Multicopter Design and Control Practice
—— A Series Experiments Based on MATLAB and Pixhawk

Lesson 05 Propulsion System Design Experiment

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Outline

1. Preliminary
2. Basic Experiment
3. Analysis Experiment
4. Design Experiment
5. Summary

Preliminary

Propulsion system

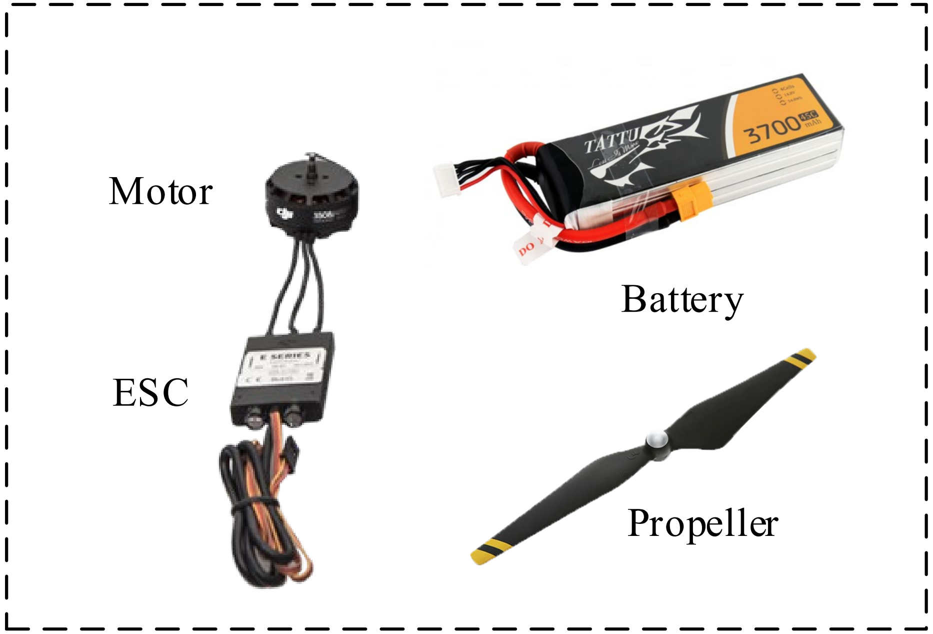


Figure. Propulsion system

Preliminary

The relationship between the airframe radius R and the maximum radius of a propeller $r_{\max}$ is (the number of arms of the multicopter is *n*)

$$R = r_{\max} \Big/ \sin\frac{180^{\circ}}{n}$$

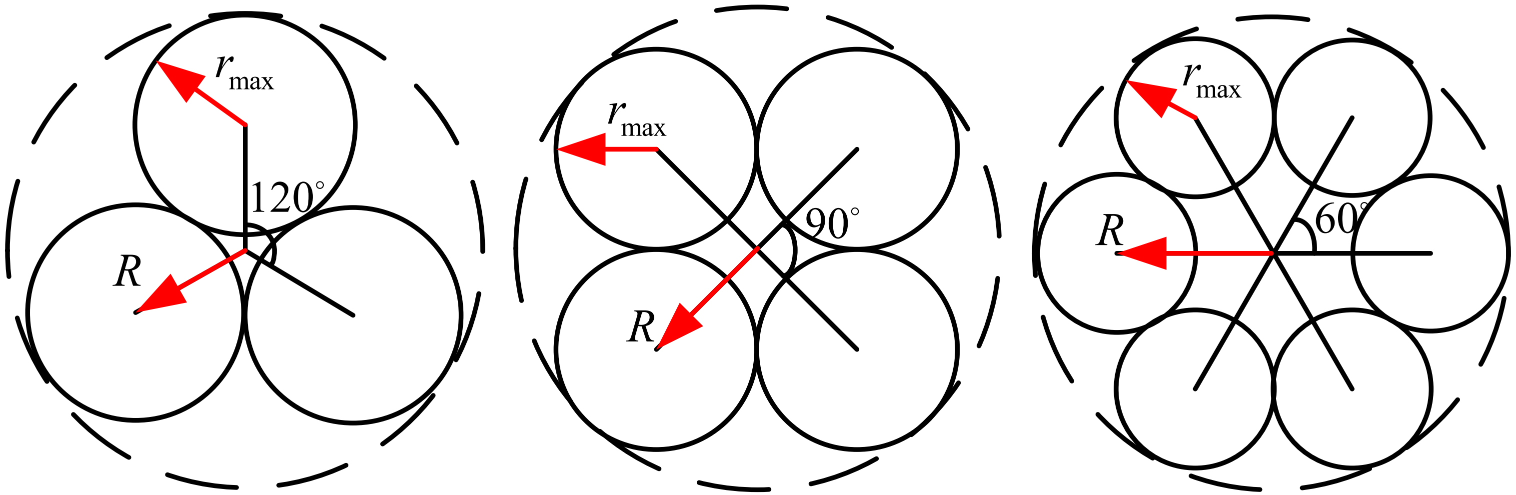


Figure. Multicopters with different airframe configurations and their geometry parameters

Preliminary

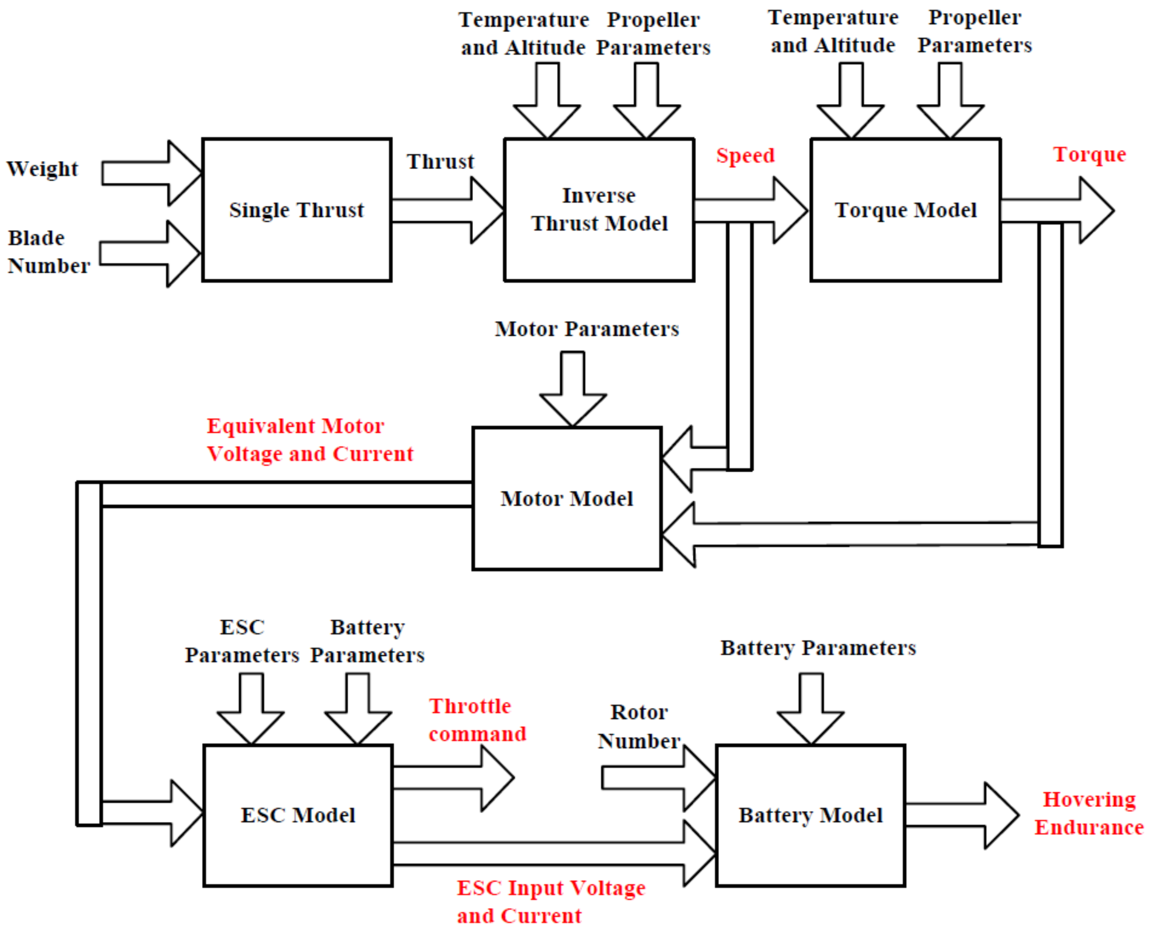


Figure. Solution to Hovering Endurance

- Propeller Model： Thrust and torque
- Motor Model
- ESC Model
- Battery Model

Preliminary

The experiment preliminary is from Chapters. 3 and 4 of *Introduction to Multicopter Design and Control.*

Basic Experiment

Experimental Objectives

Things to prepare

The multicopter performance evaluation website: https://flyeval.com/paper/

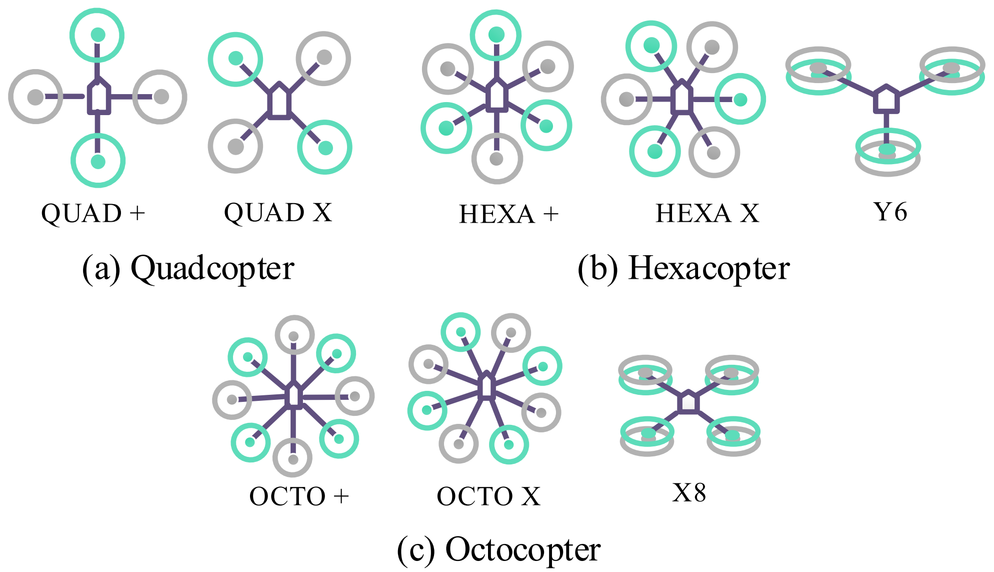


Fig. Some basic configurations of multicopters

Dongjie Shi, Xunhua Dai, Xiaowei Zhang, and Quan Quan. A Practical Performance Evaluation Method for Electric Multicopters. IEEE/ASME Transactions on Mechatronics. 2017, 22(3):1337-1348.

Basic Experiment

Experimental Objectives

■ Objectives

A multicopter (e.g., a tricopter,coaxial hexacopter, quadcopter, hexacopter, coaxial octocopter, and octocopter) should be configured with hover endurance longer than 10 min by using the evaluation website, where the flight environment parameters are "Altitude": 0 m, and "Air Temperature": 25° . In addition, all configuration parameters and basic performance parameters of the designed multicopters should be recorded from the multicopter performance evaluation website https://flyeval.com/paper/.

Basic Experiment

□ Configuration Procedure

（1）Step1: The first step is to configure a tricopter in which the“Total Weight”is set to “1.0 kg”, the “Frame Size” is set to “450 mm”, the “Altitude” is set to “0 m”, the “Air Temperature” is set to “25° C”, and the “Aero Design” is set to “medium”. Other parameters, including the weight and the resistance of each component, are estimated by statistical models from the website www.flyeval. com/paper/.

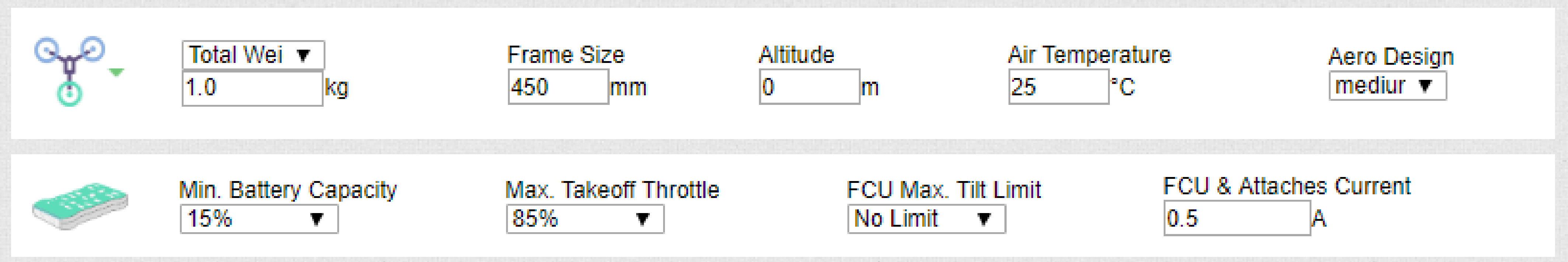


Figure. Basic configuration for tricopter configuration

Basic Experiment

□ Configuration Procedure

（2）Step2: Select the brands and type specification of the motor, propeller, ESC, and battery to comprise a feasible propulsion system.

