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Calibration of a Drive System for a Human-Driven Muti-Rotor Propulsion Aircraft

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Abstract: Road traffic and congestion control have always been an issue on Indian roads. Besides this, the burning of fossil fuels, environmental harm, and related problems are always there. To avoid this, aerial vehicles (drones) are among the best options to adopt and reduce road traffic. This paper aims to study and review the technologies for an aerial vehicle that can lift a human, i.e., a human-driven drone. Countries like the USA and China are already using big and small drones for delivery, surveillance, medical support, etc. This paper will try to upgrade the Unmanned Aerial Vehicle (UAV) system to a Manned Aerial Vehicle (MAV). The results reveal that ten 150kV outrunners BLDC motor propulsion systems (decacopter) with 12s Li-Po batteries with a 15C continuous discharge rate, 275A ESCs, and 32 x11.5inches, carbon fiber propeller blades can lift the aircraft aloft with a human weighing up to 90kg.

Keywords: UAV, Battery, Motor, Propeller, Li-ion, Li-Po, ESC, MATLAB

1. Introduction

There are different types of drones of various sizes that use different technologies and can counter different payloads based upon their size and drive system[1)]. In large air crafts that are designed to lift a huge amount of load, the RF method is used to get the proper lift[2)]. The use of electric drive system over fuel-based engines is clear in terms of stabilization and initial torque generation as electric motor provides better efficiency[3)]. The size of the aircraft or the size of the propeller is the main consideration while developing a heavy-lift multirotor system as bigger propellers generate more thrust[4)]. To get the desired thrust, the number of motors should also increase because a single electric motor can handle a certain amount of load. To build a heavy-lift multirotor propulsion system, the design should contain more than 6 motors along with large size propellers[5)]. The selection of the components for a reliable drive system should be made in a way that none of the components will get any type of damage and prevent the overheating of the circuit boards and ESCs during the flight operation[6)]. Brushless DC motors are more efficient as they have fewer contact points and can run at high rpm. The best suitable motor to drive large propeller blades is outrunner brushless DC (ORBLDC) as outrunner provides more torque than the in-runner BLDC motors[7)]. The mass of the motor should be kept as low as possible to decrease the total weight of the aircraft[8)]. Masses of other drive components are also a critical parameter to get the proper lift, masses of components should be kept to their minimum without compromising the work efficiency[9)]. The design of the propeller should be in a way that it should create a minimum air vortex at the edges as it decreases the propeller efficiency[10)]. After getting the perfect calibration, it is important to get accurate software for the programming part for stabilization and proper handling[11)]. The fixed-wing[12)] and rotary-wing[13,14)] design are the example of Micro-UAVs. The wing lifting design is the base of these two designs. Both of designs have been commonly executed in photogrammetric and geometric[15)] data collection, especially in mapping applications, reconnaissance, surveillance, and military[16)]. The fixed-wing micro-UAVs may offer better capability than the rotary-wing in standard mapping missions, however, the counterpart in terms of payload compatibility and coverage area[17)]. While, the fixed-wing micro-UAV structure may be divided into tailless[18)] configurations. Some of tailless micro-UAV designs are eBee[19)], Pacflyer S100[20)], and Skywalker X8[21)]. To predict the stall phenomenon, Navier–Stokes equations used for the incompressible flow with the efficient shear stress turbulence model[22)]. The same class of micro-UAVs are compared for the lift and drag performance i.e., Hawkeye[23)], Serindit[24)], and NUS[25)].

The present study aims to make a hoverboard type of frame design for drone. A BLDC motor with proper kV and appropriate ESC and battery can get the correct rpm, and with propellers of effective pitch and length, can get the desired thrust force. Significant results of different research in this field have also taken into consideration to get the best possible products, and it is not possible to get the required thrust with just four to six motors, as the propeller length cannot be exceeded beyond a specific torque torque to rotate the propeller. value, and so then the motors will not deliver enough

2. Parts and Design Consideration

2.1 Existing propulsion systems

The required fuel fraction method or RF method is used in large-sized aircraft that use jet fuel or gas motors[26-27]. This method is proposed only for the motor-based propulsion system, and no such process is proposed for electric propulsion systems though people are working on it. Ampatis worked on an approach that optimizes the data from the battery, ESCs, and motors to balance the payload and design of the system[5]. He defines the vehicle dimensions, motor dimensions, and battery weight.

