DRONE DESIGN AND FABRICATION BASED ON OPEN-SOURCE SOFTWARE AND HARDWARE ARCHITECTURE AIMING TOWARDS INDIGENISATION

A Project Report

submitted by

MAJOR AKHIL SHARMA

in partial fulfilment of the requirements
for the award of the degree of

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, MADRAS.

JUN 2021

THESIS CERTIFICATE

This is to certify that the thesis entitled **DRONE DESIGN AND FABRICATION BASED ON OPEN-SOURCE SOFTWARE AND HARDWARE ARCHITECTURE AIMING TOWARDS INDIGENISATION**, submitted by **MAJOR AKHIL SHARMA**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Ashok Jhunjhunwala
Research Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

Date:

ACKNOWLEDGEMENTS

I am ever thankful to Prof.Ashok Jhunjhunwala for his vision and guidance in conceptualization and materialization of the project. We, army officers feel privileged and honored to have worked under his guidance. I would like to extend my sincerest gratitude to him for guiding us, and also giving exposure to the RD processes at IITM Research Park. I would also like to express my heartfelt gratitude to the unwavering support extended by his team at TCOE and CBEEV. It was the dedicated teams here which designed the battery with BMS and motors and further guided our study on these aspects. I would like to especially thank Prof Kannan Lakshminarayan, Prof Kaushal Jha and Mrs Sandhya Ravi Kumar.

I would also like to take this opportunity to thank Prof. Satyanarayan Chakravarthy and his team at the EPlane company who have provided their support and expertise for executing the project. My deepest regards for Prof. Bhaskar Ramamurthy, Prof. David Koilpillai and my professors at IIT Madras, who have motivated and guided us towards academic excellence.

I would like to take this opportunity to thank my organization- Indian Army for giving me this opportunity to become a part of such a prestigious institution. I wish to thank my family for their support and encouragement during the entire period. I would like to dedicate this work to them.

Last but not the least, I would like to thank my team members in this project, Lt Col Yashvardhan Singh and Lt Col K Tony Joseph who provided relentless support and encouragement and worked cohesively for fruition for this project. .

ABSTRACT

KEYWORDS: ECS, IPM, Hexacopter, PMSM

Drone technology has gained much prominence in last decade and its eclectic applications has mushroomed remarkably by numerous researches in this segment. Key objective of the project is to aim towards indigenization of vitals of drone while assembling the drone. Propulsion system of the drone (Motors and ESC) is undergoing rapid transformation due to immense industrial demand. The paper proposes design of PMSM (inner rotor) IPM motor for hexacopter drone made of carbon fiber frame with microcontroller-based flight controller. Firstly, teardown analysis of commercially available motor was carried out for benchmarking of standards. Secondly, FEA was carried out to achieve torque speed profile required for drone application with optimum pole count for the base speed. Thus, the motor performance specifications are obtained by analyzing the simulation results and the shortcomings of the design were addressed. Then CAD drawings of finalized design were drawn on solid works to manufacture prototype motor. Further integration of components with the frame and interfacing with the open-source Flight controller was done. Lastly flight log analysis using Mission planner gave insight into optimizing the flight dynamics of the drone for better performance. Keywords: Hexacopter, IPM, flight controller, flight log analysis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

IITM	Indian Institute of Technology, Madras
ACC	Accelerometer
ADC	Analog Digital Converter
AHRS	Attitude Heading Reference System
ATC	Altitude Control
AUTOCAD	Automatic Computer Aided Design
BMS	Battery Management System
BLDC	Brushless Direct Current
BV-LOS	Beyond vision line of sight
EMF	Electromagnetic Force
ESC	Electronic Speed Controller
FC	Flight Controller
FDI	Fault Detection and Isolation
FEA	Finite Element Analysis
FMEA	Failure Mode effects and critical Analysis
GCS	Ground Control Station
GPS	Global Positioning System
GUI	Graphical User Interface
GNN	Grossberg Neural Network
HALE	High Altitude Long Endurance
IDE	Integrated Develop Environment

IMPM Interior Mounted Permanent Magnet

IMU Inertial Measurement Unit

LIDAR Light detection and Ranging

LIPO Lithium-Ion Polymer

PMSM Permanent Magnet Synchronous Motor

RADAR Radio detection and Ranging

RTOS Real Time Operating Software

SPM Surface Mounted Permanent Magnet

UAV Unmanned Aerial Vehicle

UAS Unmanned Aircraft System

VTOL Vertical Take-off and Landing

CHAPTER 1

INTRODUCTION

Motivation

Drone technology is one of the most promising technologies of the present era.Today Unmanned Aerial Vehicles (UAVs) have caught human imagination because of their innovative applications in the field of defense, logistics, disaster management, search and rescue, firefighting, surveillance, monitoring, agriculture, aerial photography etc. With its agility and ability to reach inaccessible places, drones are a force multiplier in any operation. Countries across the world have realized the potential of drones and are investing in the growth of innovation in this field. Though the Indian defence forces and industry have already started harnessing this technology but we are still at a nascent stage with respect to India's UAV program- indigenous development of UAVs in India. We are still primarily dependent on imported hardware and software. We need to have complete control of drone technology right from airframe to autopilot, from battery to motors, from control station to communication systems to leverage the technology and be able to customize the system as per user requirement. Only then we can actually handle the technology with trust, confidence and no sabotage risks.

This project attempts to design and develop frame structure, motors and battery in-house and further utilize open-source autopilot software for building drone. Our project team involved three Army officers working under Prof Ashok Jhunjhunwala. The project was extended technical support from Centre for Battery Engineering and Electric Vehicles (CBEEV) and Motorz startup at IITM Research

Park under Professor's guidance. CBEEV, was the nodal agency which facilitated the procurement of various components, technical support and provided us with inhouse designed and fabricated smart battery pack with intelligent Battery Management System (BMS) under guidance of Prof Kaushal Jha. For motor design and manufacturing, we were assisted by Motorz, a startup at Telecom Centre for Excellence (TCOE) under guidance of Prof Kannan Lakshminarayan. In addition, frame fabrication, assembly and professional drone pilot support, was provided by the e-plane company, a drone startup under guidance of Prof Satya Chakravarthy of Aerospace department.

The scope of work for our project team involved the following:

- Frame design, optimization and assembly.
- Sensor integration including collision avoidance and 4G communication system.
- Flight testing and post mission flight log analysis.
- Design and fabrication of BLDC motors for drones
- Live Object detection using AI application at GCS
- Smart battery Interface development and testing/ trials

The present thesis covers the designing/fabrication of a hexacopter frame,motors, drone assembly and optimization aspects and also covers the flight data log analysis for the drone. The hexacopter is intended to be used as payload type drone for camera / cargo payload.

Brief on Drones

They are complex systems made by hardware and software structures.Different variety of drones are opted for various applications and roles. There are primarily three types of drones: fixed wing, multi rotor and hybrid drones which are shown in fig 1.1. Multirotor segment varies from configuration of tricopter to octacopter, which are deployed for various application ranging from racing, surveillance, payload delivery and aerial recce or photography.

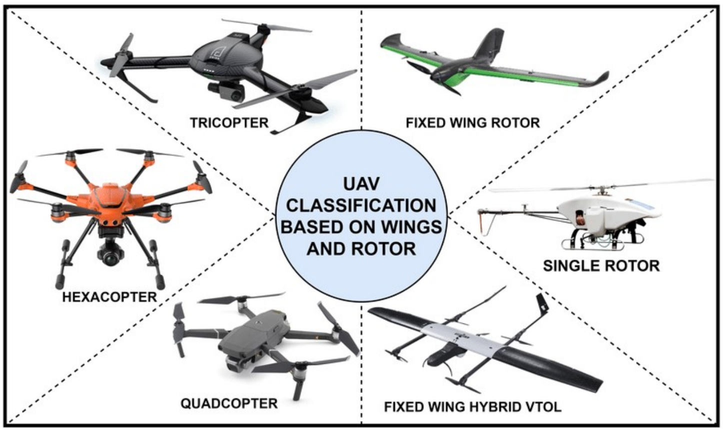


Figure 1.1: Different variants of Rotor class drone.

The application of Unmanned Aerial Vehicle and Drones have increased manifold with passage of time, for purpose of transportation, delivery and surveillance. They are being deployed for their cost effectiveness, reliability and multi functionality. Due to the limitation of low energy density of battery technology, the system total weight is the most critical aspect to minimize for a requisite power requirement. Thus, in order to enhance efficiency vis -a-vis endurance or flight time, the power density of the electric motors needs special consideration in drone systems.

Drone is a typical unmanned aircraft that is made of light composite material to increase its manoeuvrability and reduce weight. The composite material strength and selection of components depends upon its usage and requirements, where military drones are of sturdy frame material and Mil grade components and commercial drones are build from cost effective materials.

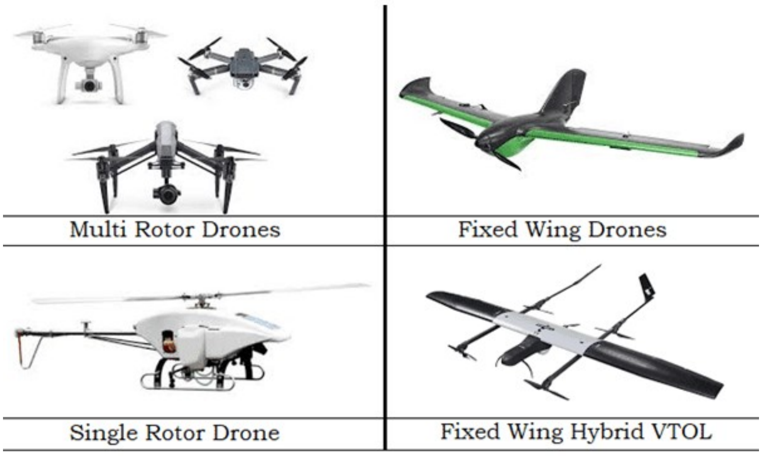


Figure 1.2: Different variants of drone.

1.1 Flight Aerodynamics of drone

Following are the forces that act on a flight explained in figure 1.3

- **WEIGHT (mg):**acts downwards and brings flight downwards.
- **LIFT(U1):** acts upwards and lifts the flight upwards.
- **THRUST (Th):** moves the flight in the forward direction.
- **DRAG:**acts backwards to resist thrust.
- **ROLL ():**Longitudinal axis which is along the front-back direction.
- **YAW () :**along the top-bottom direction.
- **PITCH () :** along left-right direction.

The movement of aircraft is controlled by rotating it along three mutually perpendicular axes. These axes are longitudinal axis/ ROLL axis which is along the front-back direction, lateral/PITCH axis which is along left-right direction and

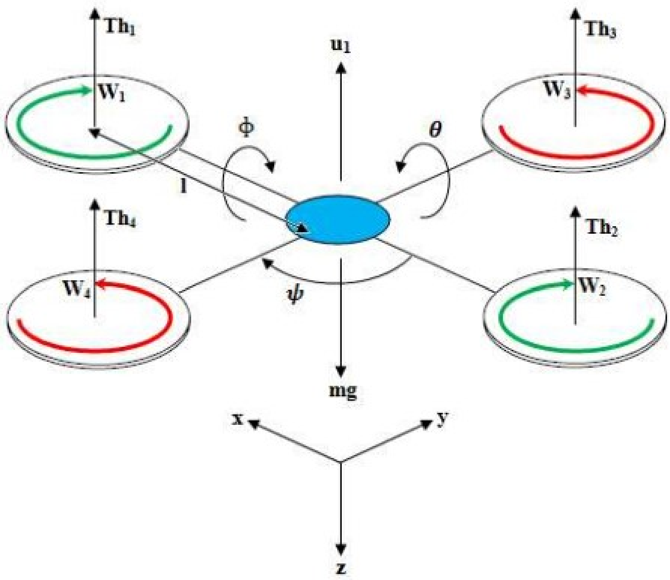


Figure 1.3: Forces acting on a flight.

perpendicular/YAW axis which is along the top-bottom direction. A combination of movement along these three axes results in the movement of the aircraft.

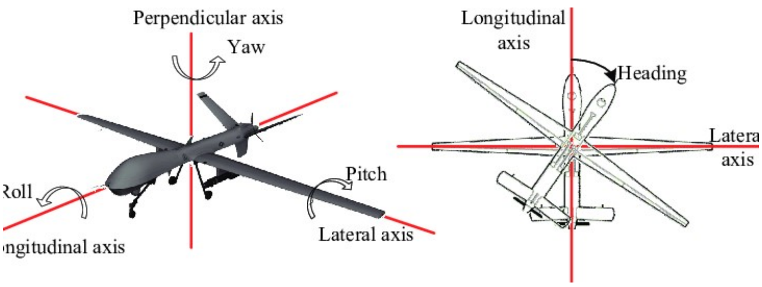


Figure 1.4: Principal axes of aerial platform.

1.2 Working of Drone

The movements of a drone are controlled by the angular speed of the propellers Lemko and Molodchyk [2015]. Each propeller generates a thrust individually by pushing the air downwards. The upward thrust and reaction torque is also produced in opposite direction of rotation of the rotor. In case of Hexacopter, three rotors spin in the clockwise direction and other three rotors spin in counterclockwise direction which provide a resultant torque of zero, when they all are spinning at same angular speed. Hexacopter's movement is controlled by varying the relative thrusts of each of the 6 rotors. Motors on one diagonal rotate in the clockwise direction and on the other in the anti-clockwise direction as shown in fig below. The movements of a hexacopter are explained as under:

1.2.1 Moving forward

To move forward we reduce the power in the front motor. This tilts the quadcopter forward and the rotors provide sufficient thrust to move forward. Speed is decided by the power given to the rotors.

1.2.2 Moving back

To move backwards we reduce the power in the back rotor, tilting the quadcopter backwards and then again, the thrust from the motors takes it in reverse.

1.2.3 Yaw

Yaw (turning left and right) is controlled by turning up the speed of the regular rotating motors and taking away power from the counter rotating; by taking away the same amount that you put in on the regular rotors produces no extra lift (it won't go higher) but since the counter torque is now less, the quadcopter rotates and control becomes a matter of which motor gets more power and which one gets less.

1.2.4 Roll

Roll (tilting left and right) is controlled by increasing speed on one motor and lowering on the opposite one.

1.2.5 Pitch

Pitch (moving up and down, similar to nodding) is controlled the same way as roll, but using the second set of motors.

1.3 Main Objectives of the project

- To study UAV flight aerodynamics and design.
- Study various frame configuration and model Hexacopter frame using CAD.
- Selection of suitable propellers for Drone and study characterstics and designing of Propellers.
- Selection of motors, holistic study on type of motors and fabrication of prototype motor.
- Study open-source software for flight controller and implementing it on microcontroller-based board.
- Integrating various sensors for satblized flight of drone.
- Design and assemble battery pack along with BMS.
- Carryout Post flight analysis of Hexacopter and optimize design.

CHAPTER 2

DRONE SYSTEM DESIGN

A drone hovers and moves in a particular direction by varying the RPMs of its motors. when we move a control on remote transmitter or controller, the command needs to be converted into the proper signal for each of the motors resulting into desired motion. This is done by the flight control system of the drone which is responsible for flight stability, navigation and autopilot. The purpose of the flight controller is to simplify the coordination and control functioning of all propellers, which is done by limiting current to the ESC. The flight control computer has the ability to connect to several other devices and sensors. The primary device that it connects to is the remote-control receiver, which is linked to remote transmitter. Typical sensors consist of GPS, gyro compass, and barometer. Collision avoidance system like Lidar, radar can also be integrated as part of the system.

2.1 Drone Subsystem

Drone working and construction can be divided into three subsystems, namely Actuating system, Power System and Controller system. All subsystems work in tandem to keep drone operational; selection of their components is dependent on each other. Actuating system is responsible for lifting and hovering of drone. Power system comprises of battery (LIPO with varied configurations) meant to provide power to motors, sensors and control system. Control system comprises of flight controller, on board computer and collision avoidance sensors.

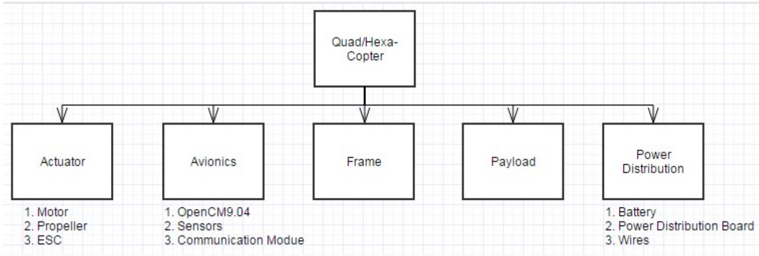


Figure 2.1: Subsystems of Drone.

2.1.1 Actuating system

The actuating system is responsible to keep drone in air and manoeuvre in desired direction by limiting power supply to motors Ding *et al.* [2014]. The motors and propellers work in pairs, in case of a hexacopter three motors and propellers in clockwise direction and other three in counter clockwise direction. The functioning of ESC and subsequently motor depends upon the input data received from flight controller whether to fly or hover. Flight controller receives input from manual operator or autopilot.
Actuating system comprises of the following

- Motor Stator
- Motor Rotor
- Electronic Speed Controllers
- Propellers
- Bearings
- Windings

2.1.2 Power System

In a typical drone system, several different components, such as propulsion systems, processors and sensors have different voltage and load requirements. Different parts of the system's mission – takeoff, landing, hovering, information gathering – will also have different power profiles. This means that the battery will be undergoing continuously varying loads and have a wide variety of demands placed on it.

The main parameters to look for when choosing a battery are voltage level, capacity (how much power the battery can hold, measured in milliamp hours) and discharge rate (how much current can be discharged from the battery at once). Other factors that affect battery selection include activation time, charging time, lifespan and cost. Following points should be considered before selecting battery for drone.

