2 Basic Composition

The compositions of multicopter systems are both simple yet complex. The compositions are thought to be simple because a multicopter system is generally composed of several well-modularized components such as the airframe, propulsion system, command and control system. These components for a multicopter can be described as the organs for a human, where the airframe corresponds to the body, carrying other hardware; the propulsion system would be the feet and hands powered by the heart and blood vessels, providing power for the multicopter; the command and control system would be the sense organs and brain, controlling the propulsion system to achieve tasks. On the other hand, the compositions are also complex, because each component is not independent, and they connect and constrain with others in a very complex way. Though there are countless combinations for a multicopter, only a few of them can really work. If designers are unaware of the principle of components and assemble multicopters blindly, then the assembled multicopters may have poor performance, or even could not work at all. Therefore, it is necessary to know the basic principle of each component and their relationship. This chapter aims to answer the question as below:

What are the basic compositions of a multicopter system?

This chapter consists of three parts, namely the airframe, propulsion system, and command and control system. The component of each part will be introduced from the corresponding function, working principle and key parameter, etc.

Q. Quan, *Introduction to Multicopter Design and Control*, DOI 10.1007/978-981-10-3382-7_2

Playing Zither

The ancient Chinese had already recognized the interdependency between the entirety and the locality. The "*Emperor's Inner Canon*" is an ancient Chinese medical literature that was treated as the fundamental doctrinal source for Chinese traditional medicine for more than two millennia. The work is composed of two volumes, namely "*Suwen*" and "*Lingshu*". According to this text, human body is composed of various organs related to each other organically. It recommends to study the etiology as a whole. Shi Su, a Chinese poet in the Song dynasty, wrote in "*Qinshi*"—one of his poems—"If the sound of a zither comes from the instrument itself, then why does not it sound when placed inside a case? If the sound of a zither comes from your fingers, then why do not we just listen to those fingers only? (The Chinese is "若言琴上有琴声,放在匣中何不鸣?若言声在指头上,何不于君指上听", translated by Miao Guang, from http://www.hsilai.org/tc/365/0321.php)" This poem illustrates that the fingers, instrument, skills and emotion of the player constitute the music. These elements are interdependent, and none of them is dispensable.

2.1 Introduction

To give an intuitive understanding of multicopters, Figs. 2.1 and 2.2 show the combination and connection of a multicopter system. As shown in Fig. 2.1, Radio Controlled (RC) transmitter, RC receiver, autopilot (also known as the flight controller), Global Position System (GPS) receiver and Ground Control Station (GCS) belong to the command and control system. Moreover, a multicopter system includes the airframe and propulsion system. In Fig. 2.2, the relationship between the components of the propulsion system and the command and control system are shown clearly. Figure 2.3 is the structure diagram of a multicopter, and it is also the structure diagram of this chapter.

2.2 Airframe

Generally, a typical airframe only includes a fuselage and a landing gear. To cover overall types of multicopters, the duct is also taken as a part of the airframe in this chapter.

2.2.1 Fuselage

2.2.1.1 Function

The fuselage acts as the 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, and weight should be carefully taken into consideration.

2.2.1.2 Parameters

(1) Weight

The weight of the fuselage is mainly determined by its size and material. Under the same thrust (also referred to as lift in some papers), a smaller fuselage weight means a larger remaining payload capacity.

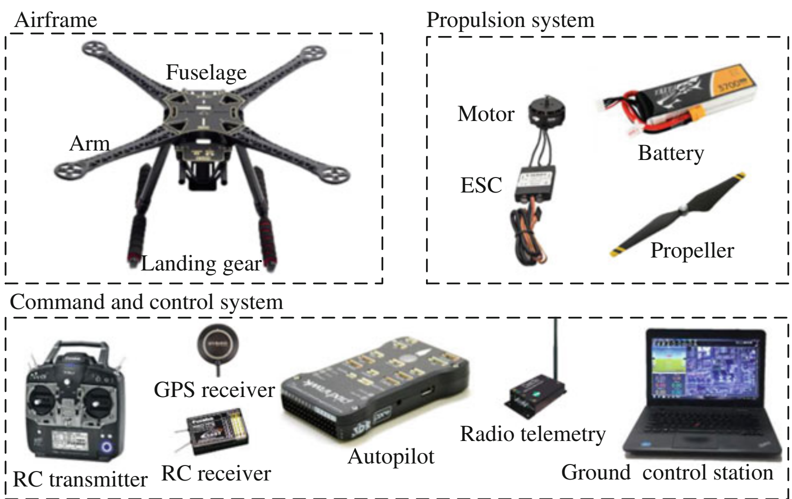


Fig. 2.1 Basic composition of a multicopter system

Fig. 2.2 Combination and connection of a multicopter system (photo by Jethro Hazelhurst from http://www.ardupilot.org)

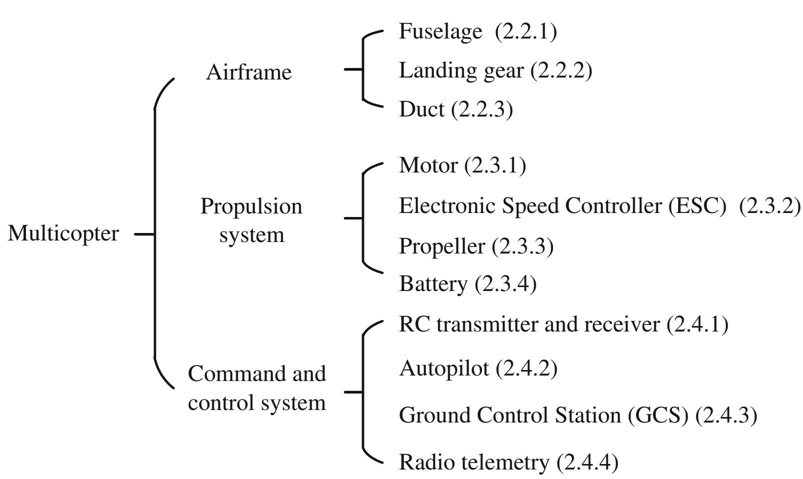


Fig. 2.3 Structure diagram of this chapter

Therefore, in the premise of ensuring the performance of the fuselage, the weight is expected to be as small as possible.

(2) Configuration
The most common configurations include tricopter, quadcopter, hexacopter, and octocopter. Figure 2.4 shows some kinds of configurations that open source autopilots support.

(3) Diagonal size
Diagonal size is the diameter (usually in mm) of the circumcircle determined by the motor axes. In general, as shown in Fig. 2.5, it is the distance of motor axes in the diagonal line and it is used to indicate the size of an airframe. The diagonal size restricts the size of propeller, which determines the maximum thrust and then the payload capacity.

