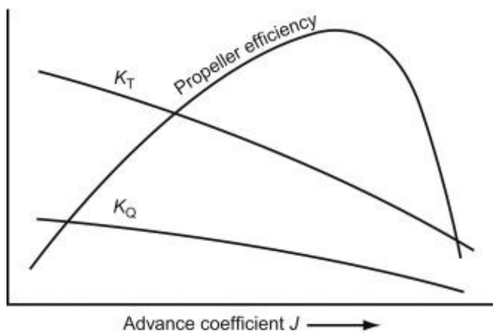

FIG 3: Variation of dimensionless thrust and torque with J

It can be observed from the graph in FIG 3 that a maximum for propeller efficiency is attained for a particular advance ratio J > 0. This maximum should occur within the operational range of a propeller to extract maximum efficiency (for quadcopters J ~ 0). **The aim of this project is to design a propeller which attains a maximum for efficiency at low advance ratios (ideally zero) as most of the quadcopters operate in this regime**.

The following are the plots of coefficient of thrust and torque v/s the advance ratio for a 10x4.7 propeller (10-inch propeller diameter, 4.7-inch blade pitch) at 2 motor RPMs: 4014 and 6513. The propeller designed by us will be of about this size only.

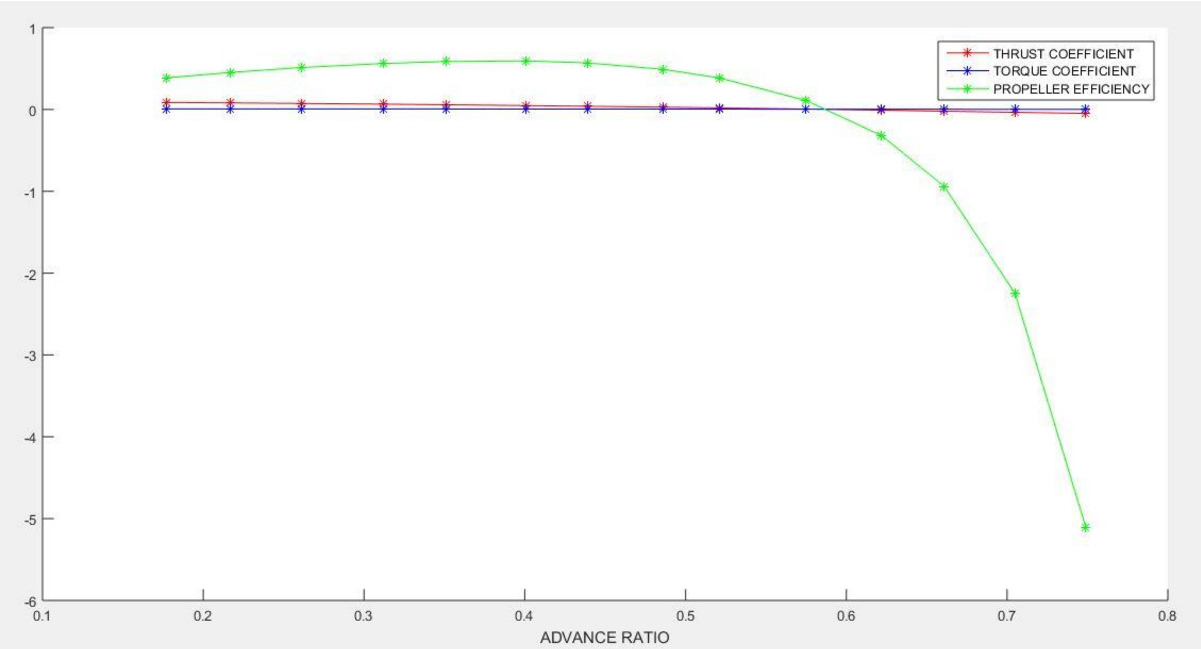

FIG 4: Experimental Data plot for RPM = 3004 (11X4.7 Propeller)

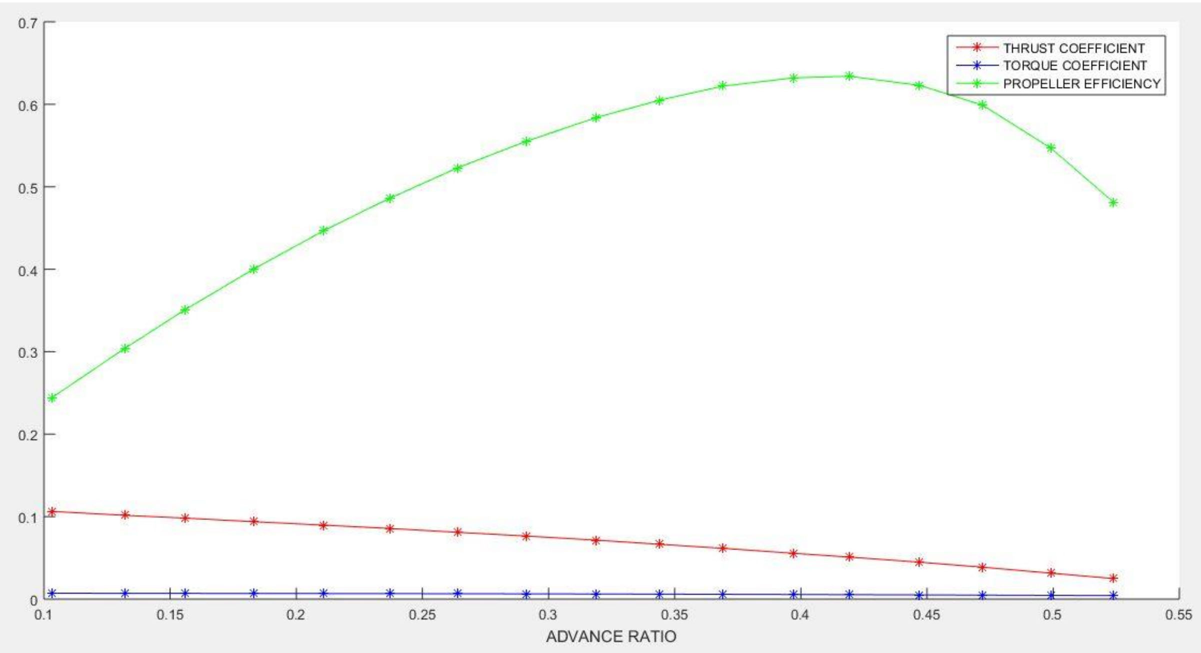

FIG 5: Experimental Data for RPM = 5003 (11X4.7 Propeller)

As seen in the above two plots, the maximum propeller efficiency occurs at relatively high advance ratios (0.468 for 4014 and 0.457 for 6513). Our aim is to bring about the maximum propeller efficiency at a much lower advance ratio (the ratios at which quadcopters usually operate) i.e. shifting the maxima in the efficiency v/s advance ratio plot towards the left side.

PROCEDURE

The project undertaken would be completed in two phases which are explained as follows:

1. **Development of Propeller Test Rig**: The propeller design would need experimental data for validation in terms of its thrust and rpm values at different RPMs. This calls for an in-house development of a propeller test rig which would be used to extract the experimental thrust performance parameters at static conditions (zero advance ratio). This Test Rig needs to be designed, fabricated and validated with an existing propeller by matching the test rig data against the existing experimental data for the propeller. The matching of the data for the 10x4.7 propeller will be done with respect to the official propeller data available in the UIUC website. The reference data gives the various values of thrust for different RPMs at static conditions. The plot for the thrust (Newtons) v/s RPM data of the 10x4.7 propeller is given by:

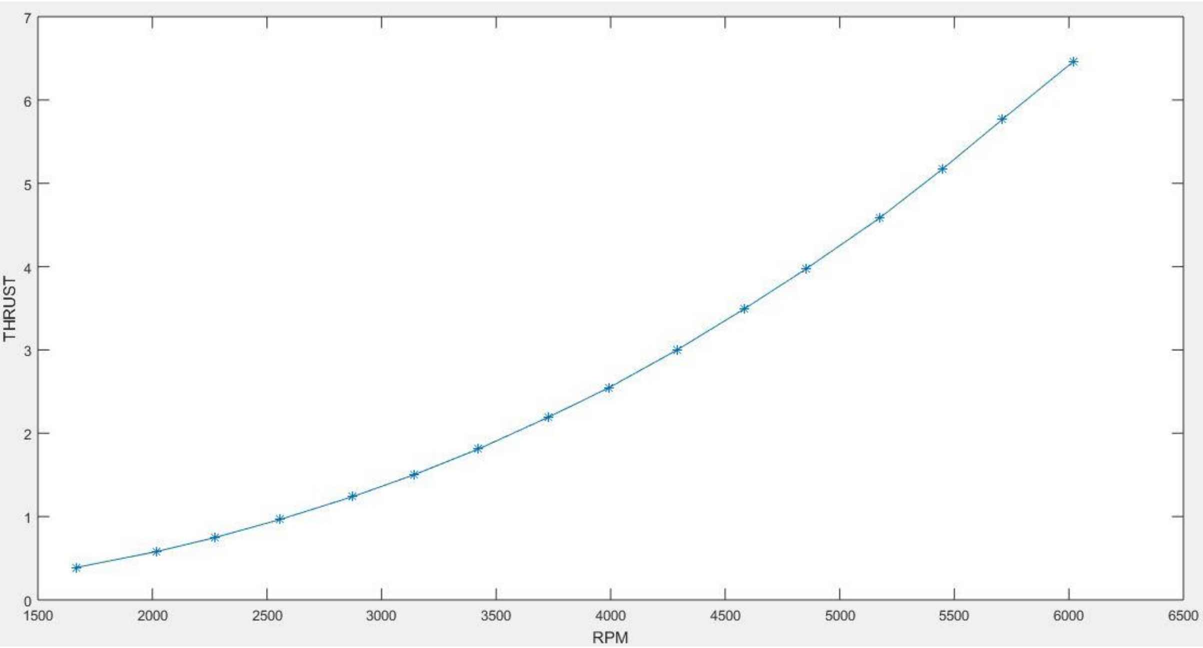

FIG 6: Experimental Data for static condition (11X4.7 Propeller)

2. **Design, Analysis and Fabrication of Propeller**: Once the test rig has been validated, the propeller design can be undertaken (in 8th semester) with the motive of getting the maxima for the propeller efficiency at the minimum possible advance ratio. This would involve the following steps:
   - Selection of airfoils, chord lengths and pitch angles at different radial locations using analytical first order tools
   - CFD Analysis of propeller and comparison with analytical data.
   - Material selection based on FEA analysis (centrifugal stresses and FSI)
   - Fabrication of propeller using 3D printer.