- Capacity(mAh)
- Voltage(V)
- Discharge Rate (C)
- Dimensions (LWH)
- Net Weight (g)

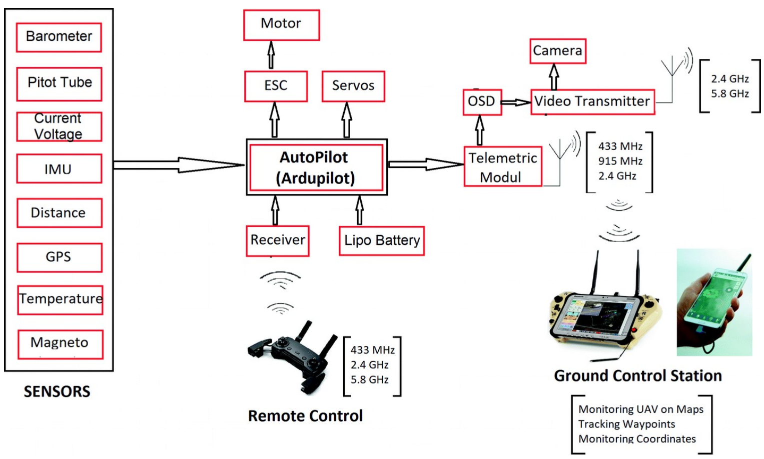


Figure 2.2: Drone subsystems.

2.1.3 Sensors

Drones utilise a wide range of instruments and sensors to enhance the operation or to gather data. Unmanned vehicles are ideal remote sensing platform with several sensors that also include Inertial measurement units (IMUs), which fuse together information from different sensors such as gyroscopes, accelerometers and magnetometers to provide measurements that can be used to calculate orientation and velocity of the UAV. This data can be combined with another source of information such as a GPS to further increase the accuracy of the calculations sensors also include Inertial measurement units (IMUs), which fuse together information from different sensors such as gyroscopes, accelerometers and magnetometers to provide measurements that can be used to calculate orientation and velocity of the UAV. This data can be combined with another source of information such as a GPS to further increase the accuracy of the calculations.

2.1.4 Flight Controller

The flight controller is the core of the navigation and flight management system, it manages the flight planning and can verify the designated trajectory and actual trajectory taken by drone in real time. Several sensors can be hooked to the flight controller managing power requirement and port linearity. Data of sensors can be acquired and utilized by flight controller for keeping drone on designated trajectory.

CHAPTER 3

AIRFRAME

Autonomous aerial vehicles are true mechatronic systems that combine elements of mechanical, electrical, software and control systems. Main components of drone can be summed in three main categories.

(a) The Aerial Platform, that includes Airframe, Navigation system, Power system, Payload to include sensors and camera .
(b) The Ground control station (GCS, which allows control for a remote emplacement).
(c) Communication system which supports the interlink between the two.

The airframe is the main structure or the backbone of the UAV, there is clearly no one-size-fits all solution. There is a stark trade-off between portability/size and endurance capabilities. Its structure has to appreciate the weight with regards to the power (battery), propulsion (Motors), Communication and control systems on board Ahmed *et al.* [2020]. Airframe design and material needs to be well researched and designed to with stand external forces during flight. Airframe should be sturdy enough that external forces don't create any deformity or vibrations beyond acceptable limits.

3.1 Configuration

The small-scale drone airframe can be categorised as following variants with varied configurations.

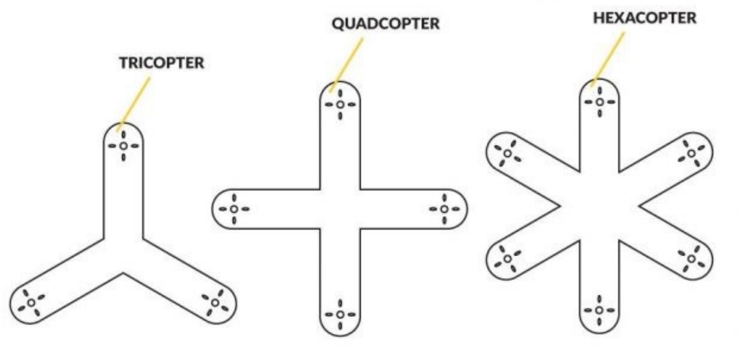


Figure 3.1: Small scale drone airframes.

3.2 Construction Material

Fixed wings are mainly constructed from polystyrene or carbon fibre; Multirotor airframe are made of aluminium or carbon fibre which gives them lightweight design and resilience. Number of arms in a multirotor is a function of expected payload or class of drone catered by same number of motors.

The major requisite for material used for construction of drone with respect to physical and mechanical properties should fulfil are

- Resistance to buckling
- High ultimate tensile strength
- Less Inflammable
- High strength to weight Ratio
- Low thermal gradient
- Ease of shape ability
- High fatigue
- Endurance limit

Material selection for drone is an important paradigm as it can alter the whole design and various operational capabilities of drone. Needless to say, every drone frame has different material requirements considering its task and payload. Following is the comparison between various materials opted for airframe design of drones. Carbon fibre reinforced plastic provides high strength and it is super lightweight. Its cost is high as it is reduced weight material with great resilience, reduced frame weight requires less thrust to lift off the drone. Airframe consists of three parts frame, landing gear and gimbal. The frame is occasionally drilled with holes to reduce weight of drone and maintain stability. The landing gear are used to lower centre of gravity and hold stability while landing.

Table 3.1: Different construction material and their specifications

Parameters	Balsawood	Carbon Fibre	Roha Cell
Weight	5	5	5
Strength to Weight Ratio	2	4.5	5
Availability	5	5	1
Cost	4	4	0.5
Machinability	5	4	3
Total	21	22.5	14.5

3.3 Drone Weight

Total weight of the drone comprises of frame weight, Motor weight (Quantity), battery and payload to include sensors, camera etc.

Drone Weight = Motor Thrust x Number of Motors x Hover Throttle

We have designed a hexacopter with H configuration on CAD, since we are using 15-inch propellers we need to consider adequate space for hovering of propellers and avoid their interference with each other. The frame is simulated for stability in terms of Roll, Pitch and Yaw interferences. Frame strength is checked with simulations against vibrations and unnecessary vibrations are cut down by reap-

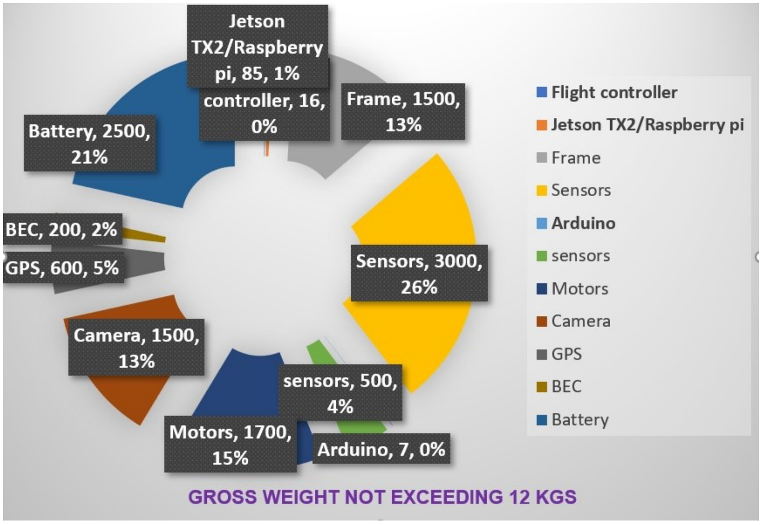


Figure 3.2: Pie chart presentation of the weight distribution of Drone.

propriating the design. Final design with exact specifications is shown in following figure. The main design consideration for the frame of drone is minimising the

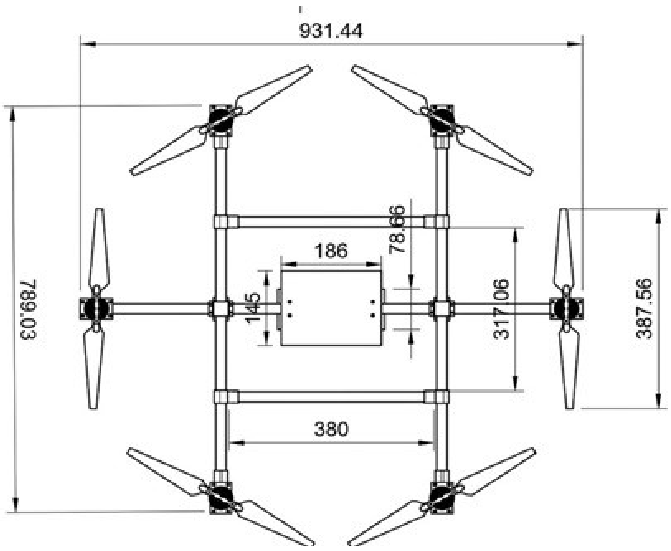


Figure 3.3: Hexacopter frame design

weight and ensuring stability. Since it is a hex copter, we have to cater for six motors on hollow cylindrical rods with following dimensions.

Table 3.2: Hexacopter drone frame components

S. No	Nomenclature	Qty	Dimensions
1.	Hollow cylindrical rod - Vertical	2	789.03
2.	Hollow cylindrical rod - Horizontal	1	931.44
3.	Horizontal Connecting rod	2	380.00
4.	Motor Base	6	
5.	Clamps	6	

3.4 Methodology for designing the frame

Identifying the load direction in the frames during its operation and its critical points where failure can happen due to fatigue by doing FEA simulations of it and preparing final CAD models with detail fiber direction of each layup.
After Designing the CAD models of manufacturing moulds for both CF tubes and CF plates, CNC manufacturing of moulds was done and proper inspection was done.
Additional consideration needs to be given while designing are robustness and ability to mount additional sensors. Total weight requirements form the base foundation for selection of motors and propellers which are able to produce required thrust to actuate the drone system. After selection of motors, propellers and ESC we need to select battery that will provide required endurance simultaneously meeting power requirement of motors at varied throttle levels.

3.5 Other frame types

To understand the concept of frame assembly and sensor integration two additional variants of frames were assembled namely X type and V type frame assembly.

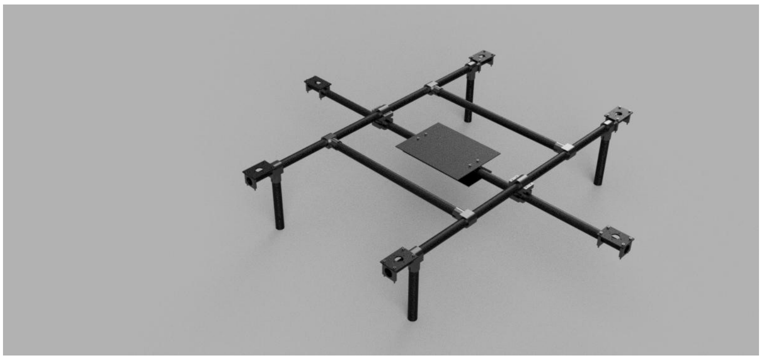


Figure 3.4: Hexacopter frame modelled in Fusion 360

3.5.1 X Type frame

The specifications of X type frame procured are as under

Table 3.3: 3 specifications of X type frame

Model	Q450
Material	Glass Fiber + Polyamide Nylon
Wheelbase (mm)	450
Weight (gm)	330 (Q450 Frame)
Arm Size (L x W) mm	220 x 40
Landing Gear Material	ABS Plastic
Landing Gear Weight (gm)	75
Battery	4S
Motor	MT 2213
Propeller	1045

3.5.2 V Type frame

The specifications for V type frame procured are as under:

Figure 3.5: X Type frame configuration

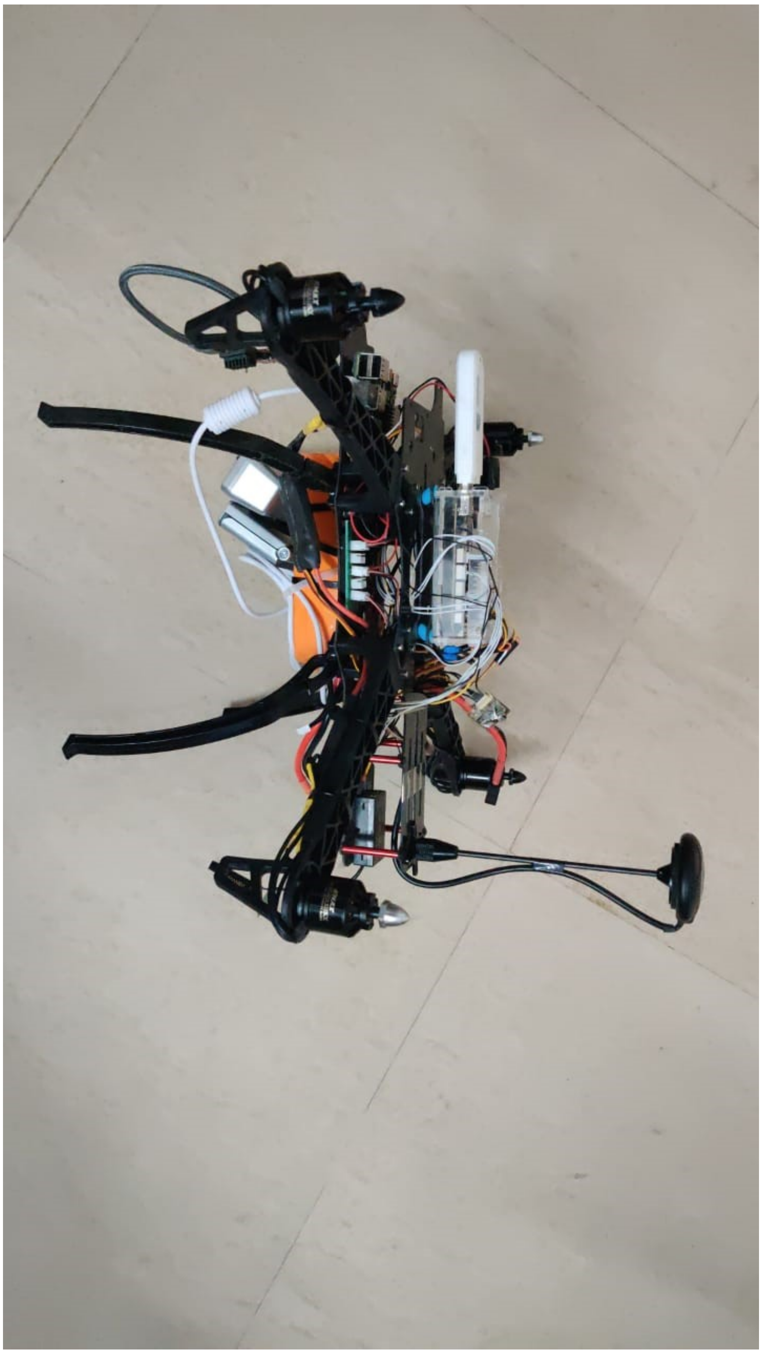


Figure 3.6: V type frame configuration

Table 3.4: Specifications of V type frame

Model	TBS 500
Material	Carbon Fiber + Polyamide Nylon
Wheelbase (mm)	500
Weight (gm)	400
Arm Size (L x W) mm	220 x 40
Battery	3S
Motor	MT 2216
Propeller	1045

3.6 Analysis

Post assembly of the components, the gross weight of X frame quadcopter was 1.3 kg whereas for V frame quadcopter it was 1.8 Kg . It was observed that both frames had their own advantages. V frame had more space for accommodating sensors and camera compared to X frame. But based on flight trials carried out on both these platforms, the X type frame was found to be more stable and efficient.

Where hexacpoter is a symmetrical model and the centre of gravity of hexacopter lies in the centre of the frame. It can be used for heavier payloads and offer excellent flight stability after configuration. It utilizes the total thrust generated by six motors for lifting movements where three motors work in clockwise direction and other three in counter clock wise direction overall cancelling overall angular momentum. The Hexacopter frame configuration is generally recognized as only two types: the Plus (+) and X configurations, we have opted for H frame or plus configuration.

Figure 3.7: Assembling Hexacopter Drone Frame

Figure 3.8: Table top testing of hexacopter X Frame for alignment

CHAPTER 4

SELECTION OF PROPELLERS

Propellers are devices that transform rotary motion into a linear thrust. Propellers provide lift for the aircraft by spinning and creatin an airflow which creates a pressure difference between top and bottom surface of propeller Saedan and Puangmali [2015]. This pressure difference accelerates a mass of air in one direction providing lift which counteracts force of gravity.

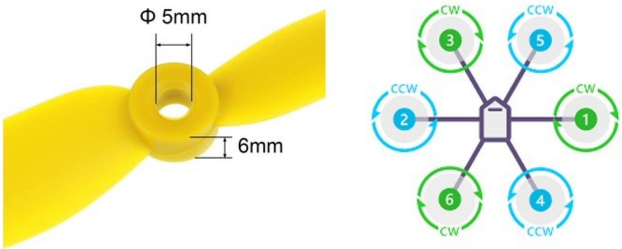


Figure 4.1: Propeller blade and its orientation in hexacopter

Propeller blades for multirotor drones such as hexacopter are arranged in pairs, spinning clockwise or anticlockwise. The spinning symmetry of propellers is used to provide horizontal, vertical or lateral movement of the drone. CW and CCW motion cancels angular momentum of one propeller with other. By varying the speed of these propellers, the drone hover, ascend, descend or affects its yaw, pitch or roll.

Propeller speeds are varied with help of ESC (Electronic speed controller) which alters the supply voltage to the motors of drone causing variation in throttle level. Flight controller controlled by operator or autopilot feeds the exact signal to the ESC, limiting the drawn current for each motor to perform desire manoeuvre.