(4) Material
Properties of some kinds of materials are shown in Table 2.1.[1] It is observed that carbon fiber material has small density, high rigidity, and high strength, but it is expensive and hard to process. So, the carbon fiber propellers are widely applied to commercial multicopters that need to carry heavy payload. As a comparison, the acrylic plastic material is light, inexpensive and easy to process, but its rigidity and strength are small. So, the acrylic plastic material is often used in toys or small model airplanes.

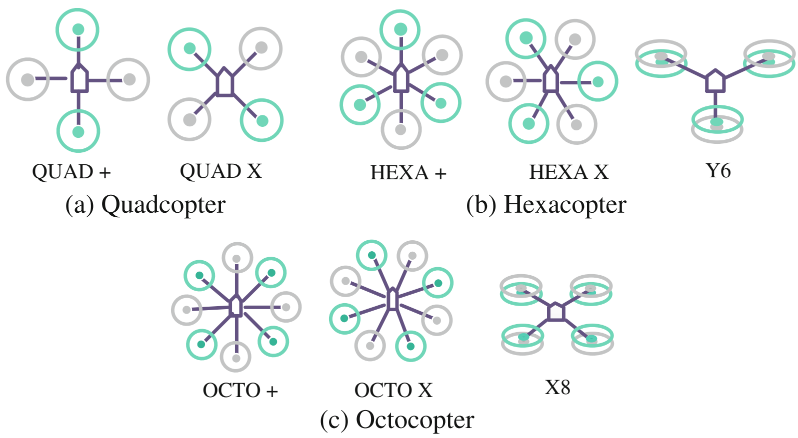


Fig. 2.4 Some basic configurations of multicopters

Fig. 2.5 Diagonal size of multicopters

[1] 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).

Table 2.1 Properties of some materials [1]

	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:cheapest)	1	6	9	9	7	10
Producibility (10:simplest)	3	7	6	7	7	10

2.2.2 Landing Gear

Figure 2.6 shows a landing gear, functions of which include the follows:

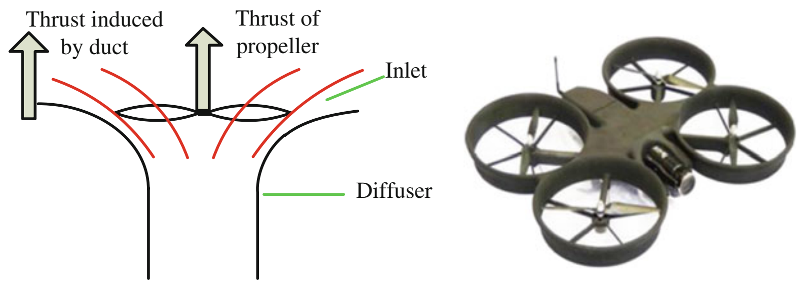
(1) Supporting the whole multicopter when landing on the ground or taking off and keeping the level balance of the multicopter.
(2) Keeping propellers off ground at a safe distance.
(3) Weakening ground effect (the downwash stream hits the ground and generates some disturbance effect) when multicopters take off or land.
(4) Consuming and absorbing impact energy when multicopters land on the ground.

2.2.3 Duct

2.2.3.1 Function

In addition to protecting the blade and ensuring personal safety, the *duct* can also enhance the efficiency of thrust and reduce noise. The thrust of a multicopter with ducts is composed of two parts, i.e., the thrust of the propeller and the additional thrust induced by the duct, as shown in Fig. 2.7.

Fig. 2.6 A landing gear



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

Fig. 2.7 Duct

2.2.3.2 Working Principle

For a rotating propeller in the duct, airflow inside the inlet flows faster than the outside, while the pressure inside is lower than the outside according to *Bernoulli's Principle*, therefore an additional thrust is obtained. Beside, varying the cross section of the duct allows the designer to advantageously change the speed and pressure of the airflow. In addition, by adding a duct, the loss due to the tip vortex which occurs when a propeller operates in free space can be reduced. Therefore, the efficiency and maximum thrust can be increased, sometimes may be significantly.

2.2.3.3 Parameters

The diffuser length and propeller diameter are important parameters for the duct, and reader can refer to [2] for its detailed optimization design method. Although the duct may improve the efficiency to increase the hovering time, the duct itself is generally heavy which may significantly increase the weight and reduce the time. So, the final optimal design needs to achieve a trade-off.

2.3 Propulsion System

A propulsion system includes propellers, motors, ESCs, and often a battery. This system is the most important part of the multicopter, which determines the main performances such as the hovering time, the payload ability, and the flying speed and distance. Moreover, components of the propulsion system have to be compatible with each other, otherwise they cannot work properly or even fails in some extreme cases. For example, in some conditions, an aggressive maneuver may make the current exceed the safety threshold of the ESC, then make the motors stop working in the air, which is very dangerous. Performance evaluation of a propulsion system will be introduced in Chap. 4.

2.3.1 Propeller

2.3.1.1 Function

Propeller is a component that produces the thrust and torque to control a multicopter. The motor efficiency varies with the output torque (depends on the type, size, speed and other factors of a propeller). Therefore, a good match should make sure that the motor works in a high efficiency condition, which will guarantee less power consumed for the same thrust and then extend the time of endurance of the multicopter. Therefore, choosing appropriate propellers is a very direct way to improve the performance and efficiency of a multicopter.

2.3.1.2 Parameters

(1) Type

Generally, the propeller model is described by a four-digit number, such as a 1045 (or 10 × 45) propeller, among which the first two represents the diameter of the propeller (unit: inch), and the latter two represents the propeller pitch (also referred to as screw pitch, blade pitch or simplified as pitch, unit: inch). Therefore, the APC1045 propeller implies that the propeller belongs to APC series, and the diameter and pitch of the propeller is 10 in. and 4.5 in., respectively. 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." For example, a 21-inch-pitch propeller would move forward 21 in. per revolution.

(2) Chord length

The definition of *chord length* of a propeller is shown in Fig. 2.8, which varies along the radius. Generally, the chord located at the 2/3 of the radius of the propeller is chosen as the nominal chord length.

(3) Moment of inertia

Moment of inertia is a quantity expressing the tendency of a body to resist angular acceleration, which is the sum of the products of the mass of each particle in the body with the square of its distance from the rotation axis. 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.

(4) Number of blades

Some typical propellers with different number of blades are shown in Fig. 2.9. Experiments indicated that the efficiency of two-blade propeller is better comparing with three-blade propeller [3, p. 65]. As shown in Fig. 2.10, the maximum thrust of the propeller is increased with the number of the blades (Fig. 2.10a), while the efficiency is decreased with the number of the blades (Fig. 2.10b). It can also be found that, to obtain the same thrust, a three-blade propeller has a less diameter compared with the corresponding two-blade propeller. Although the efficiency is reduced, the time of endurance may be improved to a certain extent by the reduction of the size and weight of the airframe.