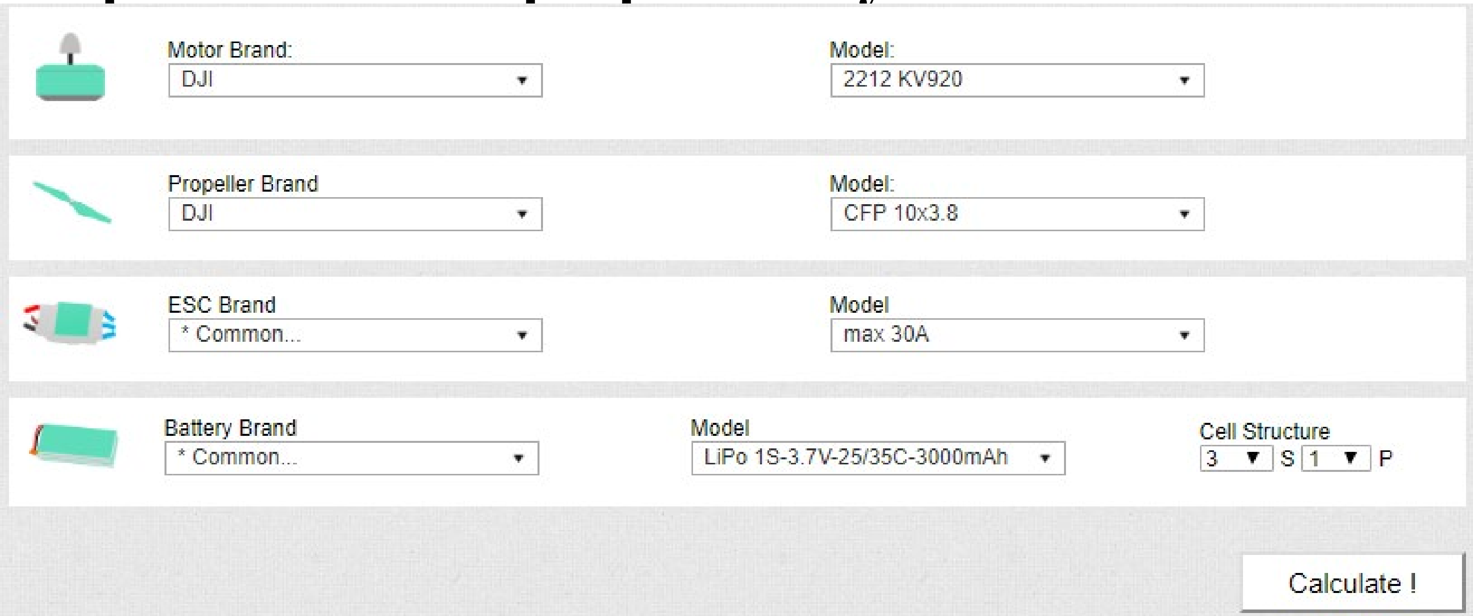


Figure. Propulsion system for tricopter

Basic Experiment

□ Configuration Procedure

（3） Step3: The parameters and performance of the multicopters are obtained by clicking the “Calculate!” button on the website.

Basic Information

Hovering Time :	14.7 min.	≥ 41.2% MultiCopters
Remaining Load :	1.08 kg	≥ 51.9% MultiCopters
Max. Takeoff Altitude:	5.76 km	≥ 65.8% MultiCopters
Flying Range:	3.87 km	≥ 43.6% MultiCopters
Forward Speed:	11.2 m/s	≥ 52.8% MultiCopters

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 14.7 min.	Flying Time	: 3.4 min.	Normal Operation	: 11.2 min.
Throttle Percentage	: 54.2 %	Total Lift	: 26 N	Total Weight	: 1 kg
Motor Current	: 3.29 A	Motor Current	: 15.1 A	Remaining Load	: 1.08 kg
Motor Speed	: 5324.1 rpm	Motor Speed	: 8679.9 rpm	Max. Takeoff Altitude	: 5.76 km
Motor Power	: 31 W	Motor Power	: 134.4 W	Max. Tilt Angle	: 61.3 °
Battery Voltage	: 11.8 V	Battery Voltage	: 11.2 V	Max. Forward Speed	: 11.2 m/s
Battery Current	: 10.4 A	Battery Current	: 45.3 A	Max. Flying Range	: 3.87 km
Power Efficiency	: 74.7 %	Power Efficiency	: 74.2 %	Wind Resistance	: 4 Degree

Basic Experiment

（4）Other configuration

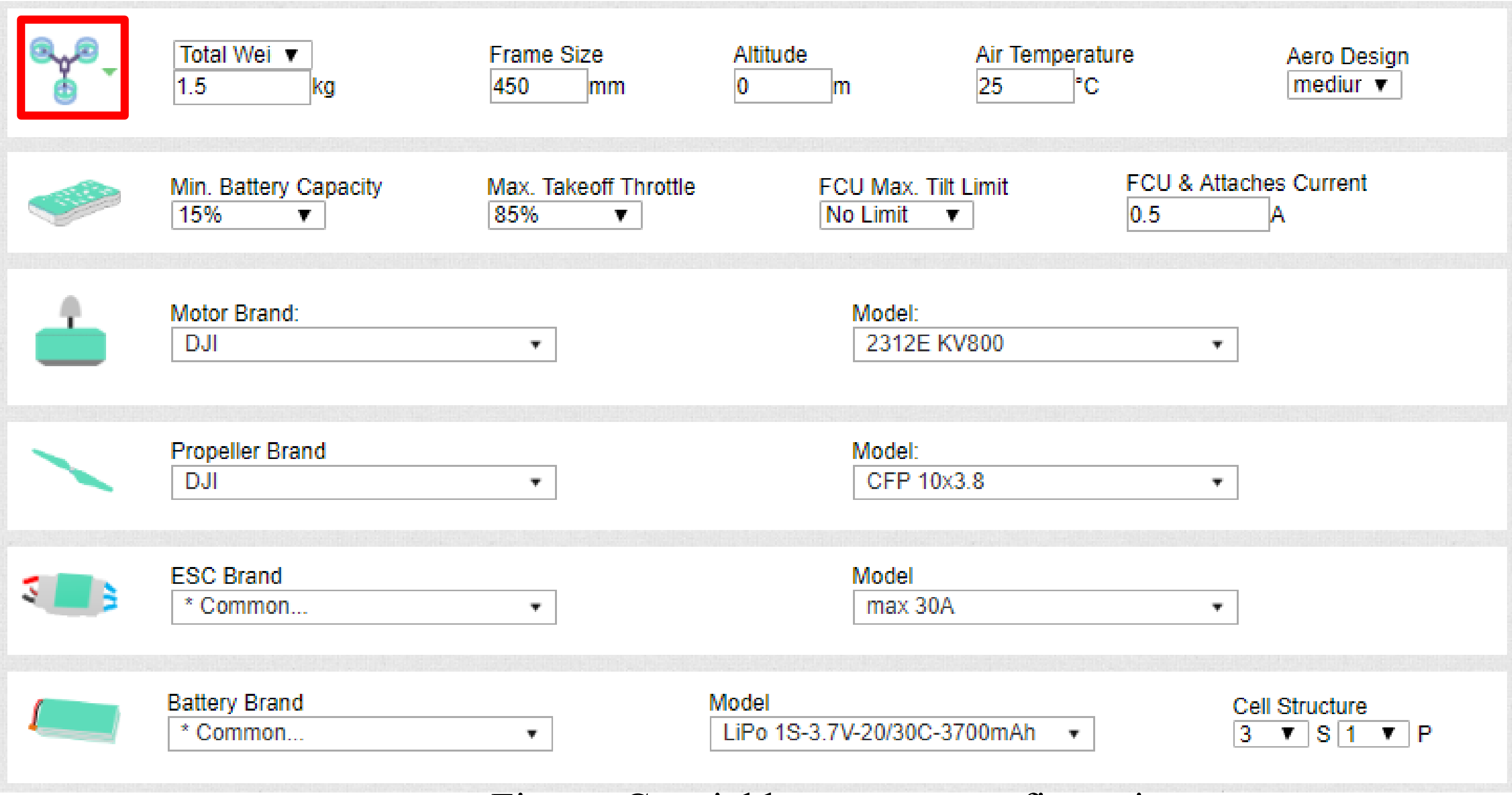


Figure. Coaxial hexacopter configuration

Basic Experiment

Basic Information

Hovering Time :	13.4 min.	≥ 39% MultiCopters
Remaining Load :	1.1 kg	≥ 52.4% MultiCopters
Max. Takeoff Altitude:	4.4 km	≥ 59.4% MultiCopters
Flying Range:	4.07 km	≥ 44.9% MultiCopters
Forward Speed:	10.6 m/s	≥ 51.5% MultiCopters

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 13.4 min.	Flying Time	: 3.9 min.	Normal Operation	: 10.6 min.
Throttle Percentage	: 60 %	Total Lift	: 32.6 N	Total Weight	: 1.5 kg
Motor Current	: 2.83 A	Motor Current	: 10.1 A	Remaining Load	: 1.1 kg
Motor Speed	: 5155.1 rpm	Motor Speed	: 7681.8 rpm	Max. Takeoff Altitude	: 4.4 km
Motor Power	: 28.2 W	Motor Power	: 93.2 W	Max. Tilt Angle	: 54.7 °
Battery Voltage	: 11.8 V	Battery Voltage	: 11.2 V	Max. Forward Speed	: 10.6 m/s
Battery Current	: 14.1 A	Battery Current	: 48.7 A	Max. Flying Range	: 4.07 km
Power Efficiency	: 80 %	Power Efficiency	: 76.5 %	Wind Resistance	: 4 Degree

Figure. Coaxial hexacopter performance

Basic Experiment

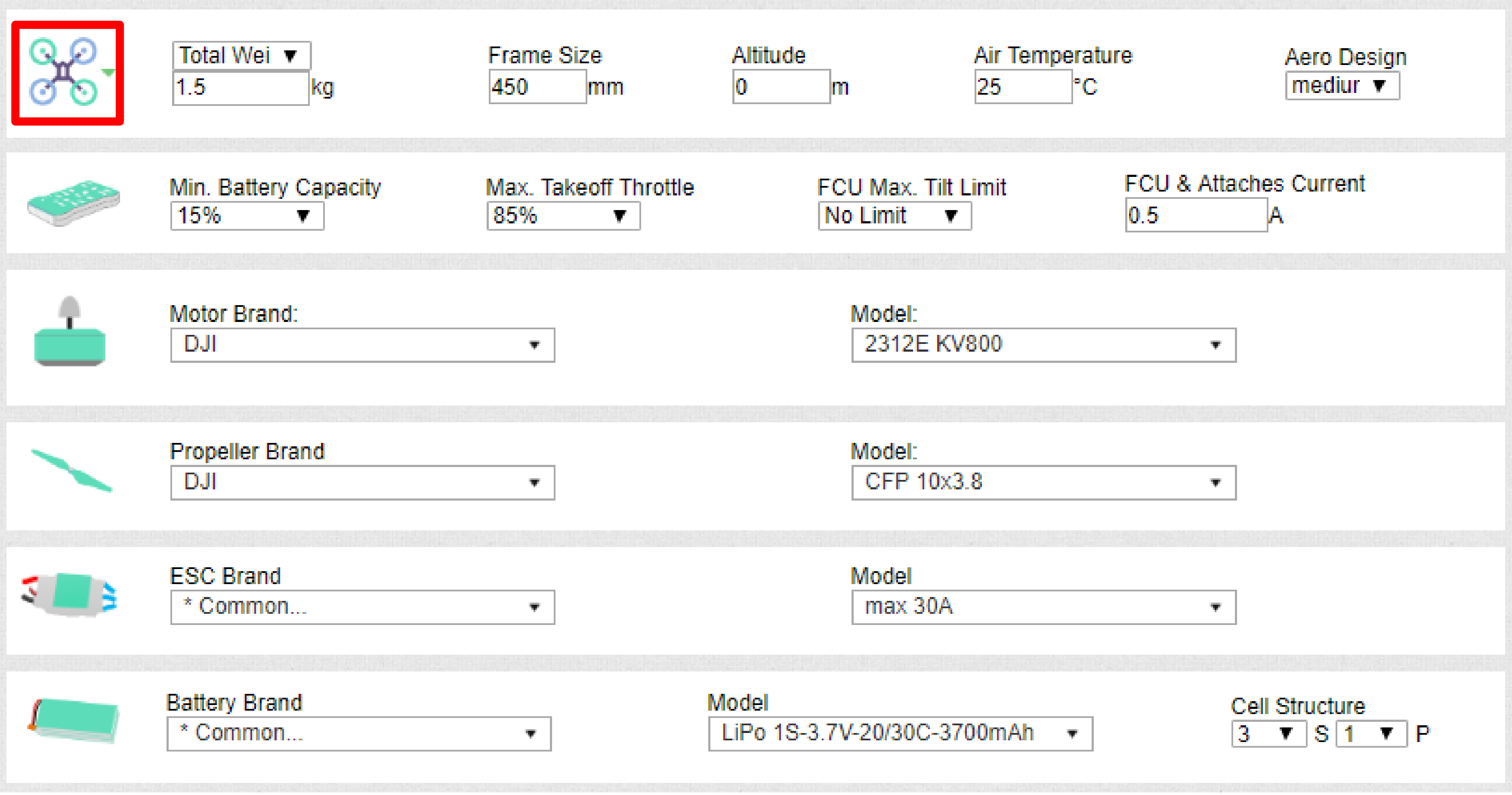
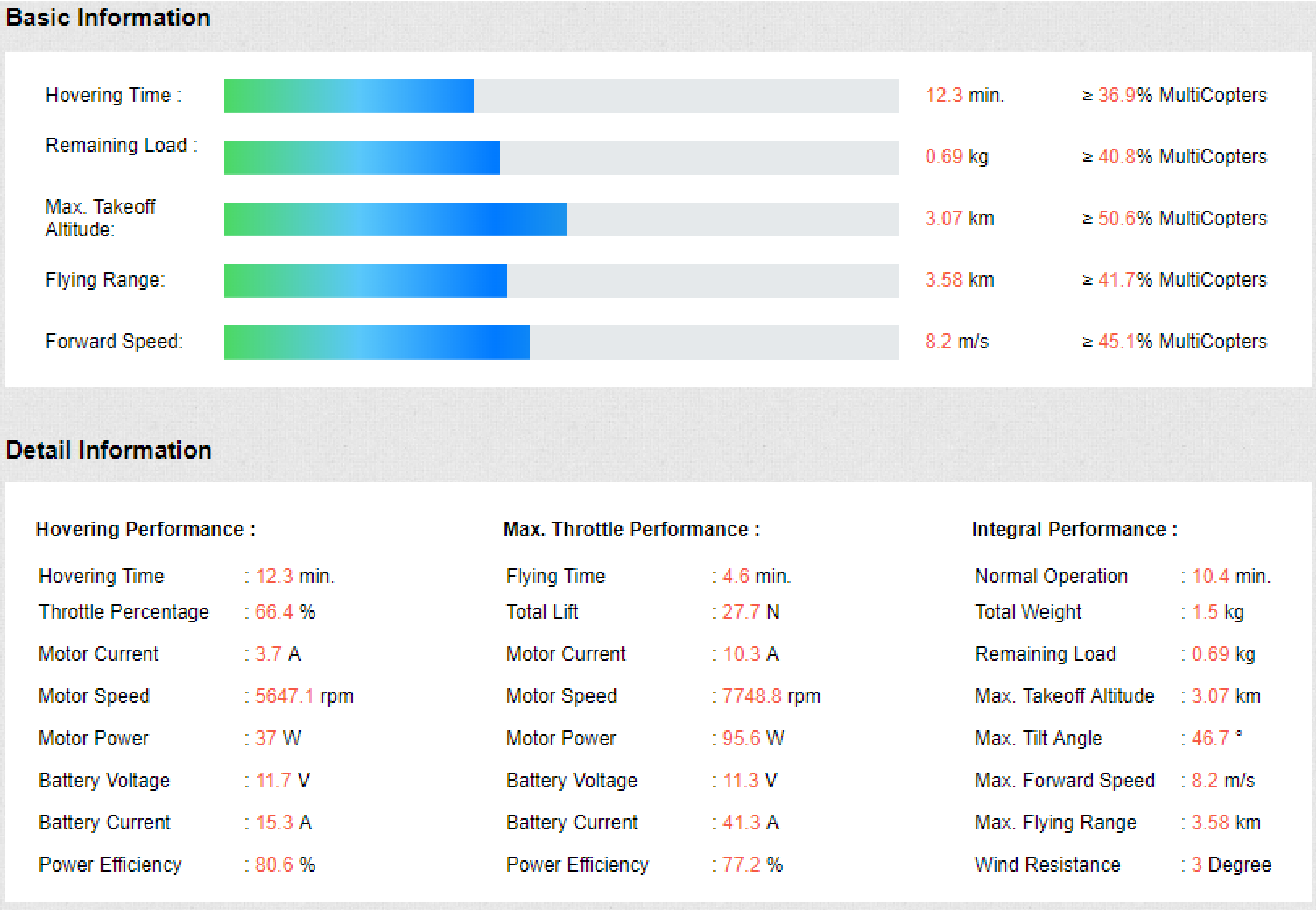