4.1 Selection of propeller for designed Hexacopter

Commercially available drone propellers are specified by two main measurements A X B, where A indicates the total length of blade from end to end and B is the pitch, which is related to the angle of the propeller. Pitch indicates how far the propeller will move forward under ideal conditions for every rotation. Following is the commercially available propeller blade with variants of length and pitch, it should be noted that performance of motor varies with different propeller dimensions (length and pitch)

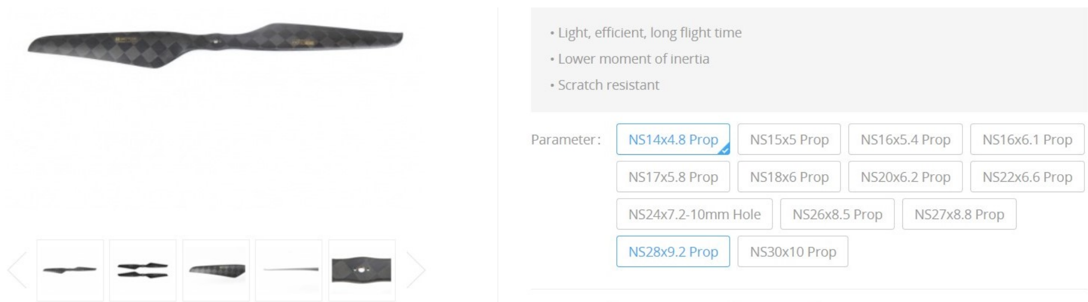


Figure 4.2: Commercially available propeller

4.2 Length of propeller (A)

Short propellers are preferred to perform quick manoeuvre as they require less energy to attain particular speed and due to reduced inertia are easier to control and quicker to vary speed. Long propellers generate more upward lift to a particular RPM and attain greater stability while hovering. Long propellers also require more power as they offer more resistance to the motors in turn impacting the motor RPM. Length of the propeller is limited by the design of drone as in what length can be accommodated without interfering the adjacent propellers motion.it is aptly explained in following figure

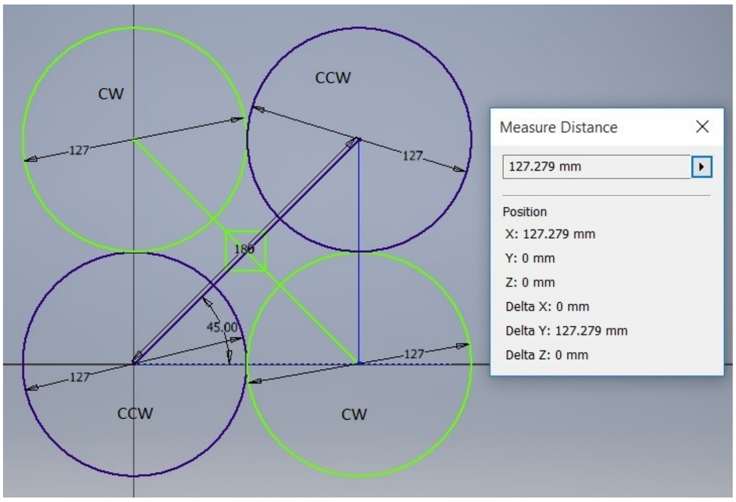


Figure 4.3: Deciding factor for maximum length of propeller

4.3 Pitch of propeller (B)

Propeller with high pitch will generate more lift as compared to the ones with flat blade, thus enabling drone to fly faster for same RPM. Thus more pitch is desirable for speed but there is tradeoff between power drawn by motor as Propeller with higher pitch will offer more resistance to motor, hence draining battery faster. Heavy drones will require long propeller blades with small pitch as stability is preferred over speed. Heavy-lift drones will typically require longer propellers with smaller pitch, as they require stability rather than speed. Impact of pitch for thrust generated can be observed by following graph

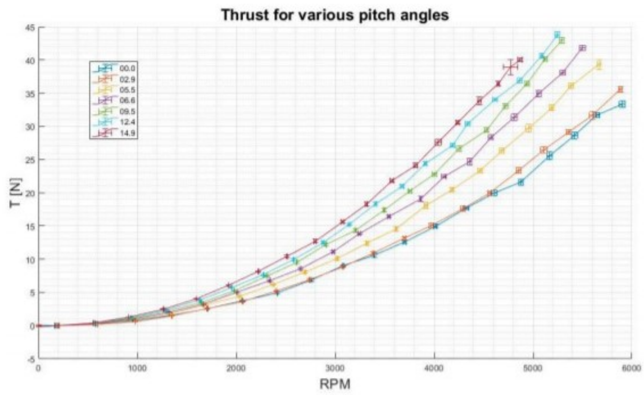


Figure 4.4: Thrust for various pitch angles

4.4 Number of propellers

Number of propellers required will vary depending on the platform, usage and payload requirements. Smaller blades, under eight inches, are most frequently used for racing drones and those used for acrobatics. Smaller blades are generally paired with smaller motors with high kV ratings. Larger blades, over eight inches, are paired with motors that have low kV ratings and can be used to carry heavier payloads, such as video equipment or spraying containers for agriculture.

4.5 Drone propeller raw material

Drones with a greater number of blades provide greater lift due to more surface area moving through the air per rotation, but they are inefficient due to increased drag.

Propeller blades are generally constructed from plastic or carbon fiber. Plastic propellers are cheaper, flexible and can absorb impact better. Carbon fiber propellers, although less durable and costly decreases vibration and improves the flight performance of the drone.

Factors to be kept in under consideration include:

- Blade material
- Power
- RPM
- Air density
- Maximum noise

4.6 Selected propellers for Hexacopter drone frame

Considering the designed frame dimensions if we consider the closest adjacent blades, the distance is 380 mm. As we desire more stability and payload capacity from our drone, we opt for maximum length of propeller which turns out to be 15 inches(380mm). For selection of the pitch we need to compare the performance of propeller with 15 inch diameter with motor.

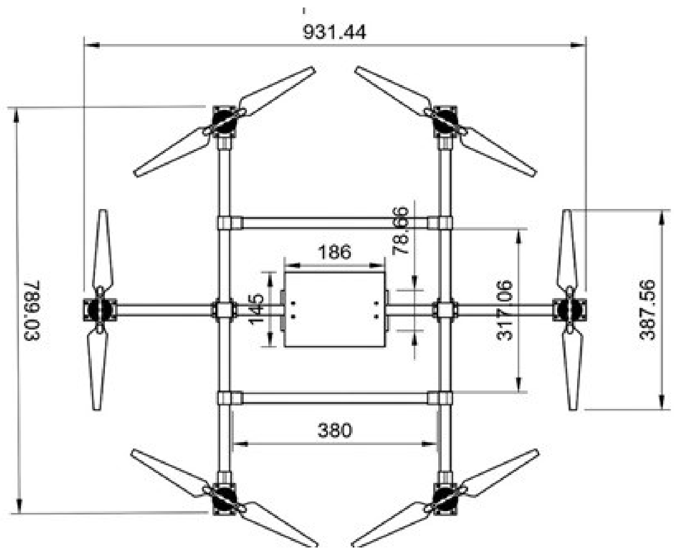


Figure 4.5: Designed model of frame with dimensions

Now for selection of pitch we have selected T Motor carbon fiber 15inch propeller with blade pitch 5 which is ensuring high RPM of 6000 at 100% throttle.

Item No.	Volts (V)	Prop	Throttle	Amps (A)	Watts (W)	Thrust (G)	RPM	Efficiency (G/W)	Torque (N*m)	Operating temperature (℃)
Antigravity 4006 KV380	24	T-MOTOR 13*4.4CF	50%	2	48.00	544	3719	11.33	0.096	30
			55%	2.5	60.00	656	4528	10.93	0.108	
			60%	3.1	74.40	753	4840	10.12	0.123	
			65%	3.7	88.80	853	5155	9.61	0.139	
			75%	5.1	122.40	1062	5451	8.68	0.172	
			85%	6.8	163.20	1286	6327	7.88	0.208	
			100%	9.7	232.80	1633	6515	7.01	0.267	
		T-MOTOR 14*4.8CF	50%	2.4	57.60	675	3961	11.72	0.116	37
			55%	3.2	76.80	798	4329	10.39	0.139	
			60%	3.8	91.20	908	4619	9.96	0.159	
			65%	4.7	112.80	1033	4925	9.16	0.179	
			75%	6.5	156.00	1286	5485	8.24	0.222	
			85%	8.5	204.00	1576	6004	7.73	0.268	
			100%	12.2	292.80	1975	6731	6.75	0.338	
		T-MOTOR 15*5CF	50%	3.1	74.40	805	3746	10.82	0.152	46
			55%	4.6	110.40	959	4089	8.69	0.178	
			60%	4.8	115.20	1093	4358	9.49	0.203	
			65%	5.8	139.20	1236	4634	8.88	0.229	
			75%	8.3	199.20	1561	5215	7.84	0.285	
			85%	10.7	256.80	1823	5627	7.10	0.334	
			100%	15	360.00	2228	6177	6.19	0.404	
		T-MOTOR 16*5.4CF	50%	3.7	88.80	928	3495	10.45	0.187	HOT
			55%	4.8	115.20	1096	3817	9.51	0.221	
			60%	5.9	141.60	1258	4079	8.88	0.252	
			65%	7.2	172.80	1427	4326	8.26	0.285	
			75%	10	240.00	1740	4803	7.25	0.343	
			85%	12.9	309.60	1970	5119	6.36	0.388	
			100%	17.5	420.00	2309	5445	5.50	0.447	
Notes:The test condition of temperature is motor surface temperature in 100% throttle while the motor run 10 min.										

Figure 4.6: Specification of propeller with varied pitch

Since current drawn is more we need to have a powerful battery pack. For selection of motor the recommended motor for this propeller is 4006KV380, where stator diameter40mm, stator length 06mm.

4.7 Design methodology of propellers

We need to Design the propeller by selecting a proper airfoil with highest aerodynamic characteristics and after proper calculations CAD model needs to be generated.

After finalizing the CAD model CFD simulations will be conducted until the desired aerodynamic characteristics are obtained. Post CFD simulations FEA for the propeller structural behaviour will be carried out. CNC manufacturing of moulds will be carried out and proper inspection of them will be done.

CHAPTER 5

MOTOR SELECTION

We have opted for hexacopter configuration with H frame design of drone with carbon fibre hollow cylindrical pipes. The dimensions of the frame allow us to opt for propeller size of 15 inches considering the weight of the drone. The propeller size is apt for the drone configuration as they don't cause any interference to each other pow.

After selection of propeller size, we need to consider the Thrust to Weight Ratio of the drone. A general thumb rule for motor selection is that the motor should be able to provide twice as much thrust as weight of the drone including the payload. If the thrust provided is too little the drone will not react well to controls or even take-off on the contrary If the generated thrust is way beyond the desired then drone becomes too agile and hard to control Mul.

5.1 Principle of Selection of motor

WEPT (Weight, efficiency, power and torque), selection of motor is done in order of principle WEPT. Weight of drone is considered first; the motor should be able to cater the thrust requirement of the drone for take-off. After shortlisting the motors which meet the thrust requirement for drone, we need to shortlist an efficient motor which draws less current and gives more endurance for the same power supply as

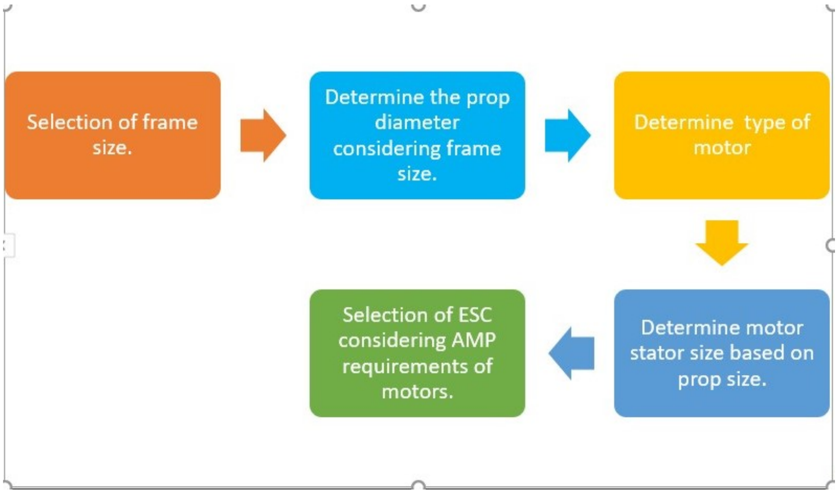


Figure 5.1: Procedure for drone assembly

compared to others. In a multirotor drone, the motor's main objective is to deliver drive to the propeller reliably. Drone motor should provide high acceleration and deacceleration swiftly for changing speed of drone. Maximum current drawn by the motor is described in motors specification sheet. Speed provided by motor (in RPM) can be calculated by following formula

Speed (in RPM) = KV rating of motor x Applied voltage

5.2 Actuating system

After creating an Auto CAD design for hexacopter drone and assembling the frame we have selected the propellers for the drone. If we look in the following figure which explains step wise methodology for selection of components of drone.

With 15inches propellers coupled with suitable blade pitch, we calculate the torque requirement of drone, that will generate speed for propeller to create an upward thrust for drone. As a thumb rule aggregated thrust at 50% throttle gen-

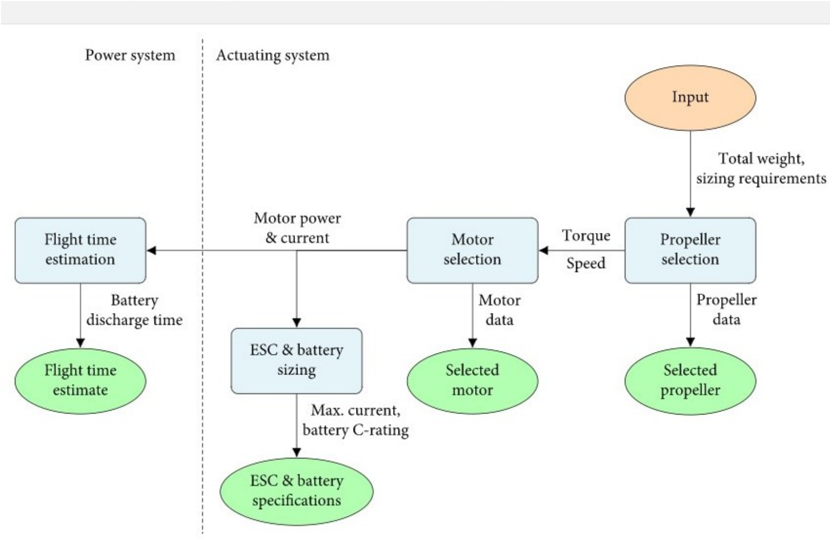


Figure 5.2: Subsystem assembly for drone

erated by motors should exceed the total weight of drone. For instance, if we have a drone that weighs 12 kgs, the total aggregated thrust created by motors at 50% throttle should be more than 12 kgs.

It is essential to ascertain following parameters of motor during selection of motor as if the motor characteristics or performance is not compatible with the drone then there will be stability issues which in turn will drain battery fast.

- Stator size
- KV Rating
- Efficiency
- Torque generated with varied voltage

5.2.1 Stator Size

Selection of motor after selection of propeller is governed by stator size as propellers come with compatibility chart with stator size. It should be noted commercial motors are indicated as four numbers **, where stator diameter and ** stator length in mm. A taller stator delivers higher top speed and terrible low speed handling while a wider stator delivers lower top speed and better handling at lower speeds.

Figure 5.3: Selection of stator size

5.2.2 KV Rating

KV rating is another vital parameter, it is theoretical increase of motor RPM (Rotation per minute) when the voltage goes up by 1 Volt without load. If while running a 2500 KV motor with a 6S1P LIPO battery (6*4.2V = 25.2V), the motor would turn around 63000 RPM appx.

5.2.3 Efficiency of motor

Drones have limited flight because their power source or batteries are compact considering drone size. Hence efficiency is of paramount importance in case of motors. To increase the output power the rated torque and rotational speed needs to be increased, it is desirable to increase the rotational speed as increase in torque tends to increase the motor size. Same motor with different voltage source and propeller size gives varied efficiency.

5.2.4 Torque generated with varied voltage

Motors deliver different characterstics (thrust,power,speed and efficiency) with varied voltage source and propeller size. Ref following figure same motor at 8V or 2S battery configuration deliver different parameters as compared to 12V supply. Even with variation of propeller size the deliverables vary.

The voltage (V)	Paddle size	current (A)	thrust (G)	power (W)	efficiency (G/W)	speed (RPM)
8	Carbon Fibre Prop 6x3	6.4	240	51.2	4.7	11910
12	Carbon Fibre Prop 5x3	7.5	310	90.0	3.4	20100
	Carbon Fibre Prop 6x3	11.5	440	138.0	3.2	16300

Figure 5.4: Motor performance with varying voltage

5.3 Number of motors

The estimation for number of motors is done by considering weight or class of drone including payload, we are planning to assemble. We have opted for a hexacopter drone with H frame considering heavier payload and to attain better flight stability. We have decided for quantity of motors for our 12 kg class drone, now these motors aggregated thrust at 50% throttle or in hovering condition should exceed 12 Kgs.

Drone weight = Motor thrust x Number of motors x Hover throttle

There are various configurations of motors which can be opted for hex-copter drone, but BLDC motors are widely preferred motors in this segment. BLDC motors paired with right propellers should meet the upward thrust requirement of drone along with safety margins. Since the motor application is pertaining to rapid acceleration and de-acceleration, we require high torque/inertia motors.

Commercially available motors are categorized by a four-digit number such as **, where represents the stator width and ** represents the stator height. The wider and taller the motor or the larger the numbers are more is the torque they can produce. After mounting the motors on frame, the RPM will decrease as the propellers will offer resistance. Higher KV motors would turn the propeller quickly with less torque where a low KV motor will create higher torque with less rotation.

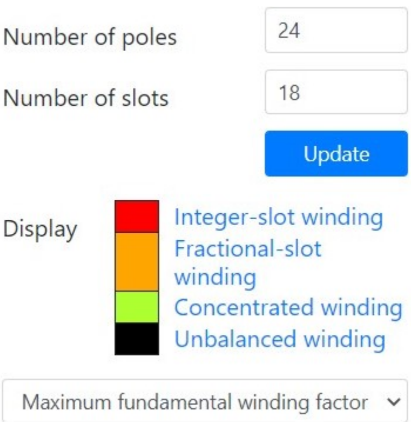
For our Hexacopter after shortlisting the propeller size and pitch we homed on to selection of motor with compatible stator size, we selected commercially available T Motors MN 4006 KV 380 with following design features:

- BLDC Motor with outter rotor
- Stator Dia 40mm, Stator height 06 mm
- KV Rating 380

It draws maximum current of 16A for 6 motors with total requirement of 96 A current. It's a compact motor with diameter of 44 mm and 68 gm weight. Its configuration is 18 N 24P.If we check for 18N 24P configuration we get maximum winding factor of 0.866, it is concentrated winding.