2.2 Design considerations of multirotor electric propulsion system

2.2.1 Motor

Brushless DC motors are considered over traditional brushed DC motors for better efficiency and long lifetime. BLDC motor comes with two configurations: outrunner (OR) and in runner (IR), define the position of stator and rotor. In IR motors, the armature runs on its axle and magnets (either permanent or electromagnet) and is positioned on the lateral side of the armature, considered stator. Whereas in the OR BLDC motor, the spinning part does not spin on the axle; instead, the whole outer magnets and the motor body rotate over the stator. Both OR and IR BLDC motors have similar efficiency with a slight difference depending upon the various dependencies. The main difference between IR and OR BLDC motor is the torque generation. OR BLDC motors have greater torque output than IR BLDC motors[5]. This forces users to choose between the IR BLDC motor for modest builds (under 100g) and the OR BLDC motor for heavy use. That is why it uses OR BLDC in our project.

2.2.1.1 Motor parameters

The most critical parameter of motor selection is the kV of motor or speed constant. One kV is one revolution per minute on applying 1 volt to an unloaded motor. It is a rating that indicates how fast an unloaded motor will run when a certain amount of potential difference is created across it, and it is measured in RPM/V (Round Per Minute/Volt). Too high voltage can damage the motor when the system is exposed to full throttle, affecting the motor's RPM and efficiency. Generally, for a heavy-duty build, a lower KV motor at high voltage is used in configuration with low pitch large propeller blades to get sufficient lift[28-31].

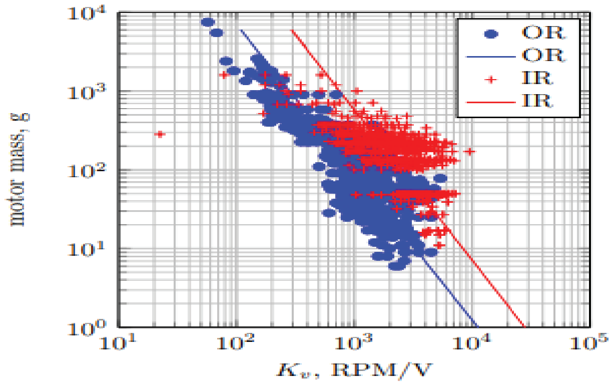

Fig. 1: OR and IR kV to mass relationship[9]

According to Gur, the above figure shows that fewer kV motors have high mass and vice versa but it also shows that OR motors are more efficient than IR motors for heavy-duty and high voltage[8]. Figure 1. Show that per unit kV of IR motor is heavier than OR motor.

2.2.2 Battery

There are mainly two types of batteries used to build heavy-duty drones: Li-ion (Lithium-ion) battery and Li-Po (Lithium Polymer) battery.

Table 1. Comparison between Li-ion and Li-Po batteries.

Basis	Li-ion	Li-Po
Aging	Charging capacity degrades with time	Retain charging power better than Li-ion
Energy density	High energy density	Low as compared to Li-ion
Conversion rate	85-95%	75-85%
Safety	Volatile	Safe
Cost	Cheaper	Expensive by 30%
Weight	Heavy	Light weight
Charging time	Longer than Li-Po	Comparatively shorter

The above table shows how Li-Po batteries are more suitable in building a drone, whether it is a small one or a big one.

2.2.2.1 Battery parameters

2.2.2.1.1 Battery capacity

Battery capacity is the amount of energy that a battery can hold. It's the sum of the current drawn from the battery until the voltage drops to a specified point for each cell. It is measured in Amp hour (Ah) and milliampere-hour (mAh) for high-capacity batteries.

a) **Discharge rate:** Discharge rate (or C-rate) is the rate of current discharge from the battery. It is the continuous discharge rate that the battery can handle Some batteries have a continuous and maximum discharge rate (like 40C/80C), which is the maximum current that can be withdrawn.

b) **Configuration:** A battery is made up of several small cells. Each cell contains 3.3 to 3.7 volt. This configuration is denoted by the letter "S." Like for a battery of 6 cells, it should be written as 6S1P. Where 6S denotes 6 number of cells and 1P denotes that they are connected in series.

2.2.2.1.2 Mass of the battery

Mass of the battery is increased as increase the number of cells. It can be understood by the graph represented below in Fig. 2.

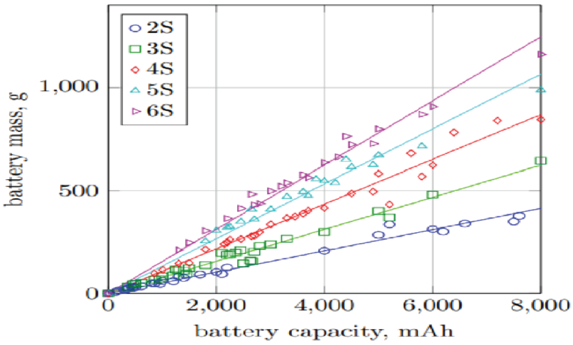

Fig. 2: Battery masses from 2S to 6S configuration[9)]

In Fig.2, This result is demonstrated by considering 30 standard Li-Po batteries. If batteries of the same chemistry are taken, the mass is linear with the number of cells it contains.