(5) Safe rotation rate

Generally, the materials of propellers used on the multicopters are flexible. So, when rotation rate 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

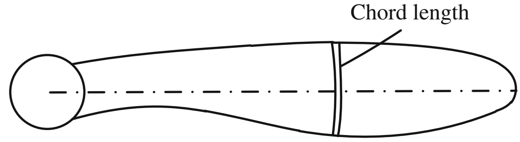
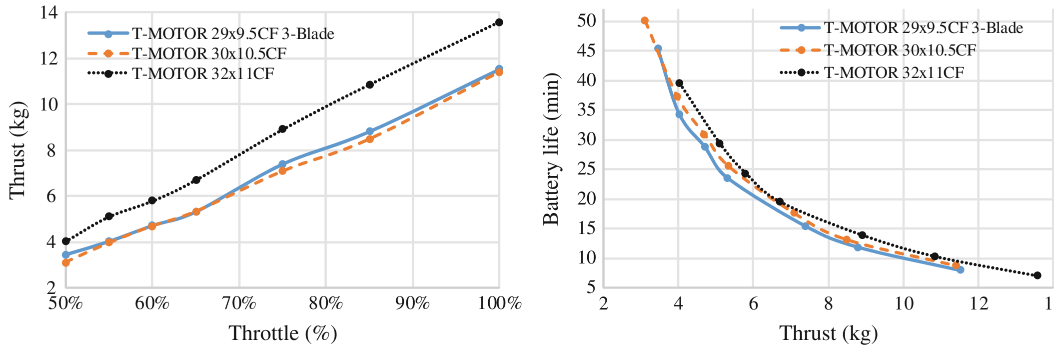


Fig. 2.8 Chord length of a propeller

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

Fig. 2.9 Propellers with different number of blades



(a) Throttle graph of T-MOTOR U12 KV90 (b) Thrust graph of T-MOTOR U12 KV90

Fig. 2.10 Thrust and efficiency of two-blade propeller and three-blade propeller. Taking T-MOTOR 29 × 9.5CF 3-Blade for example, it indicates that the propeller has three blades, and it is made of Carbon Fiber (CF). The default number of blades is two

Web site[2] gives an empirical formula for the maximum speed of multicopter propellers, which is 105000 Revolution Per Minute (RPM)/prop diameter (inches). Taking the 10-in. propeller for example, its maximum speed is 10500RPM. By contrast, the maximum speed of Slow Flyer (SF) propellers is only 65000RPM/prop diameter (inches).

(6) Propeller specific thrust

Specific thrust, also referred to as efficiency (unit: g/W), is a very important parameter to measure the efficiency of energy transformation. The propeller specific thrust is defined as

$$\begin{aligned}\text{Mechanical power (unit: W)} &= \text{Torque (unit: N}\cdot\text{m)} \times \text{Propeller speed (unit: rad/s)}\\ \text{Propeller specific thrust (unit: g/W)} &= \frac{\text{Thrust (unit: g)}}{\text{Mechanical power (unit: W)}}.\end{aligned}$$

(7) Material [4]

Material includes carbon fiber, plastic, and wood. Though the propellers made of carbon fiber cost almost twice as much as those made of plastic, they are more popular because propellers made of carbon fiber have the following advantages: 1) less vibration and noise because of its high rigidity; 2) lighter and stronger; and 3) 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 and the fiber blade can be treated as a high speed rotating razor which is too dangerous to human nearby. Propellers made of wood are much heavier and more expensive, which is suitable for multicopters with large payload capacity.

2.3.1.3 Static Balance and Dynamic Balance [5, 6]

The goal of static balance and dynamic balance is to reduce the vibration caused by the asymmetry centrifugal force which is further caused by the asymmetrical distribution of mass and shape. The imbalance of propeller is a major source of vibration for a multicopter. Propeller static imbalance occurs when the Center of Gravity (CoG) of the propeller does not coincide with the axis of rotation. Dynamic imbalance occurs when the CoG of the propeller does not coincide with the center of inertia.

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

Fig. 2.11 A Du-Bro propeller balancer

The imbalanced force not only affects the sensor measurement, but also makes the motor bearing wear down more quickly and increases the power consumption. These characteristics will shorten the lifetime of multicopters and increase the possibility of failure. Besides, an imbalanced propeller is far noisier than a balanced one. A balancer as shown in the Fig. 2.11 can be used to test the static balance of a propeller. The test of dynamic balance is often not an easy work as it needs sensors to record the data. An easy way without using sensors is introduced in a video [7]. If imbalance exists, some measures can be taken, such as pasting scotch tapes on the lighter blade or grinding the heavier one (not the edge) using sandpapers.

2.3.2 Motor [8, pp. 533–592]

2.3.2.1 Function

Motors of multicopters are mainly brushless DC motors for the various advantages such as high efficiency, potential to downsize, and low manufacturing costs. Brushless DC motors are used to convert electrical energy (stored in battery) into mechanical energy for propeller. Concretely, based on the position of rotors, brushless DC motors can be classified into the outer rotor type and inner rotor type as shown in Fig. 2.12. Considering that the motor of a multicopter is supposed to drive larger propellers to improve efficiency, the outer rotor type outperforms the inner rotor type as it can provide larger torques. Besides, compared with the inner rotor type, speed of the outer rotor type is more stable. Therefore, the outer rotor type is more popular in multicopters and most other aircraft.

2.3.2.2 Working Principle

As shown in Fig. 2.13, the control circuit generates a Pulse Width Modulated (PWM) signal to the ESC, where the signal is amplified by a driving circuit and sent to the power switch of the inverter. Then, it will control the motor winding to work in a certain sequence and generate a jump-type rotating magnetic field in the air gap of the motor. Common types of main circuits of brushless DC motors include the star-type three-phase half-bridge, star-type three-phase bridge, and angle-type three-phase bridge. Among them, the star-type three-phase bridge is used most widely. Three output signals of the position detector are controlled by a logic circuit to control the on and off states of the switch. There are two control modes: two-two conduction mode and three-three conduction mode. As shown

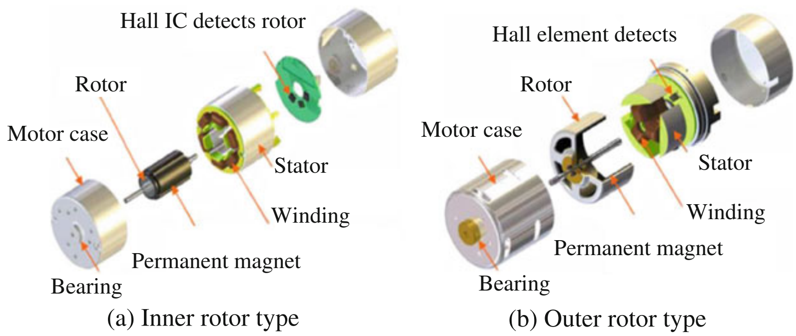


Fig. 2.12 Outer rotor type and inner rotor type (photo courtesy of www.nidec.com)

