Introduction to Multicopter Design and Control

Lesson 02 Basic Composition

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Preface

What are the basic compositions of a multicopter system?

Outline

1. Introduction
2. Airframe
3. Propulsion System
4. Command and Control System
5. Conclusion

1. Introduction

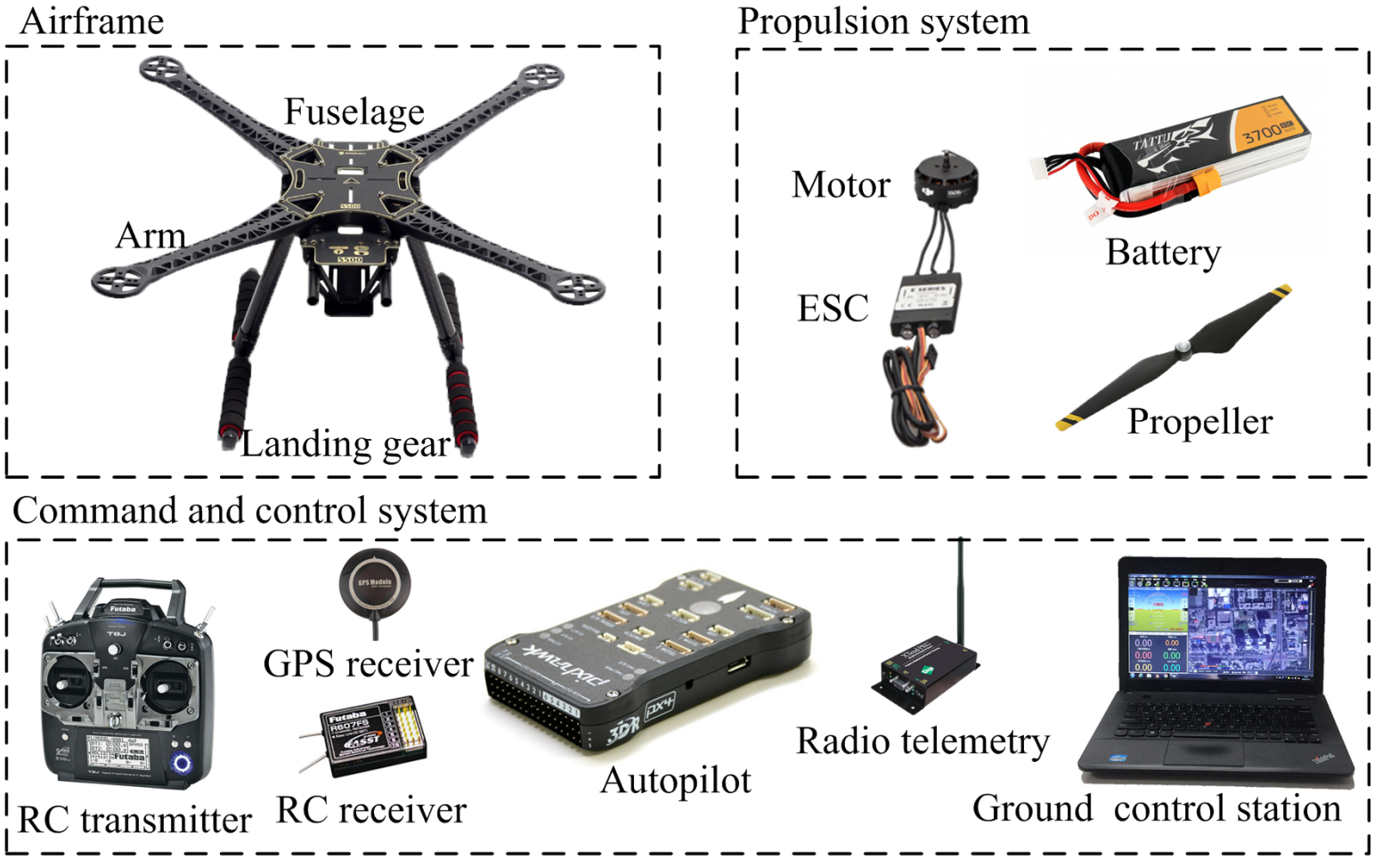


Figure 2.1 Basic composition of a multicopter, from http://ardupilot.com/

1. Introduction

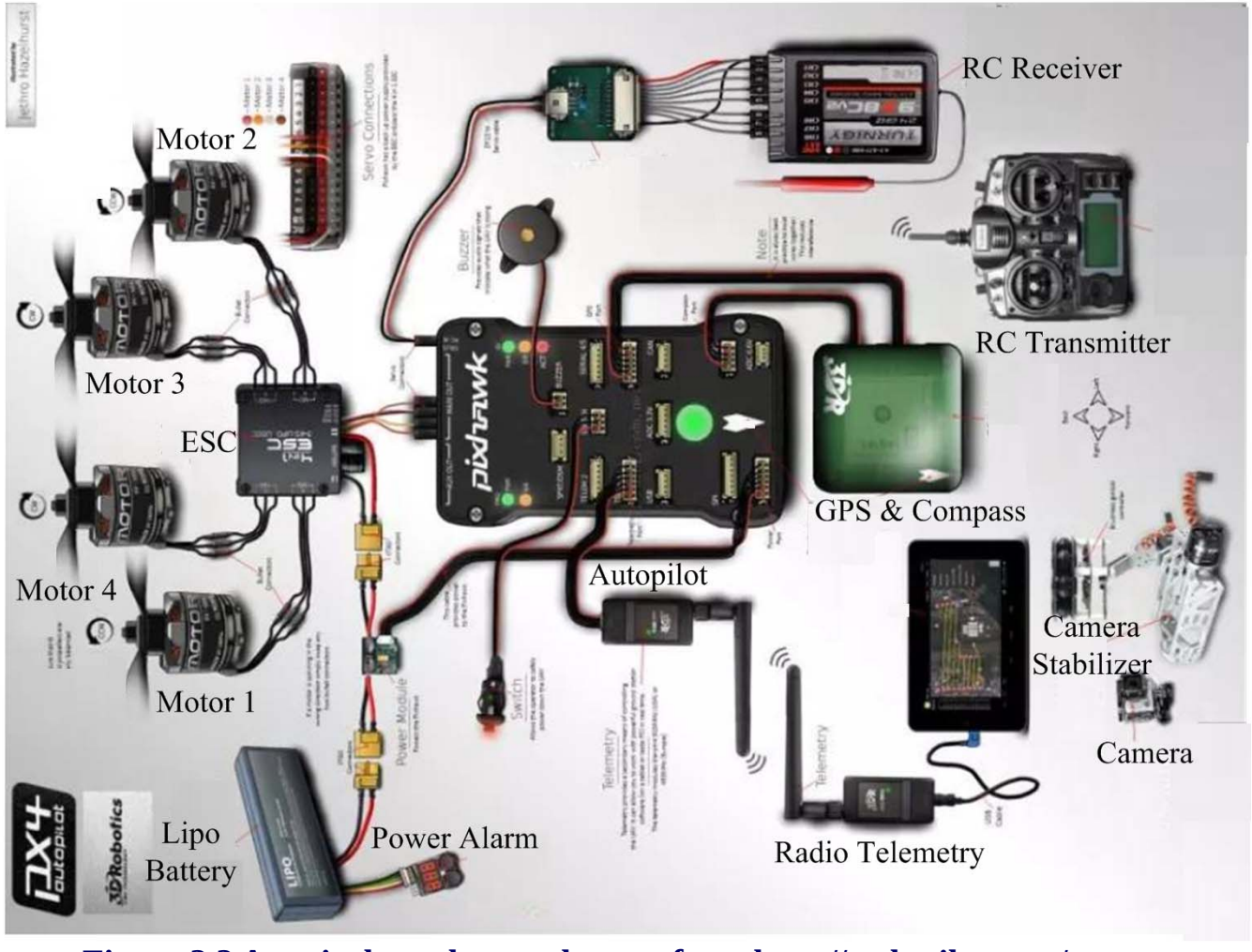


Figure 2.2 A typical quadcopter layout, from http://ardupilot.com/

2. Airframe

☐ Fuselage

（1）Function

- The fuselage acts as a platform to carry all the equipment of a multicopter. The safety, durability, usability and the performance of a multicopter are often highly dependent on the configuration of its fuselage. For a well-designed multicopter, all factors including the scale, shape, material, strength, weight, etc, should be carefully taken into consideration.

DJI F450

DJI F550

ZEROTECH HIGHONE
（Foldable airframe）

XAIRCRAFT X650 v4 Frame
（Foldable airframe）

2. Airframe

☐ Fuselage

（2）Parameter

- Weight. The weight of fuselage is mainly determined by its size and material. Under the same thrust, a smaller fuselage weight means a larger payload capacity.
- Diagonal Size. Diagonal size is the distance (usually in mm) of propeller centers in the diagonal line and it is used to indicate the size of an airframe. For example: DJIF450, diagonal size being 450mm; DJIF550, diagonal size being 550mm.