Test Report			
Test Item	AntigravityMN4006 KV380	Report NO.	MN.00034
Specifications			
Internal Resistance	194mΩ	Configuration	18N24P
Shaft Diameter	4mm	Motor Dimensions	Φ44.35×21mm
Stator Diameter	40mm	Stator Height	6mm
AWG	/	Cable Length	50mm
Weight Including Cables	68g	Weight Excluding Cables	66g
No.of Cells(Lipo)	4-6S	Idle Current@10v	0.3A
Max Continuous Power 180S	380W	Max Continuous Current 180S	16A

Figure 5.5: Motor Dimensions



	18	20	22	24	26	28	30
9		0.328	0.617	0.866	0.945	0.945	0.866
12		0.5	0.259		0.259	0.5	
15		0.866	0.711		0.389	0.199	
18		0.945	0.902	0.866	0.735	0.617	0.5
21		0.953	0.953		0.89	0.866	
24		0.966	0.958		0.958	0.966	
27	0.866	0.877	0.915	0.945	0.954	0.954	0.945

Figure 5.6: Calculation for no of poles and slots

5.4 Winding factor

The winding factor is method used for improving the RMS generated voltage in a three phase AC machine so that the torque and output voltage do not consist any harmonics that reduces the efficiency of the machine. It is assumed that the induced voltage is sinusoidal, if the flux density distribution is non sinusoidal, the induced voltage in winding factor will be non-sinusoidal.

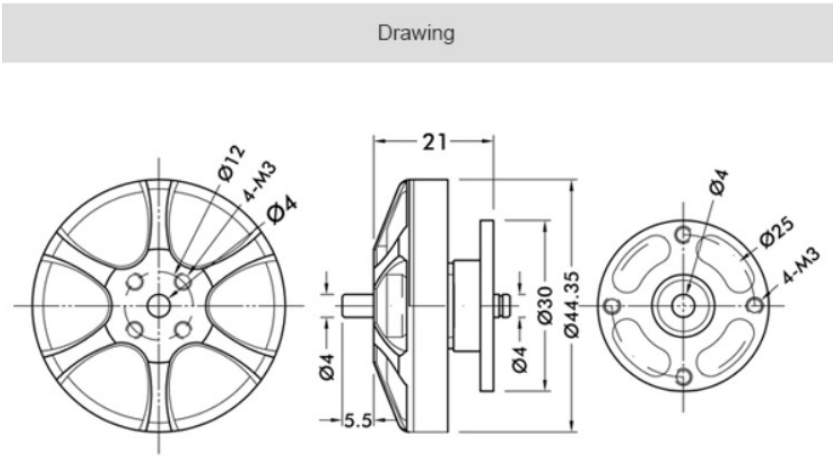


Figure 5.7: Motor Drawings with dimensions

Motor has ultra-thin design with single thick copper wire winding, which is done manually. Special emphasis has been given to thermodynamics; ventilation vents are incorporated in design that makes motor self-cooled by air propelled by air.

Ambient Temperature			/		Voltage			DC Power Supplier		
10	Voltage (V)	Prop	Throttle	Current (A)	Power (W)	Thrust (G)	RPM	Efficiency (G/W)	Torque (N*m)	Operating Temperature (℃)
Antigravity 4006 KV380	24	T-MOTOR 13*4.4CF	50%	2	48.00	544	3719	11.33	0.096	30
			55%	2.5	60.00	656	4528	10.93	0.108	
			60%	3.1	74.40	753	4840	10.12	0.123	
			65%	3.7	88.80	853	5155	9.61	0.139	
			75%	5.1	122.40	1062	5451	8.68	0.172	
			85%	6.8	163.20	1286	6327	7.88	0.208	
			100%	9.7	232.80	1633	6515	7.01	0.267	
		T-MOTOR 14*4.8CF	50%	2.4	57.60	675	3961	11.72	0.116	37
			55%	3.2	76.80	798	4329	10.39	0.139	
			60%	3.8	91.20	908	4619	9.96	0.159	
			65%	4.7	112.80	1033	4925	9.16	0.179	
			75%	6.5	156.00	1286	5485	8.24	0.222	
			85%	8.5	204.00	1576	6004	7.73	0.268	
			100%	12.2	292.80	1975	6731	6.75	0.338	
		T-MOTOR 15*5CF	50%	3.1	74.40	805	3746	10.82	0.152	46
			55%	4.1	98.40	959	4089	9.75	0.178	
			60%	4.8	115.20	1093	4358	9.49	0.203	
			65%	5.8	139.20	1236	4634	8.88	0.229	
			75%	8.3	199.20	1561	5215	7.84	0.285	
			85%	10.7	256.80	1823	5627	7.10	0.334	
			100%	15	360.00	2228	6177	6.19	0.404	

Figure 5.8: Motor specifications for various propeller dimensions

CHAPTER 6

MOTOR DESIGN

Motors used for propulsions system in drones are designed with special consideration to weight and space, as both are critical factors in design. Due to the limitation of low energy density of battery technology, the system total weight is the most critical aspect to minimize for a requisite power requirement. Thus, in order to enhance efficiency vis -a-vis endurance or flight time, the power density of the electric motors needs special consideration **?**.

The most vital step for designing the motor is benchmarking of standards for the motor which include torque delivered by motor at various throttle level. After benchmarking of standards, we opt for available magnet grade of magnet as design of motor depends upon available or selected magnet grade and shape. Different magnet grades or modes of magnetization leads to different variations of motors such as following

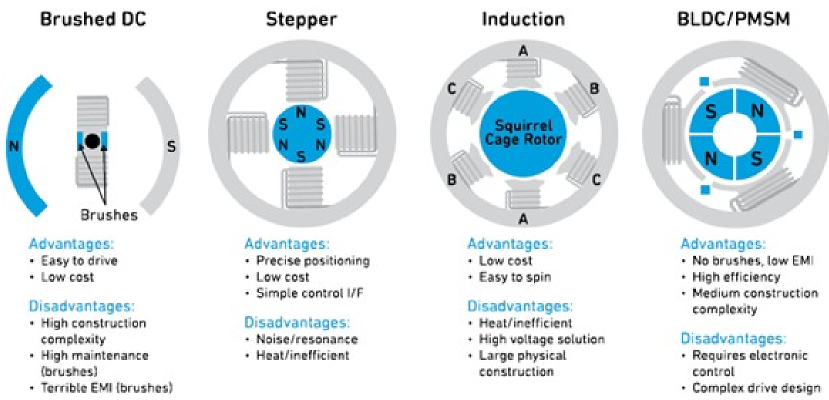


Figure 6.1: Different type of motors

6.1 Brushless Motors

The two most closely related brushless motor type are BLDC and permanent magnet synchronous motors (PMSM) Hendershot J.R. Jr. [2016]. Brushless motors are in demand as they eliminate the necessity of brushes, which causes excessive wear and tear of motor. There are several configurations of motors which use permanent magnet and stationary phase coils mot [*b*]. Brushless motors have following advantages over the brushed motors:

- Higher efficiency
- Reliability
- Lower acoustic noise
- Compact
- Greater dynamic response
- Better torque vs speed characteristics

There are several different configurations of brushless motors which use rotating permanent magnets and stationary phase coils. Different magnet grades Park *et al.* [2020] lead to different variations of motors which are used in various fields Hendershot [Nov 20, 2014]. Let's say if an application requires rapid acceleration and deacceleration of the load then the torque/inertia ratio should be as high possible. Interior rotor magnet is the best suitable model for high energy magnets. There are 2 major parts for a brushless motor called stator and a rotor mot [*a*]. A picture is shown below for reference.

The stator is the stationary part of the motor(windings) and the rotor is the rotatory part of the motor (bell with magnets). There are a several minor components of motor such as bearings, coil, magnets, shafts etc. Motor size and nomenclature

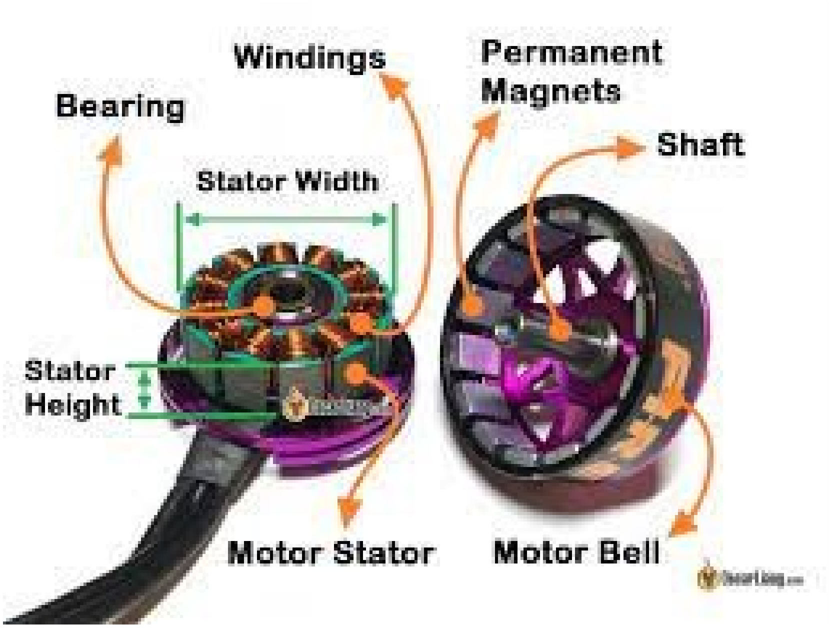


Figure 6.2: Different parts of BLDC motor

is based on the stator size (diameter and height). BLDC motors are typically categorized by a four-digit number – such as XXYY where the "XX" numbers are the stator width and "YY" the stator height. Essentially, the wider and taller the motor is or the larger the numbers are more torque motor can produce.

6.2 Magnet grade

Magnet grade is a quantification or measure of the strength of the magnet. A higher number or grade indicates a strong magnet. The number is derived from actual material property, the Maximum Energy Product of the magnet material, which is expressed in terms of MGO (Mega Gauss oersted). It represents the strongest point on magnets demagnetisation curve (BH Curve).
Pulling force of the magnet is defined by its grade or N number. Magnet with double the N number will have roughly double the pulling force. Magnet strength is defined by either pull force or strength of magnetic field. The magnetic field

strength is a measurement of the field strength and direction at a particular point near the magnet, expressed as Gauss or Tesla. Magnetic field strength depends upon magnitude and direction of current. The magnetic field strength is a measurement of magnetic field strength and direction at particular point near magnet. It is expressed in terms of Gauss or Tesla. It depends on the size, shape and grade of magnet. We can see Comparison of few magnet types in following table, where Neodymium is clearly the strongest magnet. Performance of a magnet material is

Table 6.1: Different Magnet type and respective MGO

S. No	Magnet type	Max Energy Product (MGO)
1.	Neodymium	35-52
2.	SmCo 26	26
3.	Alnico 5/8	5.4
4.	Ceramic	3.4
5.	Flexible	0.6 -1.2

defined by materials hysteresis curve or Demagnetization curve or BH curve. The Maximum Energy product is the point on this curve where the product of B and H is maximum. If we look at the point on the curve where B value (Kilo Gauss) multiplied by H (Kilo Oersted), in case of N42 grade magnet the Max Energy Product is 42 MGO. Magnets with bigger Maximum Energy Product have greater strength. If we look at following figure the shape of the BH curve decides strength and magnetic field of magnet. Availability of Permanent Magnets for design of motor is the restraining factor as the shape and strength of magnet decides the design of the motor.

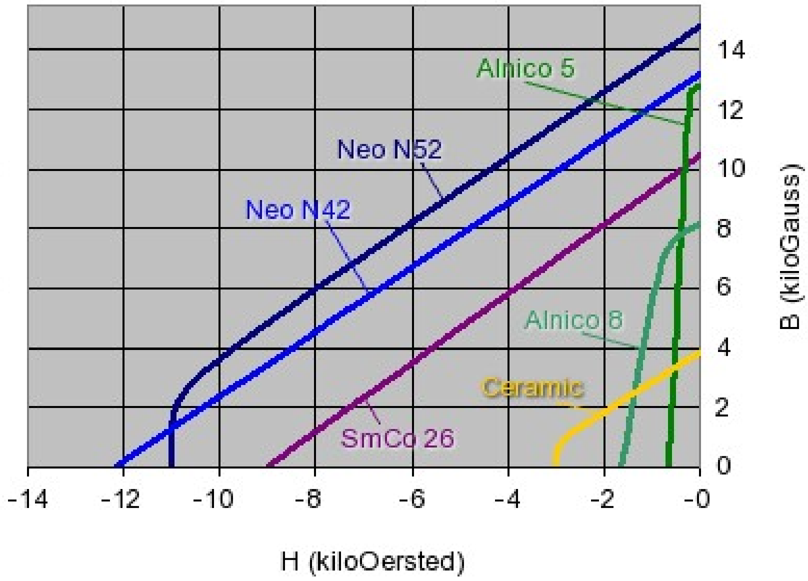


Figure 6.3: BH Curve of various grade magnets

6.3 Kilo Volt (KV)

KV is another essential parameter. It is the theoretical increase of motor rpm (rotation per minute) when the voltage goes up by 1 volt without load. For instance, while running a 2300KV motors with a 3S LiPo battery (12.6V), the motor would turn at around 28980 RPM. (2300 x 12.6V = 28980).

In any case, once you mounted a propeller on the motor, the rpm won't be that high because of the propellers resistance. Higher KV motors would turn the propeller quicker with less torque, and lower KV motors create higher torque with less rotation. Bigger props are matched with low KV motors, and smaller props with high KV motors.

By matching high KV motors with excessively large propellers, the motors will try to turn them quickly like it would do with smaller props, and this will draw a lot of current and produced an excessive amount of heat.

The kV of a motor sets the rpm which a certain voltage will produce but has no bearing on the power a motor produce. That is set by a whole series of design parameters that will determine the maximum current that the motor can handle.

6.4 Motor Design

It is essential to select one commercial motor and attain its promised technical specifications, dimensions and raw material used for its construction. Following modus operandi is opted for building a protype model.

- Selection of Commercial Drone motor
- Benchmarking of standards and specifications
- FEA analysis modelling
- Selection of permanent magnet for prototype motor
- Selection between surface PMSM (SPMSM) and interior PMSM (IPMSM)
- Electromagnetic designing of Motor
- Mechanical designing of Motor
- Thermodynamic design of Motor
- Simulation of design to obtain specifications
- Carryout few more design iterations
- Comparing designs with Original motor model design
- Selecting the design with best performance parameters
- Creating CAD Model of Motor in SolidWorks
- Estimation of Raw material for Motor construction

6.4.1 Selection of Commercial Drone motor for benchmarking:

MN 605S KV 320 is the shortlisted motor to be benchmarked for standard specifications and tear down analysis to be carried out to replicate the model. Following figure elaborates its specifications for 22inch propeller. The motor is already put in use in prototype Agricopter drone build by E-Plane company at NCCRD. Drawings with dimensions of commercial motor MN 605S, it's a compact motor typical BLDC with outer Rotor.

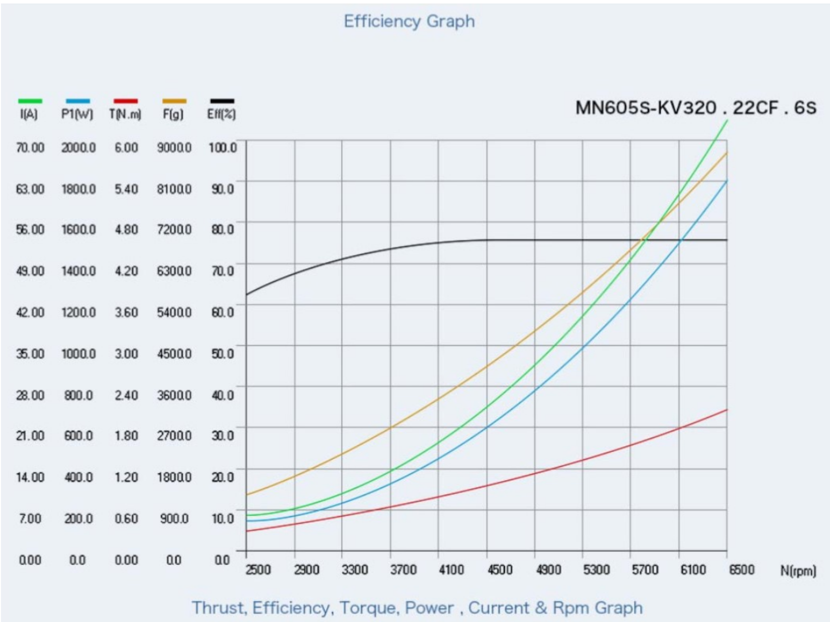


Figure 6.4: Efficiency graph of MN 605S

6.4.2 Benchmarking of standards and specifications

There are certain parameters of construction and verification of material used in motor, which are obtained by stripping down motor. It gives construction details for Electromagnetic and Mechanical aspects of design in MotorCAD.