The task of test rig development has been undertaken in the 7th semester while propeller design would be pursued in the 8th semester.

DESIGN OF TEST RIG

PRINCIPLE OF OPERATION

The main motive of the test rig is to measure the propeller Thrust (force) at the corresponding motor RPM. In order to understand how the test rig will function, a rough computational MBD (Multi-Body Dynamics) model of the test rig has been created.

MBD ANALYSIS

This computational model is just a rough illustration of the actual test rig and the further finite element analysis for structural safety of the test rig will be carried out on the actual test rig CAD model. The only purpose of this model is to demonstrate how the test rig will be calculating the propeller thrust.

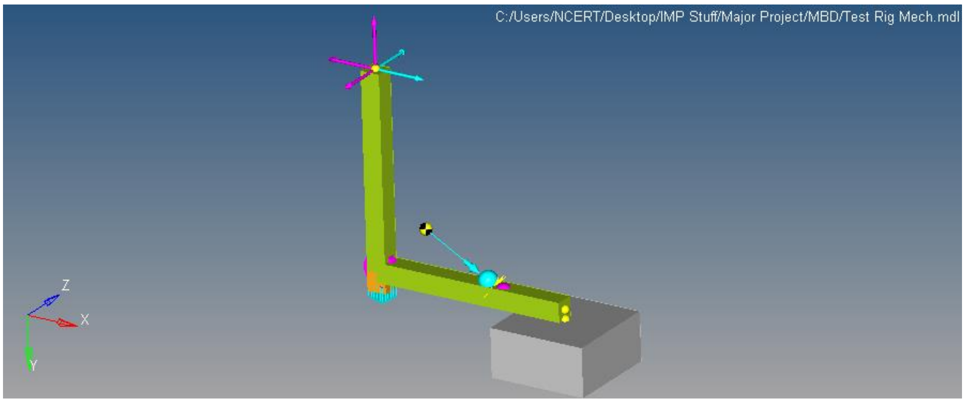

FIG 7: MBD model of test rig

The model consists of a body which has 2 links of equal length attached to it. The links are attached to a base with the help of a revolute joint, which is equivalent to a pin/hinge joint. The weighing machine is represented with the help of a box graphic in the graphical interface. One of the links lies on the weighing machine. A 3D rigid to rigid contact is introduced between the two and the contact force between the two is to be calculated.

The contact force between the two is nothing but the reaction force due to the force being measured by the weighing machine. Since the frictional forces between the link and the weighing machine are going to be negligible, thus the weighing machine and link are kept smooth (coefficient of friction = 0).

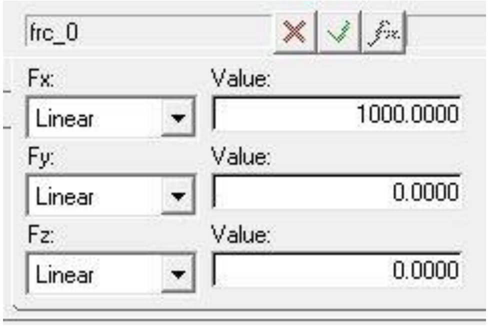

FIG 8: Thrust force in X direction

An action reaction force is introduced at the end of the other link which represents the thrust of the propeller. Our goal is to assign any random value to the thrust force and calculate the contact force between the link and the weighing machine. For this demonstration, we will be keeping the thrust force as 1000 Newtons.

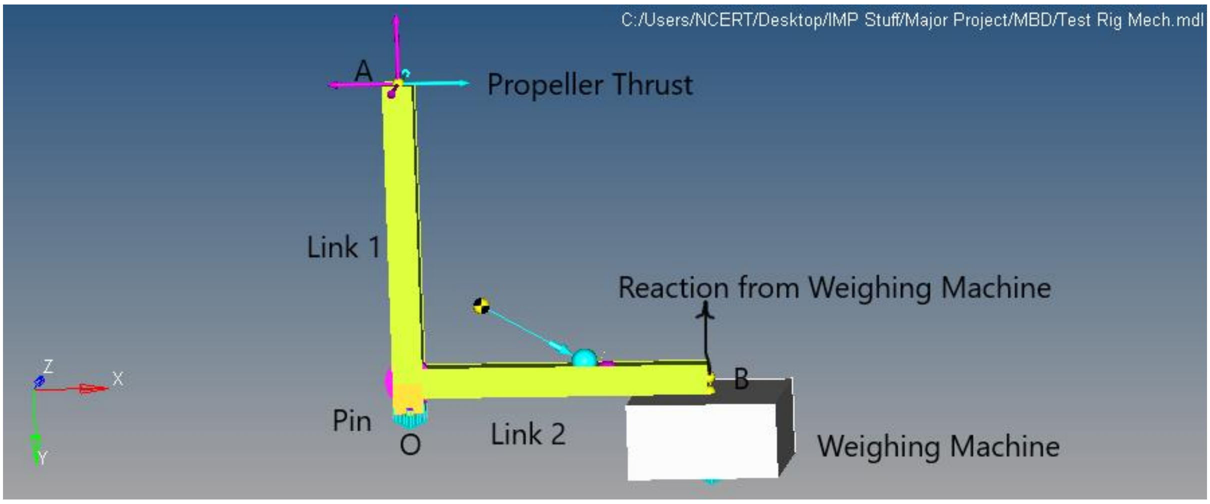

FIG 9: Illustrated Model

A transient simulation is run on the computational system for a total simulation time of 5 seconds and the contact force between the link and the weighing machine is calculated and plotted.

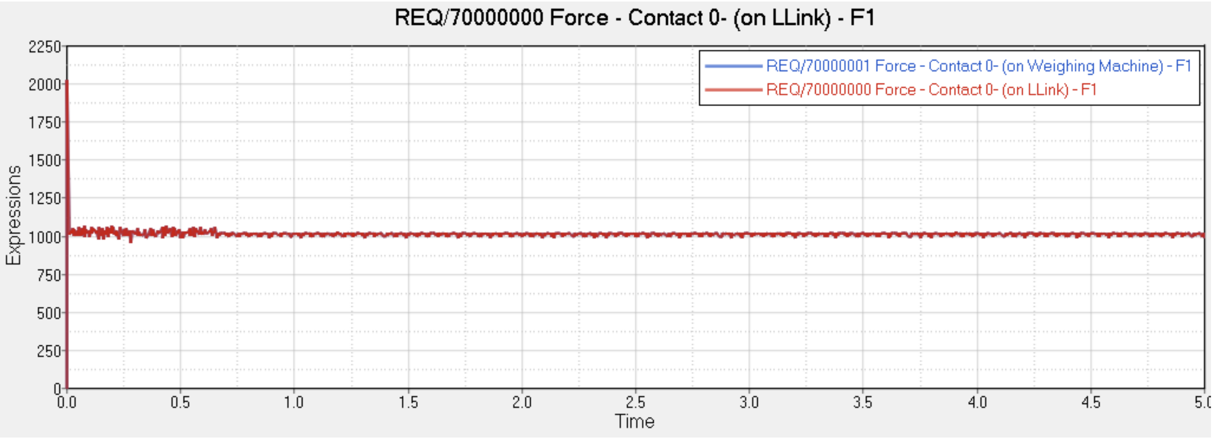

FIG 10: Contact Force Plot between link and weighing machine

As seen in the above plot, the contact force (equivalent to the reading shown on the weighing machine) comes out as 1000N. Certain disturbances exist due to imperfect contact parameters (like damping coefficient, penetration depth, contact stiffness and exponential factor).

The above computational experiment shows how the test rig will be calculating the thrust values of the propeller which is connected to the A point of the vertical link. By varying the

RPM of the BLDC motor, we can get the corresponding varying propeller thrust values on the weighing machine.

The actual representation of the test rig has been depicted in the following figure.