(a) DJI F450 (b) DJI F550

Figure 2.3 Diagonal size of multicopters

2. 机架

◘ 机身

（2）Parameter

- Configuration

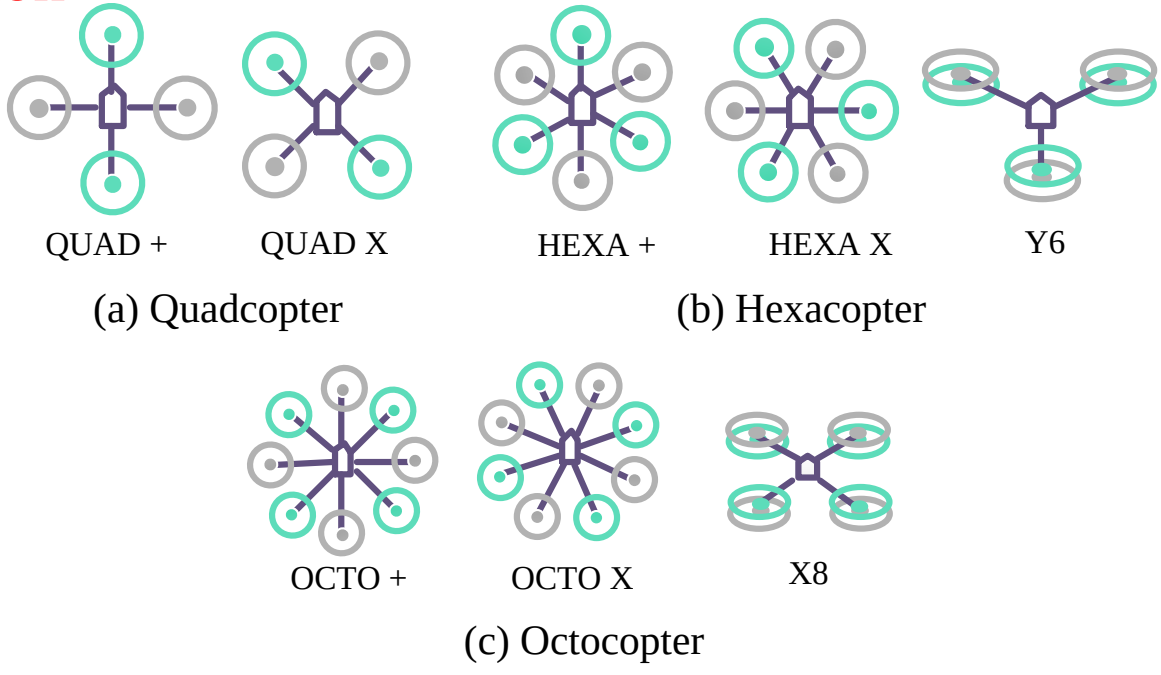
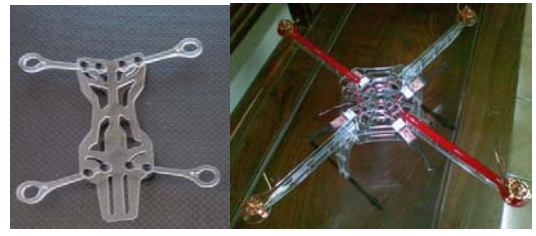


Figure 2.4 Some basic configurations of multicopters

2. Airframe

☐ Fuselage





- Material（From http://aeroquad.com/showwiki.php?title=Frame-Materials）

Table 2.1 Properties of some material

	Carbon fiber	Fiberglass	Polycarbonate	Acrylic	Aluminium	Balsa
Density（lb/cuin）	0.05	0.07	0.05	0.04	0.1	0.0027-0.0081
Young's modulus（Msi）	9.3	2.7	0.75	0.38	10.3	0.16-0.9
Tensile strength（Ksi）	120	15-50	8-16	8-11	15-75	1-4.6
Cost（10 means the cheapest）	1	6	9	9	7	10
Producibility（10 means the simplest）	3	7	6	7	7	10

Note: (a) Rigidity. Rigidity of material is a measure of the ability to overcome deformation when applied stress. It can be measured by Young's modulus (Msi). (b) Strength. Strength of material is measured by the maximum nominal tensile stress before the sample is broken when applied tensile force. It can be measured by tensile strength (Ksi).

2. Airframe

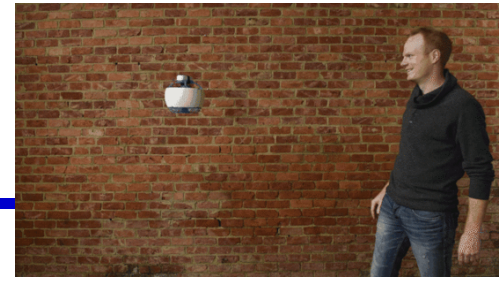
☐ Landing Gear

EHANG Ghost

Function:

- Supporting the whole multicopter when landing on the ground or taking off.
- Keeping propellers off ground at a safe distance.
- Weakening ground effect when multicopters take off.
- Consuming and absorbing impact energy when multicopters land on the ground.

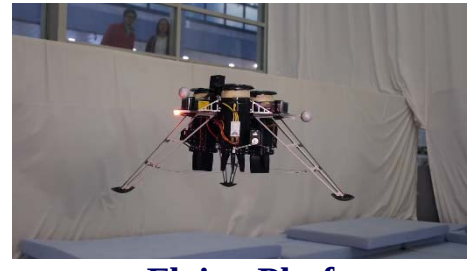
2. Airframe



Fleye

◘ Duct

In fluid dynamics, an increase in the speed of a fluid occurs simultaneously with a decrease in pressure, which is call as Bernoulli's principle



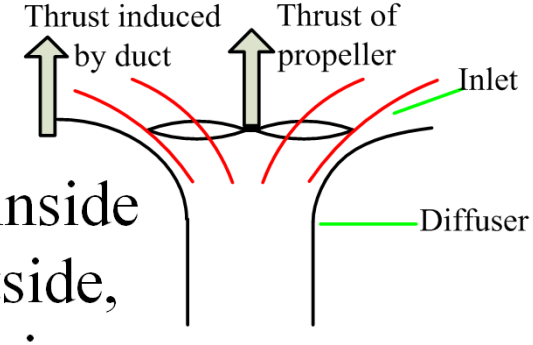
Flying Platform

（1）Function

- Enhancing the efficiency of thrust.
- Protecting the blade and ensuring personal safety.
- Reducing noise.

（2）Working principle

- For a rotating propeller, airflow inside the inlet flows faster than the outside, consequently, the pressure inside is higher than outside, which results in an additional thrust.



(a) Working principle

(b) A quadcopter with ducts

Figure 2.5 Duct

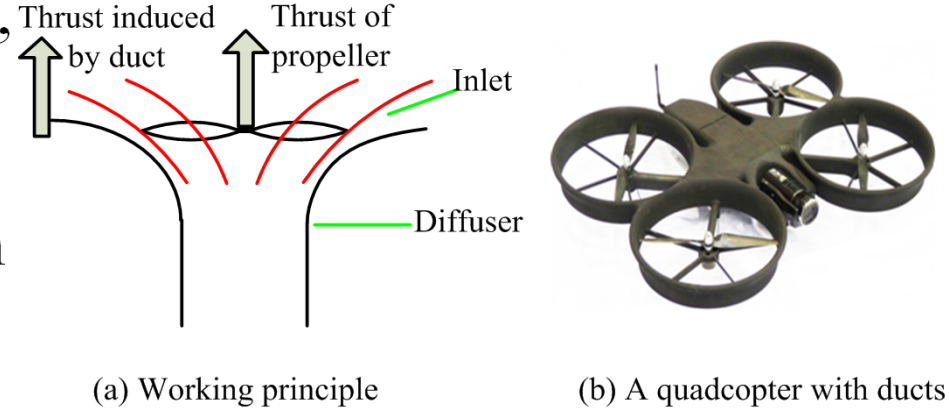
2. Airframe

☐ Duct

Although duct may improve efficiency, the duct itself is heavy which may significantly increase the weight and reduce the time. So, the final optimal design needs to achieve a tradeoff.

（3）Parameter

- Weight
- Efficiency. To get an optimal duct and improve the efficiency, there are many parameters requiring to be designed including the the diffuser length and propeller diameter. Reader can refer to[1]



(a) Working principle (b) A quadcopter with ducts

Figure 2.5 Duct

[1] Hrishikeshavan V, Black J, Chopra I. Design and performance of a quad-shrouded rotor micro air vehicle. *Journal of Aircraft*, 2014, 51(3): 779-791.

3. Propulsion System

Propulsion system

- A propulsion system includes propellers, motors, ESCs and often a battery.
- The propulsion system determines the main performances of multicopter like the hovering time, the payload ability, the flying speed and distance.
- Components of the propulsion system have to be compatible with each other, otherwise they cannot work properly or even fails in some extreme cases.

3. Propulsion System

☐ Propeller

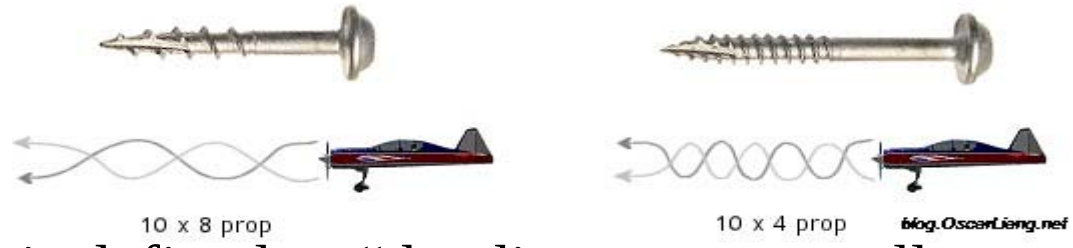
（1）Function

- Propeller is a component that produces thrust directly.
- A good match should ensure that the motor works at a high efficiency condition, which will guarantee less power to be consumed for the same thrust and then extend the time of endurance of the mulitcopter. Therefore, choosing an appropriate propeller is an easy way to improve performance and efficiency of the multicopter.