MN 605S motor was stripped down to confirm the following parameters to

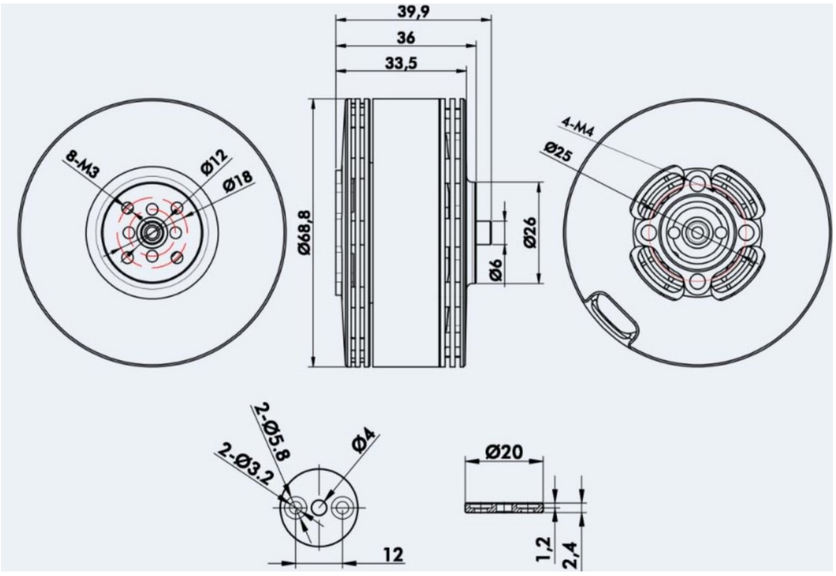


Figure 6.5: MN 605 S Drawing with Dimension

Motor Size	Φ68.8*39.9mm
Stator	Imported silicon steel sheet; Anti-rust treatment; 180℃high temperature-resisting coatings
Configuration	24N28P
Shaft Diameter	IN：6mm，OUT：6mm
Bearing	Imported 626ZZ
Magnet Level	150℃ high temperature resistance
Lead Cable	14AWG*150mm
Copper Wire	180℃ high temperature resistance: Level H
Coil Insulation Test	500V
Centrifugal Cooling Design	YES
Rotor Dynamic Balance Standard	≤5Mg
Motor Dynamic Balance Standard	≤10Mg
IP	IP45

Figure 6.6: MN 605 S Construction details

Figure 6.7: Stripping the motor

replicate the design in Motor CAD software.

- No of poles
- No of Slots
- Wire Type
- Winding pattern
- Magnet strength
- Bearing

MN 605S has silicon steel sheet stator with antirust coating, where shaft diameter in and out is 6mm. The grade of the cable is 14AWG, dynamic balancing has been carried out to eradicate any manufacturing error. Grade of the magnet haven't been defined but by measuring by Gaussmeter it was found it is Neudymium Magnet, ref figure

6.4.3 FEA analysis and modelling

The FEA model uses software computational tool to perform enigineering drawing analysis for a machine. It uses software programs based on finite element method algorithm to divide the design problem into small steps and overcoming by value

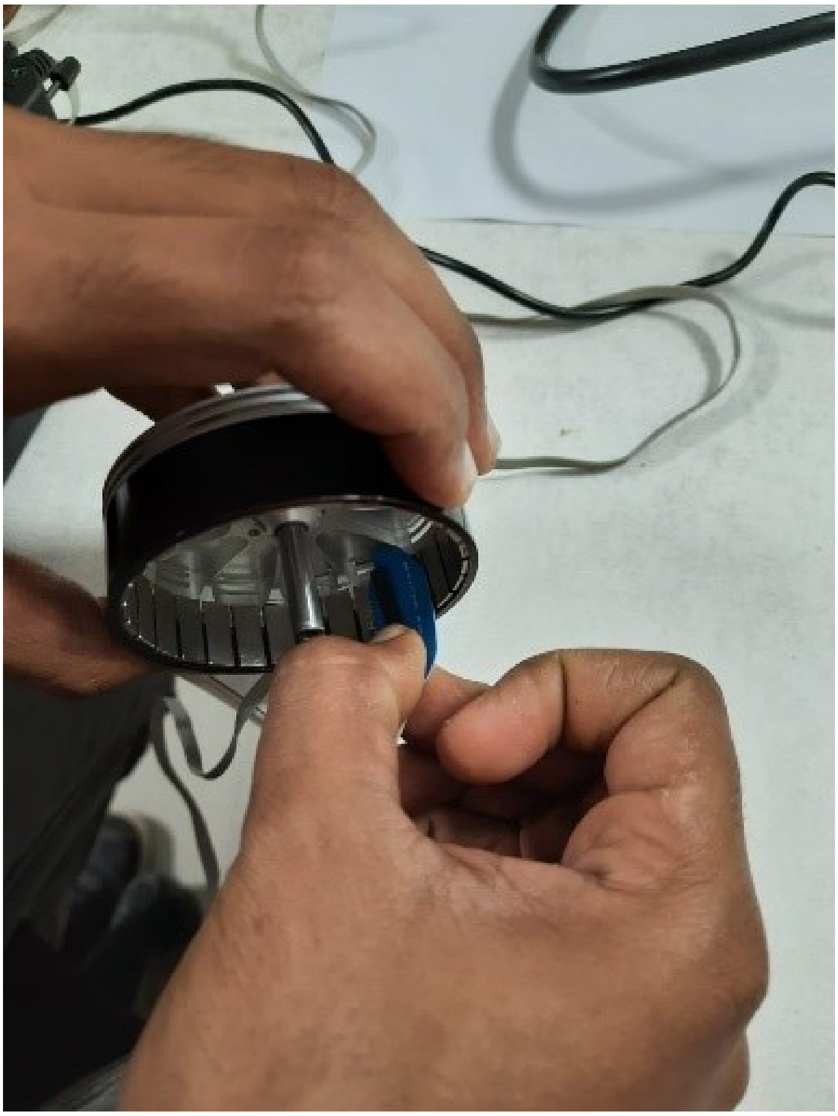


Figure 6.8: Measuring Strength

inputs.

The FEA method is a numerical technique used to find to evaluate solution to boundary value problems. This method connects many simple element equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain.

The finite element analysis (FEA) model function implements high-fidelity model simulation of an electric motor. The FEA model takes real motor characteristics into account and uses the FEA method to describe the motor behaviors The designed

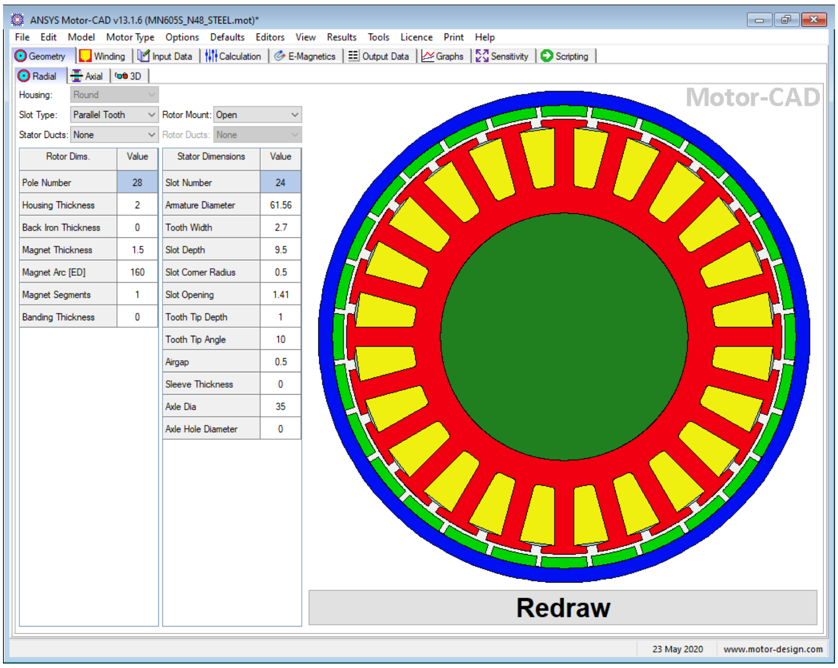


Figure 6.9: Design Replication of MN 605S

motor has 28 poles and 24 slot number with axle diameter of 35 mm. Output parameters closely match with the parameters of MN605S, it is delivering 79% efficiency and speed of 7000 RPM at 1.35 Nm torque.

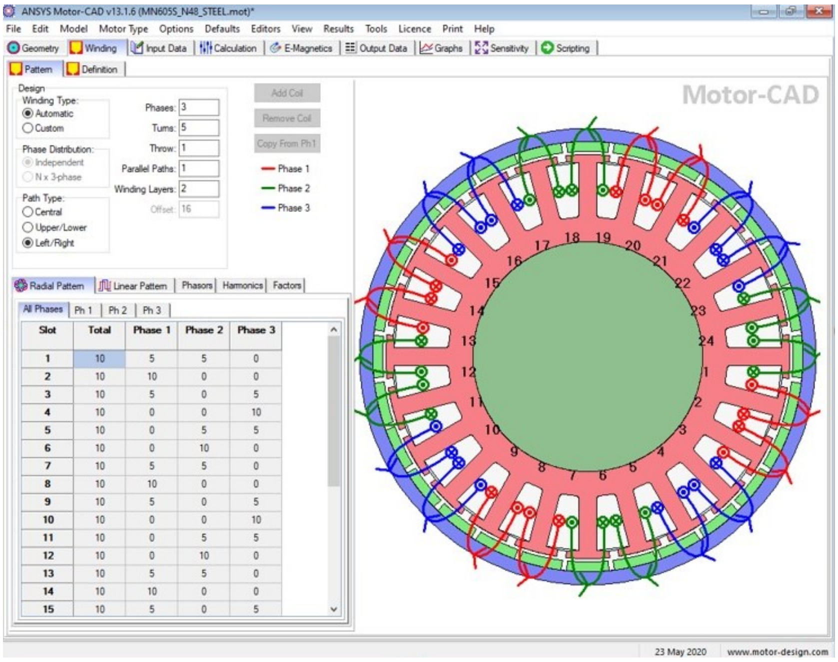


Figure 6.10: Winding Pattern

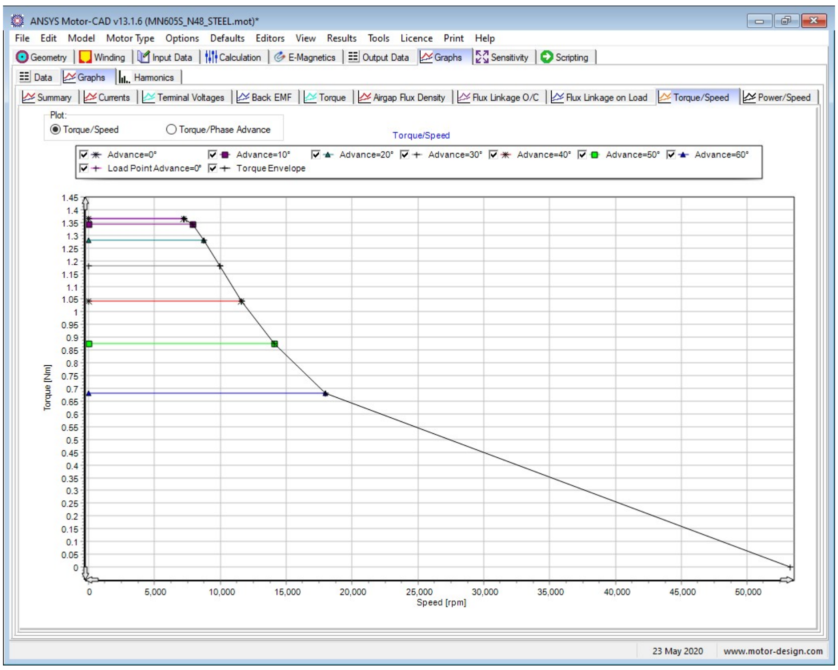


Figure 6.11: Torque vs Speed

6.4.4 Selection of permanent magnet for prototype motor

The selected magnet for prototype motor is N42UH, with flat rectangle shape. For outer rotor the magnet should be curved in shape. So, with magnet constraint we will be able to have PMSM Radial flux with IPM (Inner Rotor Motor) Miyamoto *et al.* [2015], magnet retention is good in case of IPM. It will generate sinusoidal back emf. The manufacturing of flat magnet is simple and magnet formation with Nickel copper coating makes it a sturdy magnet.

6.4.5 Selection between surface PMSM (SPMSM) and interior PMSM (IPMSM)

IPMSM's can be flux weakened using the direct axis channel of FOC, it is not impossible to do this with Surface Magnet machines, the PM's do not usually allow a path for the counter magnetic flux needed for flux weakening.
PM (Permanent Magnet) in interior permanent Magnet is flat surface magnet where in Surface mounted permanent its curved shape magnet.

6.4.6 Procedure for designing of Motor

Permanent Magnet Synchronous Motors (PMSM) are like Brushless DC motors (BLDC). PMSM are rotating electrical machines that have a wound stator and permanent magnet rotors that provide sinusoidal flux distribution in the air gap, making the BEMF inform a sinusoidal shape. The construction of the stator and rotor can provide lower rotor inertia and high-power efficiency and reduce the motor size.
Depending on how magnets are attached to the rotor, PMSM motors can be classi-

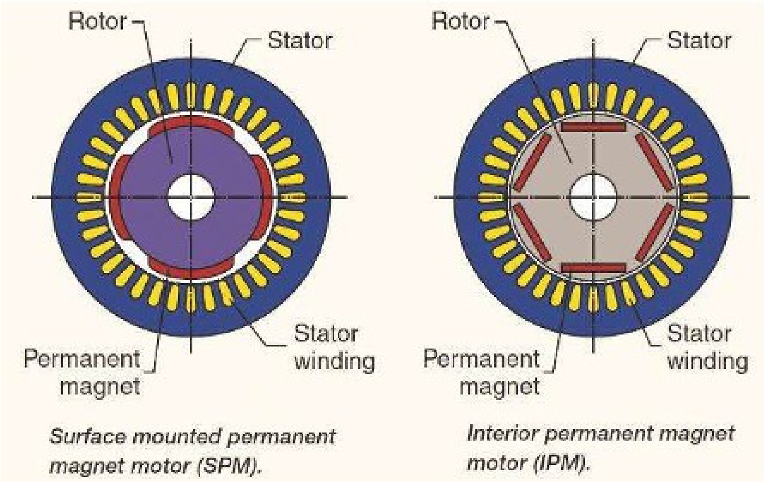


Figure 6.12: IPM SPM

fied into two types: surface PMSM (SPMSM) and interior PMSM (IPMSM). SPMSM mounts all magnet pieces on the surface, and IPMSM places magnets inside the rotor.

Calculation of Design of IPMSM is divided into two categories:

- Electromagnetic design
- Mechanical design

Electromagnetic design is performed to enhance the performance of the motor. Design calculations are further sub-divided into following stages:

- Slot pole combination
- Size of Rotor Stator
  - Air gap
  - Stack length
  - Magnet size grade
- Size of winding conductor and winding type

- Estimation of Emf induced

Mechanical design is mainly focused on the cooling of motor. Design calculations are based on the inputs from the Electromagnetic design as follows:

- Copper loss
- Steel loss
- Efficiency

Copper loss

Heat produced during current flowing through the conductors due to its resistance.This can be calculated by using Joules first law:

W=i2R, where W=power loss in watts

Core loss

Core loss is the loss that occurs in a magnetic core due to alternating magnetization, which is the sum of the hysteresis loss and the eddy current loss.

Efficiency Temperature raise of the motor depends on the efficiency of the motor at which it is running for the longer time. The total loss of the motor is generated as the heat and it should be evacuated through cooling system. Design consideration for evacuating the heat are as follows: Forced convection cooling:

- Through Ventilation
- Inlet mass flow rate
- Velocity of the inlet air
- Inlet air temperature

Through Ventilation: Due to the volume of the motor is exceedingly small but losses are significant, so it is necessary to design a motor with through ventilation.

Inlet mass flow rate: Mass flow rate of the air depends upon the Grill area on the inlet path (Drive End cover).

Velocity of the inlet air: Velocity of the air depends on the propeller which is connected to the shaft of the motor. This velocity varies with speed of the shaft.

Inlet Air temperature: Inlet temperature of the air depends upon the weather condition where the motor is going to perform. So, the design should be done with the extreme case.

Based on the above design considerations the heat from the stator can be easily evacuated. Thus, it will increase the Efficiency and pave the way for longer run.