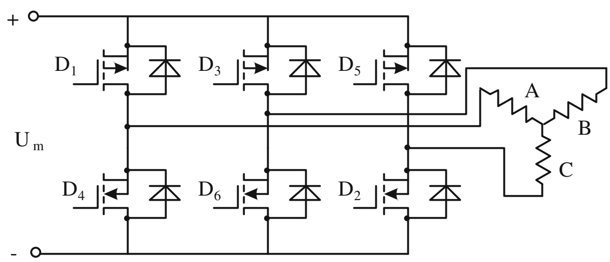


Fig. 2.13 Main circuit of star-type three-phase bridge

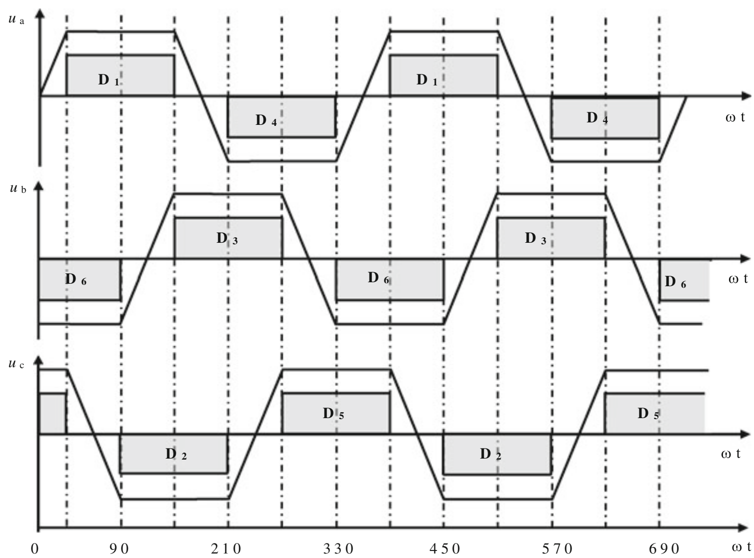


Fig. 2.14 Counter electromotive force waveform of three-phase winding and its two-two conduction mode

in Fig. 2.14, every 60° the rotor rotates, the switches of inverters commutate one time and the field of the state of stator changes one time. There are six magnetic states and three phases for motors, each phase conducts 120°.

2.3.2.3 Parameters

(1) Size

Size of motor is generally represented by its stator size with four-digit number, such as motor 2212 (or written as 22 × 12), among which the first two indicates its stator diameter (mm) and the latter two indicates its stator height (mm). For example, the motor 2212 indicates that the stator diameter of the motor is 22 mm and the stator height is 12 mm. That means, 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 large multicopters.

(2) KV value for motors

The KV value for brushless DC motors is the number of RPM that the motor will revolve when 1 V (Volt) is applied with no load attached to the motor. For example, 1000 KV just means that when 1 V is applied, the no-load motor speed will be 1000 RPM. A low KV motor has more windings of thinner wire, which means it will carry more power, produce a higher torque, and drive a bigger propeller. By contrast, a high KV motor can produce a low torque so that it can only drive a small propeller.

(3) No-load current and voltage

In the no-load test, the current passing through the three-phase winding of stator after applying nominal voltage (generally 10 or 24 V) is defined as the nominal no-load current.

(4) Maximum current/power

It is the maximum current or power the motor can undertake. For example, maximum continuous current "25A/30s" represents that the motor can work safely with continuous current up to 25A, beyond which for more than 30s the motor may be burnt out. The same definition can be applied for the maximum continuous power.

(5) 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. The existence of the resistance generates heat during the running of the motor, which may overheat the motor and reduce the efficiency.

(6) Motor efficiency

Motor efficiency is an important parameter to measure the performance. It is defined as follows:

$$\begin{aligned}\text{Electrical power (unit: W)} &= \text{Input Voltage (unit: V)} \times \text{Effective current (unit: A)}\\ \text{Motor efficiency} &= \frac{\text{Mechanical power (unit: W)}}{\text{Electrical power (unit: W)}}.\end{aligned}$$

The motor efficiency is not a constant. In general, it varies with input voltage (throttle) and load (propeller). For the same propeller, the efficiency of the motor may be reduced as the input voltage (current) is increased. That is because the larger the current is, the more the heat (caused by the resistance) and other loss will be, which makes the ratio of the effective mechanical power reduced.

(7) Overall specific thrust

The overall performance of the propulsion system depends largely on a well-matched combination of motor and propeller. To evaluate the efficiency of the motor and propeller together, the overall specific thrust is calculated as

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	

Fig. 2.15 Overall specific thrust of motor MN5212 KV420 (data from http://www.rctigermotor.com)

$$\text{Overall specific thrust (unit: g/W)} = \frac{\text{Thrust (unit: g)}}{\text{Electrical power(unit: W)}}$$
$$= \text{Propeller specific thrust} \times \text{Motor efficiency.}$$

Since both the propeller specific thrust and motor efficiency are not constant, the overall specific thrust changes with the working condition. The overall specific thrust is often given by the motor producers. Taking a motor for example, the overall specific thrust under different states is displayed in Fig. 2.15, where "Efficiency (G/W)" is in fact the overall specific thrust. This will help designers to choose combinations of a motor and a propeller according to their requirements.

2.3.3 Electronic Speed Controller

2.3.3.1 Function

The basic function of ESCs is to control the speed of motors based on the PWM signal that autopilots send, which is too weak to drive brushless DC motors directly. Furthermore, some ESCs act as a dynamic brake, or a power supply (battery elimination circuit module) for RC receiver or servo motors. Unlike a general ESC, the brushless ESC has a new function, i.e., it can act as an inverter transforming an onboard DC power input into a three-phase Alternating Current (AC) power that can be applied to brushless DC motors. Undoubtedly, there are some other auxiliary functions, such as battery protection and starting protection. The Fig. 2.16 shows the Xaircraft ESC-S20A for multicopters.