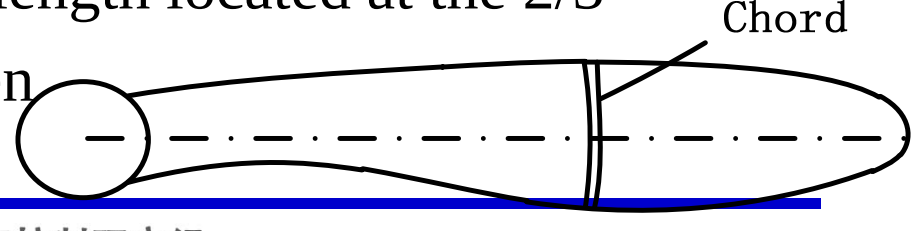

3. Propulsion System

☐ Propeller



（2）Parameter

- Type. The propeller pitch is defined as “the distance a propeller would move in one revolution if it were moving through a soft solid, like a screw through wood.” The propeller model is described by a four-digit number, such as a 10×45 propeller, among which the first two represents the propeller diameter, and the latter two represents the pitch. For example, the 10×45 propeller implies that the propeller diameter is 10 inch, and the pitch is 4.5 inch.
- Chord length. Generally, the chord length located at the 2/3 of the diameter of propeller is chosen as the mean chord length.



3. Propulsion System

☐ Propeller

(a) Two-blade propeller (b) Three-blade propeller (c) Four-blade propeller

Figure 2.6 Some propellers

- Moment of inertia. Moment of inertia is a quantity expressing a body's tendency to resist angular acceleration. A smaller moment of inertia of the propeller can improve the response speed of the motor, which is important for the control effect and performance.
- Number of blades. Experiments[2,p.65] indicated that efficiency (denoted by thrust/power) of two-blade propeller is better comparing with three-blade propeller

[2]Aaron M Harrington. Optimal propulsion system design for a micro quad rotor [Master dissertation].University of Maryland, USA, 2011.

3. Propulsion System

☐ Propeller

- Safe rotation rate. Generally, the materials of propellers used on the multicopter are flexible. So, when rotation exceeds a certain value, the propellers may deform, which will reduce its efficiency. Therefore, when calculating the safety rotation rate limit, all the possible conditions should be considered. The APC website [3] gives the maximum speed of propellers which is 105000 Revolution Per Minute (RPM)/prop diameter (inches). Taking the 10-inch propeller for example, its maximum speed is 10500RPM, while the maximum speed of Slow Flyer (SF) series propellers is only 65000RPM/prop diameter (inches).

[3] http://www.apcprop.com/Articles.asp?ID=255

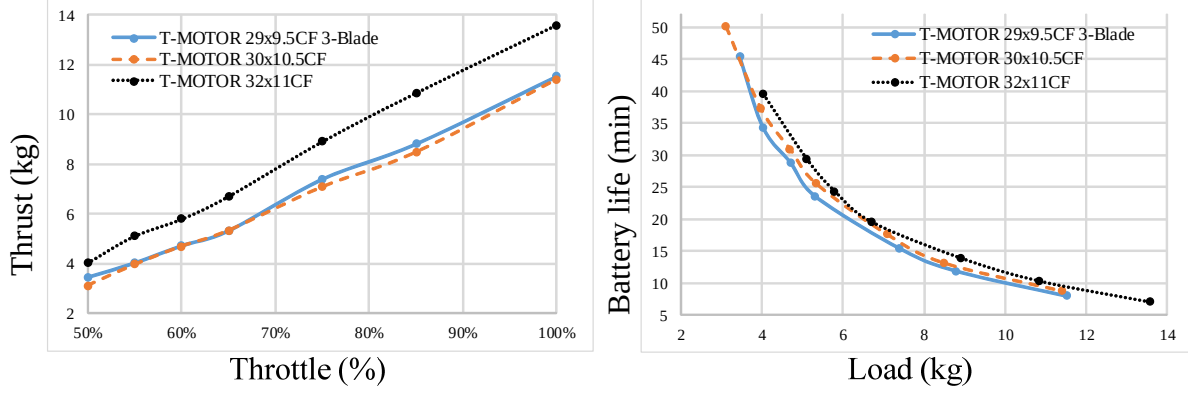
3. Propulsion System

☐ Propeller

Propeller specific thrust (or called Efficiency g/W). Propeller specific thrust is also an important parameter to measure the performance, which can be defined as

$$\text{Mechanical power (W)} = \text{Output torque (Nm)} \times \text{Propeller speed (rad/s)}$$

$$\text{Propeller specific thrust (g/W)} = \frac{\text{Thrust (g)}}{\text{Mechanical power (W)}}$$



(a) Thrust-throttle graph of T-MOTOR U12 KV90 (b) Battery life-load graph of T-MOTOR U12 KV90

Figure 2.7 Performance comparison of two-blade propeller and three-blade propeller

3. Propulsion System

☐ Propeller

- Material. Material includes carbon fiber, plastic, wood and so on, while the propellers made of carbon fiber cost almost twice as much as those made of plastic. Propellers made of carbon fiber have the following advantages[4]:
  - Less vibration and noise because of its high rigidity.
  - Lighter and stronger.
  - More suitable for the motor with high KV. However, because of the high rigidity, the motor will absorb most of the impact when a crash occurs. Wooden propeller are heavier and more expensive, and it is suitable for multicopters with large payload capacity.

[4] http://blog.oscarliang.net/carbon-fibre-props-plastic-propeller/

3. Propulsion System

☐ Propeller

（3） Static balance and dynamic balance

- The goal is to reduce vibration.
- Static balance is that the center of gravity of propeller coincides with the axis of rotation, while dynamic balance is that the center of gravity of propeller coincides with the center of inertia.
- Some measures, such as pasting scotch tapes on the lighter blade or grinding the heavier one (not the edge) using sandpapers, can compensate for imbalance.

Jello-like, wavy, warped picture

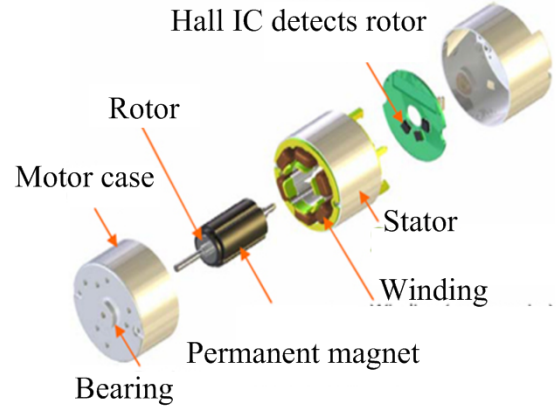
Figure 2.8 A Du-Bro propeller balancer

3. Propulsion System

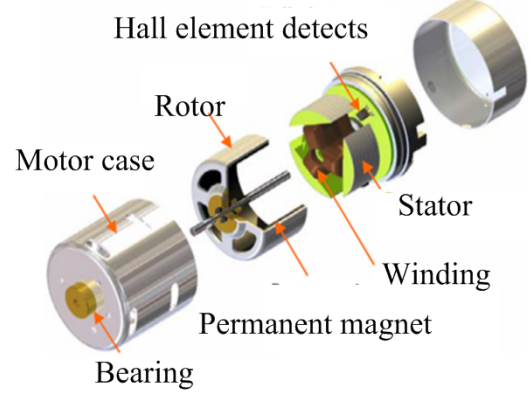
☐ Motor

（1）Function

- Motor is used to covert electrical energy into mechanical energy. Brushless DC motors are widely used in multicopter for various advantages such as high efficiency, potential to downsize and low manufacturing. Concretely, based on the position of rotors, brushless DC motors can be classified into outer rotor type and inner rotor type. Airframes with different size and load should be equipped different motors.