Figure. Quadcopter configuration

Basic Experiment



Basic Information

Hovering Time :		12.3 min.	≥ 36.9% MultiCopters
Remaining Load :		0.69 kg	≥ 40.8% MultiCopters
Max. Takeoff Altitude:		3.07 km	≥ 50.6% MultiCopters
Flying Range:		3.58 km	≥ 41.7% MultiCopters
Forward Speed:		8.2 m/s	≥ 45.1% MultiCopters

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 12.3 min.	Flying Time	: 4.6 min.	Normal Operation	: 10.4 min.
Throttle Percentage	: 66.4 %	Total Lift	: 27.7 N	Total Weight	: 1.5 kg
Motor Current	: 3.7 A	Motor Current	: 10.3 A	Remaining Load	: 0.69 kg
Motor Speed	: 5647.1 rpm	Motor Speed	: 7748.8 rpm	Max. Takeoff Altitude	: 3.07 km
Motor Power	: 37 W	Motor Power	: 95.6 W	Max. Tilt Angle	: 46.7 °
Battery Voltage	: 11.7 V	Battery Voltage	: 11.3 V	Max. Forward Speed	: 8.2 m/s
Battery Current	: 15.3 A	Battery Current	: 41.3 A	Max. Flying Range	: 3.58 km
Power Efficiency	: 80.6 %	Power Efficiency	: 77.2 %	Wind Resistance	: 3 Degree

Figure. Quadcopter performance

Basic Experiment

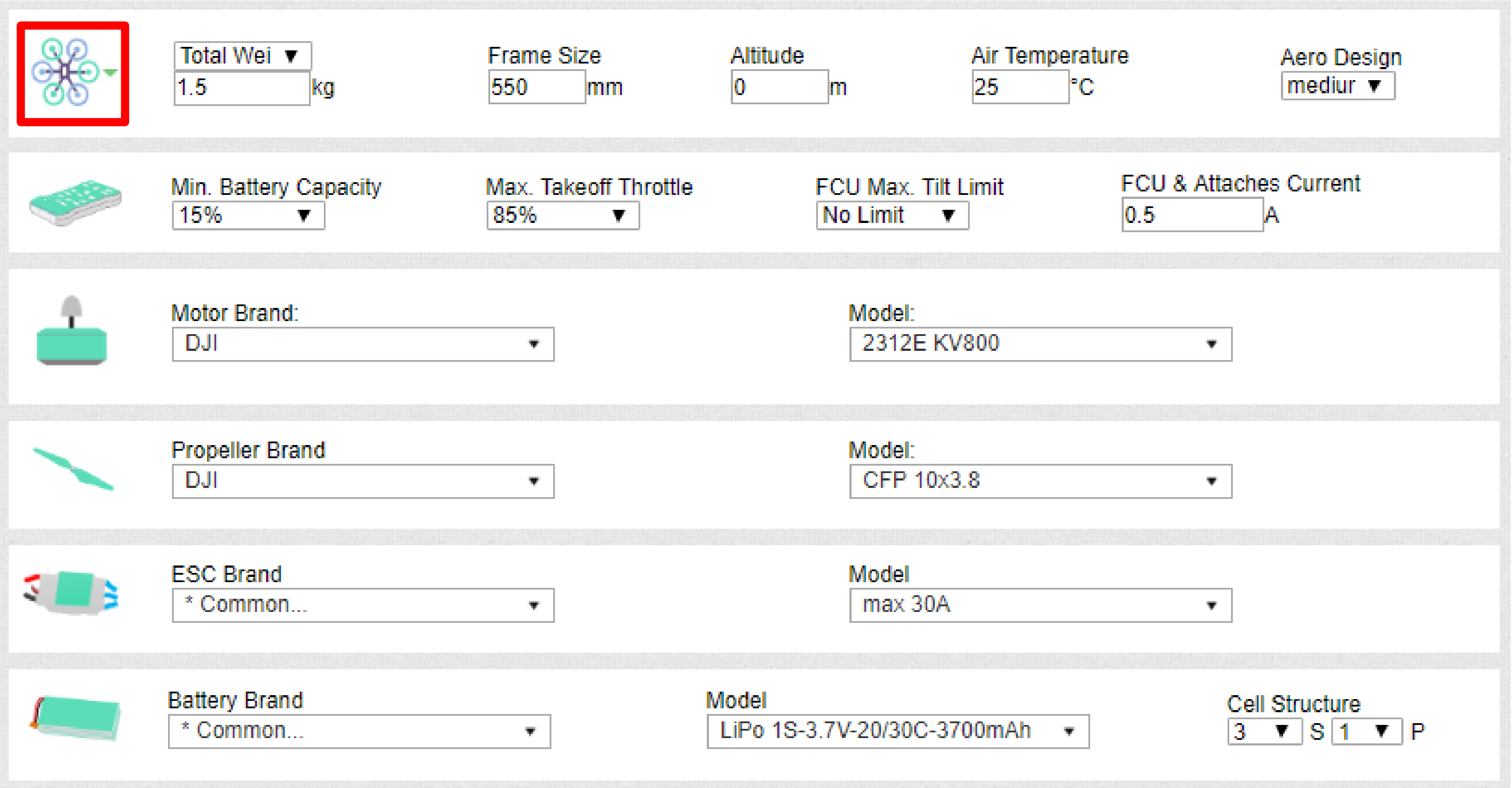


Figure. Hexacopter configuration

Basic Experiment

Basic Information

Hovering Time :	14.8 min.	≥ 41.3% MultiCopters
Remaining Load :	1.69 kg	≥ 62.8% MultiCopters
Max. Takeoff Altitude:	5.93 km	≥ 66.4% MultiCopters
Flying Range:	3.87 km	≥ 43.6% MultiCopters
Forward Speed:	11.8 m/s	≥ 54.1% MultiCopters

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 14.8 min.	Flying Time	: 3.2 min.	Normal Operation	: 11 min.
Throttle Percentage	: 53.2 %	Total Lift	: 39.7 N	Total Weight	: 1.5 kg
Motor Current	: 2.05 A	Motor Current	: 9.9 A	Remaining Load	: 1.69 kg
Motor Speed	: 4610.8 rpm	Motor Speed	: 7580.6 rpm	Max. Takeoff Altitude	: 5.93 km
Motor Power	: 20.1 W	Motor Power	: 89.5 W	Max. Tilt Angle	: 62 °
Battery Voltage	: 11.8 V	Battery Voltage	: 11 V	Max. Forward Speed	: 11.8 m/s
Battery Current	: 12.8 A	Battery Current	: 59.4 A	Max. Flying Range	: 3.87 km
Power Efficiency	: 78.8 %	Power Efficiency	: 75.4 %	Wind Resistance	: 4 Degree

Figure. Hexacopter performance

Basic Experiment

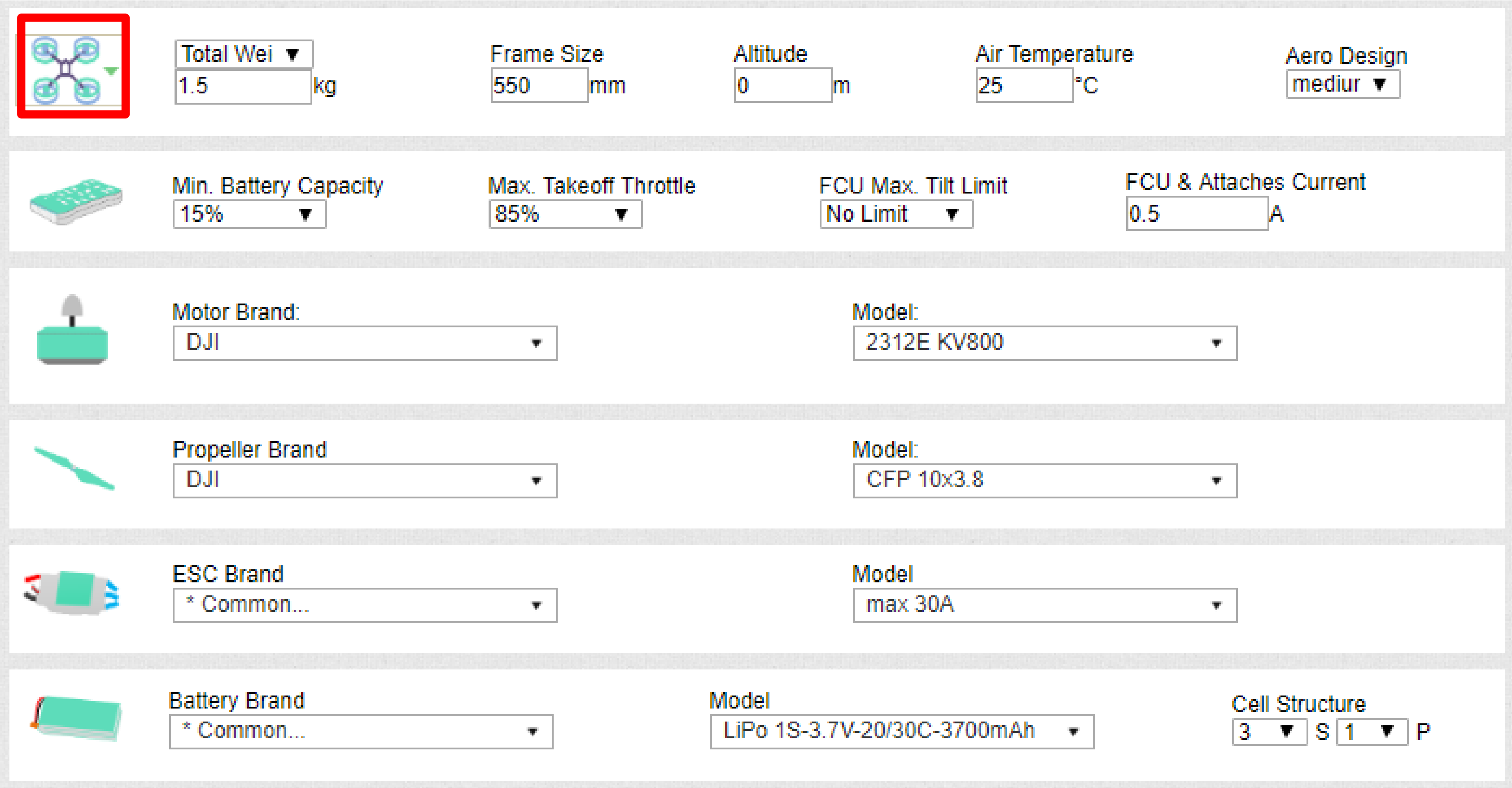
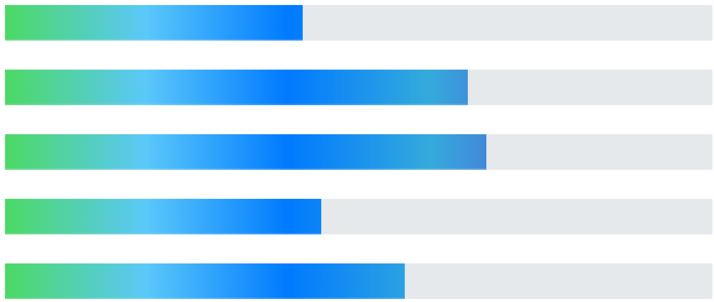


Figure. Coaxial octocopter configuration

Basic Experiment

Basic Information



Hovering Time :	15.2 min.	≥ 42% MultiCopters
Remaining Load :	1.88 kg	≥ 65.3% MultiCopters
Max. Takeoff Altitude:	6.36 km	≥ 67.9% MultiCopters
Flying Range:	4.03 km	≥ 44.6% MultiCopters
Forward Speed:	12.9 m/s	≥ 56.3% MultiCopters

Detail Information

Hovering Performance :

Hovering Time	: 15.2 min.
Throttle Percentage	: 51.3 %
Motor Current	: 1.87 A
Motor Speed	: 4464.4 rpm
Motor Power	: 18.3 W
Battery Voltage	: 11.8 V
Battery Current	: 12.5 A
Power Efficiency	: 78.3 %

Max. Throttle Performance :

Flying Time	: 3 min.
Total Lift	: 42 N
Motor Current	: 9.8 A
Motor Speed	: 7547.2 rpm
Motor Power	: 88.3 W
Battery Voltage	: 10.9 V
Battery Current	: 62.8 A
Power Efficiency	: 75 %

Integral Performance :

Normal Operation	: 11.2 min.
Total Weight	: 1.5 kg
Remaining Load	: 1.88 kg
Max. Takeoff Altitude	: 6.36 km
Max. Tilt Angle	: 63.7 °
Max. Forward Speed	: 12.9 m/s
Max. Flying Range	: 4.03 km
Wind Resistance	: 4 Degree