2.2.3 Propeller

It is evident that to get an ample thrust, and the propeller span should be significant. And the pitch of the propeller should be adequately designed so that it can displace the maximum air and gain the best efficiency. So, the composition material should be stiff enough for the large propellers to encounter deflection at the end. This effect is described thoroughly by Harrington in his work[10)]. If the pitch and number of blades are increased in a propeller, it will displace more air, thus providing more thrust. The best way to increase the thrust without increasing the number is to increase the blade radius to the extent that the motors and other electronics can handle it.

2.2.3.1 Propeller parameters

Mass of the propeller should be carefully considered while building an aerial commuter and should minimize the weight to the best without compromising the efficiency and reliability. Dmitry has shown a relationship between the masses and the diameter of different compositions on propeller blades[9)].

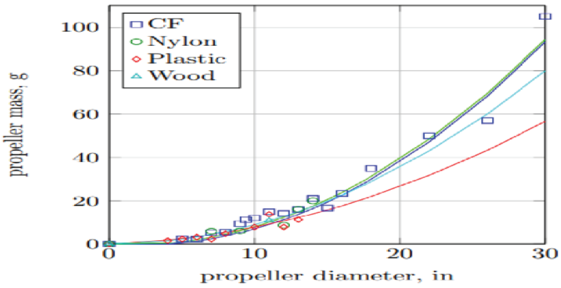

Fig. 3: Masses of different propeller with their diameters[9)]

As here can be seen in Fig. 3, that carbon fiber (CF) is the only material that can be used for large propellers. There are many manufacturers of propellers, but Eolo€ provides with best motoring designs with different test parameters. When driven at a maximum rpm of 4450, The propeller with 32 inches diameter and 11 inches pitch can produce thrust up to 23 kg.

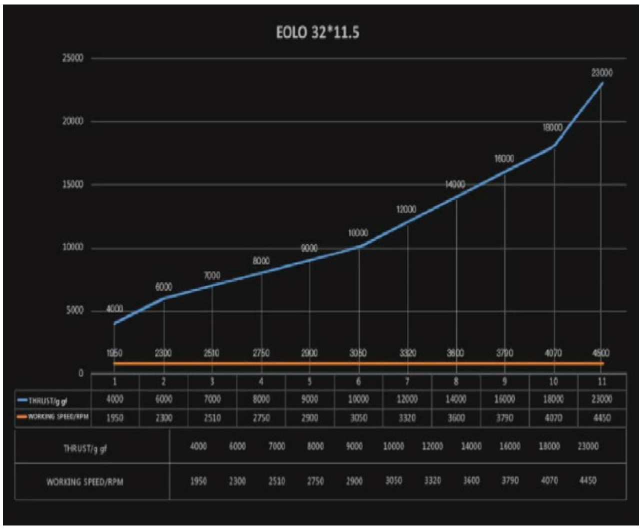

Fig. 4. Thrust w.r.t RPM graph for a 32x11.5 inches propeller

The max operating speed of the propeller cannot exceed that means the system cannot be operated at full throttle. Otherwise, it will damage the blades as well as can damage the ESC.

2.2.4 ESC (Electronic Speed Controller)

Generally, the BLDC motor comes in a three-phase configuration as they are more efficient. ESC works with PWM (Pulse Width Modulation) control signals. Onboard FETs (Field-effect Transistors) are used for switching circuits. Many ESC gives freedom to reprogram changing frequency in a range of 8 to 16 kHz to increase the rpm but at the cost of overheating FETs. Other avionics need less power to operate; BEC (Battery Eliminator Circuit) is used, but OPTO (Optoisolator) is used for better efficiency. OPTO isolates a low voltage power from the main power supply to protect the other electronics like the receiver and other control boards. OPTO inbuilt unit ESC and eliminate the use of BEC.

2.2.4.1 ESC parameters

The main parameter is the ampere of the ESC. Motor, battery, and ESC work together, so it depends on the battery used here and the battery's discharge rate. Manufacturers provide the maximum ampere value that ESC can handle. For example, if a battery of 5200 mAh is taken with a discharge rate of 40C, then (5.2 X 40 = 208A) 208A will be the current output. ESC must handle the current up to and beyond 208A; otherwise, the FETs will overheat or can short also.