(a) Inner rotor type



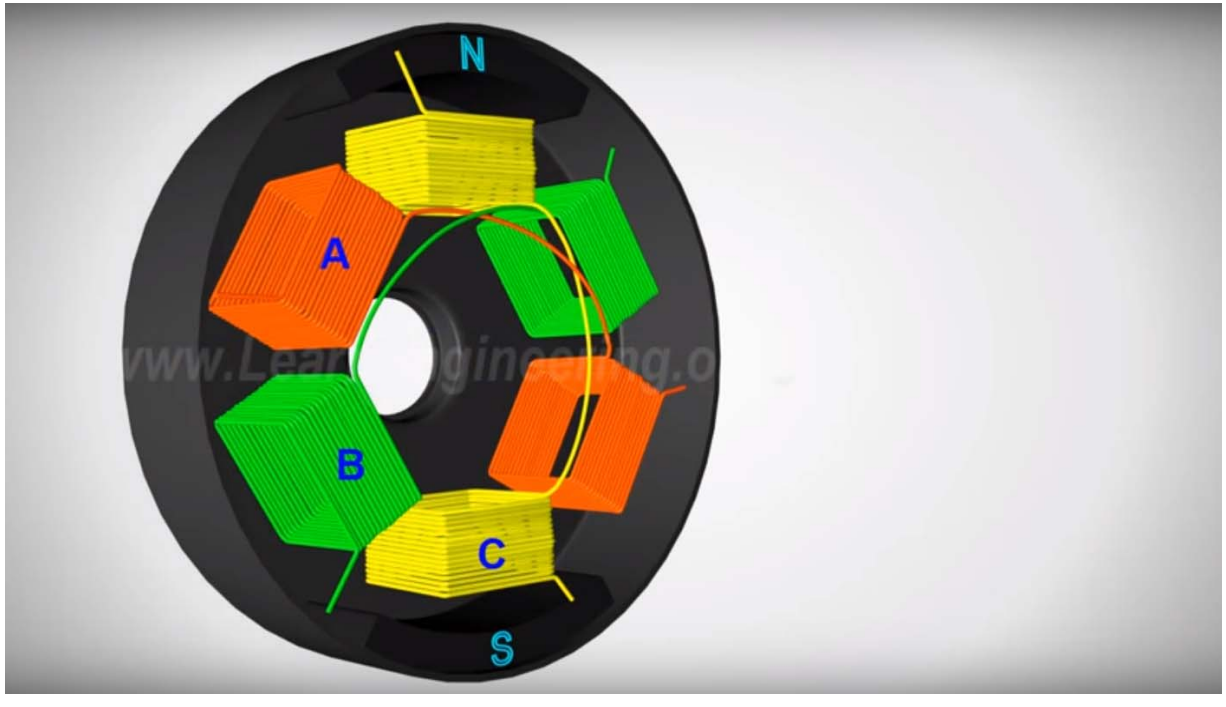
(b) Outer rotor type

Figure 2.9 Outer rotor type and inner rotor type, from http://www.nidec.com

3. Propulsion System

☐ Motor

（2）Working principle



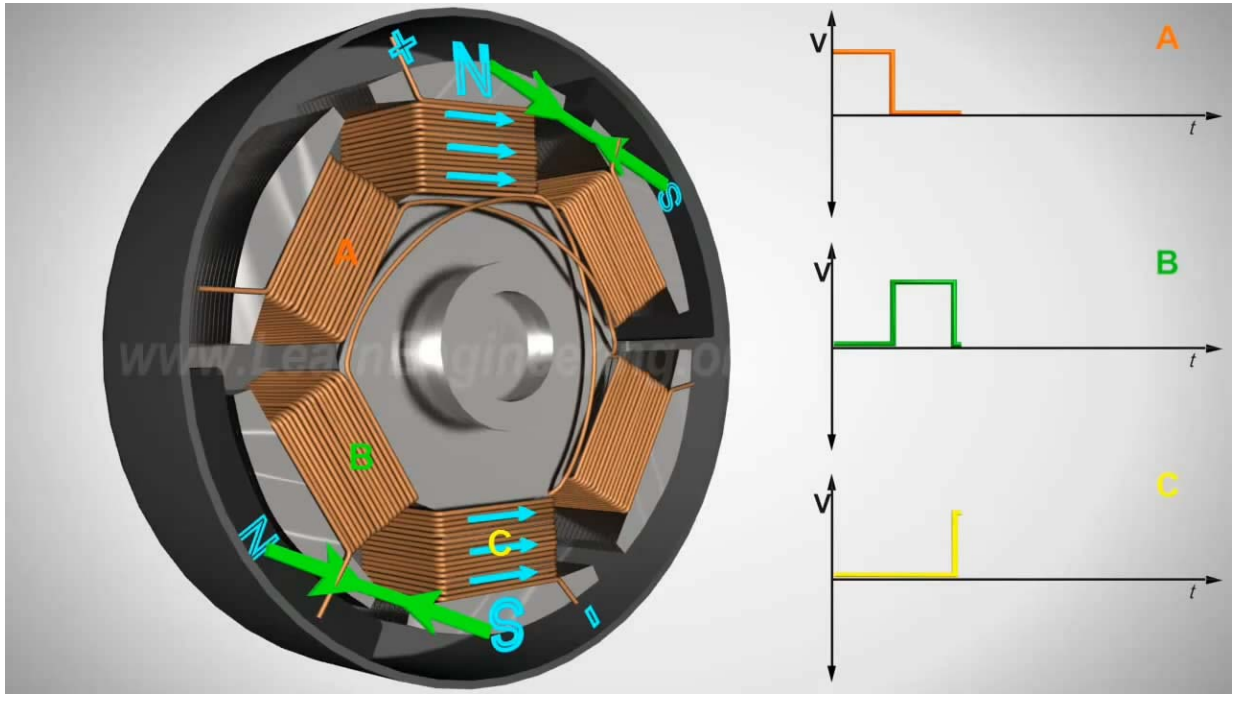
- This is a motor of outer rotor type. Its rotor is a permanent magnet, and the stator has a coil arrangement as shown in the figure. By applying power to the coil, the coil will energize and become an electro magnet. The operation of a brushless DC motor is based on the simple force interaction between the permanent magnet and the electro magnet.

Video：Brushless DC Motor, How it works ? https://www.youtube.com/watch?v=bCEiOnuODac

3. Propulsion System

☐ Motor

（2）Working principle



- In this condition, when the coil A is energized, the opposite poles of the rotor and stator are attracted to each other, as the rotor nears coil A, coil B is energized, as the rotor near coil B, coil C is energized. After that, coil A is energized with the opposite polarity. This process is repeated and the rotor continues to rotate.

Video：Brushless DC Motor, How it works ? https://www.youtube.com/watch?v=bCEiOnuODac

3. Pro

◘ Motor

（3）Parameter

- Size. Size of motor is represented by its stator size with four-digit number, among which the first two indicates its stator diameter (mm) and the latter two indicates its stator height (mm). So the motor 2212 indicates that the stator diameter of the motor is 22mm and the stator height is 12mm. In brief, the larger the former two are, the wider the motor is; the larger the latter two are, the higher the motor is. A wide and high motor has high power, which is more suitable for larger multicopters.
- KV value for motors. The KV value is the increased number of RPM that the no-load motor will revolve when 1V (one Volt) is increased. For example, 1000KV means that when voltage increased by 1V, the no-load motor speed will be increased by 1000RPM. A lower KV motor can produce a higher torque and drive a bigger propeller.

3. Propulsion System

Specifications	X2216
Stator Diameter	22mm
Stator Thickness	16mm
No. of Stator Arms	12
No. of Stator Poles	14
Motor Kv	880
No-Load Current (A/10V)	0.5A
Motor Resistance	117mΩ
Max Continuous Current	20A/30S
Max Continuous Power	320W
Weight	72g
Outside Diameter	27.7mm
Shaft Diameter	3.175mm
Body Length	34mm
Overall Shaft Length	36.5mm
Max Lipo Cell	2-4S
ESC	30A
Recommended Prop(inch)	APC1047

☐ Motor

- Nominal no-load current and voltage. In the no-load test, the current passing through motors after applying nominal voltage is defined as nominal no-load current.
- Maximum instantaneous current/ Maximum continuous current. The former is the maximum instantaneous current the motor can undertake, while the latter is the maximum continuous current that allows motors to work normally and not be burnt out.
- Resistance. There is resistance in all motor armatures. It is very small but cannot be ignored because the current flowing through the resistance is tremendously large and sometimes reaches tens of Amperes. Therefore the heat produced may overheat the motor and reduce the efficiency.

3. Propulsion System

☐ Motor

- Motor efficiency. It is defined as follows

$$\text{Electric power (W)} = \text{equivalent voltage (V)} \times \text{equivalent current (A)}$$

$$\text{Motor efficiency (\%)} = \frac{\text{Mechanical power (W)}}{\text{Input electrical power (W)}} \times 100\%$$

- Overall specific thrust (Efficiency g/W) . The overall performance of the system depends on a well-matched combination of motor and propeller. A system will be very inefficient if these two parts do not match well. The overall specific thrust is calculated as

$$\text{Overall specific thrust (g/W)} = \frac{\text{Thrust of propeller (g)}}{\text{Electrical power of motor (W)}}$$

$$= \text{Propeller specific thrust (g/W)} \times \text{Motor efficiency}$$

3. Propulsion System

☐ Motor

- Overall specific thrust. Since both the propeller specific thrust and motor efficiency have a relationship with throttle, the overall specific thrust is a function of throttle. The overall specific thrust is often given by the motor producer, where "efficiency" is in fact the overall specific thrust.

Motor model	Voltage (V)	Propeller Model	Throttle	Current (A)	Power (W)	Thrust (g)	Speed (RPM)	Efficiency (G/W)	Torque (N·m)	Temperature ℃
T-MOTOR MN5212 KV340	24	T-MOTOR 15x5CF	50%	3.3	79	745	3821	9.44	0.142	38
			55%	4.2	99.8	910	4220	9.11	0.172	
			60%	5.2	123.6	1075	4576	8.7	0.198	
			65%	6.3	150.7	1254	4925	8.32	0.232	
			75%	9.1	217.2	1681	5663	7.74	0.31	
			85%	12.2	292.1	2115	6315	7.24	0.382	
			100%	17.8	426.7	2746	7167	6.44	0.498	
		T-MOTOR 18x6.1CF	50%	5.7	137.5	1318	3596	9.58	0.29	74
			55%	7.4	178.1	1612	3958	9.05	0.344	
			60%	9.3	222	1901	4310	8.56	0.411	
			65%	11.6	278.2	2259	4622	8.12	0.472	
			75%	16.5	395.5	2835	5226	7.17	0.605	
			85%	22.1	531.1	3477	5751	6.55	0.737	
			100%	31	744.7	4355	6358	5.85	0.918	

Figure 2.10 Overall specific thrust of motor MN5212 KV420

3. Propulsion System

☐ Electronic Speed Controller

(1) Function

- In general, Electronic Speed Control is called ESC for short.
  - Controlling the speed of motors based on the PWM signal that autopilots send.
  - Supplying power for Radio Controlled (RC) servo motors.
  - Transforming the onboard DC power into the three-phase Alternating Current (AC) power that can be applied to brushless DC motors.
  - The auxiliary functions includes battery protection and starting protection.