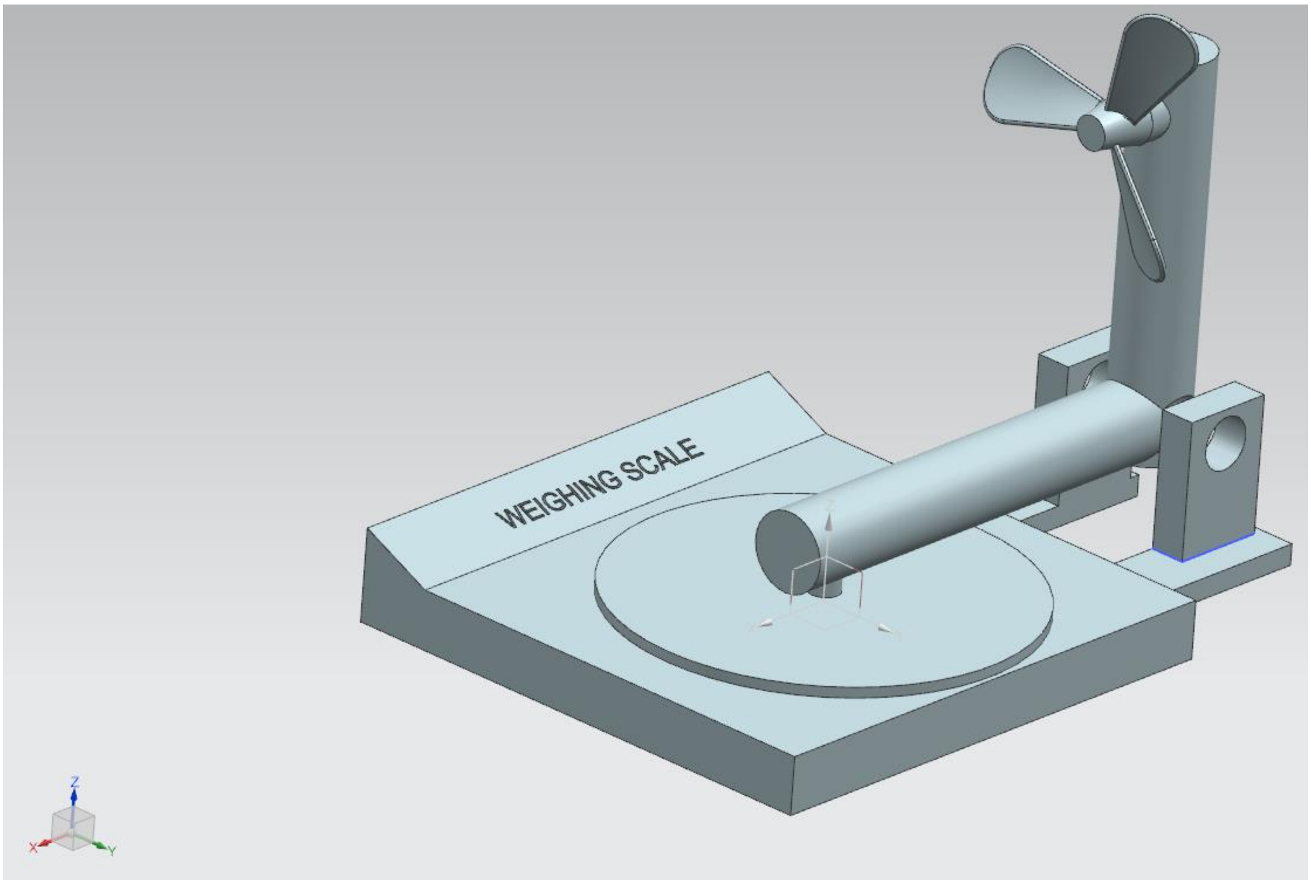

FIG 11: CAD model of Proposed test rig design

The max thrust generated from a general quadcopter propeller does not exceed 45 N, therefore component failure due to fracture is very unlikely to occur in this test rig. The links are made of wood and are hollow with a particular thickness.The main motive of this test rig design is to minimize frictional losses at the hinge joint and accurate transfer of propeller thrust as a point load on the weighing machine. Accurate measurement of the propeller RPM is also required for comparison with the experimental data for thrust vs rpm variation at static condition (J = 0). This would be done by developing a tachometer setup using Arduino as a microcontroller and a combination of infra-red sensors. The details of the above-mentioned subsystems have been explained in the upcoming sections.
The dimensions of the test rig to be fabricated are given by:

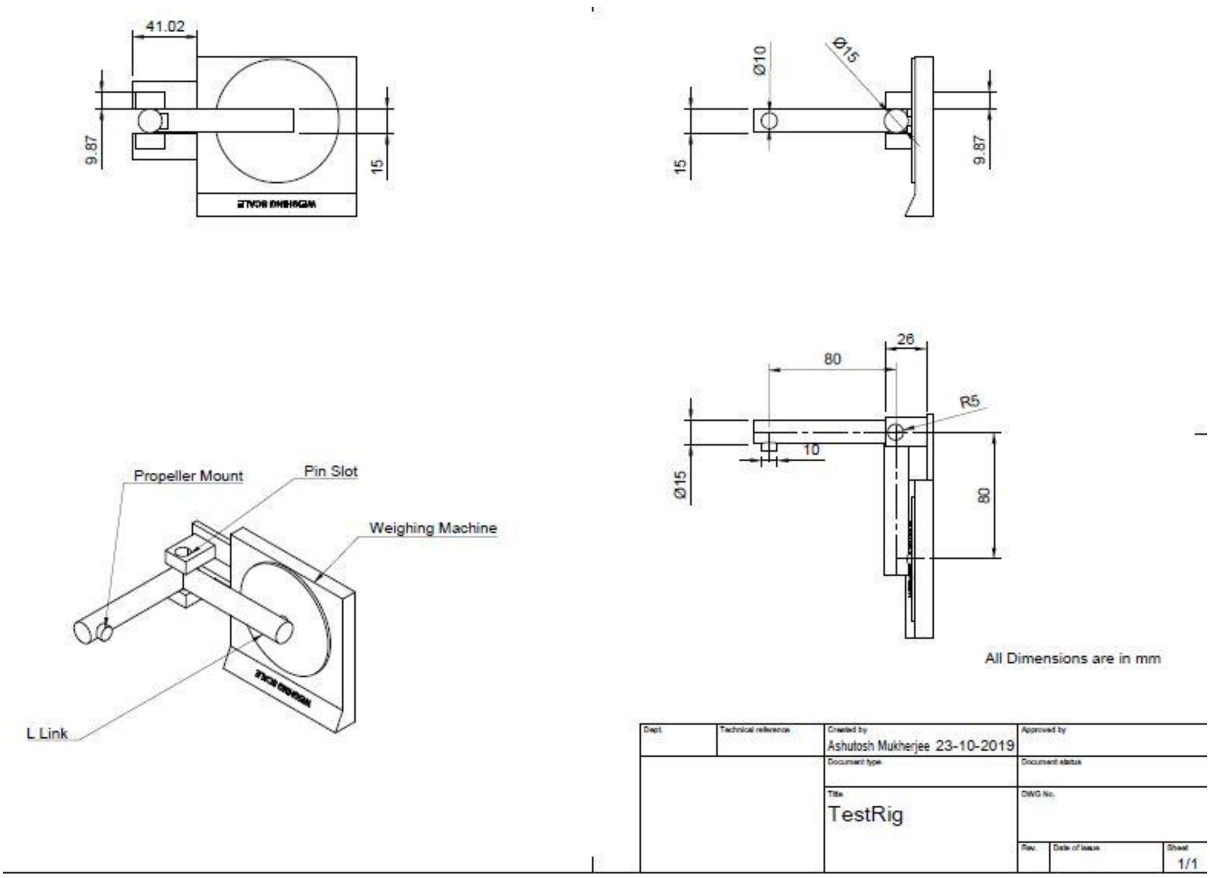

FIG 12: Engineering Drawing of Test Rig

COMPONENT SELECTION

The various components selected for use in the test rig and their desired configuration have been explained as follows:

Linkages

The linkages which would comprise the L link for transmitting the propeller thrust as a point load over a weighing machine would be made of wood in order to minimize the self-weight of the linkages themselves. If the linkages are metallic (and consequently heavy), their self would also contribute significantly to the force predicted by weighing machine. Moreover, the maximum forces generated in the setup are not likely to exceed 20N, therefore structural failure is not a significant design parameter for this setup of test rig.

Propeller

The specification of a general propeller is defined as:

$$\boldsymbol{Diameter}\ (\boldsymbol{in})\boldsymbol{X}\ \boldsymbol{Pitch}(\boldsymbol{in})$$

The propeller selected for validation of this test rig is 10 X 4.7 propeller which is the most common propeller used for quadcopters. It can be inferred that this propeller has a diameter of 10 inches and pitch of 4.5 inches. The maximum operational rpm for this propeller goes up to 17000 rpm.

FIG 13: 10 X 4.5 Propeller

Motor

The motor selected is very crucial for overcoming the resisting torque generated by the propeller. Therefore, a Brushless Direct Current (BLDC) motor has been used for this application. The specification of a BLDC motor is defined by its KV rating which is defined as:

$$\mathbf{1}\ \boldsymbol{KV} = \frac{\mathbf{1}\ \boldsymbol{RPM}}{(\boldsymbol{Voltage\ Supplied})}$$

Large diameters propellers produce higher torque which needs to be compensated by the motor. Therefore, lower KV rating motors are used for providing higher torque at the cost of speed. Therefore, for a 10-inch propeller (considered high in UAV industry), a KV rating varying from 1000 to 1500 is recommended.

The motor selected for this setup was 1400 KV BLDC motor which can give a maximum rpm of 15000 with a standard 11.1 Volt Battery.

FIG 14: BLDC motor 1400 KV

Electronic Speed Controller (ESC)

ESCs are required for controlling the motor speed and subsequently the propeller rpm. It also acts as a junction to control the power supply distribution from the battery to various components like the Arduino requiring a 5V supply whereas the BLDC motor requires variational voltage (controlled by a potentiometer) according to the desired rpm. For the selected motor and battery, an ESC of 30 Amps is desirable.

FIG 15: ESC 30 amps

Arduino Microcontroller

Arduino UNO is the most popular microcontroller based controlling device proving its unique set of hardware and software interface. It can be used for various functions in an electrical circuit which may be steady or transient. The main functions to be performed by Arduino in this test rig are:

1. RPM measurement using a combination of IR sensors (tachometer).
2. Variation of motor voltage to vary the motor RPM.
3. Display of the measured motor RPM on the LCD projector screen.