2.3.3.2 Parameters

(1) Maximum continuous/peak current

The most important parameter for brushless ESCs is current, which is usually represented by Ampere (A), such as 10 A, 20 A, and 30 A. Different motors need to be equipped with different ESCs. An inappropriate matching will burn ESCs or even cause motor failure. Concretely, there are two important parameters of the brushless ESC, namely the *maximum continuous current* and *peak current*. The former

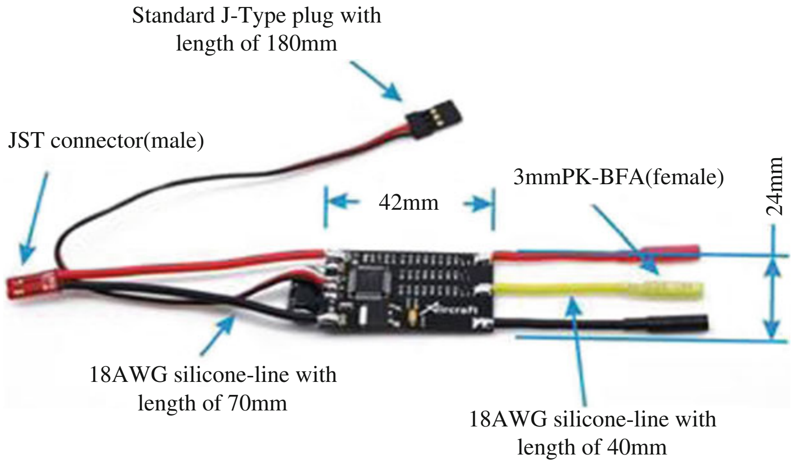


Fig. 2.16 XAircraft ESC-S20A for multicopters

is the maximum continuous current in the normal working condition, while the latter is the maximum instantaneous current that the ESC can withstand. Each ESC will be labeled with a specified value, such as Hobbywing XRotor 15 A which indicates the maximum continuous current allowed. When choosing the type of ESCs, attention should be paid to the maximum continuous current, which needs to be checked whether it leaves a safety margin (20% for example) so as to efficiently avoid burning the power tube. Taking 50A ESC for example, 10A is often left as a safety margin.

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

(3) Resistance
Since all ESCs have resistance, the heating power cannot be ignored because the current flowing through them can sometimes reach tens of Amperes. Considering the heat dissipation, the resistance of ESCs with high current is always designed to be small.

(4) Refresh rate
The motor response has a great relationship with the refresh rate of ESCs. Before the development of multicopters, ESCs were designed specifically for model airplanes or cars. The maximum operating frequency of servo motors was 50 Hz, therefore the refresh rate of ESCs was 50 Hz. Theoretically, the higher the refresh rate is, the faster the response will be. Since multicopters differ from other types of model airplanes in that the rapid thrust adjustment is realized by the rapid control of propeller angular speed, the refresh rate of multicopter ESCs is often faster. In order to ensure smooth outputs, low-pass filtering is often applied to the input or output of ESCs at the cost of reducing their response rate. This also implies the reduced control frequency.

(5) Programmability
The performance of ESCs can be optimized by tuning internal parameters. There are three ways to set the parameters of ESCs, i.e., programmable cards as shown in Fig. 2.17, computer software via the USB, and RC transmitters. The parameters that can be set up include: throttle range calibration, low voltage protection, power outage value, current limitation, brakes mode, throttle control mode, switch timing setting, starting mode, and PWM mode setting.

Fig. 2.17 Hobbywing brushless ESC programmable cards

(6) Compatibility

If the ESC and motor are incompatible, the motor is likely to be jammed, which may result in a fall and crash for a multicopter in the air. Sometimes motors may get jammed in extreme cases, such as the case that the control command for mode transitions changes sharply, generating large instantaneous current, which are not easy to be detected.

2.3.3.3 Square-Wave Driver and Sinusoidal Driver [9]

(1) Square-wave driver

Square-wave driver type ESC outputs square wave. Its control elements work in the switch state, which makes it simpler, cheaper, and easier to control.

(2) Sinusoidal driver

Sinusoidal driver-type ESC outputs sinusoidal wave, which uses Field Oriented Control (FOC). Therefore the sinusoidal driver performs better in the aspects of operation stability, speed range, efficiency, and vibration reduction of noise. Now, the optical encoder, Hall sensor and observer-based method are available to measure the angle of the rotor. For a multicopter, its motor rotors are working in a high speed state, which means the FOC can be applied based on the observation of rotor electrical angle with information including the motor model, current, and voltage. This is a good way to reduce the cost.

2.3.4 Battery

2.3.4.1 Function

Battery is used to provide energy. A battery for small multicopters is shown in Fig. 2.18. A problem often concerned on present multicopters is the time of endurance , which heavily depends on 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.

2.3.4.2 Parameters

The basic parameters of the battery include voltage, discharge capacity, internal resistance, and discharge rate. The nominal voltage of a single cell of LiPo battery is 3.7 V. When it is fully charged, the

Fig. 2.18 GENS ACE Tattu UAV battery

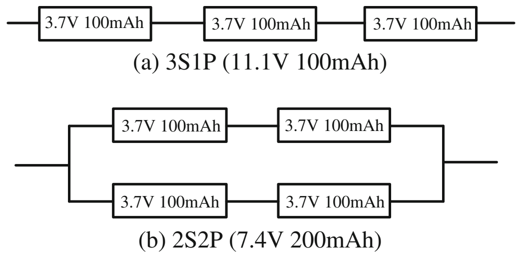


Fig. 2.19 Connection diagrams

voltage can reach 4.2 V. In order to ensure that the total battery capacity and voltage are enough, several cells can be assembled together. In an actual process, the remaining voltage is decreased gradually with the discharge of the battery. Most research shows that in a certain range, the remaining voltage is in a linear relationship with the battery remaining capacity. However, in the late stage of discharge, the voltage may drop sharply, which may result in rapid thrust loss of multicopter. To ensure that a multicopter has enough power or capacity to return home before the carried battery runs out, it is necessary to set a safe voltage threshold for the battery. Besides, the output voltage will drop as the current of discharge is increased because of more voltage allocated to the internal resistance. It should be noted that the battery should not be completely discharged, otherwise it may have an irreversible damage.

(1) Connection
By combining battery cells in series, a higher voltage can be obtained, with capacity unchanged. On the other hand, by combining battery cells in parallel, a larger capacity can be obtained, with voltage unchanged. In some cases, there exist combinations of both series and parallel in battery packs. The letters S and P are used to represent for the series connection and parallel connection, respectively. For example, as shown in Fig. 2.19a, assuming that the voltage of one cell is 3.7 V and its capacity is 100 mAh, then 3S1P represents three cells in series connection (total voltage is 11.1 V, capacity is 100 mAh). As shown in Fig. 2.19b, for the 2S2P battery, its total voltage is 7.4 V and total capacity is 200 mAh.

(2) Capacity
The milliAmpere-hour (mAh) or Ampere-hour (Ah) is a technical index that how much electrical charge a particular battery has. The capacity of 5000 mAh for a LiPo battery means that the discharge of the battery will last for an hour with the current of 5000 mA when the voltage of a single cell is decreased from 4.2 to 3.0 V. However, the discharge ability will be decreased along with the process of discharge, and its output voltage will also be decreased slowly. As a result, the remaining capacity is not a linear function of the discharge time. In practice, there are two ways to detect whether the remaining capacity of a battery can support the flight. One way is to detect the voltage of the battery by sensors in real time, which is commonly used. The other way is to estimate the State of Charge (SoC) value of batteries, which will be shown in Chap. 14.