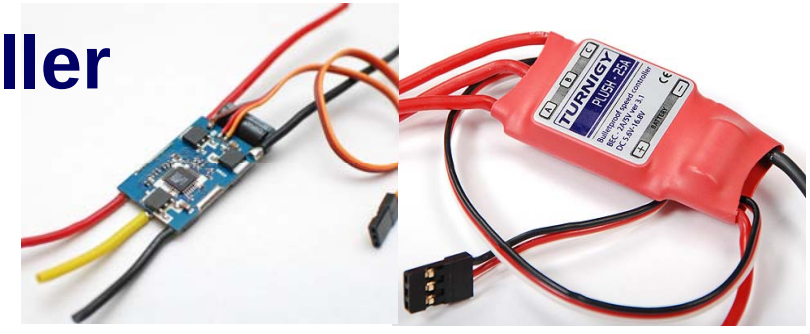
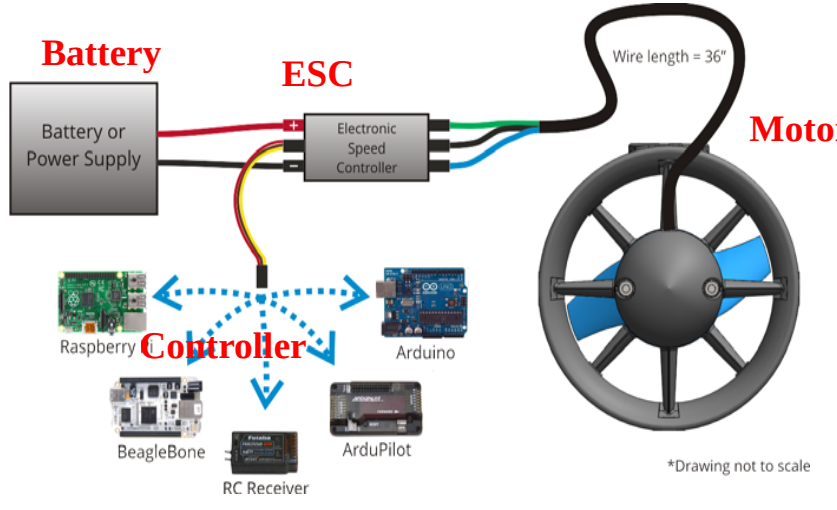


Figure 2.11 Xaircraft ESC-S20A for multicopter



From http://veevoo.jumpseller.com/t200-thruster

3. Prop

◘ Electroni

PUSH18A，BEC2A/5V
DC：5.6V-16.8V

SK-30A，BEC2A/5V
DC：2-4 LiPo/5-12NIMh

（2）Parameter

- Current
  - Current is presented by Ampere (A). Different motors should be equipped with different ESCs. An inappropriate matching will lead to a burnout ESC or even motor failure.
  - Concretely, maximum current includes the maximum continuous current and maximum instantaneous current. The former is the maximum current in the normal working mode, the latter is the maximum tolerable current.
  - When choosing ESCs, we should leave a safety margin to the maximum current to efficiently avoid burnout of the power tube.

3. Propulsion System

☐ Electronic Speed Controller

- Voltage. The range of voltage allowing the ESC to work properly is also an important parameter. Usually, the index like “3-4S LiPo” can ne found on the ESC specification, which means that the voltage range of this ESC is 3-4 cells of LiPo battery, i.e., 11.1V-14.8V.

PUSH18A，BEC2A/5V
DC：5.6V-16.8V

SK-30A，BEC2A/5V
DC：2-4 LiPo/5-12NIMh

3. Propulsion System

☐ Electronic Speed Controller

- Resistance. Since all ESCs have resistances, the heating power cannot be ignored because the current flowing through them can sometimes reach tens of Amperes. Considering the heat dissipation, the resistances of ESCs with high current are always designed to be small.
- Refresh rate. The motor response has a great relationship with the refresh rate of ESCs. Before the development of multicopters, the maximum operating frequency of RC servo motors was 50Hz, therefore the refresh rate of ESCs was 50Hz. However, multicopters can adjust the thrust rapidly by the rapid control of propellers' angular velocity. The refresh rate of ESCs is required to be faster. The higher the refresh rate is, the faster the response will be.

3. Propulsion System

☐ Electronic Speed Controller

- Programmability. The performance of ESCs can be optimized by tuning internal parameters. There are three ways to set the parameters of ESCs:
  - By programmable cards
  - By computer software via the USB
  - By RC transmitter

The parameters that can be set up include: power outage value, current limitation, brakes mode, throttle control mode, switch timing setting, starting mode and PWM mode setting, etc.

Figure 2.12Hobbywing brushless ESC programmable cards

Programmable Items	Value								
	1	2	3	4	5	6	7	8	9
Basic Items									
1. Running Mode	Forward with Brake	***Forward/ Reverse with Brake***	Forward/ Reverse (For Rock Crawler)						
2.Drag Brake Force	***0%***	5%	10%	20%	40%	60%	80%	100%	
3.Low Voltage Cut-Off Threshold	No-Protection	2.6V /Cell	2.8V /Cell	3.0V /Cell	***3.2V /Cell***	3.4V /Cell			
4.Start Mode(Punch)	Level1	Level2	Level3	Level4	***Level5***	Level6	Level7	Level8	Level9
Advanced Items									
5.Max Brake Force	25%	50%	***75%***	100%	Disable				
6.Max Reverse Force	***25%***	50%	75%	100%					
7.Initial Brake Force	***= Drag Brake Force***	0%	20%	40%					
8.Neutral Range	6% (Narrow)	***9% (Normal)***	12% (Wide)						
9.Timing	0.00°	3.75°	7.50°	11.25°	***15.00°***	18.75°	22.50°	26.25°	
10.Over-heat Protection	***Enable***	Disable							
11.Motor Rotation	***Counter Clockwise***	Clockwise							
12.Lipo Cells	***Auto Calculate***	2 Cells	3 Cells	4 Cells	5 Cells	6 Cells			

Figure 2.13 Parameter table

3. Propulsion System

☐ Electronic Speed Controller

- Compatibility. If ESC and motor are incompatible, the motor is likely to be jammed, which may result in a fall and crash in the air.

（3）Square-wave driver V.S. sinusoidal driver

- Square-wave driver. Square-wave driver outputs square wave, which is a digital signal, therefore its control elements work in the switch state. Compared with sinusoidal-wave drivers, square-wave drivers are easier to control and cheaper.
- Sinusoidal driver (Field Oriented Control). Sinusoidal driver performs better in the aspects of operation stability, speed range, efficiency and vibration reduction of noise. While owing to the high price of optical encoder and complexity of control circuit, it is inevitably expensive.

3. Propulsion

☐ Battery

(a) NiMh battery (b) LiPo battery

Figure 2.14 Common batteries

（1）Function

- Battery is used to provide energy. A problem concerned for present multicopters is the time of endurance, which is mainly determined by the capacity of batteries. Now, there are many types of batteries, where the Lithium Polymer (LiPo) battery and Nickel Metal Hydride (NiMH) battery are the most commonly-used ones because of superior performance and cheap price. For multicopters, it is the energy density restricts the flight time and task.

3. Propulsion System

◻ Battery

（2）Parameter

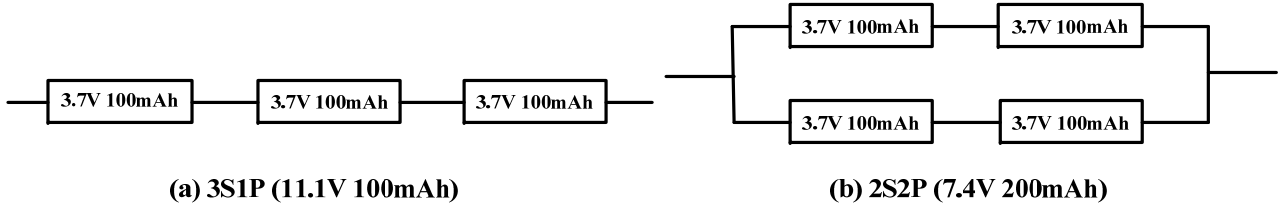


Figure 2.15 Connection diagrams

- Voltage
  - The LiPo battery includes two parts: power and protective circuits.
  - A single battery voltage is 3.7. The letters S and P are used to represent for the series connection and parallel connection, respectively. 3S1P is three battery cells in series and the total voltage is 11.1V; 2S2P is two series of two battery cells in parallel, therefore the total voltage is 7.4V and the current is doubled. the output voltage will be decreased as the current of discharge is increased because of the internal resistance

3. Propulsion System

☐ Battery

- Capacity
  - mAh is the unit for capacity. 5000mAh means that the discharge of battery can last for an hour with the current of 5000mA. However, the discharge ability and output voltage can be decreased with the discharge process. As a result, the remaining capacity is not a linear function of the discharge time.
  - There are two ways to detect the remaining capacity. One way is to detect the battery voltage, which is commonly used. The other way is to estimate the State of Charge value of batteries.
  - Note: the battery voltage in full charge is 4.2V, and decreases to 3.0 when fully discharged. In general, when it decreases to 3.6V, there will be a power alarm.