Figure. Coaxial octocopter performance

Basic Experiment

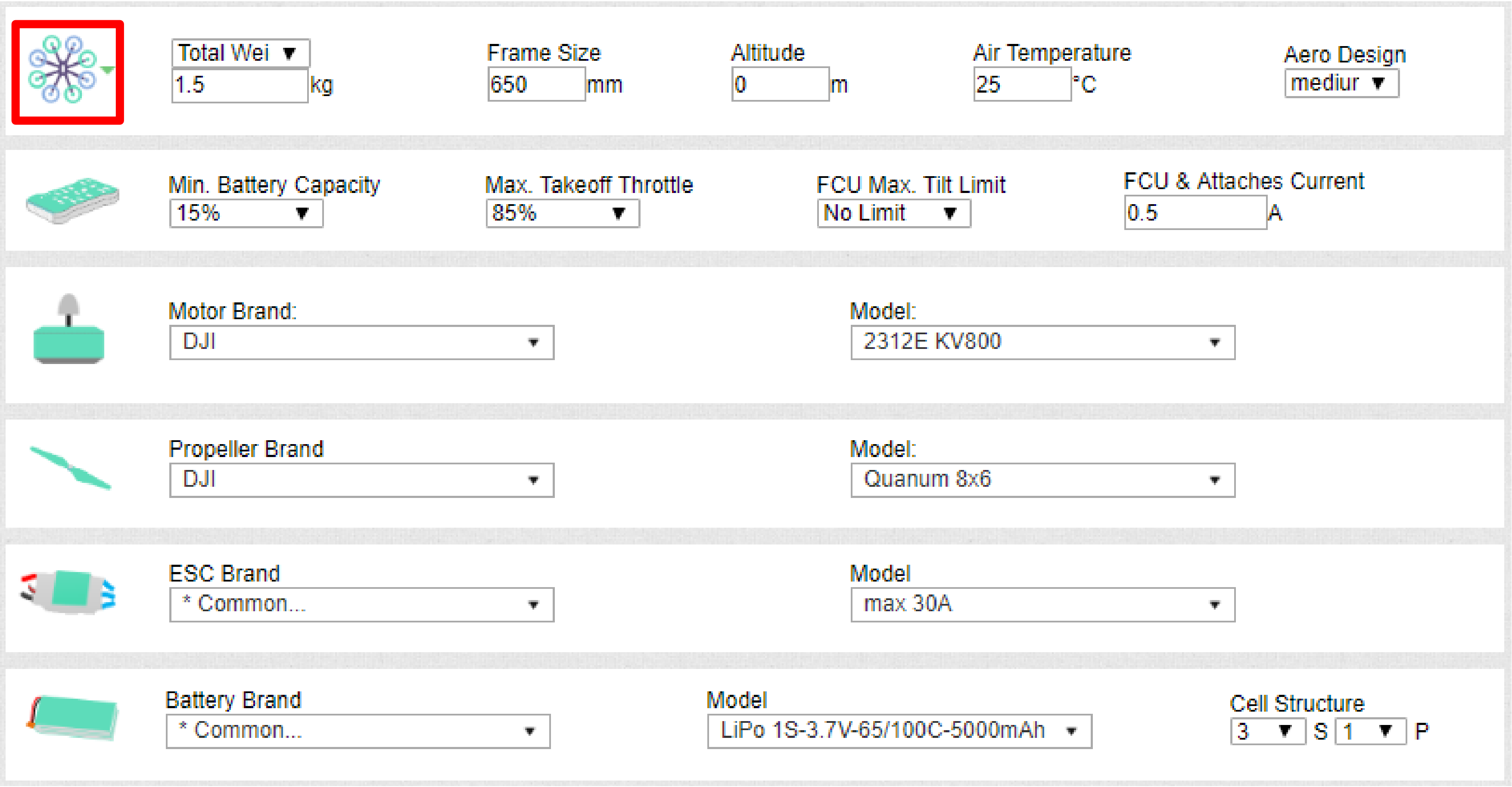


Figure. Octocopter configuration

Basic Experiment

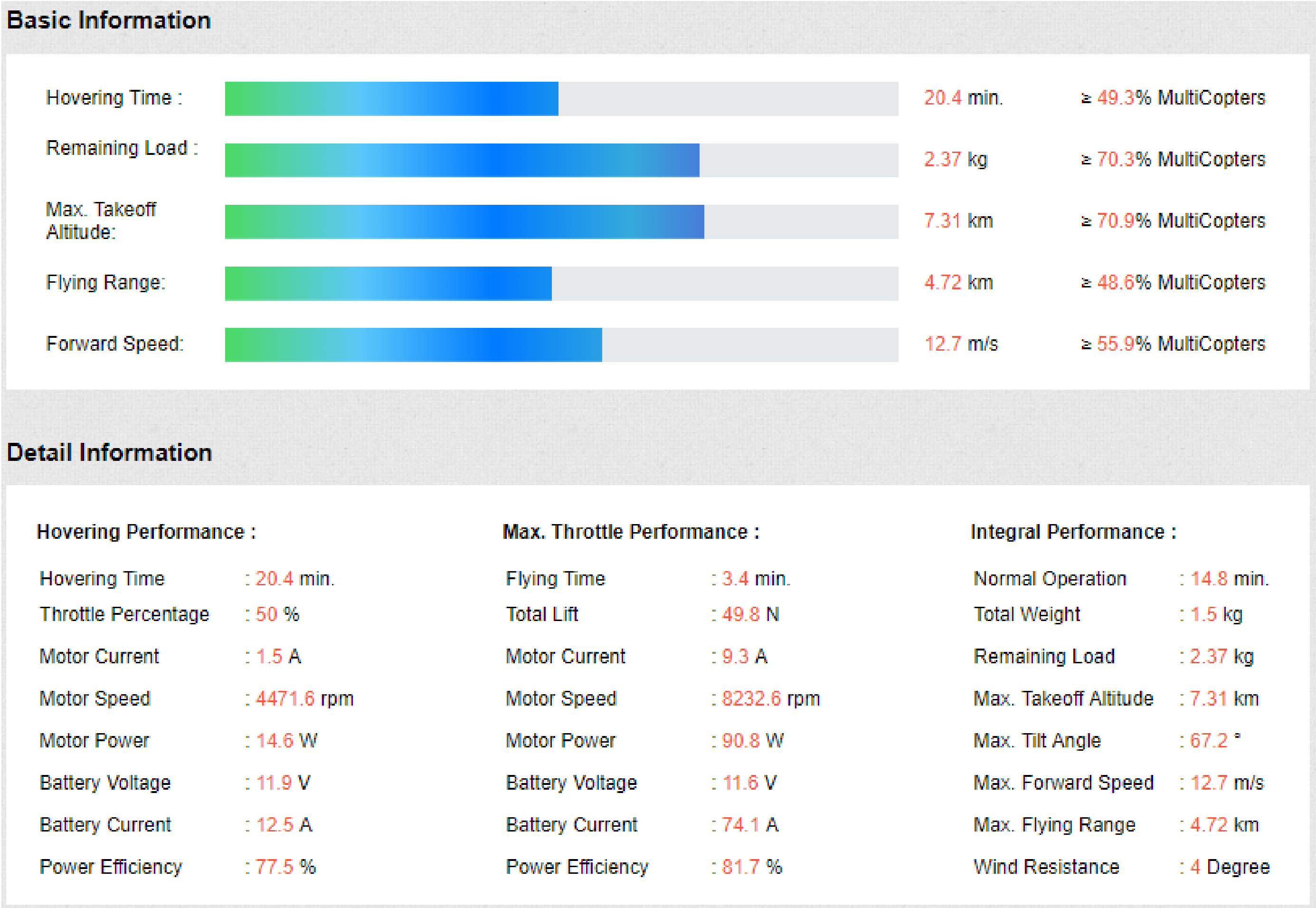


Figure. Octocopter performance

Basic Experiment

□ Remarks

（1） Diagonal size is too small

When the “Propeller Brand” option in the website is chosen as “CFP 10×3.8” (i.e, the diameter is 10 in ~ 25.4 mm), the minimum diagonal size for the tricopter is obtained from Eqs.（3.1） and （3.2）

diagnal size = 10×25.4/sin(180° /3) ×1.2

= 352 mm

Basic Experiment

☐ Remarks

（1） Diagonal size is too small

If the diagonal size is selected too small such as 100 mm, the website will return an error message.

An error message:

*** The vehicle body frame does not match with the chosen propeller, please change the body frame of the propeller**

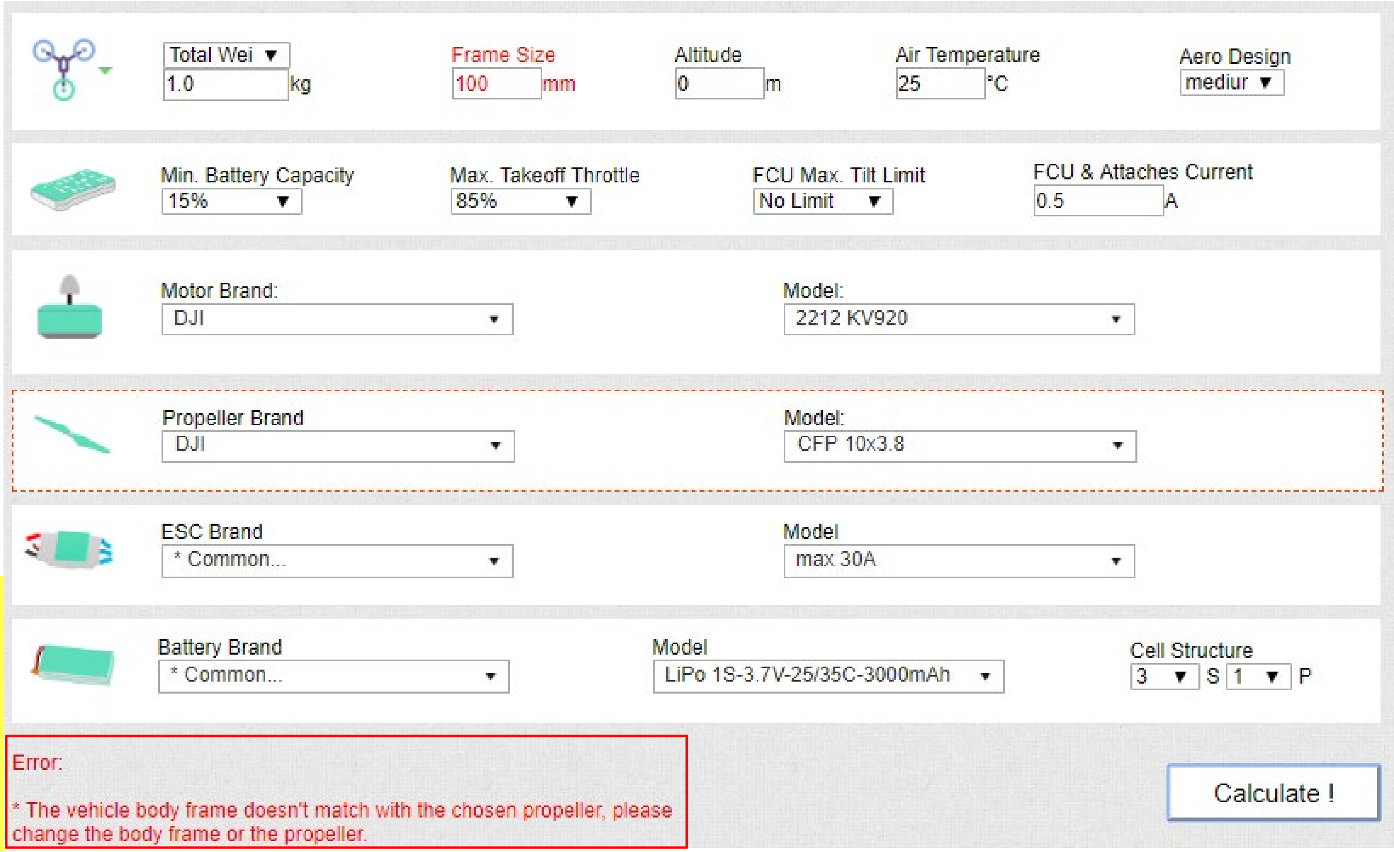


Figure. “Diagonal size is too small” error

Basic Experiment

Remarks

（2） Current is too large

An error message：

*** The motor current is excessive, please verify the limits (current, power, rpm) of the motor defined by the manufacturer.**

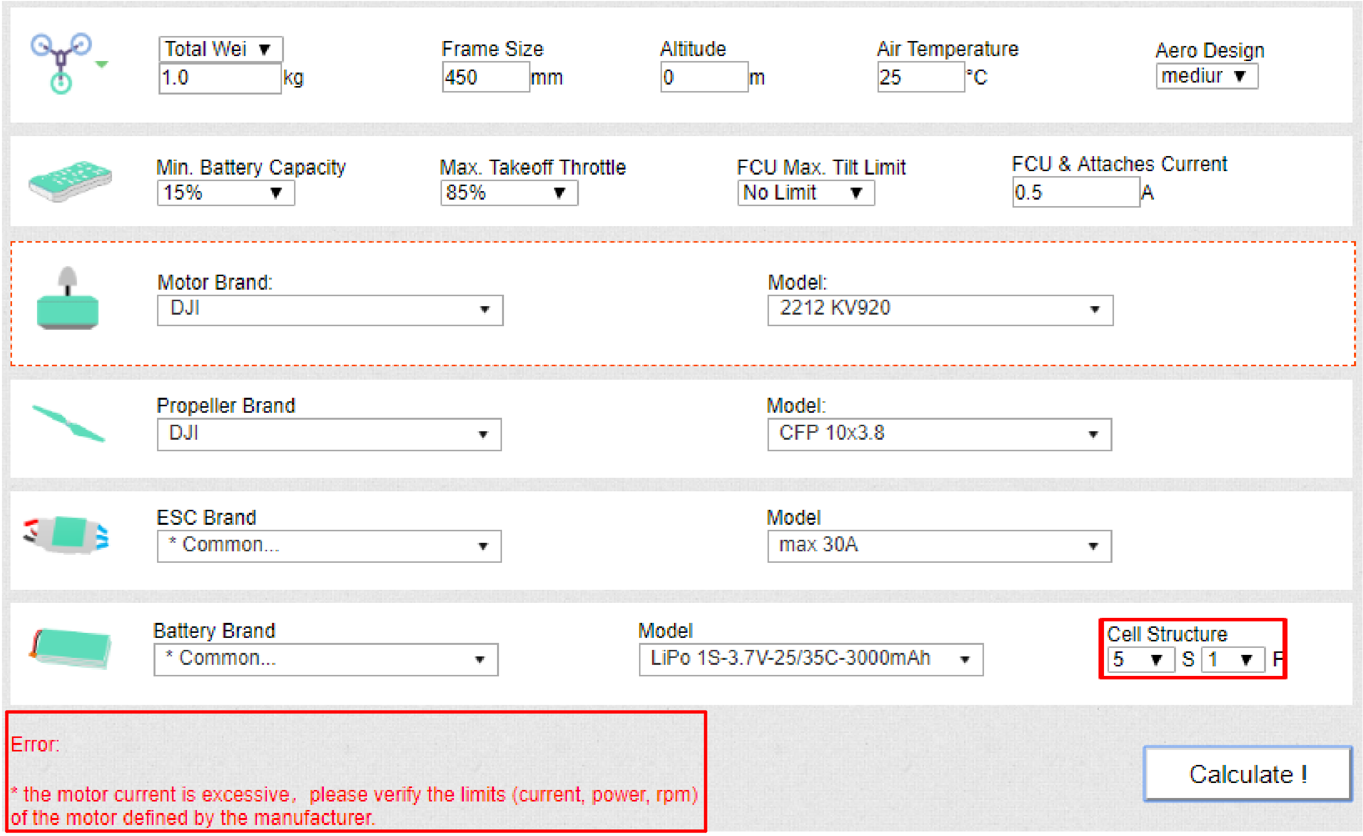


Figure. “Current is too large” error

Analysis Experiment

□ Experiment Objectives

■ Things to prepare

The experiment requires a quadcopter whose total weight is 1.5kg, and a scenario where the flight altitude is 50m and the local temperature is 25° C.