3. Result and Discussion

3.1 Calibration of the drive system

From the matter which discussed in previous sections, now a perfect and reliable combination of motors, propellers, ESCs, and batteries to lift a human can be executed. The details of these components as shown in Table 2, 3, 4, and 5.

Table 2. Selection of Appropriate Battery

Battery type	Li-Po
Capacity	8000mAh
Configuration	12S1P
Continuous/max discharge rate	15C/30C
Voltage per cell	3.7v
Battery voltage	44.4v
Weight	2200g

Suggested Battery: OKCELL 44.4V 12S 8000mAh

Table 3. Selection of Appropriate ESC

Peak ampere	275A
Max volt	51.8v (14S)
Programming support	Yes
BEC support	OPTO
Weight	456g

Suggested ESC: Turnigy D-lux 250A HV 14s 60v

Table 4. Selection of Appropriate Motor

KV	150
Max current	190A
Max voltage	14S/51.8v
Suggested ESC	250A 14S
Weight	2530g

Suggested Motor: Turnigy RotoMax 150cc Brushless Outrunner

Table 5. Selection of Appropriate Propeller

Composition	Carbon Fiber and Nylon composite
Size	32X11.5"
Max working rpm	4450rpm
Weight	197g

Suggested Propeller: Eolo carbon fiber reinforced nylon propellers 32X11.5

3.2 Load Calculations

The load calculation is done according to a ten-motor propulsion system (Decacoptor). The analysis is done in the multiple of 10.

Weight of motors 2530g X 10 = 25300g

Weight of propellers 197g X 10 = 1970g

Weight of ESCs 456g X 10 = 4560g

Weight of batteries 2200g X 10 = 22000g

The total weight of the drive system will be the sum of the above-calculated weights, that is,

25300g+1970g+4560g+22000g=52830g

Therefore, converting it into kilograms

52830g = 52.83kg ~ 53kg

The total weight of the drive system would be ~ 53kg payload

The maximum allowed weight of passenger along with the safety gears will be 100kg,

90kg + 10kg = 100kg

(human weight) + (safety gears)

3.2.1 Weight of frame

Considering the best material for frame fabrication, carbon fiber, the flexibility for frame weight is given up to ~20kg.

So, the total weight calculation for the take-off will be,

Table 6. Total weight of aircraft with the passenger.

Drive system	53kg
Payload	100kg
Frame	20kg
Total	173kg

For better understanding, the weight calculation is done in kilograms (kg). Still, the actual unit will be kilogram-force (FGF) as all the weight considered is exerting that much force on the Earth's surface, or in other words, gravity is pulling it to Earth's centre.

3.2.2 Thrust generation

Thrust is the propulsive force of an aircraft. To hover an aircraft, the value of thrust should be greater than the force of attraction by the gravity on the aircraft.

With the drive system discussed in this Paper, throttle response concerning thrust generation is shown below in the table,

Table 7. Thrust generation w.r.t % throttle response.

Throttle (%)	Thrust (kgf)	Aircraft position
41.29	80	Grounded
43.54	90	
45.79	100	
49.98	120	
54.05	140	
56.90	160	
61.11	180	Take off
66.81	230	

The above table is constructed with the help Fig. 4. and the rpm of mentioned 150kV BLDC motor. The voltage obtained from one battery is 44.4v, and the kV rating of the motor is 150kV. So, the rpm of the motor can be calculated by multiplying the kV rating with the supplied voltage as,

$$150 \text{ X } 44.4 = 6660\text{rpm}$$

The throttle percentage and the thrust production corresponding to that were calculated by dividing the specified various rpm, which can be observed (in Fig. 4) by the achieved rpm.

4. Conclusion

It was challenging to calibrate a proper propulsion system without damaging or burning the ESCs, motors, and wires while extracting the most controllable current and potential difference from the batteries.

This paper concluded as follows:

Based on the above research following components with their correct specifications should be used to build a heavy lift multirotor aircraft

Motors 150kV Outrunner BLDC * 10

Batteries 12s15C Li-Po * 10

ESC 275A * 10

Propeller 32*11.5inchs CF Propeller * 10

After examining the complexity, the system's probable loads are concerned, and the frame is given flexibility up to 20 kg and the system is capable to lift a human weighing up to 90 Kg.

The maximum payload and the aircraft's weight were calculated around 173 kg (round off to 180 kg), and the calibrated propulsion system can churn out a max thrust of 230 kg, which is more than the requirement.

The throttle should be restricted to 65% otherwise motors can damage the propellers. The best suitable flight controller for discussed propulsion system would be Pixhawk 2.1 flight controller. And frame the of aircraft should be made up of carbon fiber.

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