3. Propulsion System

☐ Battery

- Discharge rate. Discharge rate is represented by

Discharge = Current of Discharge/Rated Capacity

Obviously, the discharge rate measures the rate of discharge. If the capacity is discharged completely in an hour, then its discharge rate is 1C, while if it is discharged in five hours, then its discharge rate is 1/5=0.2C. When the maximum discharge rate of a battery with the nominal capacity of 5000mAh is 20C, the maximum current of discharge is calculated as 5000mA×20C=100A. LiPo batteries belong to high-rate batteries, which can provide more power. So, they are suitable for driving multicopters.

3. Propulsion System

☐ Battery

- Resistance
  - There are many factors effecting resistance , including the battery size, structure, assembly and material, etc.
  - Resistance of battery is not a constant value, and it varies with the power status and service life. In general, it has a linear relationship with the logarithm of current density.
  - Resistance is relatively small in the initial state. Battery with smaller resistance has higher discharge ability.
- Energy density. Energy density is the amount of energy stored in a given system or region of space per unit volume or mass.

4. Command and Control System

☐ RC Transmitter and Receiver

（1）Function

- The RC transmitter is used to transmit commands from remote pilot to the corresponding receiver, then the receiver passes the commands to the autopilot after decoding them, finally, the multicopter flies according to the commands. Some flight parameters can be set on the transmitter, such as the throttle direction, stick sensitivity, neutral position of RC servo motors, function definitions of channels, record and remind setting of flight time, and lever function setting.

4. Command and Control System

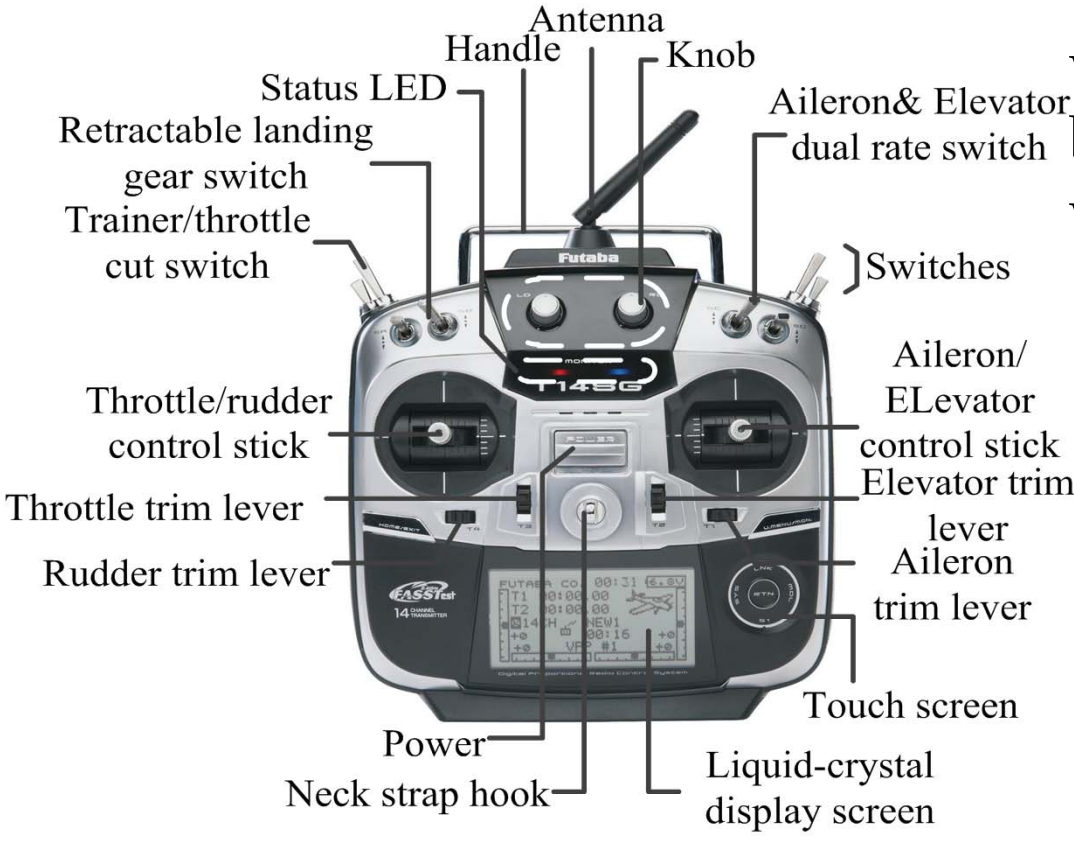


Figure 2.16 Futaba RC tranmitter

The transmitter left is for fixed-wing aircraft. The correspondence between multicopter and fixed-wing aircraft is as follows:

Table 2.2 Correspondences between multicopter and fixed-wing aircrafts

Fixed-wing aircraft (Mode 1)	Multicopter（Mode 2）
Elevator	**Throttle, upward-downward movement**
Rudder	**Yaw, yaw movement**
Throttle	**Pitch, forward-backward movement**
Aileron	**Roll, rightward-leftward movement**

4. Command and Control System

☐ RC Transmitter and Receiver

（2）Parameter

- Frequency
  - The commonly-used radio frequency includes 72MHz and 2.4GHz, and 2.4GHz is more popular.
  - The 2.4GHz falls in the microwave range, which has the following advantages: high frequency, less chance of co-channel interference, low power consumption, smaller volume, rapid response and high control accuracy.
  - Performance will be bad when there exists an obstacle between the RC transmitter and multicopter, therefore the obstacle between them should be avoided to maintained line of sight.

4. Command and Control System

☐ RC Transmitter and Receiver

- Modulation[5, pp.129-133],[6]
  - PCM (Pulse Code Modulation) implies the encoding of signal pulses, and PPM (Pulse Position Modulation) implies the modulation of high frequency signal. The former is the code method for signal pulse, while the latter is the modulation for high-frequency circuit.
  - The advantages of PCM are not only the strong anti-interference capacity, but also the convenience to be programmed by a computer. Compared with PCM, PPM is easier to realize and cheaper, but is more susceptible to interference.

[5] Norris D. *Build Your Own Quadcopter*. New York: McGraw-Hill Education, 2014.

[6] Peter Rother. PCM or PPM? Possibilities, performance? [Online], available: http://www.aerodesign.de/peter/2000/PCM/PCM_PPM_eng.html, January 29, 2016.

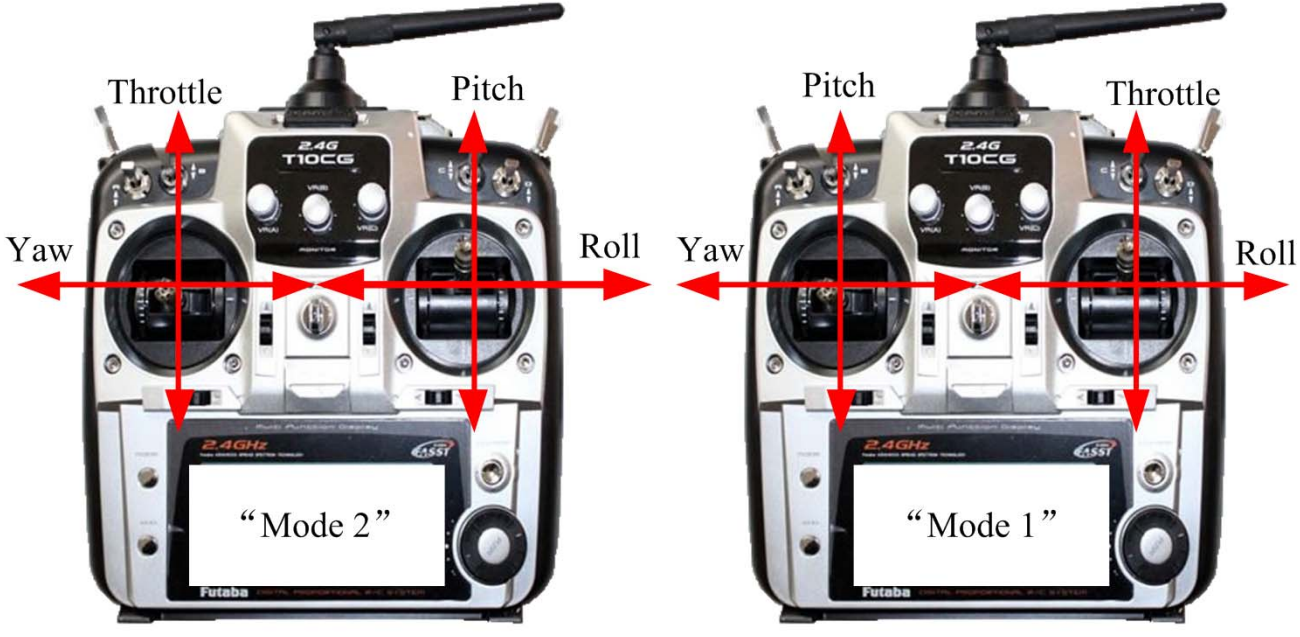
4. Command and Control System

☐ RC Transmitter and Receiver

- Channels. One channel corresponds to one separate operation, and generally there are six-channel transmitters, eight-channel transmitters and ten-channel transmitters to control multicopters. The operations needed include: throttle control, yaw control, pitch control, and roll control. In this way, an RC transmitter requires four channels at least..
- Mode. RC transmitter modes refer to the way how an RC transmitter is configured to control a multicopter. For example shown in figure 2.17, “Mode 1”: pitch/yaw on the left stick, throttle/roll on the right (also called right-hand mode, popular in Japan, more suitable for fixed-wing
- aircraft); “Mode 2”: throttle/yaw on the left, pitch/roll on the right (also called left-hand, popular in the U.S and other parts of the world including China, more suitable for multicopters)