Table. Propulsion system parameters

Component	Parameters
Propeller	APC1045 (D_p=10 in, H_p=4.5 in, B_p=2), C_T=0.0984, C_M=0.0068
Motor	Sunnysky A2814-900 (K_{V0}=900 RPM/V, R_m=0.08 Ω, W_{mMax}=335 W, I_{eMax} = 0.6 A, U_{m0} = 10 V)
ESC	I_{eMax}=30 A, R_e=0.008 Ω
Battery	ACE (C_b=4000 mAh, U_b=12 V, R_b=0.0084 Ω, K_b = 65 C

Analysis Experiment

□ Experimental Objectives

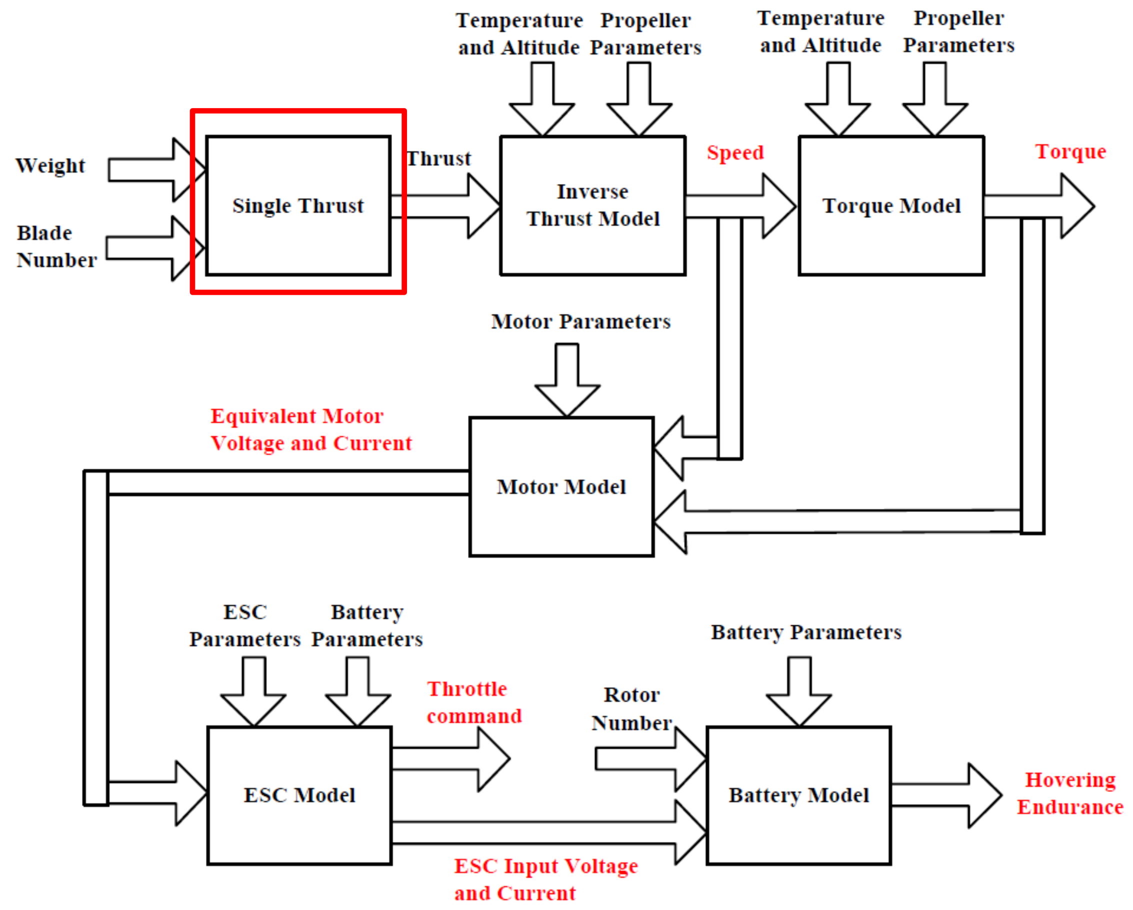
■ Objectives

（1）Show a detailed process for calculating the hover endurance and compare the obtained result with the result from the multicopter performance evaluation website https://flyeval.com/paper/;

（2）Calculate the hover endurance values under different temperature 0° C，10° C，20° C，30° C，40° C at different locations such as Beijing, Shanghai, Lhasa, and Changsha. Then, based on the obtained results, analyze the hover endurance with respect to altitude and temperature;

（3）Analyze the hover endurance with respect to the size and number of propellers.

Calculation Procedure for First Objective



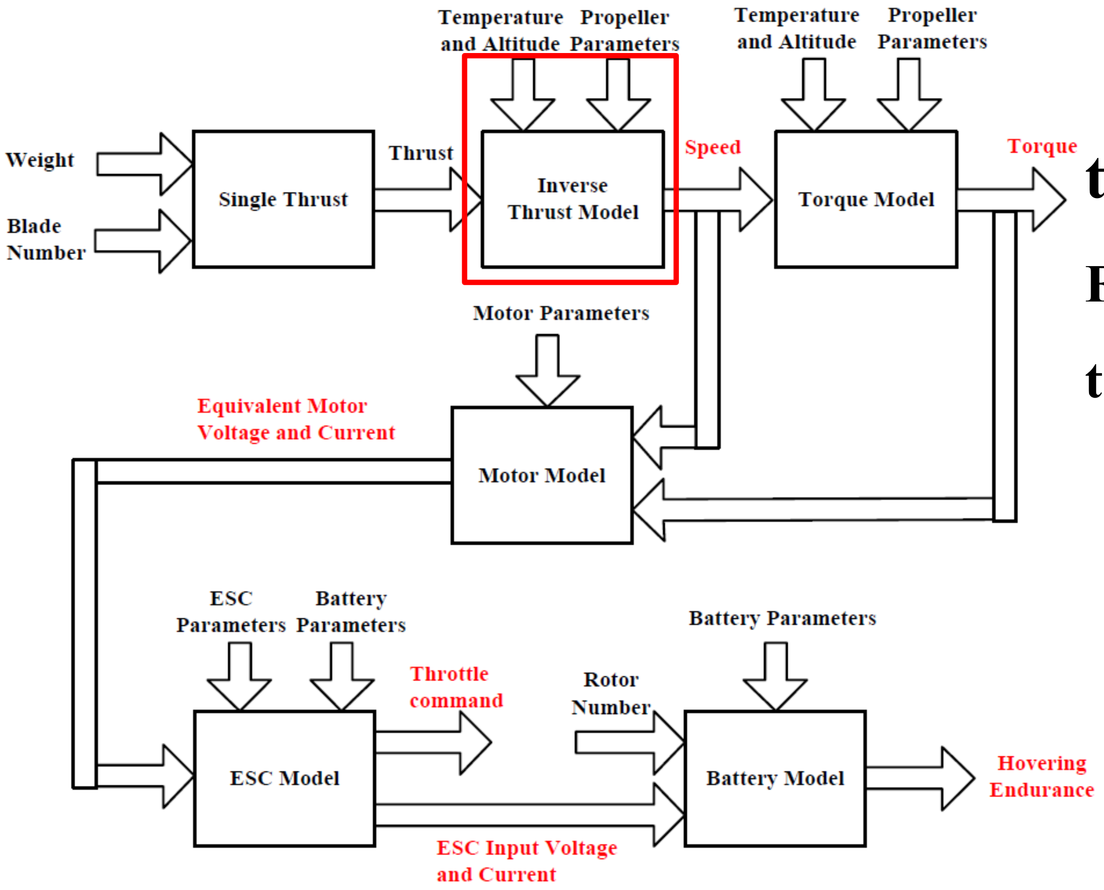
（1）Step1: Calculate the thrust

The thrust generated by a single propeller is calculated based on the total weight of the quadcopter as follows

$$T = \frac{G}{n_r} = \frac{1.5 \times 9.8}{4} = 3.675\text{N}$$

Analysis Experiment

◻ Calculation Procedure for First Objective



（2）Step2: The motor speed and the propeller torque is calculated based on the thrust model

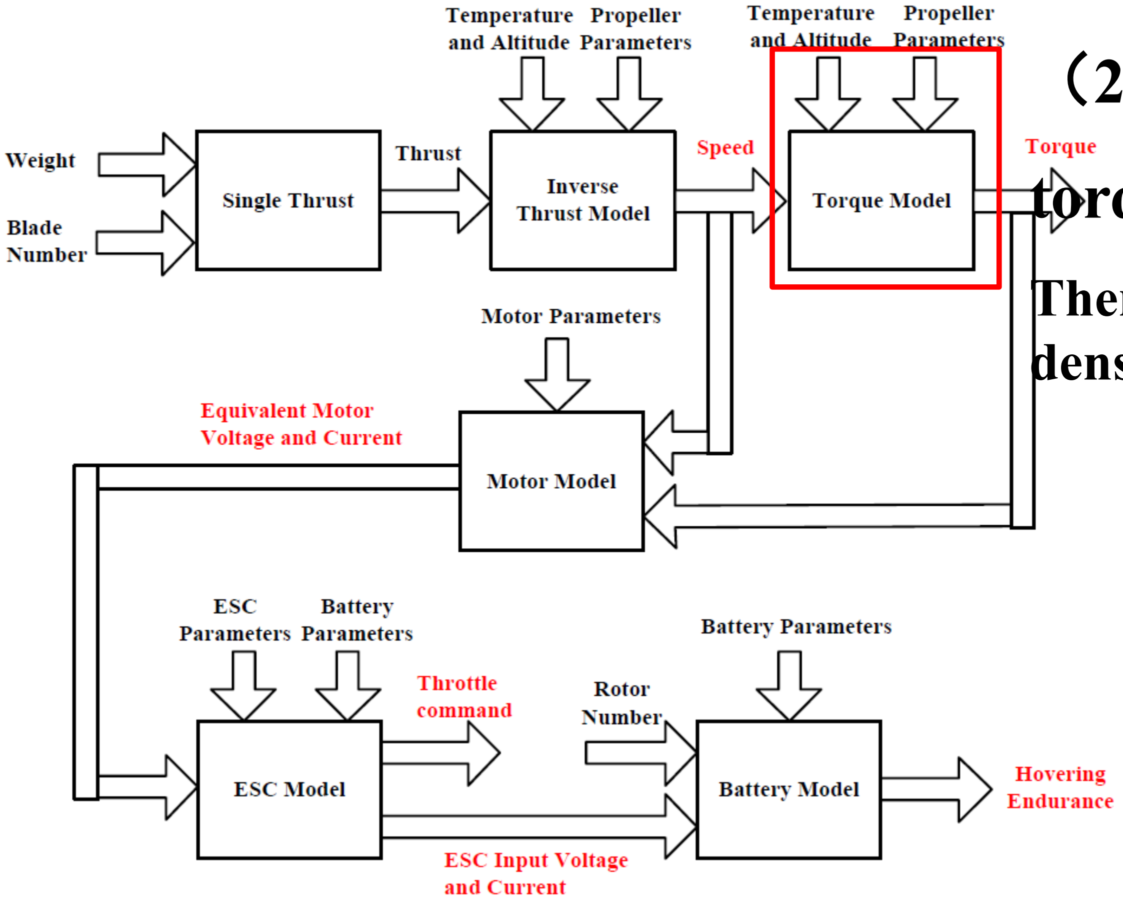
First of all, by using the flight altitude and the temperature, the atmospheric pressure is obtained as

$$P_a = 101325\left(1 - 0.0065\frac{h}{273 + T_t}\right)^{5.2561}$$

$$= 101325\left(1 - 0.0065\frac{50}{273 + 25}\right)^{5.2561}$$

$$= 100745.52\text{Pa}$$

Calculation Procedure for First Objective



（2）Step2: The motor speed and the propeller torque is calculated based on the thrust model

Then, by using the obtained atmospheric pressure, the air density is obtained

$$\rho = \frac{273P_a}{101325(273+T_t)}\rho_0 = \frac{273*100745.52}{101325(273+25)}1.293 = 1.178\,\mathrm{kg/m^3}$$

Analysis Experiment

□ Calculation Procedure for First Objective

（2）Step2: The motor speed and the propeller torque is calculated based on the thrust model