6.4.7 Electromagnetic, Mechanical and Thermodynamic designing

The electromagnetic modelling of the design is done by giving inputs to software like Number of poles, Number of slots, Winding factor, Stator Diameter, Width and slot opening. After completion of required information, the electromagnetic model is simulated. For Mechanical design we need to specify type of winding, wire gauge, thickness of lamination, Stator width and stator diameter. After completion of information slots mechanical design is simulated. For thermodynamic design of motor, we need to define whether motor is self-convection or forced-convection and we are required to provide following inputs

- Through Ventilation
- Inlet mass flow rate
- Velocity of the inlet air
- Inlet air temperature

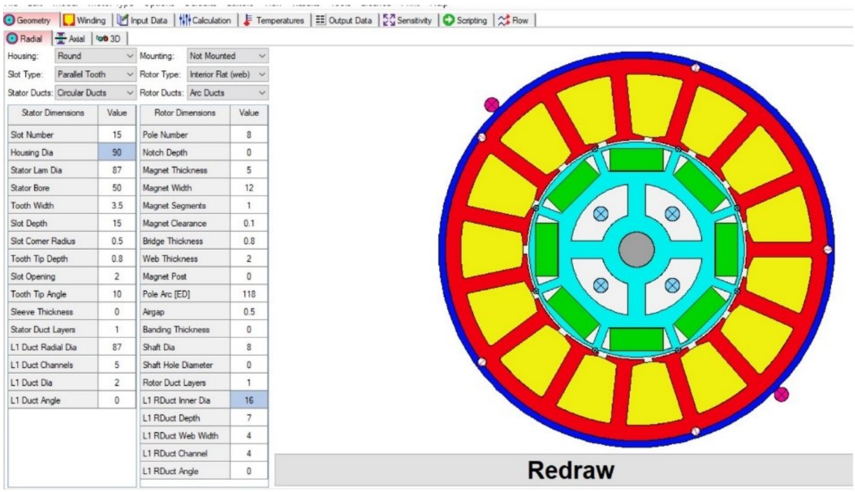


Figure 6.13: Construction Layout

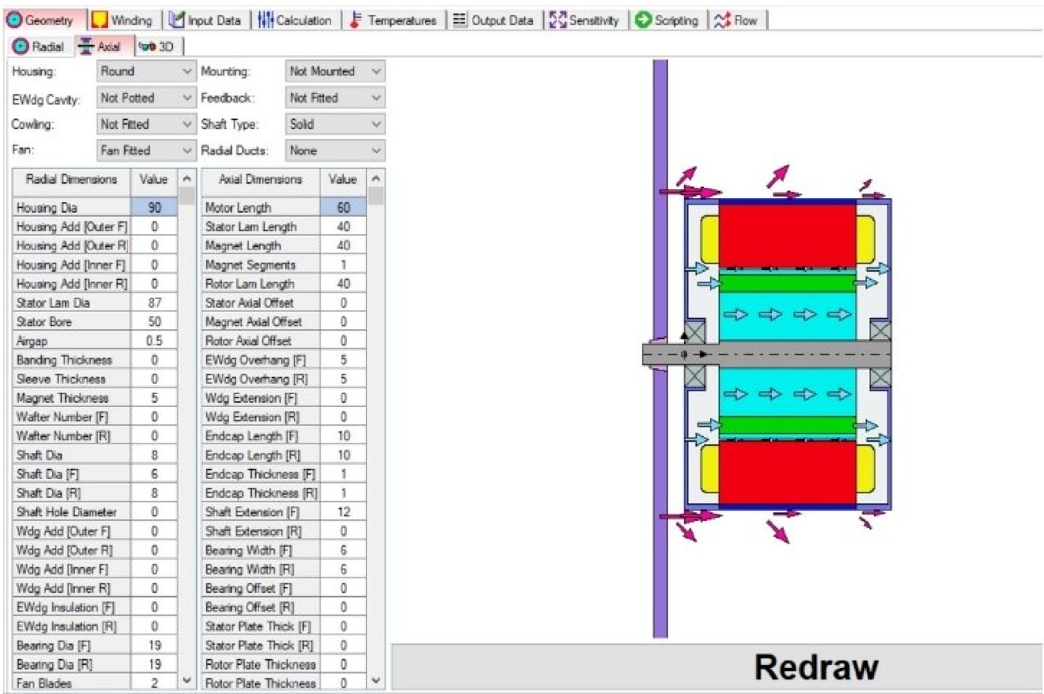


Figure 6.14: Thermodynamic design

6.4.8 Simulation of design to obtain specifications

After simulation of design following specs were achieved for the motor

	RPM	g	W	g/W	Actual Torque Nm	Column
40%	2832	1502	148.27	10.13	0.50	
42%	2988	1696	171.66	9.88	0.55	
44%	3084	1772	183.25	9.67	0.57	
46%	3197	1913	203.29	9.41	0.61	
48%	3311	2092	228.11	9.17	0.66	
50%	3462	2294	256.02	8.96	0.71	
52%	3586	2483	287.05	8.65	0.76	
54%	3704	2658	315.30	8.43	0.81	
56%	3801	2797	339.03	8.25	0.85	
58%	3926	2989	375.50	7.96	0.91	
60%	4031	3140	407.79	7.70	0.97	
62%	4137	3277	428.93	7.64	0.99	
64%	4265	3509	476.77	7.36	1.07	
66%	4346	3620	499.31	7.25	1.10	
68%	4465	3875	540.45	7.17	1.16	
70%	4584	4054	579.14	7.00	1.21	
75%	4859	4584	685.20	6.69	1.35	
80%	5105	5038	789.65	6.38	1.48	
90%	5591	6108	1035.13	5.90	1.77	
100%	6008	7178	1300.36	5.52	2.07	

Figure 6.15: Performance of Motor

6.4.9 Carryout few more design iterations and Comparison with Original motor model design

Few more iteration with varied electromagnetic, mechanical and Thermodynamic design were carried out, the comparison of all three iterations with MN605S can be seen in the following figure

	Paramters	T-Motor (MN605 320KV)	ver-01-15S8P	ver-02-thin	ver-03-15S8P-87OD
Throttle Level	B.emf (V/krpm)	2.35	1.96	2.03	2.33
100% @58.6Arms	RPM	6008	6008	6008	6008
	Act. torque (Nm)	2.07	1.95	1.95	2.39
	Tot. torque (Nm) with Impeller	1.75	1.63	1.63	2.1
	Net torque (Nm) with Mass	#REF!	#REF!	#REF!	#REF!
	Net Thrust (g)	**#REF!**	**#REF!**	**#REF!**	**#REF!**
	Act. output power at shaft (W)	1308	1500	1450	1504
	Eff (g/W) (Thrust/ Shaft Power)	***#REF!***	***#REF!***	***#REF!***	***#REF!***
	Eff (g/W) (Thrust/Input Power)	***#REF!***	***#REF!***		***#REF!***
	Eff	78%	81.50%		90.00%
60% @17.40Arms	RPM	4031	4031	4031	4031
	Act. torque (Nm)	0.97	0.57	1	1.26
	Tot. torque (Nm) with Impeller	0.80	0.4	0.83	1.09
	Net torque (Nm) with Mass	#REF!	#REF!	#REF!	#REF!
	Net Thrust (g)	**#REF!**	**#REF!**	**#REF!**	**#REF!**
	Act. output power at shaft (W)	407	247	495	515
	Eff (g/W) (Thrust/Shaft Power)	***#REF!***	***#REF!***	***#REF!***	***#REF!***
	Eff (g/W) (Thrust/Input Power)	***#REF!***	***#REF!***		***#REF!***
	Eff	77%	88%		90%

Figure 6.16: Performance comparison of Motors

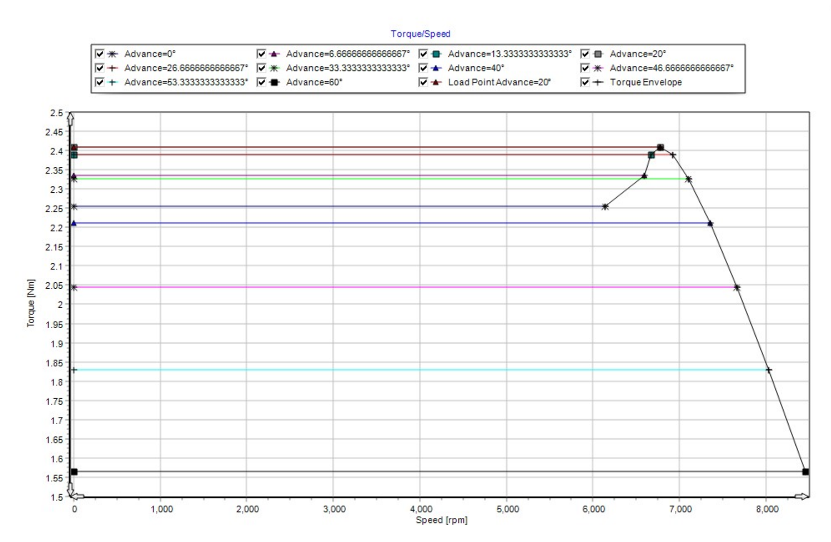


Figure 6.17: Torque speed curve for designed motor

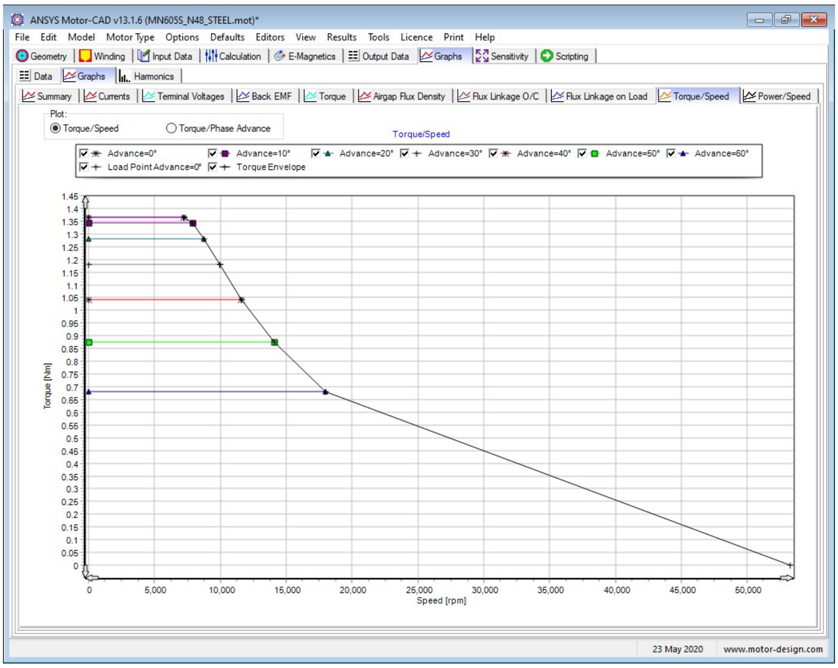


Figure 6.18: Torque speed Curve MN 605S

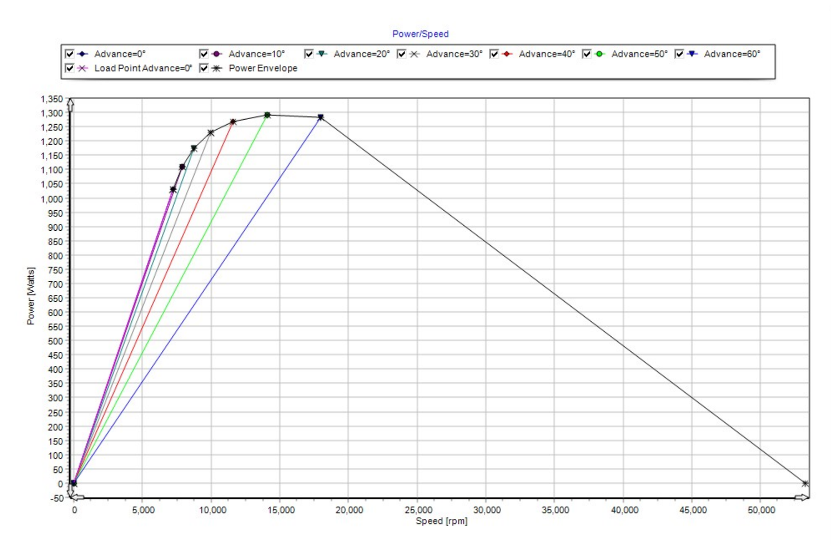


Figure 6.19: Power speed curve for MN 605S

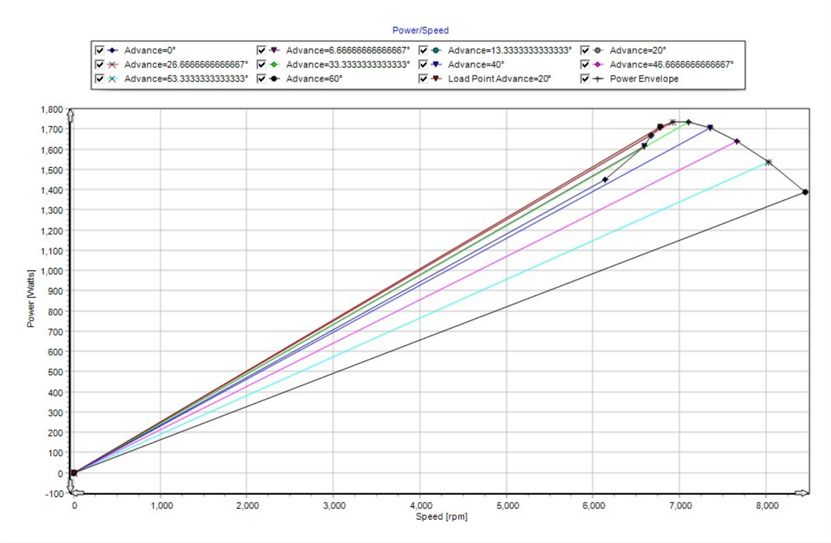


Figure 6.20: Power speed curve for Designed motor

6.4.10 Selecting the design with best performance parameters

Version 3 of Motor design with 15 stator count and 8 pole count delivers efficiency of 90% at both 100% and 60% throttle. It delivers net thrust of 7452 g at 100% throttle and 3213g at 60%. Although the weight of motor is high considered to MN605S but net torque is higher than MN605S. Where,

Net Torque = (Total Torque – Motor Mass)/Thrust

Net Torque x Thrust = Net Thrust

Efficiency = g/w

g = Net thrust

w= Output of Motor

6.4.11 Creating CAD Model of Motor in SolidWorks

Solidworks is a solid modelling CAD (computer aided design) and CAE (computer aided engineering) software program published by Dassault systems that runs on latest versions of Microsoft windows. Following are the outer physical design images of motor in different views.

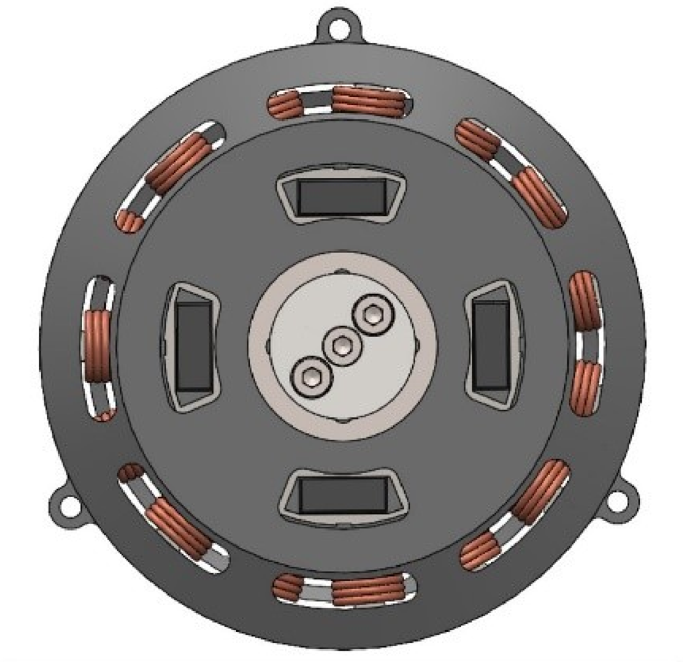


Figure 6.21: Top View of Motor

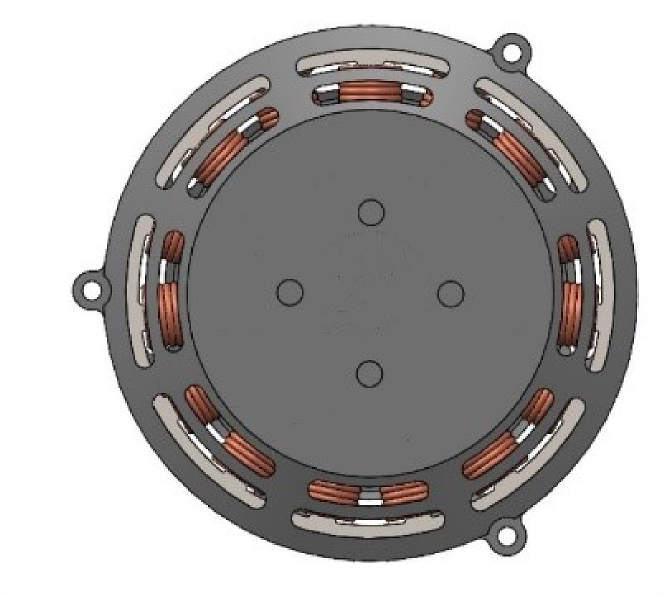


Figure 6.22: Bottom View of Motor

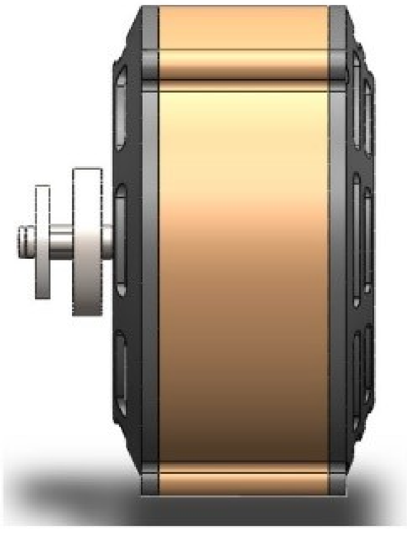


Figure 6.23: Side View of Motor

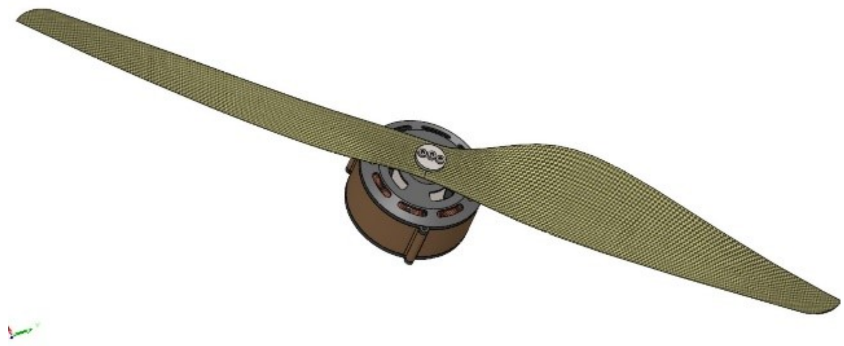


Figure 6.24: Full Configuration Motor

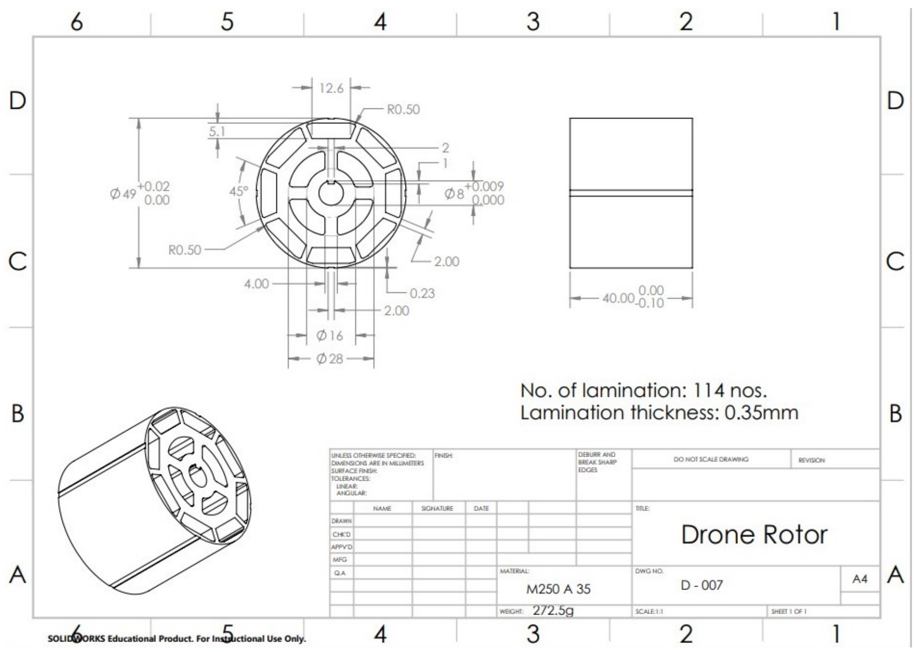


Figure 6.25: Drone Rotor (Top, Side and Isotropic view)