4. Command and Control System

RC Transmitter and Receiver



For multicopters	For fixed wing aircraft
Throttle : control up-down movement	corresponding to throttle stick
Pitch : control forward-backward	corresponding to the elevator
Yaw : control the head direction	corresponding to the rudder
Roll : control the left-right movement	corresponding to the aileron

Figure 2.17 Different control modes of the RC transmitter

4. Command and Control System

☐ RC Transmitter and Receiver

- Throttle
  - The direct-type RC transmitter refers to the type whose throttle is designed to be unable to recover back to its original position automatically and the total thrust is proportional to the deflection of the throttle control stick.
  - The increment-type RC transmitter refers to the type whose throttle can go back to the midpoint automatically once it is released and the throttle control stick's deflection is proportional to the desired vertical speed or thrust rate.
- Remote control distance. The control distance of an RC transmitter is restricted by its power. In order to extend the control distance, power amplifier and antennas can be used.

4. Command and Control System

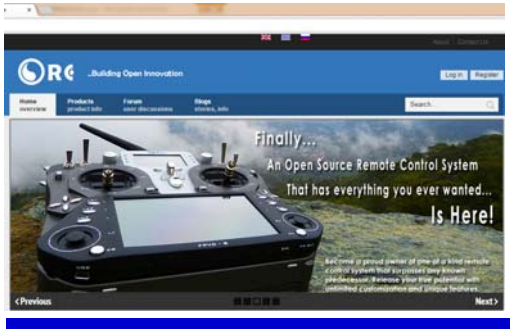
☐ RC Transmitter and Receiver

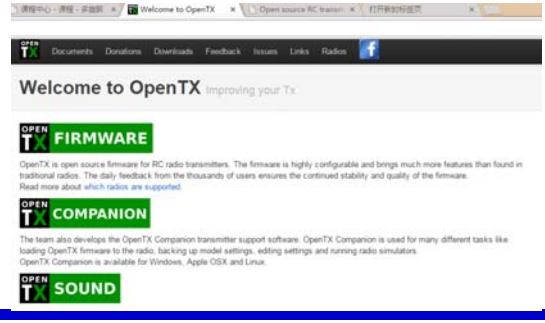
（3） Open source transmitter

Currently, there are many free open source transmitters for multicopters. Reader can refer to the following websites:

- http://www.os-rc.com/
- http://www.open-tx.org/
- http://www.reseau.org/arduinorc/

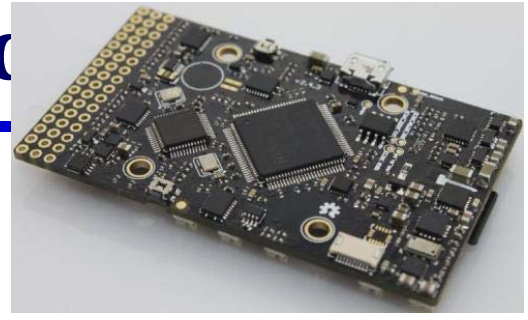
Based on which transmiters can be customized.





4. Command and

☐ Autopilot



Microcomputer

GPS receiver

（1）Composition

- A multicopter autopilot can be divided into the software part and hardware part：
  - Global Position System (GPS) receiver. It is used to obtain the location information of multicopters.
  - Inertial Measurement Unit (IMU). It includes: three-axis accelerometer, three-axis gyroscope, electronic compass (or three-axis magnetometer). It is used to obtain attitude information of a multicopter.

4. Command and Control System

☐ Autopilot

- Height sensor. Height sensor includes the barometer and ultrasonic range finder, which are used to obtain the absolute height and relative height, respectively.
- Microcomputers. It is a platform used to receive information and run algorithms to produce control command.
- Interface. It acts as a bridge between the microcomputer and the other devices, like the sensors, ESC and RC receiver.

Barometer

Ultrasonic range finder

IMU module

4. Command and Control System

☐ Autopilot

（2）Function

- Perception. Perception is to solve the problem of “ where the multicopter is ”. This mainly corresponds to Lessons 7-9.
- Control. Control is to solve the problem of “ how the multicopter flies to a desired position ”. This mainly corresponds to Lessons 10-12.
- Decision. Decision is to solve the problem of “where the multicopter will go ”. This mainly corresponds to Lessons 13-14.

4. Command and Control System

☐ Autopilot

（3）Open source autopilot

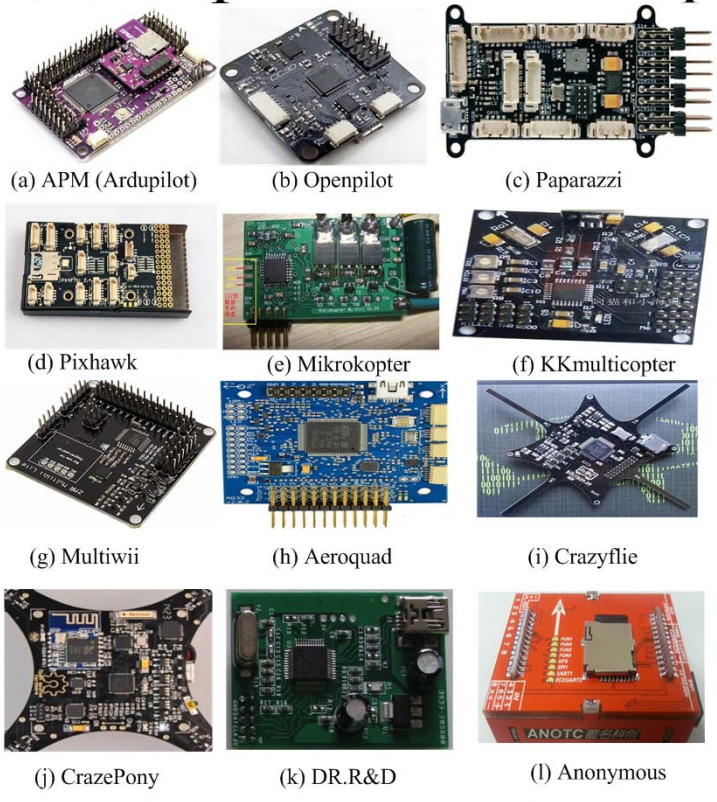


Figure 2.18 Open source autopilots of multicopters

Table 2.3 Website of open source project

Open-Source Projects	Web site URL
Ardupilot	http://ardupilot.com
Openpilot	http://www.openpilot.org/
Paparazzi	http://paparazziuav.org
Pixhawk	https://pixhawk.ethz.ch/
Mikrokopter	http://www.mikrokopter.de
KKmulticopter	http://www.kkmulticopter.kr/
Multiwii	http://www.multiwii.com/
Aeroquad	http://www.aeroquadstore.com/
Crazyflie	https://www.bitcraze.io/category/crazyflie/
CrazePony (China)	http://www.crazepony.com/
DR.R&D (China)	http://www.etootle.com/
Anonymous (China)	http://www.anotc.com/
Autoquad	http://autoquad.org/
MegaPirate	http://megapiratex.com/index.php
Erlerobot	http://erlerobotics.com/
MegaPirateNG	http://code.google.com/p/megapirateng

4. Command and Control System

☐ Autopilot

（3）Open source autopilot

Open-Source Projects	Web site URL
Taulabs	http://forum.taulabs.org/
Flexbot	http://www.flexbot.cc/
Dronecode(Open source operating system for Drone)	https://www.dronecode.org/
Percepto(Open source optical platform for Drone)	http://www.percepto.co/
Parrot API(Open source SDK)	https://projects.ardrone.org/embedded/ardrone-api/index.html
3DR DRONEKIT(SDK)	http://www.dronekit.io/
DJI DEVELOPER(SDK)	http://dev.dji.com/cn
DJI MATRICE 100+ DJI Guidance	https://developer.dji.com/cn/matrice-100/
SDK for XMission(SDK)	http://www.xaircraft.cn/en/xmission/developer
EHANG GHOST SDK(SDK)	http://dev.ehang.com/