- by using the air density and the parameters of the propeller, the motor speed is

$$N = 60\sqrt{\frac{T}{\rho D_{\mathrm{p}}{}^{4} C_{\mathrm{T}}}}$$

$$= 60\sqrt{\frac{3.675}{1.178(10*25.4/1000)^{4}*0.0984}}$$

$$= 5236.51\mathrm{RPM}$$

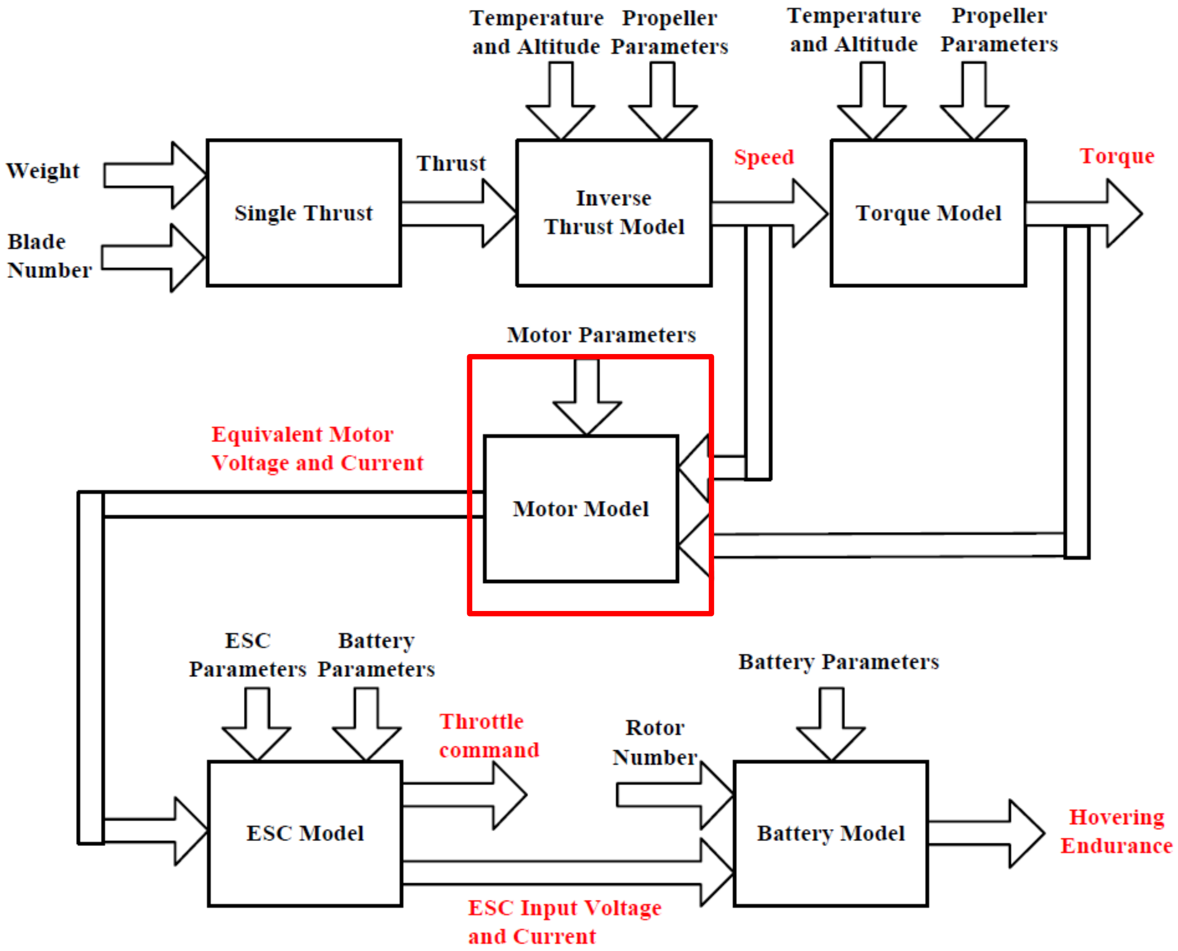
- the torque of the propeller is

$$M = \rho D_{\mathrm{p}}^{5} C_{\mathrm{M}} \left(\frac{N}{60}\right)^{2}$$

$$= 1.178*(10*25.4/1000)^{5}*0.0068*\left(\frac{5236.51}{60}\right)^{2}$$

$$= 0.0645\mathrm{N}\cdot\mathrm{m}$$

Analysis Experiment

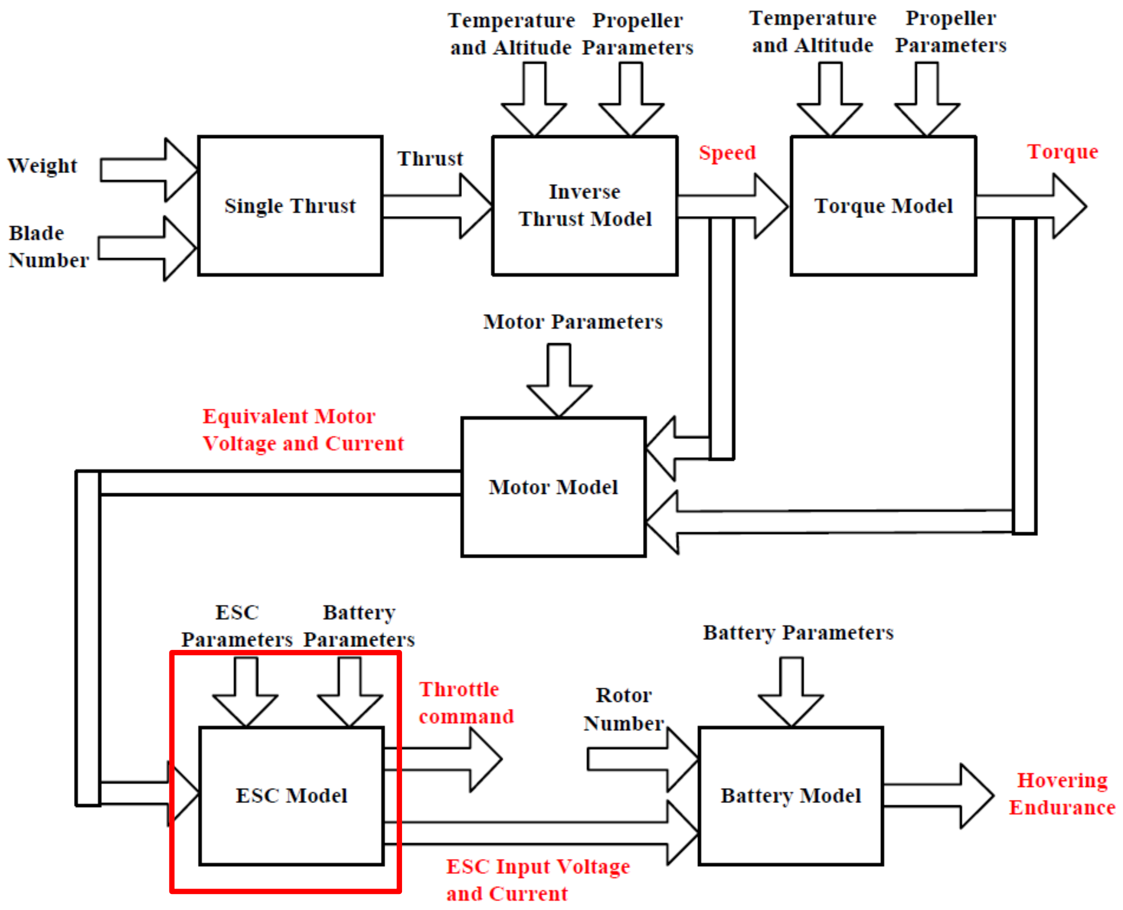


(3) Step3: The equivalent motor current I_m and the equivalent motor voltage U_m is calculated based on the motor model

$$I_m = \frac{MK_{V0}U_{m0}}{9.55(U_{m0} - I_{m0}R_m)} + I_{m0} = \frac{0.0645*900*10}{9.55(10-0.6*0.08)} + 0.6 = 6.708A$$

$$U_m = \left(\frac{MK_{V0}U_{m0}}{9.55(U_{m0} - I_{m0}R_m)} + I_{m0}\right)R_m + \frac{U_{m0} - I_{m0}R_m}{K_{V0}U_{m0}}N = \left(\frac{0.0645*900*10}{9.55(10-0.6*0.08)} + 0.6\right)*0.08 + \frac{10-0.6*0.08}{900*10}5236.51 = 6.327V$$

Analysis Experiment



（4）Step4:

The ESC input throttle σ :

$$\sigma = \frac{U_m + I_m R_e}{U_b} = \frac{6.327 + 6.708 * 0.008}{12} = 0.532$$

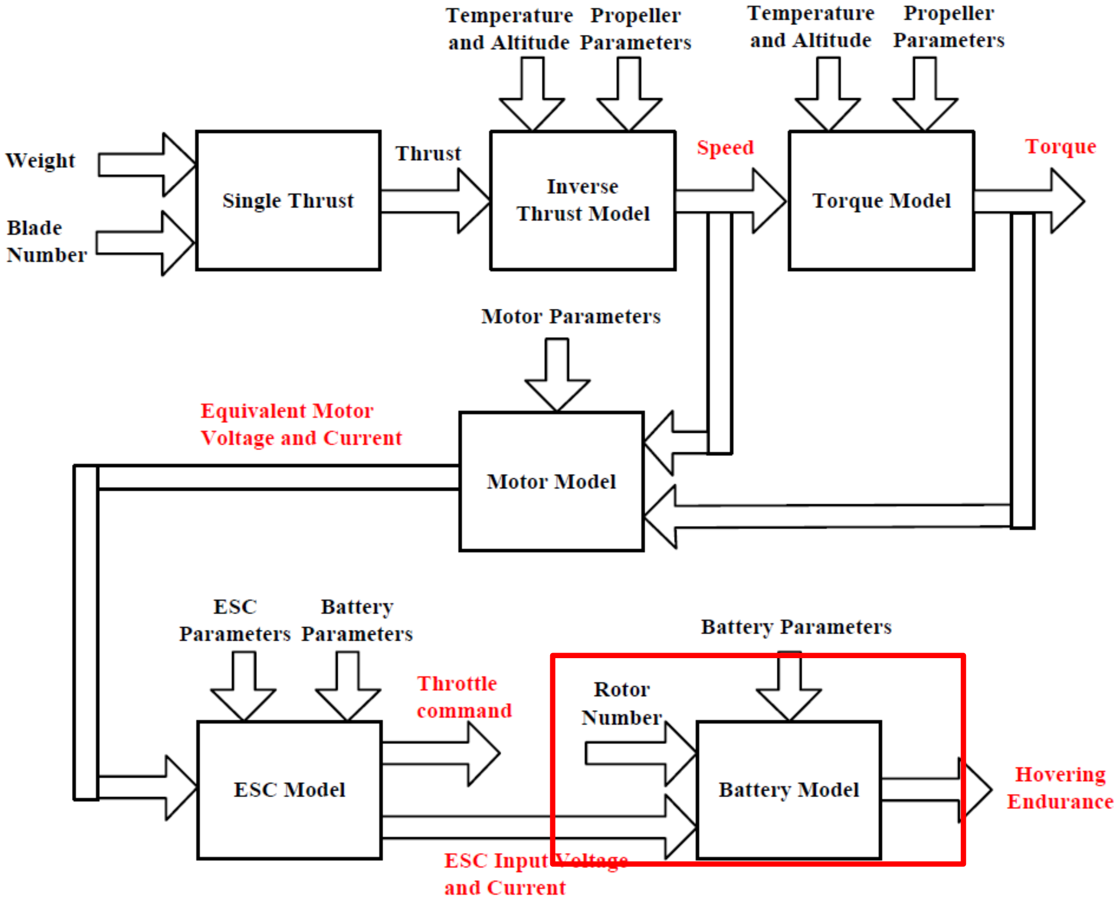
the ESC input current I_e :

$$I_e = \sigma I_m = 0.532 * 6.708 = 3.567A$$

the ESC input voltage U_e :

$$U_e = U_b - I_b R_b = 12 - 14.768 * 0.0084 = 11.876\text{V}$$

Analysis Experiment



(5) Step5: The hover enduranceis calculated based on the battery capacity and the battery current model

- **the battery current I_b :**

$$\begin{aligned} I_b &= n_r I_e + I_{other} \\ &= 4 \times 3.567 + 0.5 \\ &= 14.768\text{A} \end{aligned}$$

- **the minimum battery capacity is taken as 15% of the total capacity, hover endurance T_b:**

$$\begin{aligned} T_b &= \frac{C_b - C_{\min}}{I_b} \times \frac{60}{1000} \\ &= \frac{4000 - 4000 \times 0.15}{14.768} \times \frac{60}{1000} \\ &= 13.8\ \text{min} \end{aligned}$$

Analysis Experiment

□ Calculation Procedure for First Objective

（6） Step6: The result calculated above is verified by using the multicopter performance evaluation website

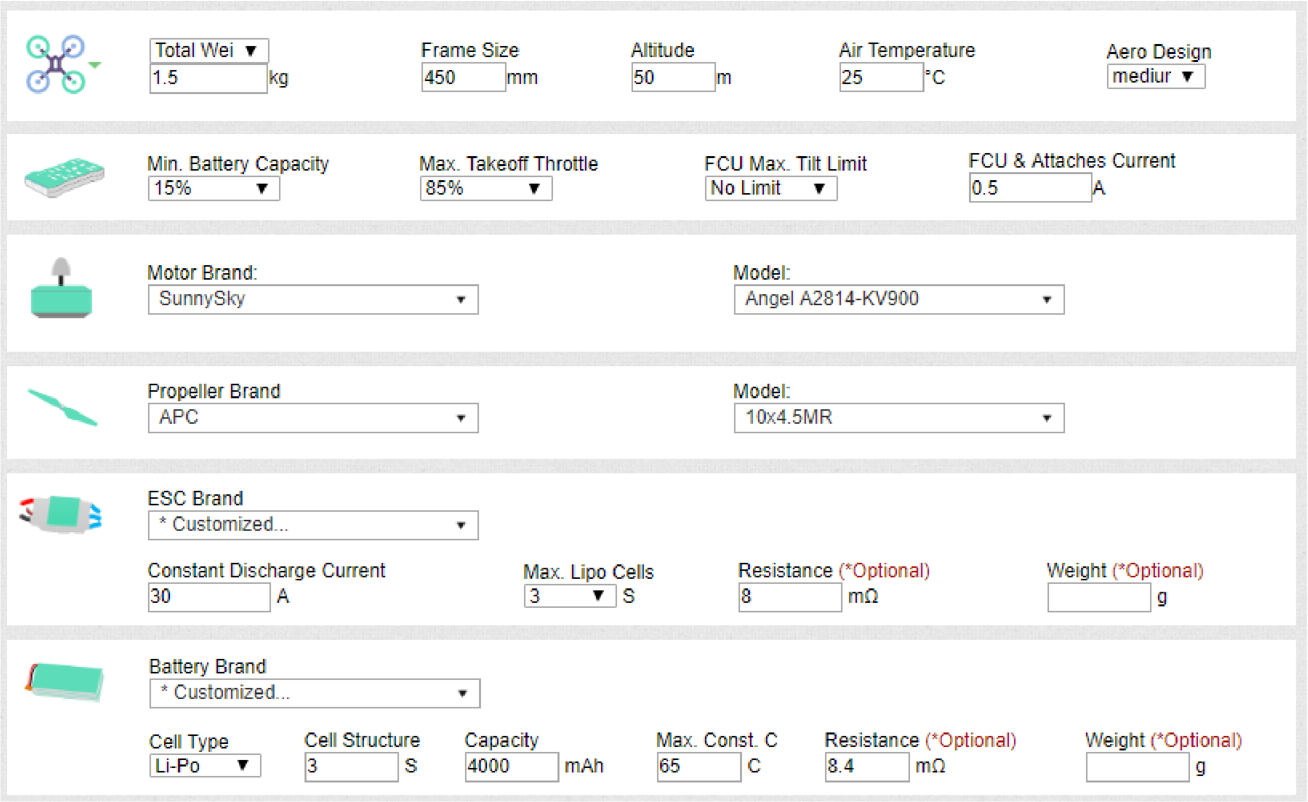


Figure. Quadcopter configuration

Analysis Experiment

☐ Calculation Procedure for First Objective

the obtained result is

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 13.8 min.	Flying Time	: 2.9 min.	Normal Operation	: 10.3 min.
Throttle Percentage	: 53.7 %	Total Lift	: 41.4 N	Total Weight	: 1.5 kg
Motor Current	: 3.56 A	Motor Current	: 17.7 A	Remaining Load	: 1.76 kg
Motor Speed	: 5235.8 rpm	Motor Speed	: 8788.1 rpm	Max. Takeoff Altitude	: 6.14 km
Motor Power	: 35.2 W	Motor Power	: 166.6 W	Max. Tilt Angle	: 62.6 °
Battery Voltage	: 11.9 V	Battery Voltage	: 11.4 V	Max. Forward Speed	: 14.7 m/s
Battery Current	: 14.7 A	Battery Current	: 71 A	Max. Flying Range	: 4.43 km
Power Efficiency	: 79.6 %	Power Efficiency	: 78.3 %	Wind Resistance	: 5 Degree