(3) Discharge Rate
Discharge rate is represented by

$$\text{Discharge Rate (unit: C)} = \frac{\text{Current of Discharge (unit: mA)}}{\text{Capacity (unit: mAh)}}.$$

For example, the discharge rate of a battery will be 0.2 C when its nominal capacity is 100 mAh and the discharge current is 20 mA. Obviously, the discharge rate measures the rate of discharge. When the maximum discharge rate of a battery with the nominal capacity of 5000 mAh is 20C, the maximum current of discharge is calculated as 5000 mA $\times$ 20C = 100 A. The total current of a multicopter cannot exceed its maximum current limit of the battery; otherwise, the battery may be burnt out. The battery having higher discharge rate can generate more current, which can be applied to multicopters demanding higher current because of heavier bodies and more motors.

(4) Resistance
Resistance of a battery is not a constant value, and it varies with the power status and service life. The resistance of a rechargeable battery is relatively small in the initial state. However, after a long period of use, because of the exhaustion of electrolyte and decrease in chemical substance activity of the battery, the internal resistance will be increased gradually until to a certain degree where the power in the battery cannot be released. Then, the battery can be regarded as being run out of.

(5) Energy Density
Energy density is the amount of energy stored in a given system or region of space per unit volume or mass, and the latter is more accurately termed specific energy. In general, the units for energy density and specific energy are (Watt $\times$ hour)/kg and (Watt $\times$ hour)/L, i.e., Wh/kg and Wh/L, respectively. Batteries with higher energy density are more popular due to the contradiction between volume (weight) and endurance for a product. Lithium-ion battery as a kind of clean energy is getting more and more attentions and is widely used in many applications. The energy density of Lithium-ion batteries varies from chemistry to chemistry and the energy density can range from 240 to 300 Wh/L (double of the NiCd, 1.5 times of NiMH).

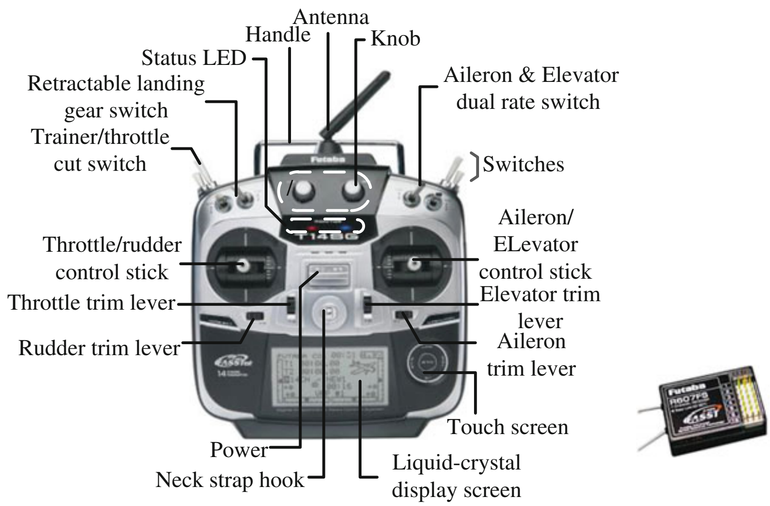
2.4 Command and Control System

2.4.1 RC Transmitter and Receiver [10]

2.4.1.1 Function

An *RC transmitter*, as shown in Fig. 2.20a,[3] is used to transmit commands from remote pilots to the corresponding receiver. Then, the *receiver*, as shown in Fig. 2.20b, 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. Advanced functions include battery voltage and current flight data of multicopters. At present, there are several open source transmitters. Readers interested in detailed information can refer to the Web site http://www.open-tx.org or http://www.reseau.org/arduinorc, based on which transmitters can be customized.

[3] For a multicopter, the *throttle control stick* is to control the upward-and-downward movement, and the *rudder control stick* is to control the yaw movement, while the *aileron stick* is to control the roll movement, and the *elevator stick* is to control the pitch movement.



(a) RC transmitter (b) RC receiver

Fig. 2.20 Futaba RC transmitter and receiver

2.4.1.2 Parameters

(1) Frequency

The RC transmitter and the receiver communicate by radio waves, and the commonly used radio frequency is 72 MHz and 2.4 GHz. Before the utilization of 2.4 GHz, the chance of co-channel interference was very high. The phenomenon might occur when one RC transmitter controls two model aircraft. With the development of model airplane, the safety becomes a serious issue. Therefore, 2.4 GHz transmitters emerged. The 2.4 GHz radio frequency falls in the microwave range, which was used in wireless audio transmission initially. The 2.4 GHz radio communication technology has the following advantages. 1) High frequency. The technology relies on microcomputers to plan frequencies automatically instead of setting the frequency by controlling the crystal. 2) Less chance of co-channel interference. When several transmitters work together, this technology allows frequency-hopping automatically to avoid mutual interference. 3) Low power consumption. As no crystal is used as frequency control parts, the power consumption is reduced significantly. 4) Smaller volume. Since the control wavelength is very short, transmitting and receiving antennas can be shortened greatly. 5) Rapid response and high control accuracy. Although the 2.4 GHz RC transmitter can deal with the co-channel interference, some problems still exist. For example, the 2.4 GHz microwave is of good straightness. In other words, the control signal has a bad performance when there exists an obstacle between the RC transmitter and the multicopter. As a result, the transmitting antenna and receiving antenna should be maintained line of sight; and the obstacles between them, such as houses and warehouse, should be avoided.

(2) Modulation [11, pp. 129–133], [12]

Pulse Code Modulation (PCM) implies the encoding of signal pulses, and Pulse Position Modulation (PPM) refers to the modulation of high-frequency signal. By operating sticks on the transmitter, the value of potentiometer varies accordingly. By the encoding circuit, it can be read and converted into a pulse coded signal, namely PPM or PCM, which will be further modulated through a high-frequency modulation circuit and sent by high-level 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.

(3) Channels

One channel corresponds to one separate operation, and generally there are six-channel transmitters, eight-channel transmitters, and ten-channel (or more) 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. Considering the mode transition and control of camera gimbal, transmitters with at least eight channels are recommended.

(4) Mode [13]

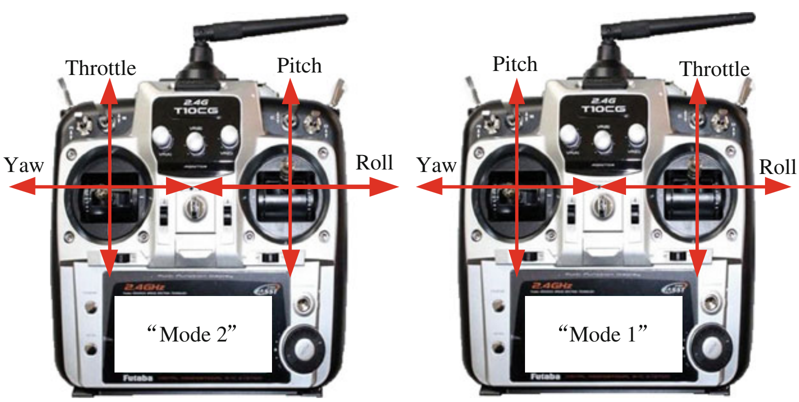
RC transmitter modes refer to the way how an RC transmitter is configured to control a multicopter, i.e., the relationship that sticks correspond to movements. For example shown in Fig. 2.21, "Mode 1": pitch/yaw on the left stick, throttle/roll on the right (also called right-hand mode, popular in Japan, more suitable for fixed-wing aircraft); "Mode 2": throttle/yaw on the left, pitch/roll on the right (also called left-hand mode, popular in the U.S. and other parts of the world including China, more suitable for multicopters).