The details of various electrical and electronic circuits along with their physical connections and Arduino codes have been discussed in detail in the upcoming sections.

FIG 16: Arduino UNO Microcontroller

Battery

High endurance batteries are required for power intensive applications such as running a propeller. Therefore, a standard 3S Lipo battery (3 cell lithium ion) has been selected for use as the main power source. This is a rechargeable battery.

FIG 17: 11.1 V battery 3S Lipo

Weighing Scale

The propeller thrust after being converted into an equivalent vertically downwards point load would be projected upon a weighing scale. This weighing scale would thereby provide the magnitude of the projected force equivalent to the thrust generated by the propeller in advance. This can be converted to Newtons or any other unit of convenience. The weighing scale of maximum capacity of 10 Kg has been used as the maximum thrust is not expected to exceed 20N (2 Kg approx.).

FIG 18: Weighing scale used (capacity 10 Kg)

MOTOR CONTROL

A 1400KV Brushless DC motor will be used for providing the rotary movement to the propeller. The rating KV means RPM/Volt i.e. if we provide X Volt power to the motor, the RPM of the output shaft will be 1400*X revolutions per minute (at no load condition). Since we will be varying the RPM of the motor in order to get the thrust values for the propeller, we need to provide a significant amount of power to the motor. The movement and the speed of the motor can be controlled with the help of an Electronic Speed control (ESC). The combinations of various electrical and electronic circuits (governed by the Arduino uno micro-controller) used for this subsystem have been illustrated and explained in the following sections.

Brushless Direct Current (BLDC) Motors

A BLDC motor has 2 parts: a stator and a rotor. The stator has a certain number of poles to which there is a coil attached. The rotor consists of a permanent magnet with north and south poles.

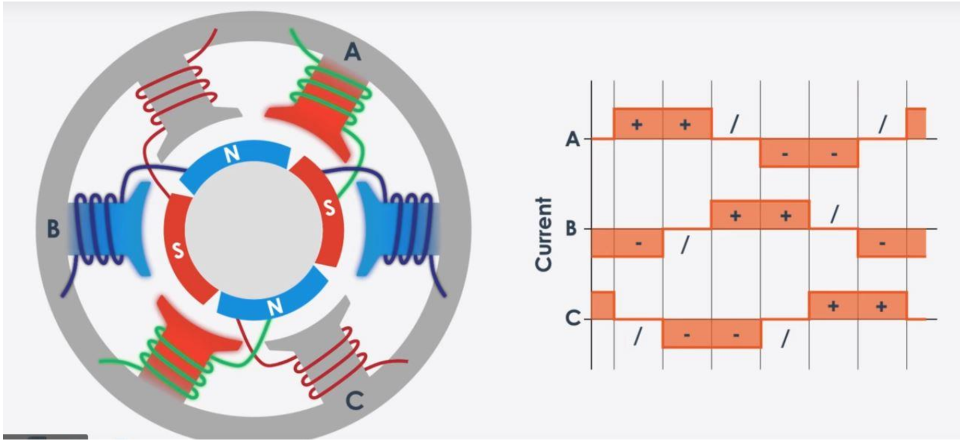

FIG 19: Brushless DC motors working

We will be using a BLDC motor which will have 6 poles (shown above). All the opposite poles form one phase i.e. at a time, current is passed through the opposite poles. When current is passed through the coils on the poles, a magnetic field is created (and the poles become electromagnets) which interacts with the poles of the permanent magnet and makes the rotor rotate. To increase the speed of rotation, current can be passed in opposite senses through 2 poles at a time, which creates an attractive and a repulsive interaction with the permanent magnets of the rotor and makes it rotate faster.

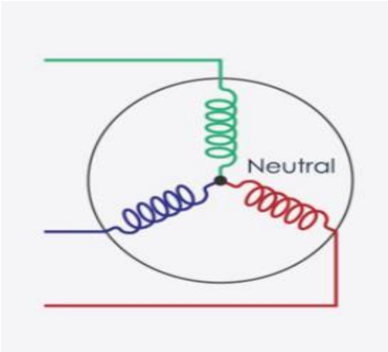

FIG 20: 3 phases of BLDC Motor

Electronic Speed Control (ESC)

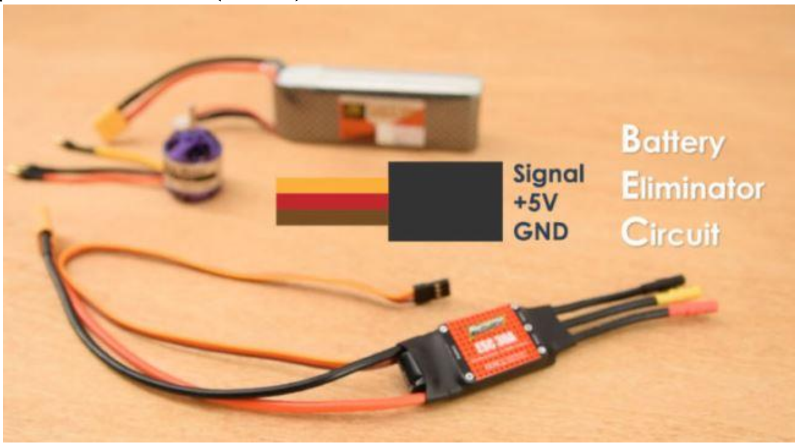

FIG 21: Electronic Speed Control

We will be using a 30A ESC which will be controlling the speed and the rotation of the BLDC motor. The ESC has several wires coming out of it:
1). On one side 3 wires come out which connect to the BLDC motor. These three wires provide current/energise the three phases of the BLDC and control them each.

2). On the other side there is a VCC wire (live wire) and a ground wire which draw power from an external power source (in this case a 11.1V battery)

3). There are other 3 wires (shown in the above picture), namely the signal wire which connects to one of the output pins on the Arduino Uno board, the +5V wire which connects to the corresponding pin on the board and the ground wire which connects to the GND pin on the Arduino. These three wires play the role of a battery eliminator circuit, that is by powering the Arduino, they eliminate the need for a battery for the purpose of powering the microcontroller.

The ESC controls the rotation and the speed of the BLDC motor. It decides which two phases to energise at a given time so that the rotor rotates.

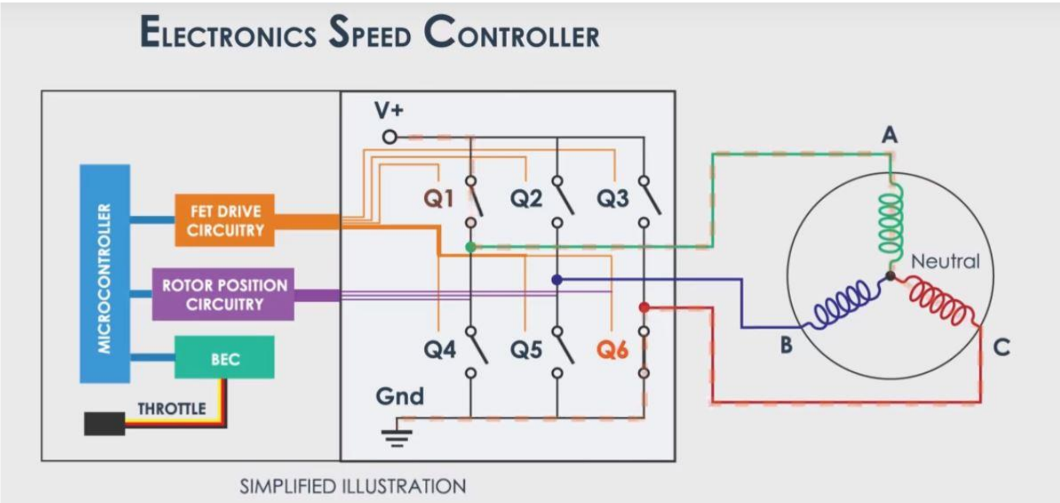

FIG 22: ESC controlling BLDC motor

The throttle mentioned in the above picture refers to the analogue signal which is generated from the Arduino. The maximum voltage that can be provided to the BLDC motor is 11.1 V

The Analog signal is generated in the form of pulse width modulates waves (pulses). Each pulse has a certain pulse width (in terms of milliseconds) and a frequency. These pulses will control the rotary velocity of the motor and the value of the signal generated varies from 0 to 1023. A potentiometer is attached to the Analog input of the Arduino board which controls the pulse widths of the pulses generated. Based on the lowest and the highest pulse width generated, the motor RPM will vary from minimum to maximum.

We will be generating a 50 Hz analogue signal from the Arduino, and for that purpose we will be treating the ESC analogous to a servo motor. There are alternate ways of treating the ESC but we might get different frequency values from them. For this project, we will keep 1ms as the minimum pulse width and the 2ms as the maximum pulse width. The 1ms pulse width refers to the 0 value of the Analog signal and the minimum RPM and the 2ms pulse width refers to the 1023 value of the Analog signal and the maximum RPM.