It can be observed that the calculated hover endurance is consistent with the result on the multicopter performance evaluation website

Analysis Experiment

☐ Analysis Procedure for Second Objective

The basic configuration parameters of our chosen testing multicopter are shown

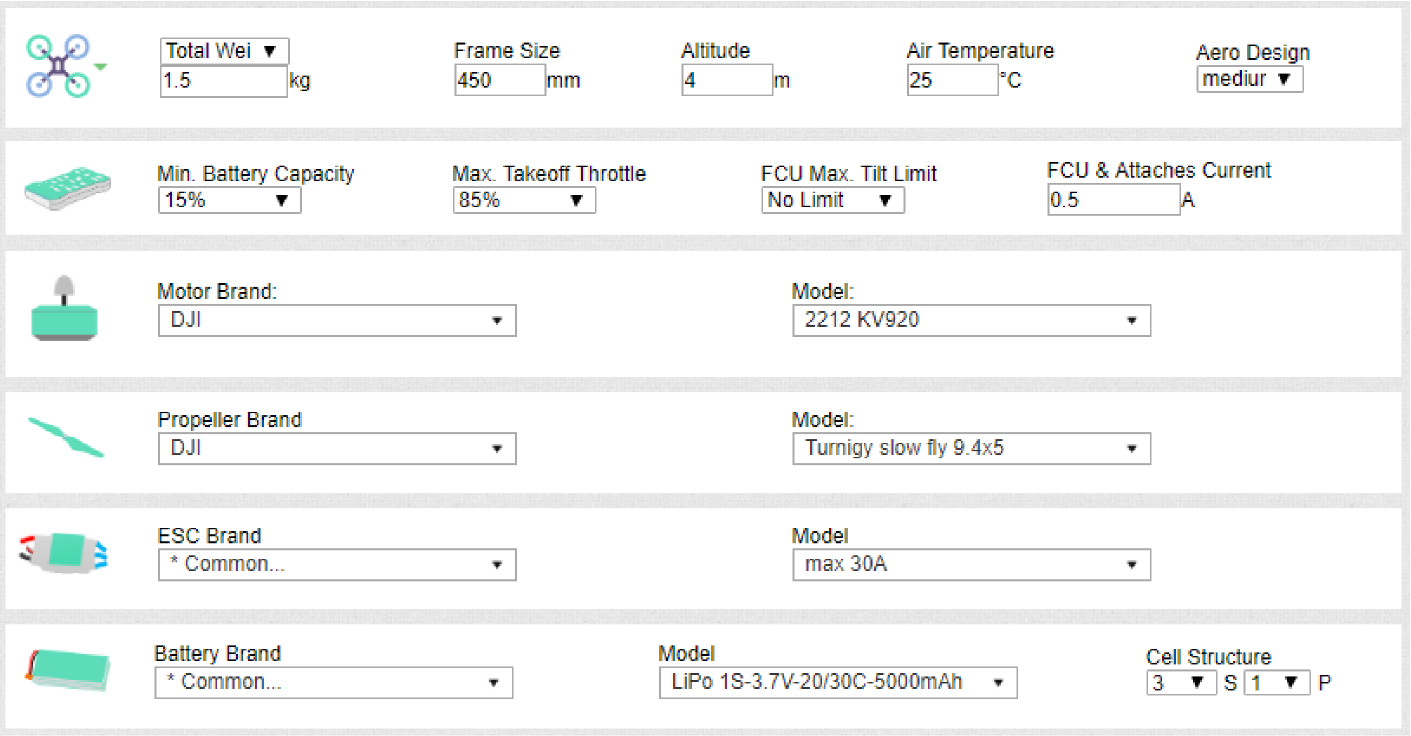


Figure. Multicopter configuration for temperature test

Analysis Experiment

□ Analysis Procedure for Second Objective

（1）Step1: Hover endurance with respect to altitude

With the other configurations unchanged, the altitude is modified, and then a table of hover endurance at a different altitude is obtained.

Table. Hover endurance with respect to altitude

Site	Altitude/m	Hover endurance/min
Shanghai	4	16.5
Beijing	43.5	16.5
Changsha	500	16.1
Lhasa	3658	13.5

Analysis Experiment

□ Analysis Procedure for Second Objective

Table. Hover endurance with respect to altitude

Site	Altitude/m	Hover endurance/min
Shanghai	4	16.5
Beijing	43.5	16.5
Changsha	500	16.1
Lhasa	3658	13.5

A conclusion can be drawn that the higher the altitude is, the shorter the hover endurance will be. This is because the air density is decreased as the altitude is increased. When the propeller thrust is the same, the smaller the air density is, the greater the motor speed will be. When the propeller torque is constant, the higher the motor speed is, the larger the equivalent motor voltage will be. Furthermore, the ESC input current will be increased, and then the battery discharge current will be also increased. Therefore, when the battery capacity is constant, the higher the battery current is, the shorter the hover endurance is. These results, as given by the website, are consistent with theoretical analysis.

☐ Analysis Procedure for Second Objective

（2）Step2: Hover endurance with respect to temperature

Table. Hover endurance with respect to temperature

Temperature/°C	Hove endurance/min
0	17.1
10	16.8
20	16.6
30	16.3
40	16.1

With the other configurations left unchanged, the temperature is modified, and then a table of hover endurance at different temperatures is obtained. According to Table 5.4, one can conclude that the higher the temperature is, the shorter the hover endurance is, as the air density decrease with increased temperature. By recalling the conclusion of the altitude test, one can further conclude that the lower the air density is, the shorter the hover endurance is.

Analysis Experiment

☐ Analysis Procedure for Third Objective

（1）Step1: Hover endurance with respect to propeller size

The "Frame Size" is set to 450mm， r_{max}=1.1r_p, and the radius r_p is selected from choices up to 11.4 in. The hover endurance with respect to propeller size is obtained as

Table. Hover endurance with respect to propeller size

Propeller size(in)	Hove endurance(min)
10	17
9.4	16.5
9	15.9
8	14.5

One can conclude that the larger the propeller is, the longer the hover endurance is.

□ Analysis Procedure for Third Objective

（2）Step4: Hover endurance with respect to the number of propellers

A table can be obtained by modifying the "Frame Shape"

Table. Hover endurance with respect to the number of propellers

Type	Hover endurance/min
Octocopter	18.4
Coaxial octocopter	17.2
Hexacopter	16.8
Quadcopter	14.5
Coaxial hexacopter	15.5
Tricopter	too heavy to take off

Analysis Experiment

☐ Analysis Procedure for Third Objective

Table. Hover endurance with respect to the number of propellers

Type	Hover endurance/min
Octocopter	18.4
Coaxial octocopter	17.2
Hexacopter	16.8
Quadcopter	14.5
Coaxial hexacopter	15.5
Tricopter	too heavy to take off

one can conclude that when the number of propellers is equal, the hover endurance is shorter for a coaxial multicopter. For example, a coaxial octocopter has a shorter hover endurance than a corresponding octocopter. However, it should be noted that the coaxial multicopter has a smaller size than a corresponding multicopter with the same propellers. In general, when the total weight is the same, the more the number of propellers is, the longer the hover endurance is.

Design Experiment

□ Experimental Objectives

- **Things to prepare**
  The multicopter performance evaluation website
  https://flyeval.com/paper/.

Dongjie Shi, Xunhua Dai, Xiaowei Zhang, and Quan Quan. A Practical Performance Evaluation Method for Electric Multicopters. IEEE/ASME Transactions on Mechatronics. 2017, 22(3):1337-1348.

Design Experiment

■ **Objectives**

(1) Design a multicopter. The altitude is 0 m, the local temperature is 25° C, the load weight is 1.0kg, the weight of airframe, autopilot, and other accessories is also 1.0kg, the total weight is lighter than 5kg, the circumferential circle radius is smaller than 39.37 in (approximately 1 m), the hover endurance is longer than 15min, and the hover throttle is less than 65% of the full throttle;

(2) The configuration parameters and basic flight performance parameters of the multicopters should be listed and compared with the results from multicopter the performance evaluation website https://flyeval.com/paper/.

Design Experiment

☐ The way of design

Select the motor based on the thrust of a single propeller

Select ESC and the battery based on the maximum current of the motor

Determine the size of the propeller

（1）**Select the motor based on the thrust of a single propeller.** Each motor manufacturer will provide the single-axis take-off weight of the motor, the thrust that can be provided under different currents, and the size of the propeller will be recommended. These data are obtained based on experiments by the motor manufacturer and can be used as a reference for designing multicoptors.

Design Experiment

☐ The way of design

Select the motor based on the thrust of a single propeller

Select ESC and the battery based on the maximum current of the motor

Determine the size of the propeller

（2）After the motor is selected, the ESC can be selected based on the maximum current of the motor, and the battery is selected based on the motor voltage, motor current and hover endurance when the quadcopter is hovering.

（3）The size of the propeller can be chosen based on the propeller size recommended by the motor manufacturer and the relationship between the maximum size of the frame and the propeller.

Design Experiment

◻ Steps

（1）Step1: Choose to design a quadcopter

（2）Step2: Determine the thrust of a single propeller

Determine the thrust of a single propeller based on the total weight

$$T = \frac{5}{4} \times 9.8 = 12.25\text{N}$$

T is the thrust when the quadcopter is hovering, To leave a safety margin, the maximum thrust of a single propeller is 24.5N.

（3）Step3: Based on the maximum size limit of the quadcopter

calculate the maximum size of the propeller

$$r_{\max} = R \times \sin\frac{\theta}{2} = \frac{1}{2} \times \sin\frac{180}{4} = 353\text{mm}$$

In order to leave a safety margin, the maximum size of propeller has to satisfy as

$$r_p = r_{\max} / (1.05 \sim 1.2) = 346 \sim 294\text{mm}$$

The size of the propeller is often expressed in diameter and the maximum size of the propeller is between 27.2 in and 31 in.

Design Experiment

Steps

（4）Step4: Select a motor

Appropriate motors are selected by browsing the manufacturer's official website, such as T-MOTOR motors. Readers can go to the T-MOTOR official website:

http://uav-en.tmotor.com/

to select multicopters and the MN4014 motor in the MN series is selected such as the right figure.

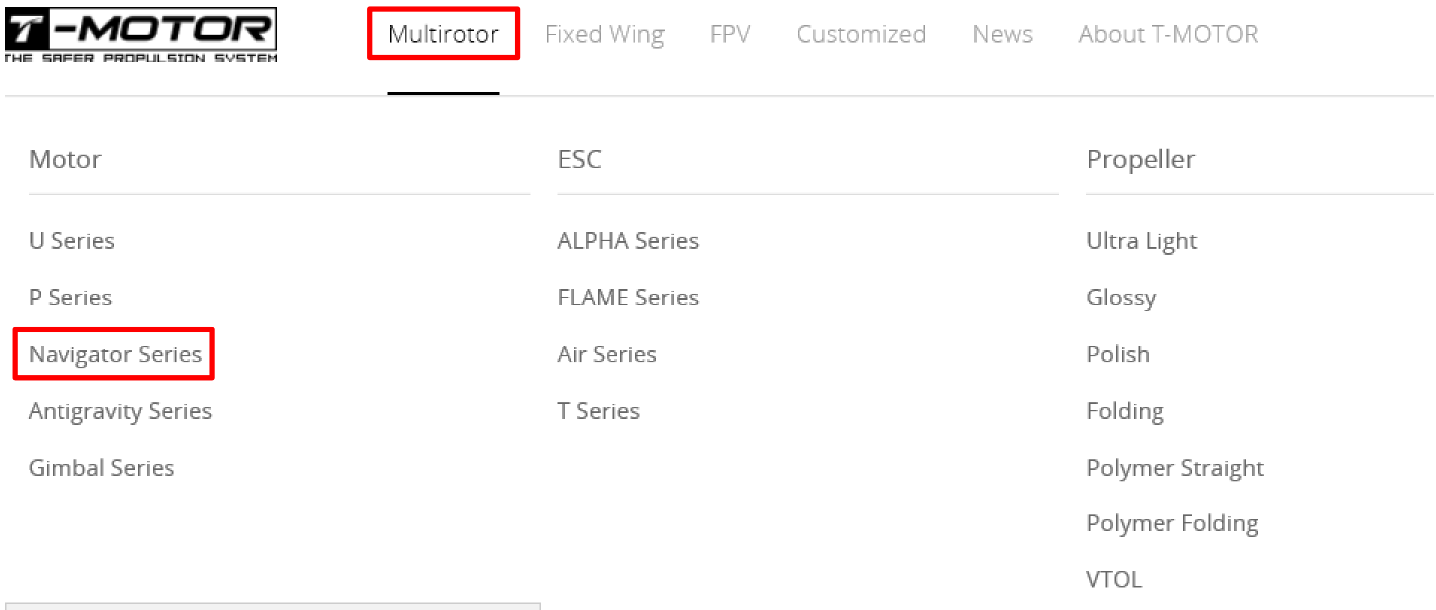


Figure. T-MOTOR motor selection interface

Design Experiment

☐ Steps

Load Testing Data									
Ambient Temperature		/			Voltage			DC Power Supplier	
Item No.	Voltage (V)	Prop	Throttle	Current (A)	Power (W)	Thrust (G)	RPM	Efficiency (G/W)	Operating Temperature (℃)
MN4014 KV330	22.2	T-MOTOR 15*5CF	50%	3.6	79.92	830	3900	10.39	45
			65%	5.9	130.98	1150	4600	8.78	
			75%	7.8	173.16	1430	5100	8.26	
			85%	10.1	224.22	1690	5600	7.54	
			100%	11.9	264.18	1920	6000	7.27	
		T-MOTOR 16*5.4CF	50%	4.3	95.46	950	3700	9.95	50
			65%	7	155.40	1420	4400	9.14	
			75%	9.6	213.12	1750	4900	8.21	
			85%	12.5	277.50	2060	5400	7.42	
			100%	14.7	326.34	2390	5600	7.32	
		T-MOTOR 17*5.8CF	50%	4.7	104.34	1050	3400	10.06	55
			65%	8	177.60	1580	4100	8.90	
			75%	10.7	237.54	1970	4600	8.29	
			85%	14.4	319.68	2300	5100	7.19	
			100%	17	377.40	2600	5400	6.89	