(5) Throttle

In general, the throttle control stick in an RC transmitter is designed to be unable to recover back to its original position automatically. The *direct-type* RC transmitter in this book refers to the type that the total thrust has a positive correlation with the deflection of the throttle control stick. Furthermore, a connected motor will stop with the throttle control stick at the bottom and work at a full speed with the throttle control stick at the top. The transmitter can also be set to recover back to the midpoint automatically once it is released, which is called the *increment-type* RC transmitter in this book. Correspondingly, the motor speed will be increased when the stick is higher than the midpoint and decreased when lower than the midpoint. The mode transition can be realized by loosening and tightening the spring washers behind the stick and then using specified algorithms.

(6) Remote control distance

The control distance of an RC transmitter is restricted by its power. For example, the effective control distance of the "Md-200" is claimed to be 1000 m. In order to extend the control distance, power amplifiers and antennas can be used.



For multicopters / For fixed-wing aircraft

Throttle : control the upward-and-downward movement — corresponding to the throttle stick
Pitch : control the forward-and-backward movement — corresponding to the elevator
Yaw : control the yaw movement — corresponding to the rudder
Roll : control the leftward-and-rightward movement — corresponding to the aileron

Fig. 2.21 Different control modes of an RC transmitter

2.4.2 Autopilot

A multicopter *autopilot* is a flight control system used to control the attitude, position, and trajectory of a multicopter. It can be semi-automatically (needs commands from remote pilot) or fully automatically. Autopilots have a control framework which is often based on Proportional-Integral-Derivative (PID) controllers, leaving parameters to be tuned for different multicopters.

2.4.2.1 Composition

A multicopter autopilot can be divided into the software part and hardware part. The software part is the brain of a multicopter and it is used to process and send information, while the hardware part generally includes the following components:

(1) GPS receiver. It is used to obtain the location information of multicopters.
(2) Inertial Measurement Unit (IMU). It includes: the three-axis accelerometer, three-axis gyroscope, and electronic compass (or three-axis magnetometer). It is used to obtain attitude information of a multicopter. In general, a six-axis IMU is the combination of a three-axis accelerometer and a three-axis gyroscope; a nine-axis IMU is the combination of a three-axis accelerometer, a three-axis gyroscope and a three-axis magnetometer; and a ten-axis is the combination of a nine-axis IMU and a barometer.
(3) Height sensor. The barometer and ultrasonic range finder are used to obtain the absolute height (altitude) and relative height (distance to the ground), respectively.
(4) Microcomputers. It acts as a platform to receive information and run algorithms to produce control command.
(5) Interface. It acts as a bridge between the microcomputer and the other devices, such as the sensors, ESC, and RC receiver.

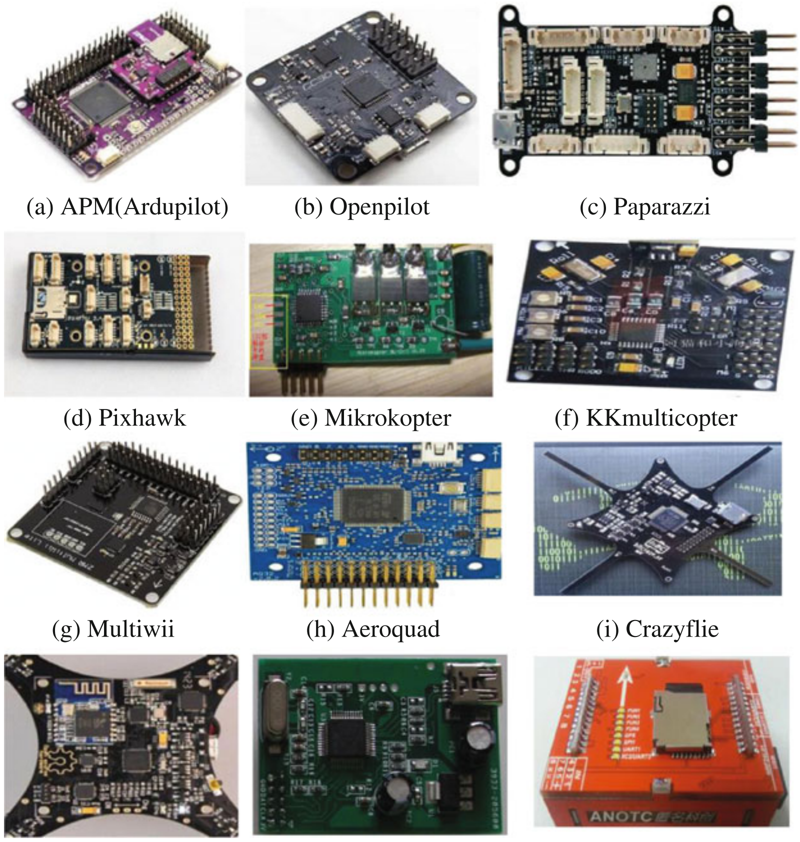
2.4.2.2 Function

(1) Perception. It is used to solve the problem of "where the multicopter is." The GPS receiver, IMU, and height sensors all have a lot of noises, and their refresh rates are not the same. For example, the refresh rate of a GPS receiver is 5 Hz, while the refresh rate of an accelerometer may be 1000 Hz. One task of an autopilot is to fuse these information together to obtain accurate position and attitude. This mainly corresponds to Chaps. 7–9 in this book.
(2) Control. Control is to solve the problem of "how the multicopter flies to a desired position." Based on the position and attitude measured and given, the low-level flight control law is carried out, generating commands for ESCs to control the motors of a multicopter to achieve a desired position. This mainly corresponds to Chaps. 10–12 in this book.
(3) Decision. Decision is to solve the problem of "where the multicopter will go." The decision-making mainly includes the mission decision-making and failsafe. This mainly corresponds to Chaps. 13 and 14 in this book.

2.4.2.3 Open Source Autopilot

Currently, there are many free open source autopilots of multicopters. The Web sites can be found from Table 1.3 in Chap. 1. Open source autopilot flight control boards (hardware) are shown in Fig. 2.22. The types and performance of components of some autopilots are shown in Table 2.2.