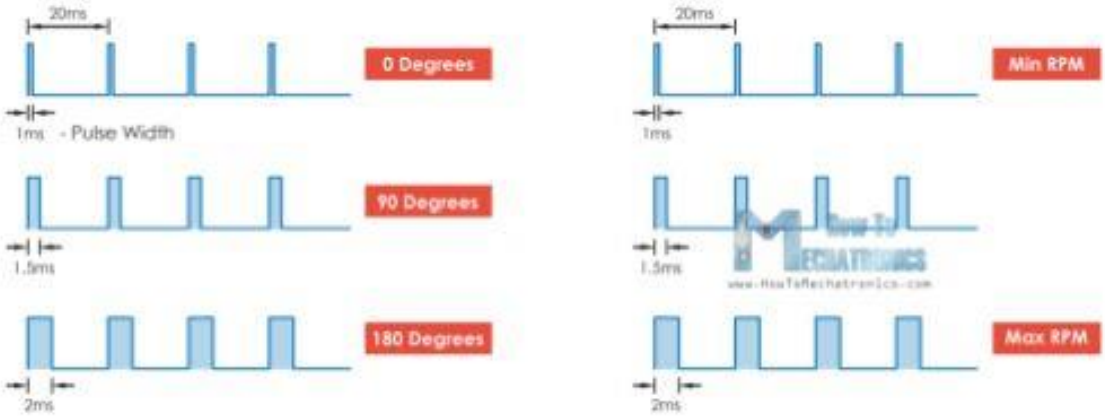

FIG 23: PWM of Servo motor and BLDC motor

As we can see, the 2ms maximum pulse width refers to the maximum RPM and 180 degrees (in servo) and 1ms minimum pulse width refers to the minimum RPM and 0 degrees (in servo).

Circuit Diagram

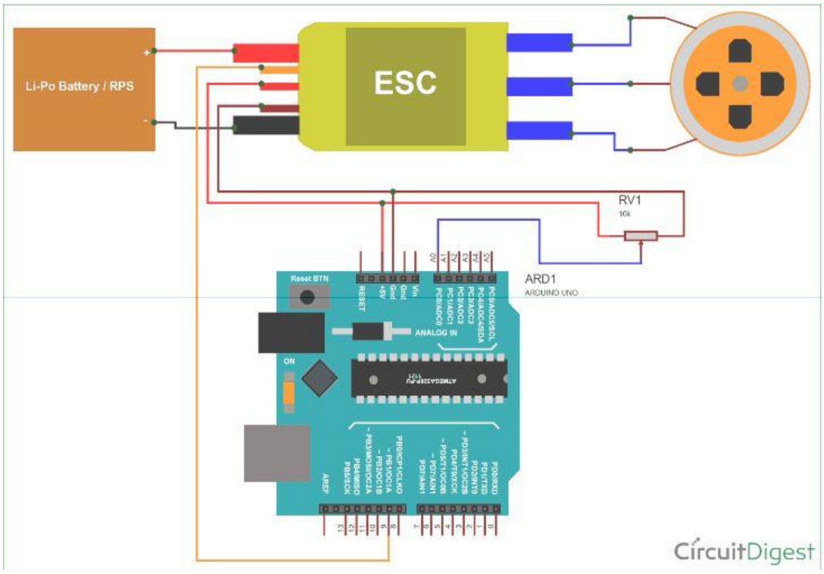

FIG 24: Circuit for BLDC control using ESC

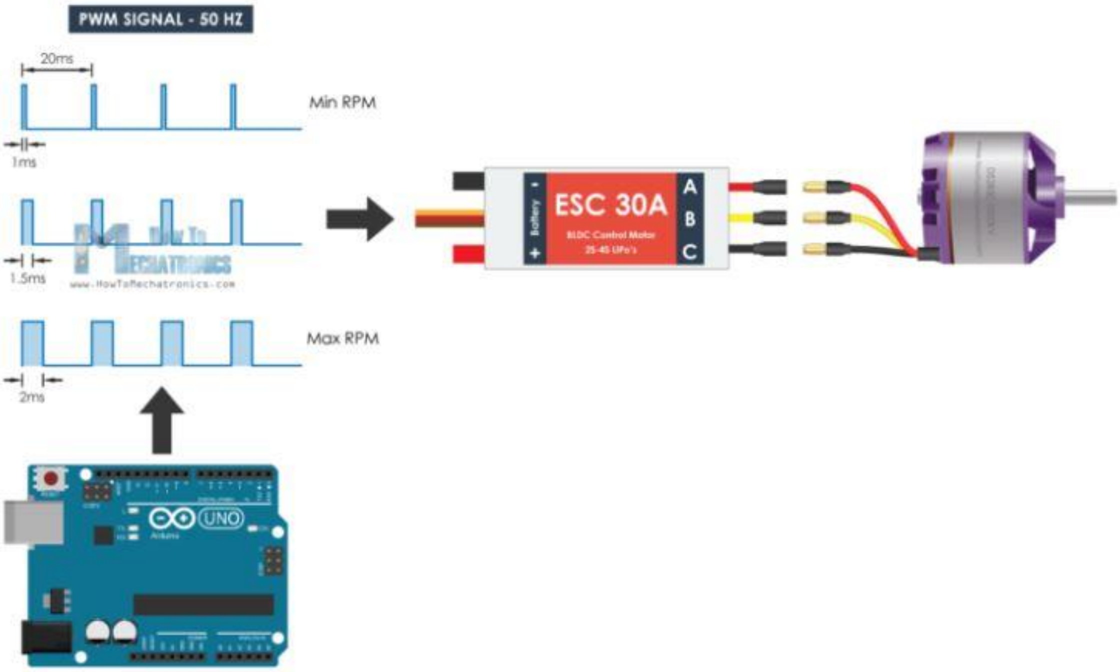

FIG 25: PWM Analog signals for controlling motor speed through the ESC

RPM Measurement

Since we do not get a definite value of the velocity in terms of RPM, we will be calculating the RPM using an IR sensor which is connected to the Arduino for displaying the RPM value on a 16x2 LCD screen.

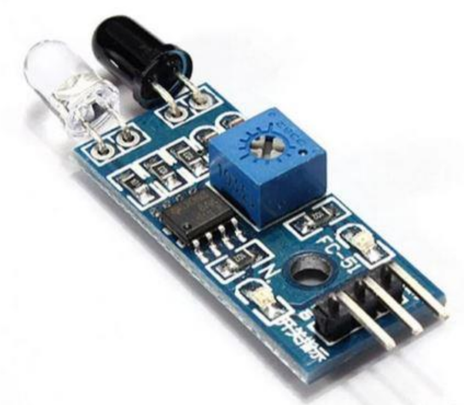

Fig 26: IR sensor

The above shows a picture of an IR sensor. It has a photodiode (white LED) and an infrared LED (black LED). It has 3 output ports; one connects to an input digital pin on the Arduino board, the other two connect to the +5V and GND pins on the Arduino board. When we place the rotating propeller in front of it, it will detect the blades when they pass in front of it and then calculate the RPM of the propeller and feed it to the Arduino. A 16x2 LED screen is connected to the Arduino which takes the RPM data from the Arduino and displays it.

IR Sensor specifications:

1. Operating Voltage: 3.0V – 5.0V
2. Detection range: 2cm – 30cm (Adjustable using potentiometer)
3. Current Consumption: at 3.3V: ~23 mAat 5.0V: ~43 mA
4. Active output level: Outputs Low logic level when an obstacle is detected
5. Onboard Obstacle Detection LED indicator

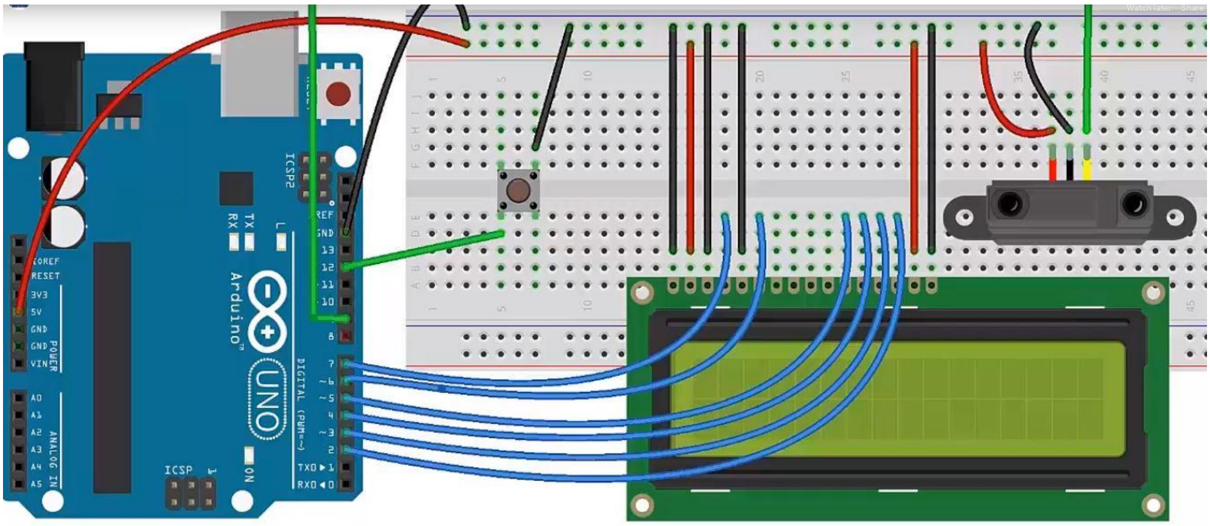

FIG 27: Basic circuit design of an Arduino and LCD screen arrangement

CODE

Controlling BLDC:

```
//controlling BLDC motor using ESC

//speed of BLDC motor controlled using PWM signals controlled by potentiometer

//analog input control required for controlling speed of motor shaft

#include<Servo.h>

Servo ESC;//defining the ESC under servo library

int potValue;

void setup() {

  ESC.attach(9,1000,2000);//ESC attached to pin9 on arduino board //(pin#,minimum pulse
width/low point,maximum pulse width/high point)

}

//minimum pulse width refers to a particular signal pwm value and the corresponding motor rpm is
minimum rpm
```

```
//maximum pulse width refers to a particular signal pwm value and the corresponding motor rpm is maximum rpm

void loop() {

  potValue = analogRead(A0);//reading the pwm signal (value between 0 and 1023 from the potentiometer and stroing it in a variable

  potValue = map(potValue,0,1023,0,180);//mapping the analog value to between 0 and 180 to suit the servo library

  ESC.write(potValue);//signal is sent to ESC and according to the pwm value of the signal, the motor has a certain RPM

}
```