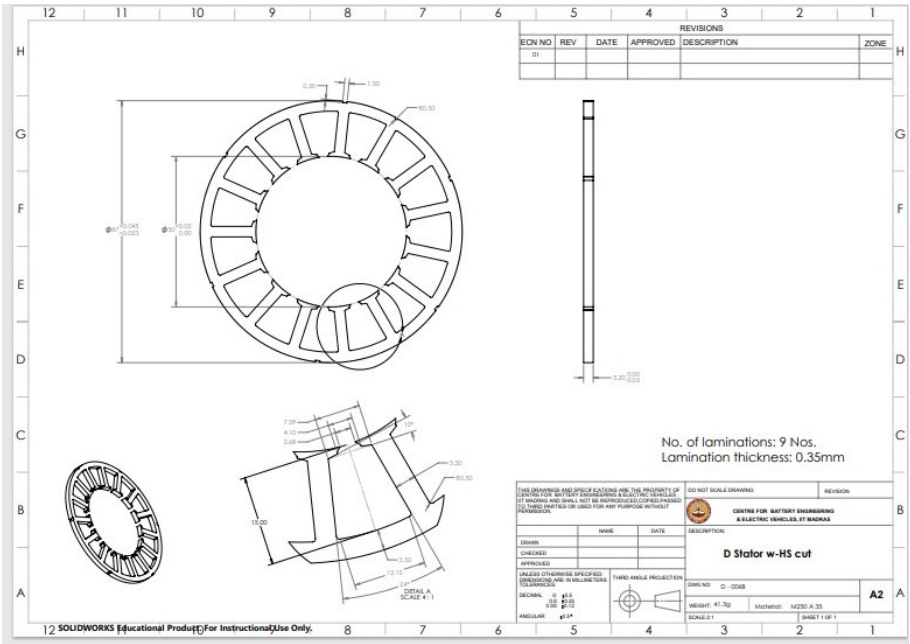


Figure 6.26: Drone Stator (Top, Side and Isotropic view)

CHAPTER 7

DRONE ASSEMBLY – HEXACOPTER CONFIGURATION

Introduction Hardware integration of Hexacopter drone involves following steps.

- Frame Assembly and testing
- Mounting battery on frame
- Wiring and Power supply Connections
- Mounting BLDC motors on arms of drone
- Connecting ESC with Motors
- Assembly of Flight controller and companion computer
- Integration of Sensors
- Synchronization of Transmitter and Receiver
- Configuring drone with Ardupilot
- Test Flight

7.1 Frame assembly

Carbon fiber is the preferred material for the frame assembly Based on FEA analysis results. Carbon fiber as construction material is resilient and light weight, frame weight can further be reduced by making holes in the frame. Frame assembly was carried out using prefabricated hollow cylindrical carbon fibers pipes of 20mm diameter for drone arms whereas 1 mm thickness plates were used for motor plates and center plate. Post assembly the weight of the carbon fibre frame is approx 1.49 kg.

Figure 7.1: Frame protype Assembly

7.2 Mounting battery on frame

A six cells LiPo battery is selected for this project to meet the power requirements of the hexacopter. Battery provides (6 x 4.2 V)25.2 V with a continuous discharge rate of 16 amps which can provide a subsequent amount of power to the hexacopter for various maneouvres. Different step-down converters are used to provide power to different components.

7.3 Motor Mounting and Assembly

We have opted for hexacopter configuration with H frame design of drone with carbon fibre hollow cylindrical pipes. The dimensions of the frame allow us to opt for propeller size of 15 inches considering the weight of the drone. The propeller size is apt for the drone configuration as they don't cause any interference to each other. After selection of propeller, we have opted for T-motor Antigravity MN4006 380KV motors with 15x5.5 propellers to obtain the desired thrust and table show the motors specifications.

Test Report			
Test Item	AntigravityMN4006 KV380	Report NO.	MN.00034
Specifications			
Internal Resistance	194mΩ	Configuration	18N24P
Shaft Diameter	4mm	Motor Dimensions	Φ44.35×21mm
Stator Diameter	40mm	Stator Height	6mm
AWG	/	Cable Length	50mm
Weight Including Cables	68g	Weight Excluding Cables	66g
No.of Cells(Lipo)	4-6S	Idle Current@10v	0.3A
Max Continuous Power 180S	380W	Max Continuous Current 180S	16A

Figure 7.2: Motor specifications

7.4 Electronic Speed Controllers (ESCs)

ESCs control the speed of BLDC motors according to the signals from the controller for maneuvering and hovering. As they are selected based on the maximum current drawn by the motors, each motor draws a maximum of 16 amperes of current while producing maximum thrust of 2.2kg. We need the maximum thrust resulting motors to draw 30 amps, considering these factors 30A ESCs (Figure 49) are selected to control the motors.

Figure 7.3: ESC with 30A rating

7.5 Propellers/Rotors

Considering the designed frame dimensions if we consider the closest adjacent blades, the distance is 380 mm. As we desire more stability and payload capacity from our drone, we opt for maximum length of propeller which turns out to be 15 inches(380mm). For selection of the pitch we need to compare the performance of propeller with 15 inch diameter with motor.

Propeller Pitch : The quadcopter propeller pitch is a measurement of how far that a propeller will move through the air for every single rotation of the motor/propeller. The higher the pitch value, the faster the drone goes.

Six 1555 Tarot folding propellers (CW/CCW) TL100D04 (Figure 7) were utilized for this project as they can provide the required thrust to perform hovering and other maneuvers easily.

Figure 7.4: Foldable 1555 propeller pair

7.6 Flight Controller

The flight controller is the core of the navigation and flight management system, it manages the flight planning and can verify the designated and actual trajectory taken by drone in real time. Several sensors can be hooked to the flight controller managing power requirement and port linearity. Data of sensors can be acquired and utilized by flight controller for keeping drone on designated trajectory Romano *et al.* [2019]. Flight controller also acquires data and telemetry logs for flight undertaken by drone, these logs can be utilized for monitoring drone performance, battery health and any critical failure encountered during flight.

We are developing the flight controller on Texas Instruments robotics development board Beagle Bone Blue. TI is a US based company. The Beagle Bone Blue uses Linux Operating system with Ardu Pilot auto pilot stack running on it and can perform limited functionality of onboard computer too.

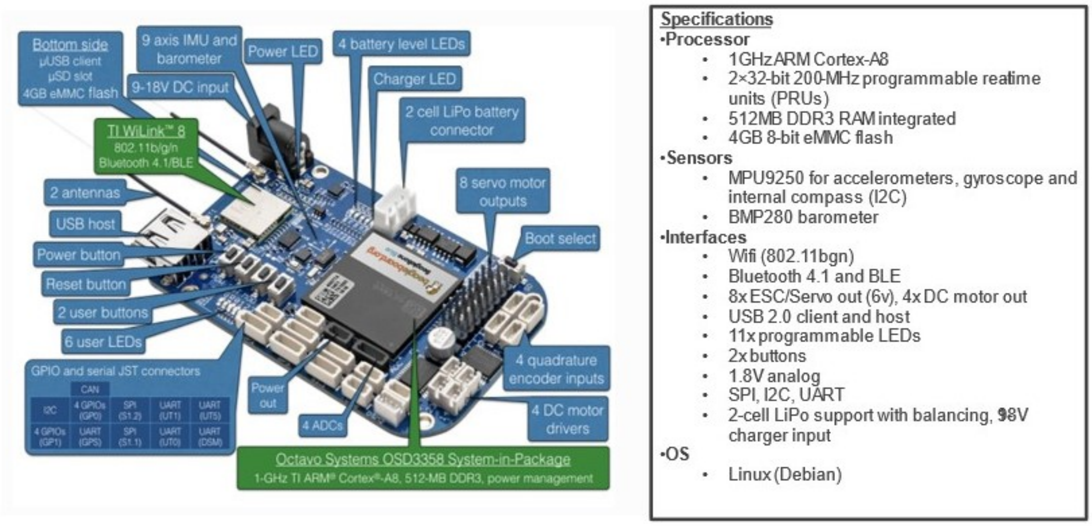


Figure 7.5: Flight Controller

7.7 Companion computer

The FC is responsible purely for a flight control, and should not be burdened perform complicated computations which may then lead to catastrophic failure. For this reason, this project configuration enables to use a companion computer, in order to perform complicated calculation and pass only a navigation decision to FC. The companion computer installed on the vehicle communicates with (and control) the flight controller, gets all the MAVLink data produced by the autopilot (including GPS data) and use it to make decisions during flight. This functionally enables to process live vision feed from onboard camera or other onboard data source (radar, lidar) and process it to the specific navigation decision. Navigation decision is sent to execution to the FC. That hardware configuration enables to perform and test the different modern methods i.e. obstacle avoidance, visual navigation. The drone has a Jetson Nano working as companion computer, integrated with the FC. It is a small, powerful computer designed to support multiple applications in parallel.

7.8 GPS Module

Drones typically orient themselves using GPS, which helps keep them stable while in flight. Drones are able to carry out waypoint navigation, position-hold and incase of failure- able to return to base because of GPS guidance. We have used GPS Module Ublox NEO-7M in our system.

Figure 7.6: Companion Computer

Figure 7.7: GPS Module Ublox

7.9 Collision Avoidance system

As the name suggests, collision avoidance system is a system designed to reduce or prevent collision accidents. Also known as collision warning system, collision mitigation system or pre-crash system, the system uses sensors or radars to detect any potential obstacle and send warnings to the pilot of a likely collision. Pilots can choose to ignore or take action. However, some drones have been designed to detect and avoid obstacles by themselves without pilot's decision. Two different collision avoidance sensors have been integrated on the hexacopter.

7.10 Lidar

Lidar employ the use of laser beams to calculate distance of objects around and also create clear images of nearby features. The use of laser beams in Lidar sensors gives it an upper notch over its partners who use radio waves. Laser beams are less interfered as compared to radio waves. Its operation is similar to the IR sensor. A beam is sent out by an emitter which will travel through the air and in case of an obstacle, it is reflected and measured by a receiver. This information can be used to calculate distance and even give exact position and altitude of the obstacle in reference to drone's position. The hexacopter is running with RP A2 360 Lidar. It is a 360-degree 2D laser scanner (LIDAR) which can take up to 4000 samples of laser ranging per second with high rotation speed.

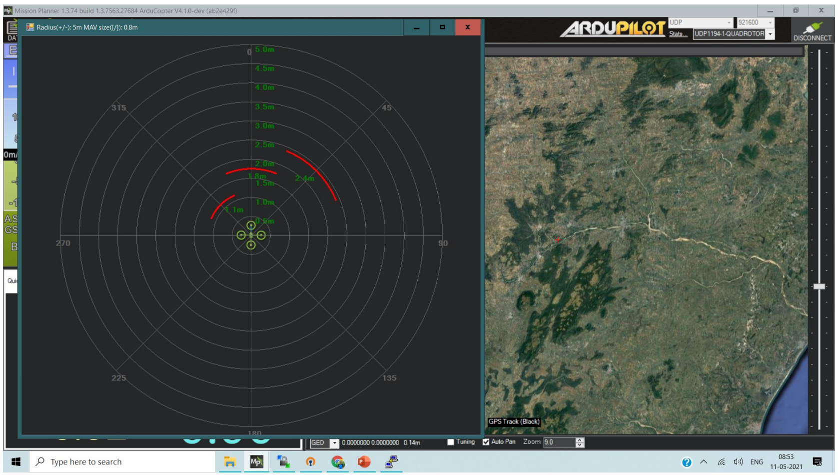


Figure 7.8: a) RP A2 360 Lidar b) Lidar Output

7.11 Millimeter wave Radar

Radar systems transmit electromagnetic wave signals that object in their path then reflect. By capturing the reflected signal, a radar system can determine the range, velocity and angle of the objects. We have integrated mm wave radar from Texas Instruments (TI) IWR6843 Antenna on Package (AoP) as proximity sensor for obstacle detection and collision avoidance. is an integrated single chip mmWave sensor based on FMCW radar technology capable of operation in the 60-GHz to 64-GHz band.

7.12 Camera with gimbal

Drone gimbals keep a camera in the same position regardless of the motion of the drone. A gimbal is designed to keep the camera at the same angle regardless of the movement of the drone by automatically compensating using calibrated and often remotely controlled electric motors. A camera has been mounted for surveillance capability and further object identification is being done at ground station terminal using AI enabled software. We have mounted Amigo HD camera on a Tarot make gimbal on the hexacopter.

7.13 Radio transmitter and receiver

The radio receiver is connected to the flight controller board of the Hexacopter. This receiver consists of six channel receiver pins and a 5V pin for switching on. The four channel (CH1, CH2, CH3, CH4) pins of receiver are connected to the controller (1, 2, 3, 4) input pins by jumper wires. The function of the receiver is to send the signal to the controller according to the stick movements of radio control transmitter by which the motion of the Hexacopter can be controlled according to the requirement. FrSky Taranis Q X7 Access Transmitter which supports upto 16-channels at 2.4 GHz frequency is paired with the onboard receiver FLY SKY FS IA6B RF 2.4GHz 6CH.

7.14 Final Prototype

The final assembly involved detailed process of planning the power distribution and space management for mounting the flight controller and Companion computer and positioning of various sensors to avoid interference.

7.14.1 Layout

A 3-tier arrangement has been done at the centre of the hexacopter for ease of access for repairs and to maintain Centre of gravity. The 24V battery pack has been mounted on the Battery support plate underneath the central carbon fibre plate.

Figure 7.9: a) HD camera b) Gimbal

Figure 7.10: a) RC Transmitter

The power components i.e all the power distribution boards, DC-DC converters have been assembled on the central carbon fibre support plate. On top of this plate, an acrylic board has been mounted which houses the flight controller and the companion computer.

7.14.2 Power supply Arrangement

The 24 V power supply is fed directly to the six BLDC motors and is also stepped down to 12 V to be fed to the Beagle bone Blue controller. The 12 V is further stepped down to 5V using DC-DC converters to power various sensors ie GPS, Lidar, Camera, radio. Though the flight controller is capable of powering the sensors but to avoid any damage, power distribution to all the sensors have been separated from the Flight controller and have been given separately from 5V DC supply.

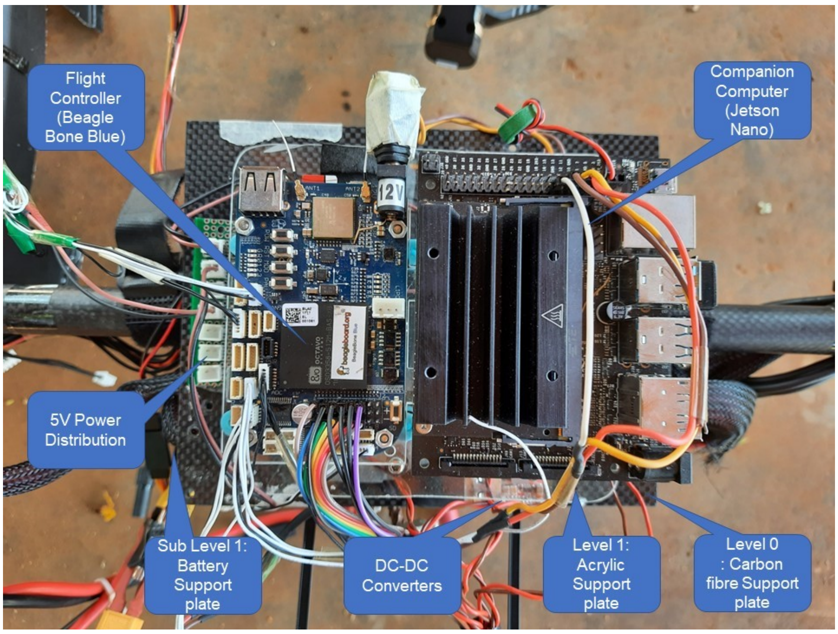


Figure 7.11: Assembly of Flight controller System

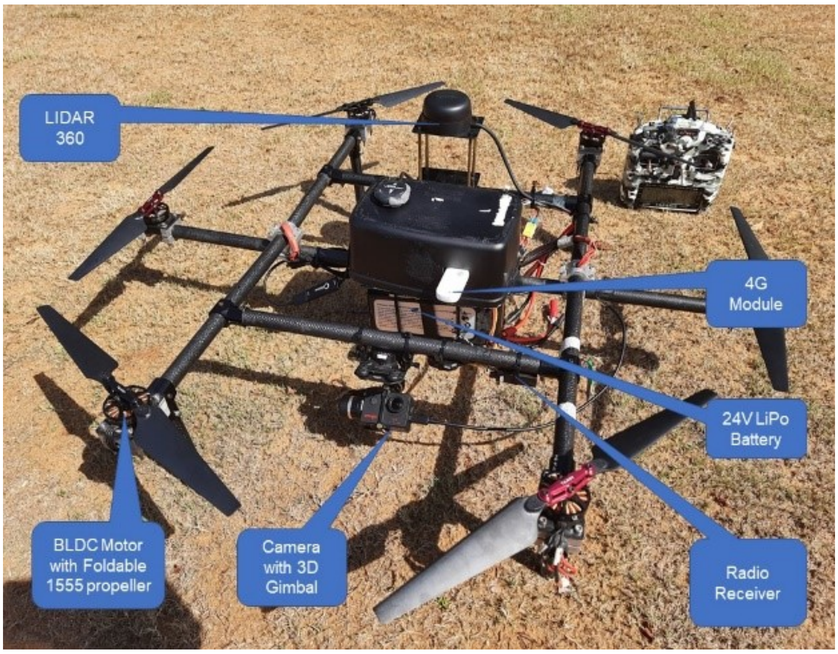


Figure 7.12: a) Top View of Hexacopter b) Front view of hexacopter

7.14.3 Weight Calculation

The total weight of the hexacopter is 5,492 grams. Now taking Thrust to Weight Ratio (TWR) as 2, the required thrust from each motor is determined as follows:

Thrust = Total weight x TWR

Thrust =5492 x 2 = 10984 grams

number of motors = 6

Required Thrust per motor = 1831 grams = 18 N

Thus, for the ability to fly and hover, the heavy-lift hexacopter must overcome the gravity force. Based on the above calculation, each motor must produce a thrust of 18N with the assumption that all motors have equal thrust. To ensure the thrust of the rotor that is used is capable of lifting and moving the hexacopter, it is necessary to measure the thrust of the rotor.