Fig. 2.22 Open source autopilots of multicopters



(a) APM(Ardupilot) (b) Openpilot (c) Paparazzi

(d) Pixhawk (e) Mikrokopter (f) KKmulticopter

(g) Multiwii (h) Aeroquad (i) Crazyflie

(j) CrazePony (k) DR.R&D (l) Anonymous

2.4.3 Ground Control Station

2.4.3.1 Function

An important part of a GCS is the software. Remote pilots can interact with the software using the mouse, keyboard, button, and joystick. So, way points can be planned by remote pilots for multicopters in advance. Furthermore, remote pilots can monitor the flight status in real time and set new missions to intervene flight. Besides, the software can record and playback flight for analysis.

2.4.3.2 Open Source GCS Software

There are a lot of free open source GCS software available for multicopters now. Figure 2.23 shows some screenshots of GCS software. Most of the GCS software can be downloaded from the corresponding autopilot Web sites, which are listed on the Table 1.3.

2.4.4 Radio Telemetry

2.4.4.1 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

Table 2.2 The parameters of open source autopilot flight control boards

Description	Size (mm)	Weight (g)	rocessor	Process frequency (MHz)	Gyroscope	Accelerometer	Magnetometer	Barometer
Arducopter	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)	38.9 × 39.55	20	STM32f103T8U6	72	MPU6050	MPU6050	HMC5883L	MS5611
Dr.R&D(2015)IV	33 × 33	300 (the 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 [14]

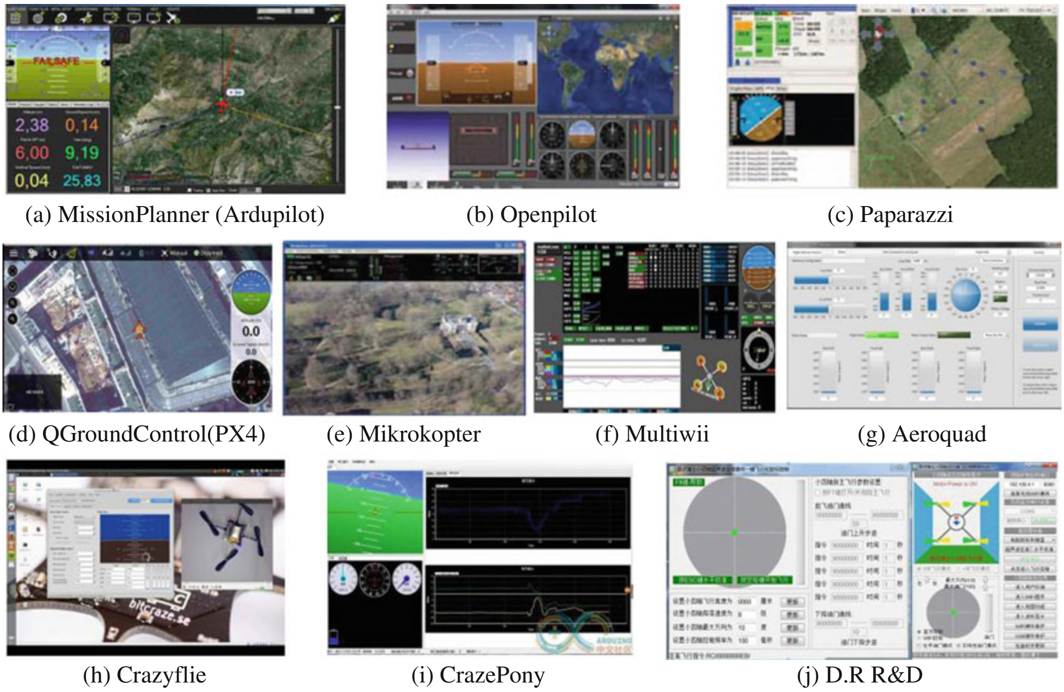


Fig. 2.23 Screenshots of some GCS softwares

of forward error correction and balanced soft decision. In contrast to analog radio telemetry which is made up of analog Frequency Modulation (FM) station and modem, digital radio telemetry provides transparent RS232 interface whose transmission rate is 19.2 Kbps. It is able to send and receive data in less than 10 ms and shows some parameters such as field intensity, temperature, voltage, state error statistics, alarm, and network management. As a medium of communication, radio telemetry has specific area of applications. In some special conditions, it can provide real-time and reliable data transmission for the monitoring signals in private network. Technology of radio telemetry is suitable for geographical environment which is scattered and complex as it features low cost, easy installation and maintenance, strong diffraction capability, flexible network structure, far coverage, etc. One end of radio telemetry is connected to the GCS software, and the other end is connected to the multicopter. Communication is performed using certain protocols to maintain the two-way communication of a multicopter and the corresponding GCS.

2.4.4.2 Parameter

(1) Frequency.
(2) Transmission distance.
(3) Transmission rate.

More parameter information on data links can be found in [15, pp. 191–246].

2.4.4.3 Communication Protocol

Communication protocol is also called *communication regulations*, referring to as the convention of the data transmission on both sides. The convention includes uniform rules of data format, synchronous method, transmission rate, procedure, error checking, and correct on and definition of control characters, which should be recorded by both sides of communication. It is also called *link control regulations*. The formulation of communication protocol is advantageous to the separation of GCS and autopilot. 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. It is on the basis of the GNU (GNU's Not Unix) Lesser General Public License (LGPL) and MAVLink can efficiently encapsulate C-data structure through a serial port, and send the data packet to the GCS. This communication protocol is widely tested by PX4 , APM, and Parrot AR. Drone. There are other protocols. For example, Openpilot autopilot adopts UAVTalk protocol to communicate with GCS.

2.5 Summary

As the Chinese idiom says, "small as the sparrow is, it possesses all its internal organs (small, but complete!)." This proverb is also applicable to a multicopter. This chapter introduces each component of a multicopter mainly in the aspects of function and key parameters. The composition of a multicopter introduced above can support the fully-autonomous flight of a multicopter. For the multicopter under the Semi-Autonomous Control (SAC) mode, some components can be removed, such as GCS and GPS receiver. In order to choose better components and improve the performance or find out the causes of failure, it is necessary to have a deep and comprehensive understanding of multicopters. For example, by adjusting the ESC parameters and choosing appropriate propellers, the flight performance can be improved; by considering the compatibility of ESCs and motors in advance, some crashes can be avoided.

Exercises

2.1 Find a multicopter with the airframe, propeller, ESC, motor, battery, and then explain the meaning of the key parameters of each component in detail.

2.2 Give a method of checking propeller dynamic balance.

2.3 Explain the principle of ESC with sinusoidal driver.

2.4 Choose and compare two autopilots, then clarify their advantages and disadvantages.

2.5 In order to combine the advantage of airplanes and multicopters, there are some kinds of aircraft able to take off and land vertically being available online. Find out a product and analyze its flight principle, advantages and disadvantages.

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