Tachometer Circuit Code:

```
/* Optical Tachometer

 *

 * The Infrared LED is connected to pin 13.

 * The Infrared phototransistor is connected to pin 2 which is interrupt 0.

 *

 */


volatile byte breakNum;       // "volatile" is used with interrupts

unsigned int rpm;


#include <LiquidCrystal.h>

LiquidCrystal lcd(13, 12, 11, 10, 9, 8);


// Counts the number of interrupts

void break_count()

 {

     breakNum++;

 }


void setup()

 {

   // Was first using the serial port to print results.
```

```
  // Serial.begin(9600);
  lcd.begin(16,2);

  //The Infrared phototransistor is connected to pin 2 which is interrupt 0.
  //Triggers on change from HIGH to LOW
  attachInterrupt(0, break_count, FALLING);
  breakNum = 0;
  rpm = 0;
}

void loop()
{
  // Update RPM every second
  delay(1000);
  // Don't process interrupts during calculations
  detachInterrupt(0);
 // Depending on what you are testing you might need to change the formula for the rpm
 // For instance testing a prop would give 2 breaks per rotation so (60 * rpmcount) / 2
  rpm = (60 * breakNum)/2;// for 2 blades of propeller

 // Was using the serial port initially to print results
 // Serial.print(rpm);
 // Serial.println(" RPMs");
 // Serial.println();

  breakNum = 0;

  //Print out result to lcd
  lcd.clear();
  lcd.print("RPM=");
  lcd.print(rpm);
```

```
//Restart the interrupt processing
attachInterrupt(0, break_count, FALLING);
}
```

FINITE ELEMENT ANALYSIS FOR SAFETY OF TEST RIG

We will be validating the safety of the test rig with the help of 2 methods:

1). ROUGH HAND CALCULATIONS:

The upper link (to whose end the propeller is attached) can be assumed to be a cantilever beam with an outer diameter 15mm and inner diameter 10mm (thickness = 2.5mm). We consider the worst case of the load (propeller thrust) being applied on the link to be 50N.

The length of the links is taken as 80mm. We wish to calculate the maximum bending stress developed in the beam.

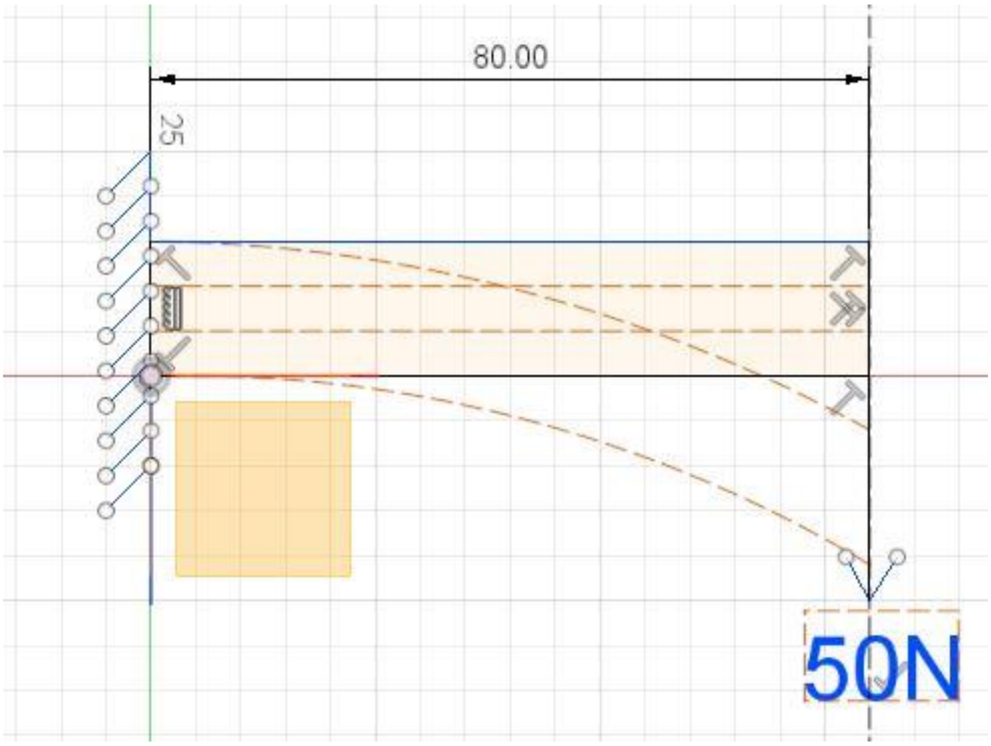

FIG 28: Cantilever like Upper Link

The propeller thrust tends to hog the link. The maximum bending moment can be found out to be 4Nm.

We can use the bending stress formula to calculate the maximum tensile stress produced in the link. The area moment of inertia can be calculated as: $\boldsymbol{I = \frac{\pi}{64}\{D^4 - d^4\}}$‘

The maximum stress can be found out by the relation:

$$\boldsymbol{\sigma_x = \frac{M \cdot y}{I}}$$

Where y = 7.5 mm and M denotes the maximum bending moment.

The links are made up of wood, for which the maximum tensile strength is given by:

$$\boldsymbol{\sigma_{ut} = 2.10MPa}$$

After calculations, the maximum tensile strength comes out to be $(\boldsymbol{\sigma})\mathbf{max} = \mathbf{50 \cdot 77}\boldsymbol{P_a}$

As can be seen from the above calculations, the design is **VERY SAFE.**

2). STATIC STRESS ANALYSIS USING FINITE ELEMENT METHOD

In order to validate our rough calculations, we will be making use of finite element analysis to calculate the stress generated in both the links and the safety factor. The material of the links is wood which is an orthotropic material i.e. it has isotropic properties along 3 planes (XY, YZ, ZX). Any orthotropic material is defined by 9 constants: Poisson's ratio in the 3 planes, elastic modulus in the 3 planes and the shear modulus in the 3 planes.

Properties of Outline Row 4: wood

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	0.57	g cm^-3		
3	Orthotropic Elasticity				
4	Young's Modulus X direction	1.2066E+10	Pa		
5	Young's Modulus Y direction	1.2066E+10	Pa		
6	Young's Modulus Z direction	1.2066E+10	Pa		
7	Poisson's Ratio XY	0.37			
8	Poisson's Ratio YZ	0.37			
9	Poisson's Ratio XZ	0.37			
10	Shear Modulus XY	6.6366E+08	Pa		
11	Shear Modulus YZ	6.6366E+08	Pa		
12	Shear Modulus XZ	6.6366E+08	Pa		
13	Compressive Yield Strength	3.5E+06	Pa		
14	Tensile Ultimate Strength	2.1E+06	Pa		

FIG 29: Mechanical Properties of Wood

The computational model created is given a revolute constraint at the location of the pin joint and a fixed constraint at the location at which the lower link touches the weighing machine. The propeller thrust is applied in the form of a horizontal force which acts at the end of the upper link.