Table 7.1: Hexacopter Weight Calculations

S.No	Components	Weight(gm)
1.	Carbon fibre Frame	1490
2.	Flight Controller	36
3.	Companion computer	249
4.	BLDC motors (6 nos)	408
5.	Electronic speed Controller (ESC) (6 Nos)	327
6.	Propeller (1555)	396
7.	Li-Po battery 16000mAh	1900
8.	GPS module	26
9.	RPLidar A2 360 degree	190
10.	mmWave Radar	20
11.	Camera	110
12.	3D Gimbal	160
13.	Miscellaneous	180
	Total Weight	5492

7.15 Flight Testing

Figure 7.13: Test flight in progress

Table 7.2: Test Flight Results of Hexacopter

S. No	Design Criterion	Design Parameter	Test Flight Results
1.	Payload capacity	Up to 1 kg	A maximum of 0.8 kgs was tested
2.	Flight endurance	Up to 15 mins	15 mins for 0.8 kgs payload
3.	Fly options	Manual, GPS aided, Autonomous	All tested successfully
4.	Fly height	Up to 500 ms	Tested up to 50 m due to Flight Zone restrictions
5.	Fly range	Up to 2 Kms	Tested up to 1.8 kms with clear line of sight

7.16 Challenges faced and addressed during trials of hexacopter:

- Lidar Vibrations.
- Centre of Gravity
- Heating issues
- Power supply components and sensors segregation
- Port Linearity
- Wire color coding

CHAPTER 8

FLIGHT DATA ANALYSIS

Introduction

Mission Planner is a ground controller station (GCS) software application which communicates with the open-source autopilot firmware ie ArduPilot residing on the flight controller using Micro Air Vehicle Link (MAVlink) protocol. The aim of Mission Planner is to connect to the autopilot in order to receive telemetry data and control the vehicle. The basic GCS configuration consist of a Windows PC with installed Mission Planner Software or an Android phone running the same. Linux users are provided with APM Planner 2 software. The GCS communication channels can be established via Internet/radio/ WiFi/ Bluetooth, all using MAVLink protocol.

Features:

Mission Planner supports:

- updating the automatic pilot firmware (Figure 10a);
- live reading of telemetry data and reading offline sensor data (Figure 10b); setting up and adjusting the autopilot system and planning a flight mission;
- connecting with a flight simulator;
- downloading log files and analyzing them

Mission Planner Setup:

Initial Setup section is for initial set up and configuration of FC to prepare it for particular vehicle. Configuration Tuning part is to configure the parameters how FC is control particular UAV and how pilot is control UAV, tuning and adjusting

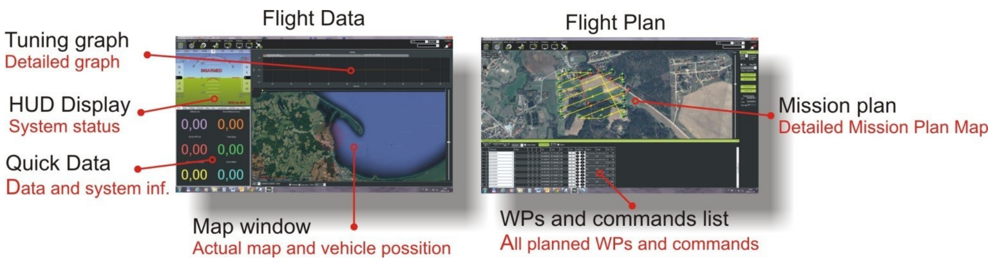


Figure 8.1: Basic Mission Planner Window

PID loops. The simulation tool is designed to perform Software In The Loop (SITL) simulation.

Figure 8.2: Mission Planner GUI, a. Firmware choice, b. Live telemetry data read

Flight Log Data : Flight log data provides information about various operating parameters such as: UAV (pitch, yaw, roll) and velocity data on the three axes; data about GPS parameters (position, speed, altitude, compass head), mission type data; data on navigation and servo output signals; data about radio signals.
Flight data logs can be used to analyse and diagnose mechanical defects, vibrations, magnetic interference, or engine operation, these flaws occurring in the form of pitch, roll, or girth leaps. Vibrations with significant values can be read by displaying data provided by accelerometers (AccX, AccY, AccZ values) of IMU messages

for horizontal position control. Magnetic interferences that may be generated by the power distribution board, motors, accumulators, ESCs can cause malfunction of the compass that causes unwanted UAVs, these interferences can be viewed at CUSTOM / VFRHUD.

The Flight Data View interface also allows data export in *.txt, *.csv, and Matlab files for post- processing and numerical analysis. There are two types of flight log data recorded about the flight data which can be analyzed:

Table 8.1: Comparison of Log files on Mission Planner

Feature	Data Flash Logs	T Logs
Tasks	Recorded on Drone Autopilot	Recorded by Ground station
Storage location	SD card	On GCS PC via telemetry link
File Format	.bin	.tlog

8.1 Analysis of Flight Data

All the data collected after around 15 experimental flights of implemented UAV. Figure below indicates the altitude hold performance. This is one of the important curves which indicate the stability and behavior of our drone. Here Holt for desire altitude and Alt for altitude at which drone travels. This carve contains several mode of operations characteristics. When we shift from stabilize (manual) mode to hover mode or GPS lock mode then DAlt curve generate and then altitude calculated from IMU unit and also generate the barometer altitude curve shown in the Figure, as blue line. Alt and DAlt line lies close together that means altitude hold performance is good in different modes.

Figure 8.3: Position Hold

8.1.1 GPS Fix Accuracy

Location: IITM RP.

Flight Duration: 12 Minutes

Observation: Satellite Visibility - Ranged between 11-13 (value ¿11 is required) with mean of 11.85.Satisfactory GPS Fix: The GPS fix accuracy varied between 3.5 m to 8 m.

Analysis: Sufficient GPS signal coverage received despite flying at low altitude closed environment (surrounded by buildings).

8.1.2 Altitude

Altitude Gain: Max 10.26m, Mean 6.82m

Rate of Climb: 0.79m/sec (Max)

Observation: Phase wise alt gain 0m to 6m, 6m to 10m. Hexacopter was stable during both the climbs.

Analysis: To check stability of Hexacopter phase wise alt was increased @constant climb rate. Initial alt hold for duration of 10 minutes, then elevated to alt of 10 m

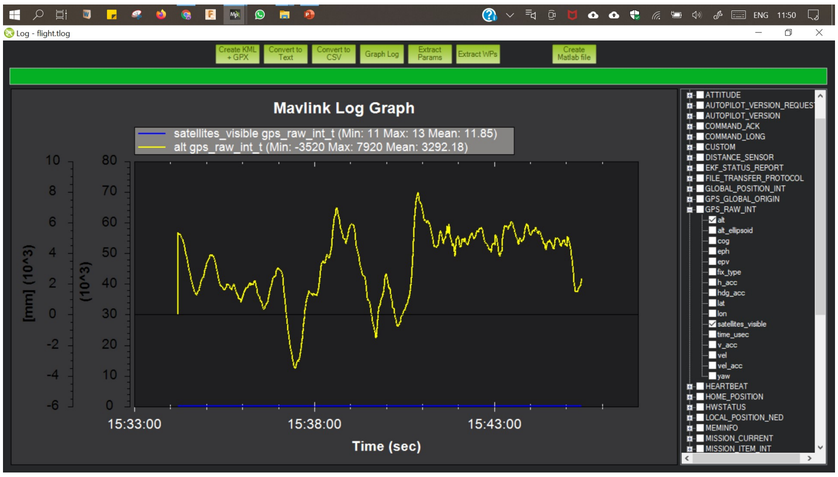


Figure 8.4: GPS signal

(appx) for 5 minutes. Stable Flight

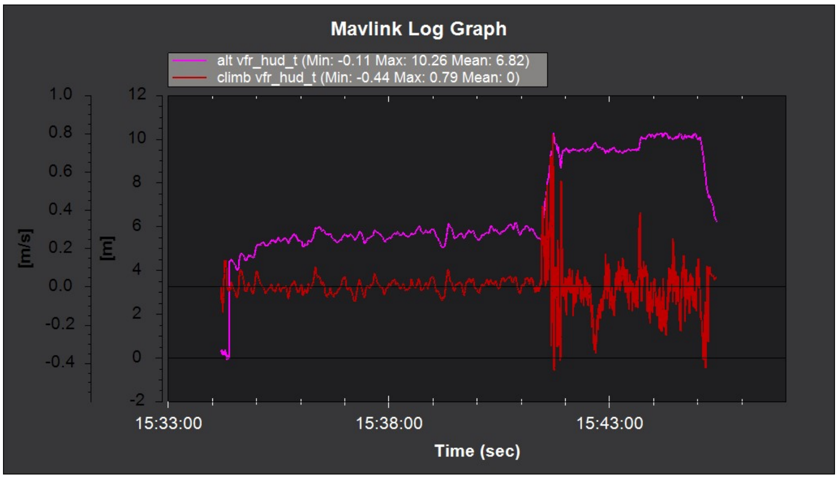


Figure 8.5: Altitude

8.1.3 Vibration Analysis

Observation: At an alt of 6m, vibrations observed were negligible. Spike in vibration with an alt gain, but within permissible limits.

Analysis: The graph shows acceptable vibration levels which are consistently below 30m/s/s which indicate the frame is sturdy.

Values above 30m/s/s may cause problems with position or altitude hold.

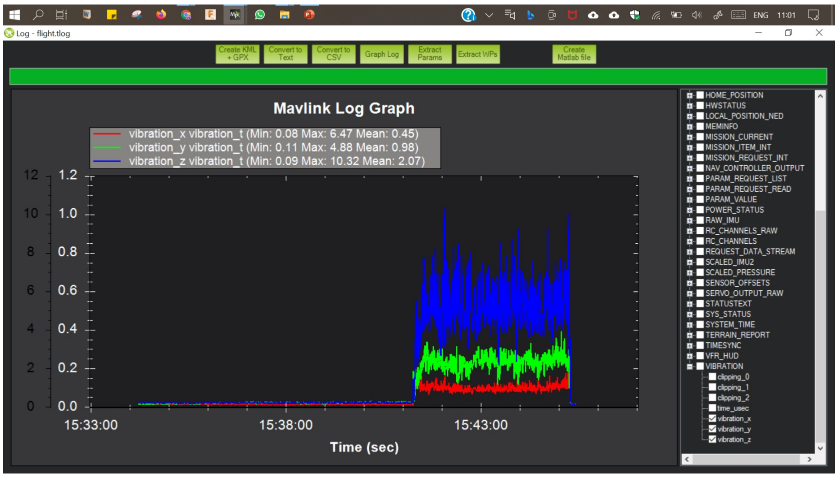


Figure 8.6: Vibrations x,y,z axes

8.1.4 Desired vs Achieved Roll

The vehicle's input roll follows the desired output roll for the entire part of the log, with no divergence.

No Mechanical issues in Roll. However further tuning required to enhance efficiency.

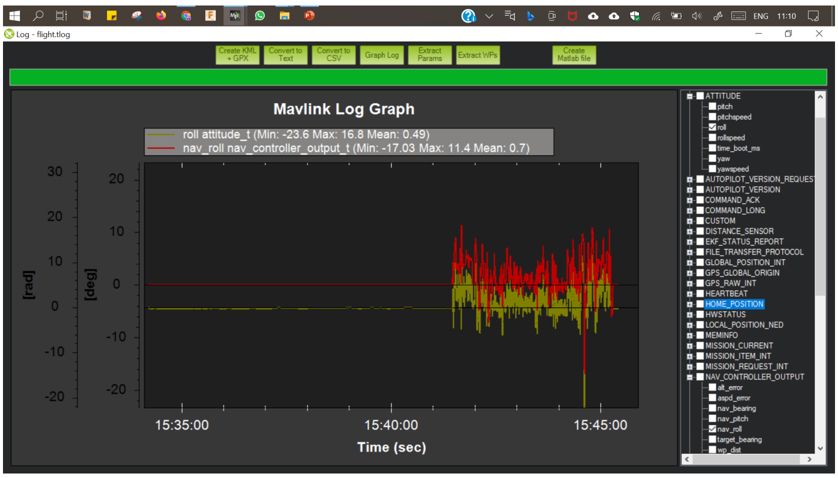


Figure 8.7: Flight parameters: Desired vs Achieved Roll

8.1.5 Desired vs Achieved Pitch

The vehicle's input Pitch follows the output Pitch for the entire part of the log with no divergence.

No Mechanical issues in Pitch.

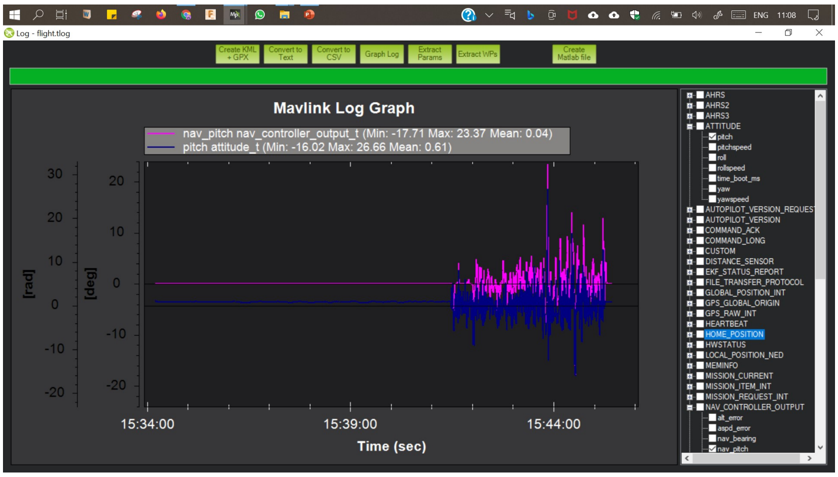


Figure 8.8: Flight parameters: Desired vs Achieved Pitch

8.2 Flight Performance

Fig 8.8, shows the pitch response and Fig 8.7, shows the roll response of UAV in different modes. Here, DesPitch and DesRoll for desire pitch and roll respectively. And only pitch and roll indicate the pitch roll response. If we observe the curves than we see that pitch and roll curve is similar to desire pitch and roll curve. We see in stabilize (manual) mode and altitude hold mode we get some spike which indicate pitch roll action. Though stabilize mode is manual mode so we change pitch manually. In altitude hold mode- altitude maintain automatically but pitch roll is also manual control. In loiter mode that means in GPS lock mode- all parameters controlled automatically without human interface. So, in loiter mode spike is less which indicate it holds a constant coordinate with stability.

8.3 CONCLUSION

From all of curve analysis we can conclude that overall performance of our system is stable. This system is capable to fly in different mode without complexity. It's performance, movement, orientation, motion, stability also good. This drone is capable to fly in several modes. The main modes are manual mode, hover mode, auto mode and return to launch mode. In manual mode drone is controlled by remote device and in others mode drone flies autonomously. This system has facility to see flight data by using powerful ground station and user can upload or override a mission in real time flight condition when a mission running. The overall total weight of implemented design is 5.49 kg and its payload capacity is upto 1kg.

REFERENCES

https://ardupilot.org/ardupilot/ on.

motor-design.com/.

motor-engineer.net/engineering-center/learn/.

powerelectronicsnews.com/electronic-speed-control-for-drones/.

Ahmed, M. F., **M. N. Zafar**, and **J. C. Mohanta**, Modeling and analysis of quadcopter f450 frame. *In 2020 International Conference on Contemporary Computing and Applications (IC3A)*. 2020.

Ding, J., **Q. Fan**, **D. Luo**, and **X. Shen**, Research of a multi-uav flight controller. *In 11th IEEE International Conference on Control Automation (ICCA)*. 2014.

Hendershot, J. R., Electric traction machine choices for hybrid electric vehicles. *In Florida International University*. Nov 20, 2014.

Hendershot J.R. Jr., M. T., Design of brushless permanent-magnet motors. 2016.

Lemko, O. and **O. Molodchyk**, Aerodynamic and flight characteristics of prospective uav scheme "flying wing". *In 2015 IEEE International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD)*. 2015.

Miyamoto, S., **A. Yamada**, and **I. Miki**, Development of ipmsm with rare earth and ferrite magnets. *In 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*. 2015.

Park, Y., **H. Kim**, **H. Jang**, **S.-H. Ham**, **J. Lee**, and **D.-H. Jung** (2020). Efficiency improvement of permanent magnet bldc with halbach magnet array for drone. *IEEE Transactions on Applied Superconductivity*, **30**(4), 1–5.

Romano, M., **P. Kuevor**, **D. Lukacs**, **O. Marshall**, **M. Stevens**, **H. Rastgoftar**, **J. Cutler**, and **E. Atkins**, Experimental evaluation of continuum deformation with a five quadrotor team. *In 2019 American Control Conference (ACC)*. 2019.

Saedan, M. and **P. Puangmali**, Characterization of motor and propeller sets for a small radio controlled aircraft. *In 2015 10th Asian Control Conference (ASCC)*. 2015.