4. Command and Control System

Description	Size(mm)	Weight(g)	Processor	Frequency (MHz)	Gyroscope	Accelero-meter	Magnet-ometer	Barometer
APM(Ardupilot)	66×40.5	23	ATmega2560	16	MPU-6000	MPU-6000	HMC5843	MS5611
Openpilot	36×36	8.5	STM32F103CB	72	ISZ/IDC-500	ADX330	HMC5843	BMP085
Paparazzi(Lisa/M)	51×25	10.8	STM32F105RCT6	60	MPU-6000	MPU-6000	HMC5843	MS5611
Pixhawk	40×30.2	8	LPC2148	60	ISZ/IDC-500	SCA3100-D04	HMC5843	BMP085
Mikrokopter	44.6×50	35	ATmega644	20	ADXRS610	LIS344ALH	KMZ51	MPX4115A
Kkmulticopter	49×49	11.7	ATmega168	20	ENC-03	——	——	——
Multiwii	N/A[a]	N/A[a]	Arduino[b]	8-20	ISZ/IDC-650	LIS3L02AL	HMC5883L	BMP085
Aeroquad	N/A[a]	N/A[a]	Arduino[b]	8-20	ITG3200	ADXL345	HMC5883L	BMP085
Crazyflie 2.0	90×90	19	STM32F405	168	MPU-9250	MPU-9250	MPU-9250	LPS25H
CrazePony-II(4版)	38.9×39.55	20	STM32f103T8U6	72	MPU6050	MPU6050	HMC5883L	MS5611
Dr.R&D（2015）IV	33×33	300（whole）	STM32F103	72	MPU6050	MPU6050	HMC5883L	Ultrasound HC-SR04
Anonymous V2	75×45	40	STM32F407	168	MPU6050	MPU6050	AK8975	MS5611

Note. a: uncertain. Because Multiwii and Aeroquad support dynamic hardware configuration, their sizes are related with construction. b: the flight control board is developed based on Arduino, so the processor can be changed. Most data is cited from Lim H, Park J, Lee D, et al. Build your own quadrotor: Open-source projects on unmanned aerial vehicles. *IEEE Robotics & Automation Magazine*, 2012， 19(3): 33-45.

4. Command and Control System

GCS

(1) Function

- Software is an important part of GCS.
- Remote pilots can interact with the software using the mouse, keyboard, button and joystick.
- Remote pilot can plan the way point in advance, therefore the remote pilot can monitor the flight status in real time and set new missions to intervene flight.
- The software can record and playback flight for analysis

Figure 2.19 Software interface of APM GCS

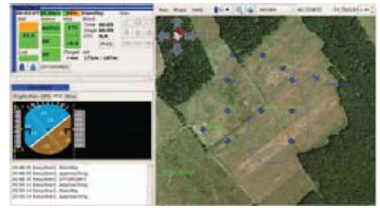
4. Command and Control System

GCS

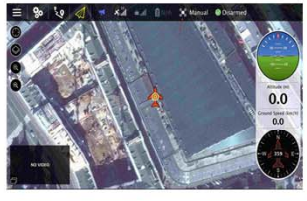
（2）Open source GCS

(a) MissionPlanner (Ardupilot)

(b) Openpilot



(c) Paparazzi



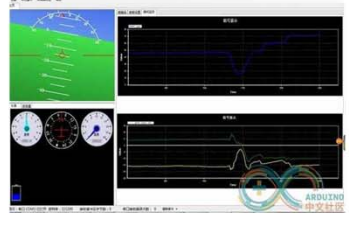
(d) QGroundControl (PX4)

(e) Mikrokopter

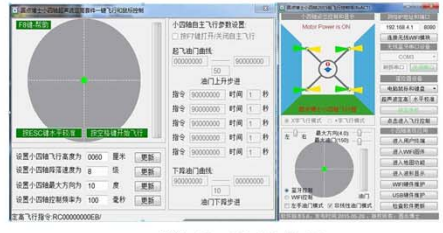
(f) Multiwii

(g) Aeroquad

(h) Crazyflie



(i) CrazePony



(j) D.R R&D

Figure 2.20 Screenshots of some GCS softwares

4. Command and Control System

☐ Radio Telemetry

（1）Function

- Radio telemetry refers to using Digital Signal Processing (DSP) technology, digital modulation and demodulation, radio technology to transmit data with high accuracy, and it is equipped with functions of forward error correction and balanced soft decision.

Figure 2.21 3DR radio telemetry

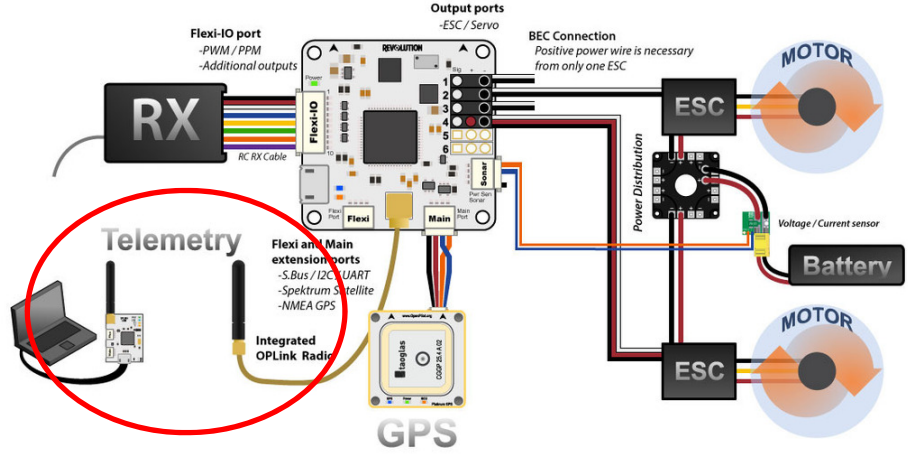


Figure 2.22 Connection diagram of Openpilot radio telemetry

4. Command and Control System

☐ Radio Telemetry

One end of radio telemetry is connected to the GCS software, and the other end is connected to the multicopter. Communication are performed using certain protocols to maintain the two-way communication of multicopter and ground station.

（2）Parameter

- Frequency. The frequency includes 433MHz and 915MHz. 915MHz is available in north America, while its forbidden in China and Europe.
- Transmission distance.
- Transmission rate.

4. Command and Control System

☐ Radio Telemetry

（3）Communication protocol

- Communication protocol is also called communication regulations, referring to the convention of the data transmission on both sides. As long as communication protocols are obeyed, the GCS software can be compatible with different autopilots.
- MAVLink communication protocol is a library organization which only has the header files and it is designed for micro and small aircraft. MAVLink is published by L.Meier on the basis of the GNU Lesser General Public License (LGPL) in 2009. Openpilot autopilot adopts UAVTalk protocol to communicate with GCS.

5. Conclusion

（1）Multicopter system is introduced from three parts:

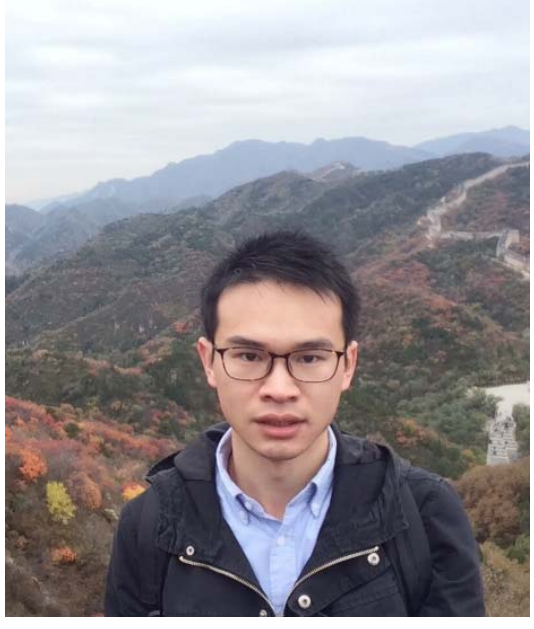
- Airframe (Lesson 3)
- Propulsion system (Lesson 4)
- Command and control system (Navigation (Lessons 7-9), Control (Lessons 10-12), Decision (Lessons 13-14))

（2） " Small as the sparrow is, it possesses all its internal organs ".Unmanned vehicle has the same composition as a multicopter.

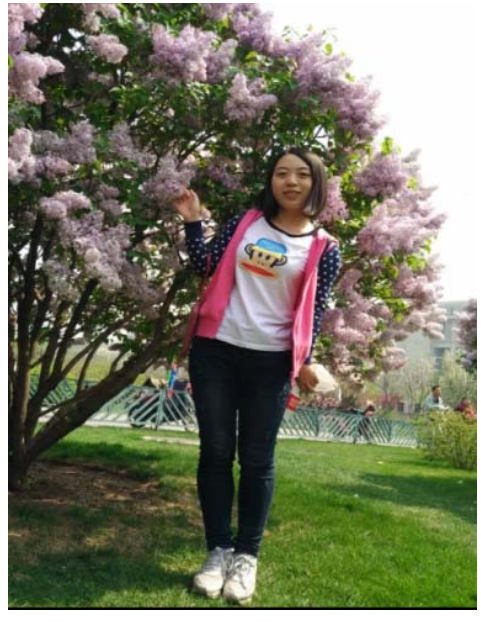
（3） In order to improve the overall performance or find out the causes of failure, it is necessary to have a comprehensive and deep understanding of multicopters.

Acknowledgement

Deep thanks go to



Xunhua Dai
for material preparation



Jing Zhang

Thank you!

All course PPTs and resources can be downloaded at
http://rfly.buaa.edu.cn/course

For more detailed content, please refer to the textbook:

Quan, Quan. Introduction to Multicopter Design and Control. Springer, 2017. ISBN: 978-981-10-3382-7.

It is available now, please visit http://www.springer.com/us/book/9789811033810