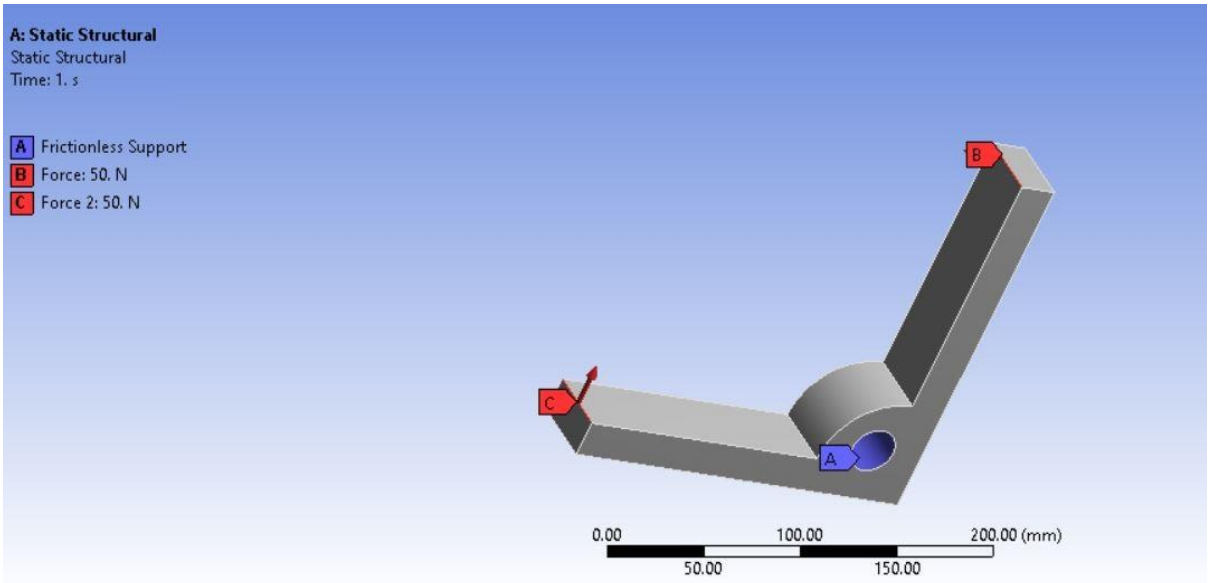

FIG 30(a): Computational Model Setup**:** Structural Conditions

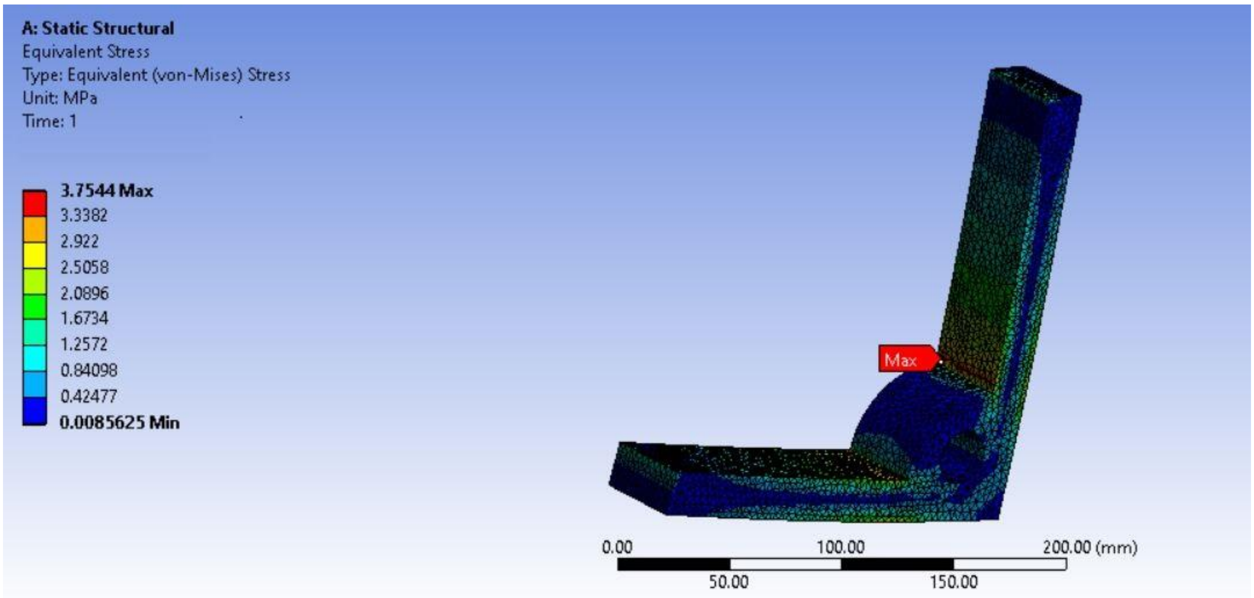

FIG 30(b): Computational Model Post Processing Results: Equivalent Stress

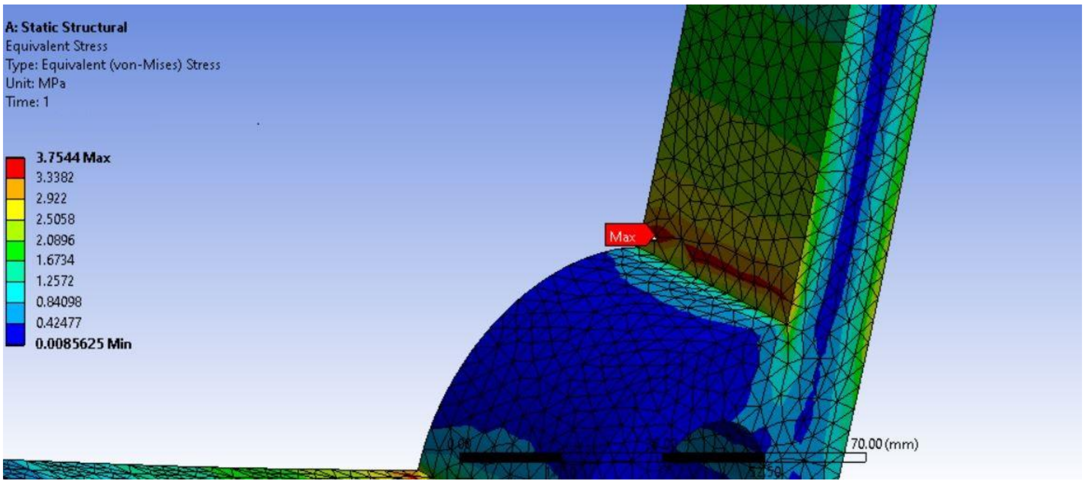

FIG 31: Computational Model Post Processing Results: Maximum Equivalent Stress

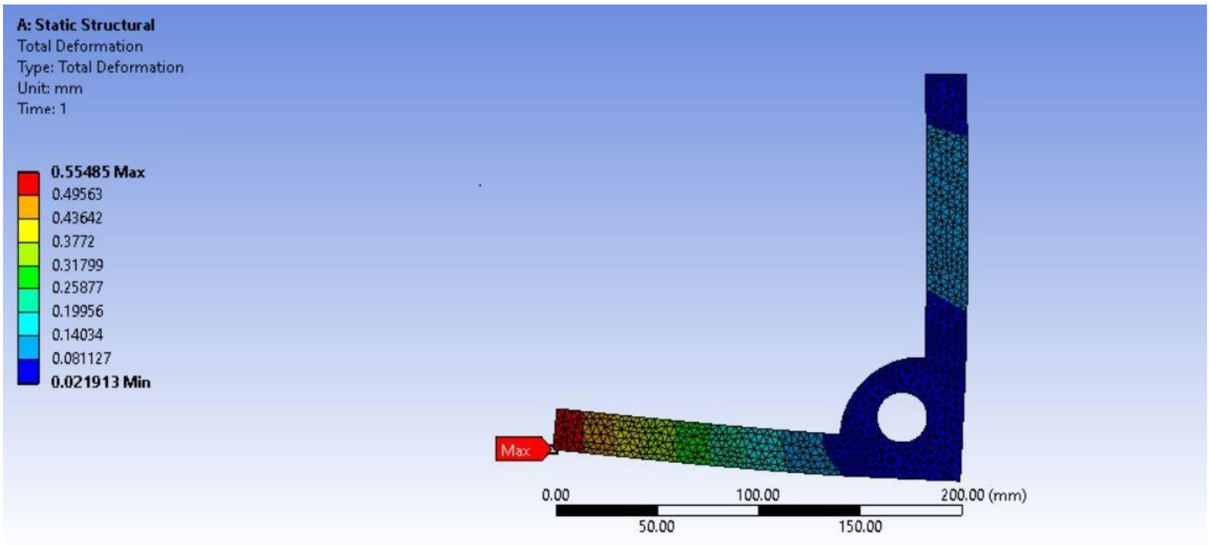

FIG 32: Computational Model Post Processing Results: Total Deformation

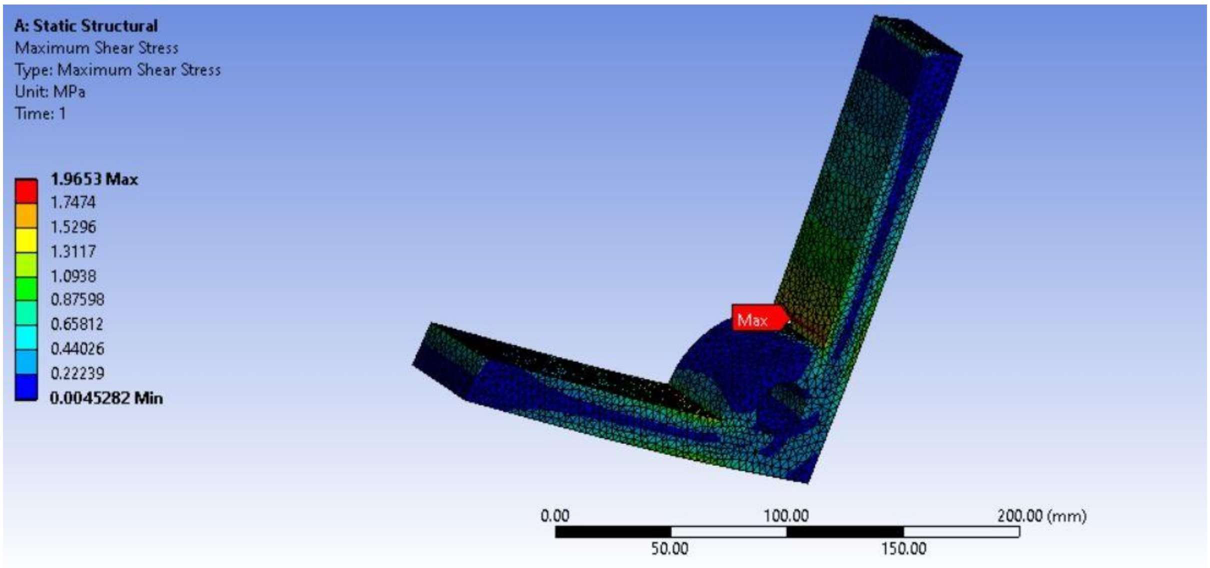

FIG 33: Computational Model Post Processing Results: Maximum Equivalent Shear Stress

FINAL ASSEMBLY

The final assembly consists of the following components:
1). 2x Arduino Uno
2). 2x Breadboard
3). 1x SMPS
4). 1x Weighing Machine
5). 2x Clamps
6). 1x L Link
7). 1x BLDC Motor
8). 1x IR Sensor
9). 1x 10” x 4.5” Propeller
10). NSK- 6000Z Ball Bearing

All these components have been assembled on a single sheet of plywood.