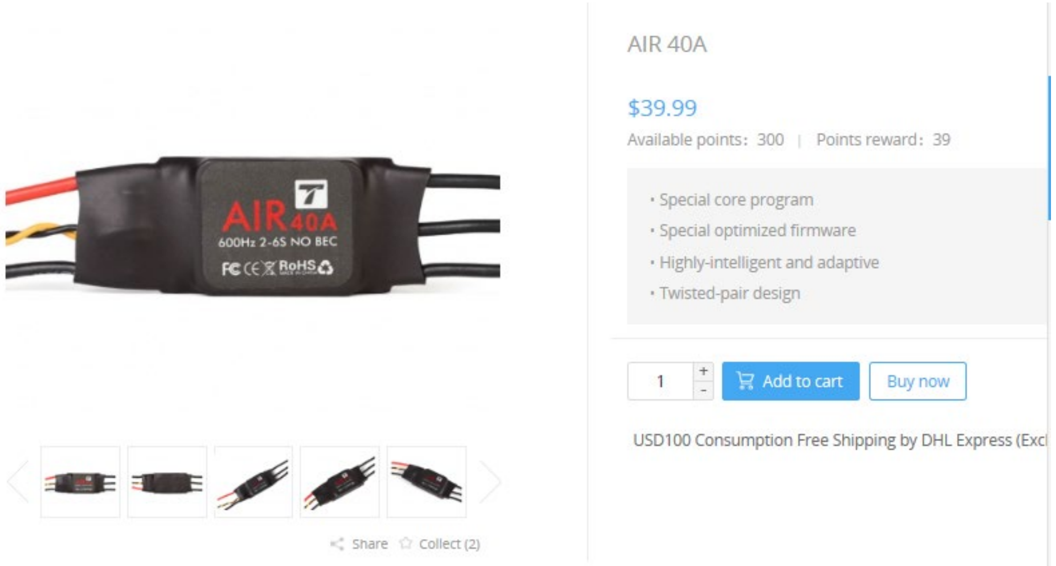
In"Load Testing Data", readers can observe the thrust of the motor under different throttle values. When the voltage is 22.2V and the propeller is T-MOTOR 15× 5 CF, the max thrust is 1.92 kg.

Figure. Motor specifications

Design Experiment

☐ Steps

（5）Step5: Select an ESC



SPECIFICATIONS

Model	Con,Current	Peak Current (10S)	BEC	Lipo	programmable Item	Weight	Size(L*W*H)
AIR 40A	40A	60A	NO	2-6S	Timing (Intermediate/High)	26g	55.6mm*25.2mm*11.3mm

Figure. T-MOTOR ESC selection interface

If “T-MOTOR ESC” is selected and the maximum current of the selected motor is 25 A, then the “AIR 40A ESC” with a continuous current of 40A is selected.

Design Experiment

☐ Steps

（6）Step6: Select a propeller

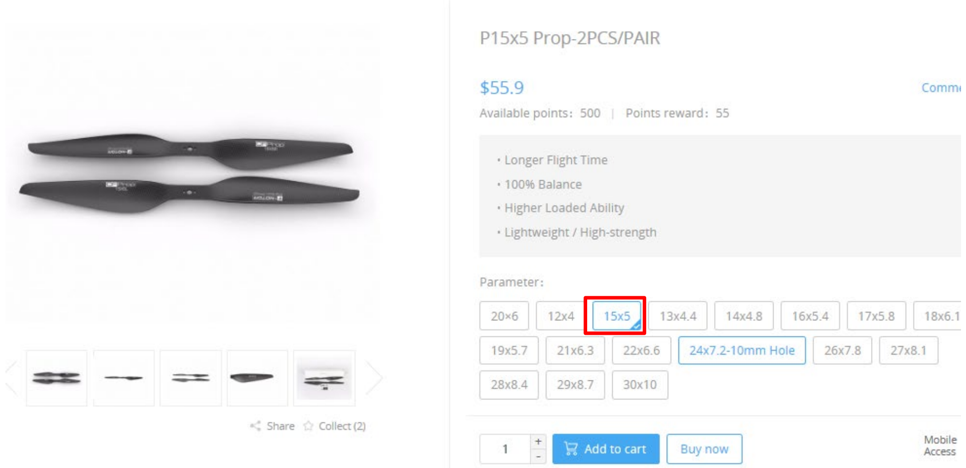


Figure. T-MOTOR propeller

Specifications			
Diameter/Pitch	15" *5 (381mm*127mm)	Working Temp	-40℃ ~ 65℃
Weight (single propeller)	26.5g	Storage Temp	-10℃ ~ 50℃
Material	CF+Epoxy	Storage Humidity	<85%
Surface Treatment	Polished	Optimum RPM	5200-7000 RPM/min
Propeller type	2blades-integrated	Thrust Limitation	6kg

Figure. Specifications of T-MOTOR

Here, the T-MOTOR propeller is selected. Moreover, according to the matches being offered, the P15×5 propeller is selected. From the basic parameters, the weight of a single propeller is 26.5g.

Design Experiment

◻ Steps

（7） Step7: Select a battery

Here, if GENSACE batteries are selected, readers can go to search the desired products on E-commerce Sites and then select the high voltage version.

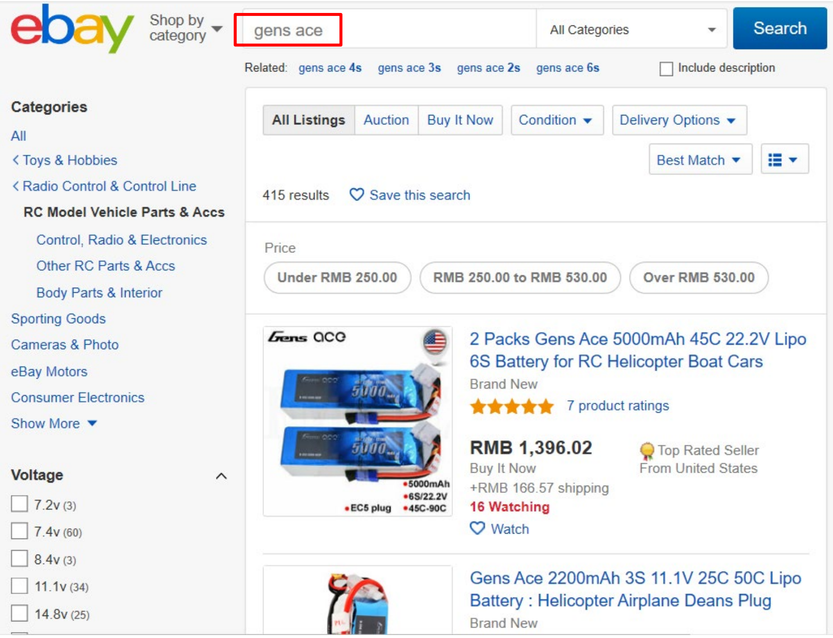


Figure. GENS ACE batteries

If a 12000mAh battery is selected, according to the motor, ESC and propeller selected above, the total weight is as follows

$$G=\left(2+\left(0.171+0.026+0.0265\right)\times 4+1.46\right)\times 9.8=42.6692\ \mathrm{N}$$

Then, the thrust provided by a single propeller is as follows

$$T_{\mathrm{h}}=\frac{\mathrm{G}}{4}\times 9.8=10.6673\mathrm{N}.$$

The throttle at this time is less than 65% of the full throttle. Then, it can be determined that the thrust is 10.662N and the motor current is 5.78 A, by using simple linear interpolation between 50% and 65% of the throttle. The hover endurance is calculated as

$$T=\frac{C_{\mathrm{b}}-C_{\min}}{I_{\mathrm{b}}}\cdot\frac{60}{1000}=\frac{0.85\times 16000}{5.78\times 4+0.5}*0.06=25.9\,\mathrm{min}$$

Design Experiment

☐ Steps

（8）Step8: Recalculate the diagonal size

The diagonal size is recalculated based on the size of propeller

$$2R = \frac{2 \times r_p}{\sin\left(\dfrac{180}{n_{\mathrm{r}}}\right)} = \frac{15 \times 25.4}{\sin(180/4)} = 539\mathrm{mm}$$

To leave a safety margin, a diagonal size of 600mm is adopted.

Design Experiment

□ Steps

（9）**Step9: Compare with the basic configuration set on the performance evaluation website https://flyeval.com/paper/.**

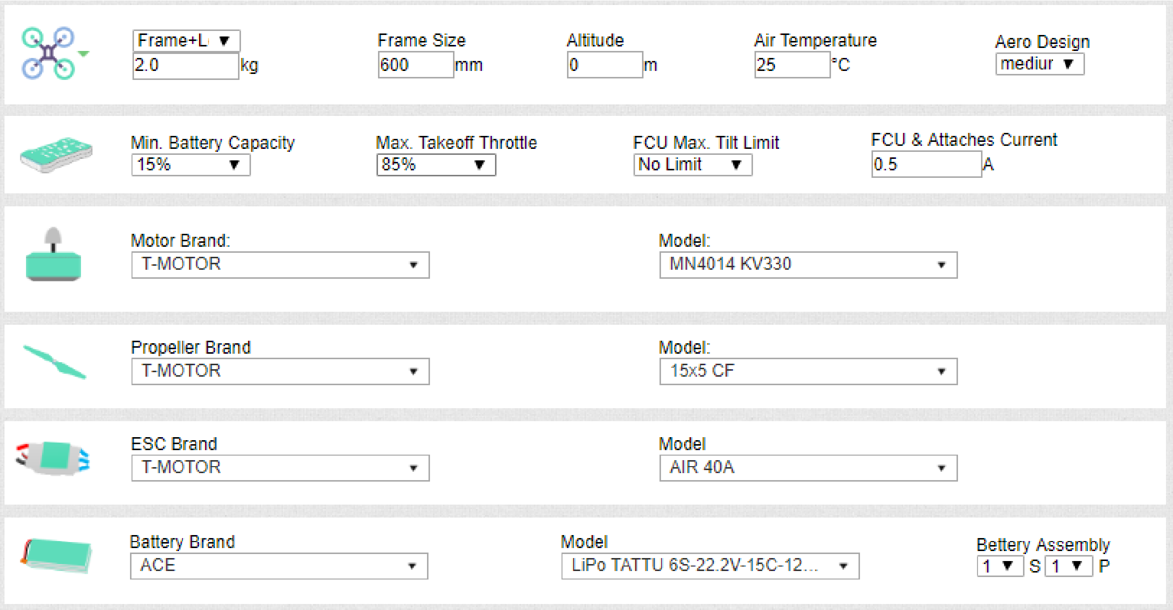


Figure. Multicopter configuration for design experiment

Design Experiment

□ Steps

Detail Information

Hovering Performance :		Max. Throttle Performance :		Integral Performance :	
Hovering Time	: 22.5 min.	Flying Time	: 7 min.	Normal Operation	: 17.8 min.
Throttle Percentage	: 63.6 %	Total Lift	: 94.3 N	Total Weight	: 4.56 kg
Motor Current	: 6.69 A	Motor Current	: 21.8 A	Remaining Load	: 2.8 kg
Motor Speed	: 4623.5 rpm	Motor Speed	: 6716.3 rpm	Max. Takeoff Altitude	: 3.85 km
Motor Power	: 132.2 W	Motor Power	: 417.8 W	Max. Tilt Angle	: 51.7 °
Battery Voltage	: 23.7 V	Battery Voltage	: 22.9 V	Max. Forward Speed	: 12.4 m/s
Battery Current	: 27.2 A	Battery Current	: 87.3 A	Max. Flying Range	: 8.5 km
Power Efficiency	: 80.9 %	Power Efficiency	: 79.8 %	Wind Resistance	: 4 Degree

Figure. Flight performance of designed multciopter

It can be concluded that the hover endurance calculated by the website is close to the hover endurance by estimated. The remaining load of the aircraft is still very large and about 5.44kg. If want to continue to increase the battery life, the readers can increase the battery capacity without changing the overall structure.

Summary

(1) The performance evaluation of a multicopter can be easily obtained through the multicopter performance evaluation website https://flyeval.com/paper/. After the propulsion system and flight environment are set, performance results can be obtained, such as the hover endurance, available payload, one-way flight distance, and maximum forward flight speed.

(2) Based on the propeller, motor, ESC, and battery model we have established, the hover endurance of a multicopter can be estimated with the given propeller parameters, motor parameters, ESC parameters, and battery parameters. Under the same condition, according to the above model analysis, it can be inferred that the higher the altitude or the higher the temperature is, the shorter the hover endurance is; the larger the radius of the propeller or the more the number of propellers is, the longer the hover endurance is.

Summary

(3) Given the flight environment of a multicopter, load capacity, maximum weight, maximum size, and minimum hover endurance, readers can select the propulsion system that meets their design requirements based on the product data provided by the manufacturers of the motor, ESC, propeller, and battery.

(4) The following modeling experiments (in Chapter 6) are based on the parameters generated by this experiment.

Thanks