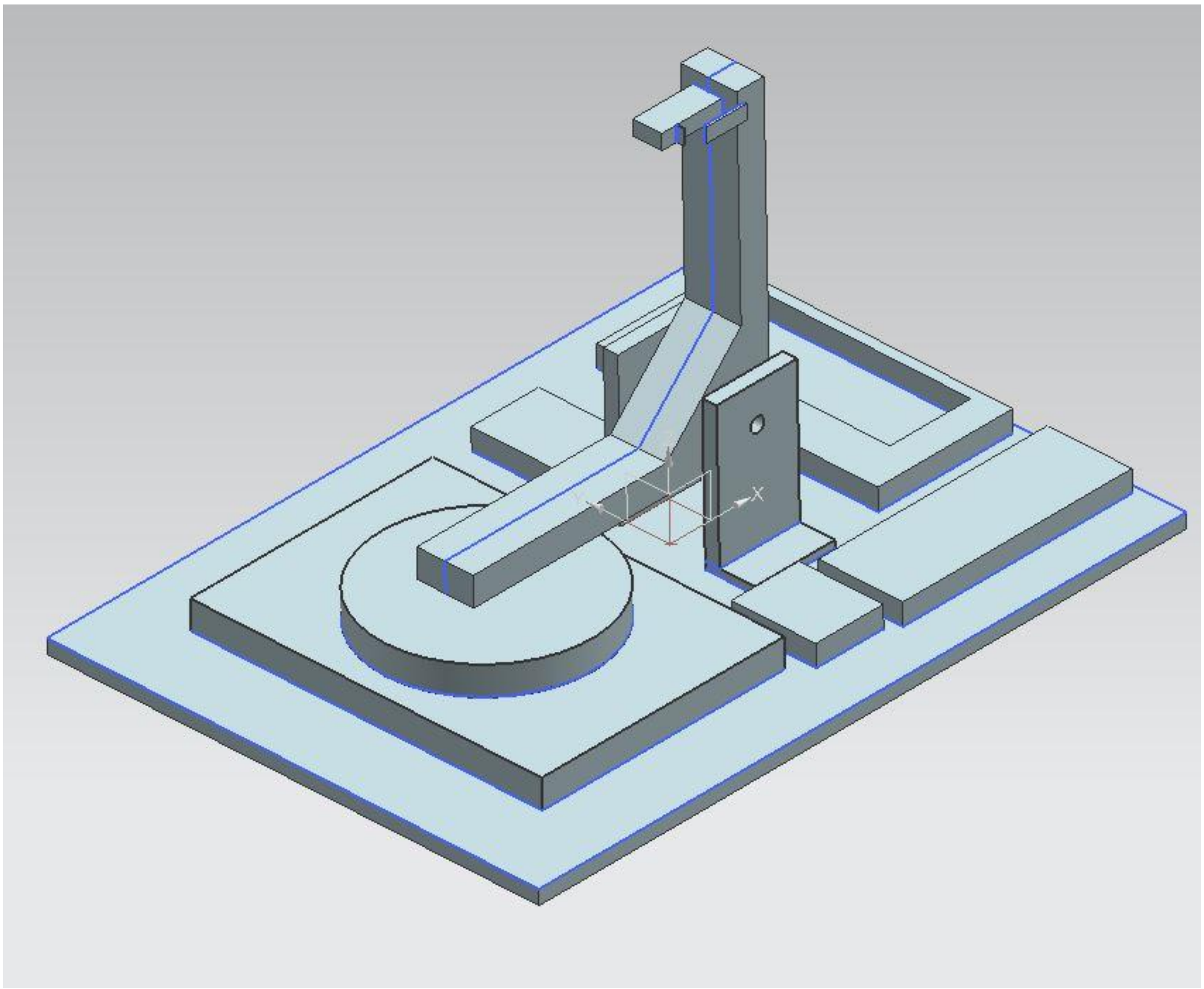

FIG 34: Assembled Model Isometric View

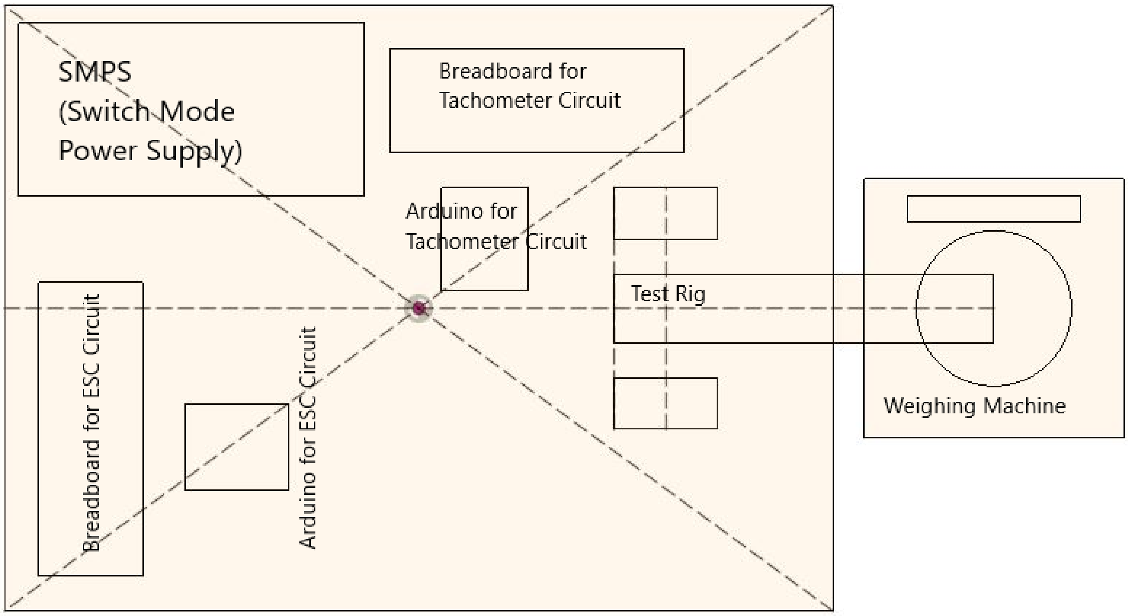

FIG 35: Detailed Assembly

COST ANALYSIS

Material Cost	Plywood: Rs. 250
Machining Cost	N/A (Machine and carpentry shop)
Equipment Cost	ESC: Rs 350 IR Module: Rs 50 Potentiometer x 2: Rs 40 SMPS: Rs 470 Breadboard x2: Rs. 100 Wires: Rs. 160 10”x4.5” Propeller: Rs. 100 Arduino Uno x2: Rs. 720 BLDC Motor: Rs. 350 12 V Battery: Rs. 420 Total: Rs. 2760
Total Cost (Material + Machining + Equipment)	Rs. 3010

THRUST DATA COMPARISON

Test rig experimental thrust values were obtained for the 11x4.7 propeller at certain RPMs and were compared with the actual experimental values available for the same propeller at nearby RPM ranges.

The experimental data has been acquired for RPM ranges lower than 5000 RPM due to power source and sensory equipment limitations.

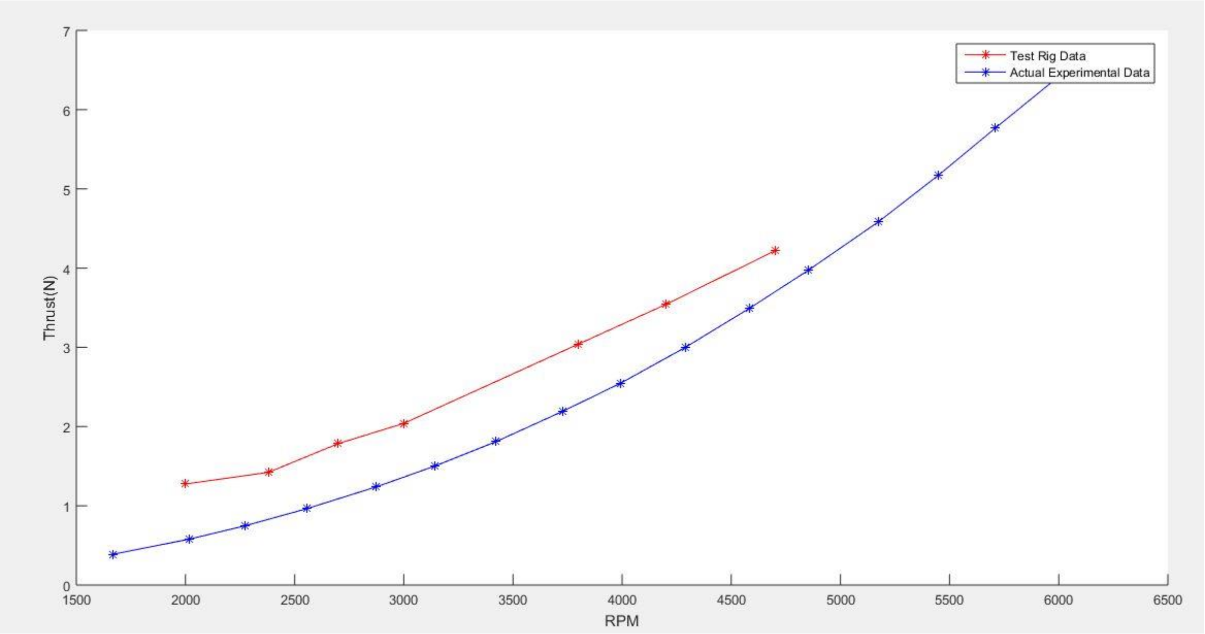

FIG 36: Thrust Data Comparison

Sources of error:

1. The propeller being used is a replica of the stated actual propeller brand therefore exact same performance cannot be obtained.
2. Sensitivity of IR sensor is very high which needs to be calibrated for different ranges of rpms. For example, the IR sensor at one calibration may calculate RPM up to 3000 but might not be able to calculate RPMs above 3000. On the other hand, some calibrations may calculate higher RPMs but might be unable to do so for lower RPMs.
3. Vibrations induced in the test rig deviate the load pointer from the centre of weighing machine at high rpms.
4. Current fluctuations can occur in the motor which can also very the results.
5. Tachometer reading fluctuates in a certain range which needs to be averaged.

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