Abstract

Quadrotor aircrafts are developing extremely fast in recent years, however, most of self-designed aircrafts are basis on C language and Arduino, which are limited the future development. Thus, in this project, the core program is basis on JAVA which is more powerful and more flexible. In addition, mobile remoter is another development direction as well. It can not only decrease the demand of model aircraft remoter but also bring more convince to users.

This dissertation will start from the development history of aircraft and followed by basic knowledge and components. And after that, the program language and integrated development environment (IDE) are introduced. Software structure and hardware structure are the core parts of this project. Software orders the hardware work reasonable and hardware provide an accurate response to software.

The last part will talk about the flight preparation and possible development. To improve flight performance propeller dynamic balance and center gravity adjustment are essential. Furthermore, it is possible to use mobile as control board.

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1. Introduction

1.1. Background

Quadrotor aircraft is a multi-axis aircraft, there are four rotors to hover, to maintain the attitude and flat fly. Unlike a fixed-wing aircraft, it lifts the airplane by the thrust provided by the rotor. Its four rotor sizes are the same, and the distribution is close to symmetry. For simple designs, it is possible to control the aircraft to maintain a posture or to complete a variety of maneuvering operations by adjusting the relative speed between the different rotors to adjust the thrust at different locations and overcoming the momentary torque between each rotor.

The recent quadrotor aircraft in the field of unmanned aerial vehicles get a new life. With the development of smart phones, electronic gyroscope, GPS, telex flight control system, and the rapid response of the throttle motor system, the advantages of quadrotor aircrafts are amplified. quadrotor aircrafts have benefits such as flight stability, flexible control and can be used indoors and outdoors.

In addition, compared with other aircrafts, it has many advantages including fixed rotor angle, simple structure. The blade of each rotor is relatively short, the end of the blade line, the speed is slow, the collision impact is small, not easy to damage, more secure for people. Some small four-axis aircraft have rotor frame, to avoid collision.

1.2. History

Quadrotor aircraft is not only one of the micro-aircraft, but also a smart robot. In 1907, the French Breguet brothers made the first Quadrotor helicopters, this flight did not use any rotor-type helicopters and the flight did not use any control, so the flight stability is poor.

In 1921, George De Bothezat tried to build a large quadrotor helicopter in the United States Air Force Department in Dayton, southwestern United States. However, even though he had more than 100 flight tests, he still not managed to control its flight well, and did not meet the US Air Force standards.

In 1924, there was a quadrotor aircraft called Oemichen which managed to achieve a 1km vertical flight for the first time.

In 1956, Convertawing built a quadrotor aircraft, which had more than 19 feet in diameter, used two engines, and controlled the aircraft by changing the thrust provided by each propeller.

After decades, the quadrotor aircraft did not make any big progress. Over the past decade, with the micro-system, sensor and control theory and other technical development of quadrotor aircraft, quadrotor aircraft has aroused great interest. The study focused on the structure of small or micro four quadrotor aircraft, flight control, energy power and so on.

1.3.Classification

According to the size of the quadrotor aircraft, the aircraft will be roughly divided into large quadrotor aircraft and small quadrotor aircraft. The most of parts are the same, for example, the flight control part is basically the same; but there are also differences, such as the power part (including motor and motor drive) may be completely different.

1.3.1. Small quadrotor aircraft

The small four-axis is relative to the large four-axis, here we refer to the palm-sized four-axis aircraft. In general, the small four-axis can direct use the circuit board as a bearing bracket. Of course, it also can use a separate bracket.

Small four-axis because of its small size, generally it cannot carry too heavy load. But it is completely more than enough to be used to study the principles of the aircraft. The main components are flight control, electric transfer, motor, remote control, battery and bracket but they may be changed based on the characteristics of the small four-axis. The following are the benefits of the small quadrotor aircraft.

- Cheap, relative to the big four-axis which always cost of thousands of dollars. A small four-axis is generally hundreds of dollars to be able to get.
- The risk is very small, basically it can fly everywhere.
- Design their own flying control circuit board, write their own open source flight control procedures and algorithms. The large four-axis flight control is generally a commercial company's product and open source is limited.
- Due to the small four-axis flight distance is limited, you can direct use of smart phone to control instead of a remote control.

1.3.2. Large quadrotor aircraft

Large quadrotor aircraft need to have more professional knowledge, such as the electronic part of the connection, the adjustment of the center of gravity of the aircraft structure, remote control of the frequency and interference, according to the aircraft structure or flight site wind and other factor to adjust the control parameters.

In short, if there is a problem in a link, it will cause the aircraft cannot fly, or t the aircraft may fell down from the air or out of control.

Moreover, what need to pay attention is that the large quadrotor aircraft because of its large size and high propeller speed, it will be more dangerous if it hit people or things. So, it is important to choose no one, wide space and good field of vision to fly. A common accident is a paddle problem. The propeller problem means the propeller of

the aircraft shoot out, because the rotation speed is too high, beyond the design of the tensile strength of the rotor. In addition, the blade root may fracture, due to the rotation of the great inertia, the residual razor may be shot out like shell fragments in a great power.

Sometimes the loosened rotor fixing screws or touched by foreign matter can also cause the paddle problem. It would be dangerous if the creature hit the human, especially the fragile parts such as eyes. So, for the novice, it is the crucial to protect the eyes with goggles when test large quadrotor.

2. Basic knowledge

2.1.Terminology

Flight control: flight control refers to the electronic control part of the aircraft, the hardware includes the sensor part of the inertial navigation module and control part of the MCU. The software includes control algorithms.

pitch, yaw, roll: refers to the three-dimensional space in the aircraft rotation state.

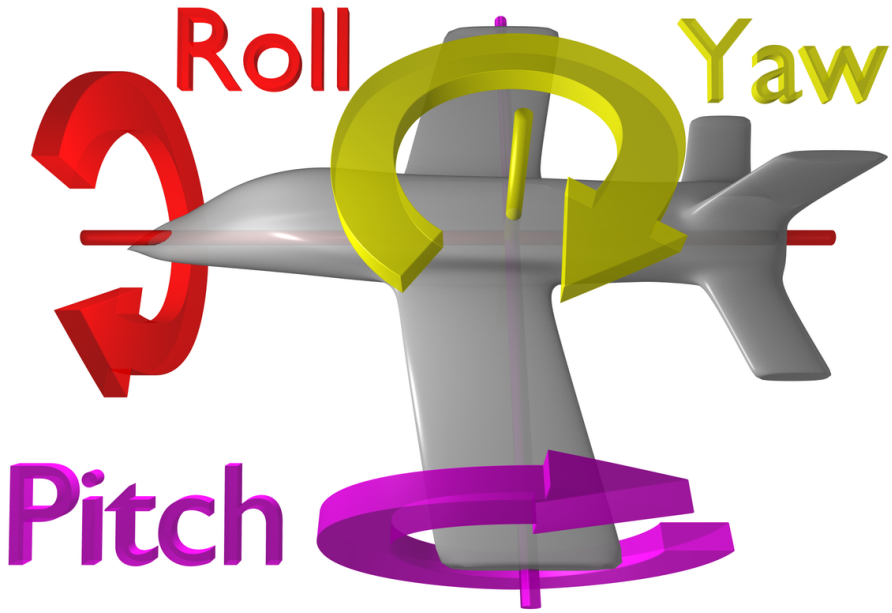

Figure 1 Attitude angle

Inertial navigation module: referred to as IMU, gyro sensor and acceleration sensor provides three-axis motion data module.

Geographic coordinate system: refers to the Earth's coordinate system, the coordinate system is fixed, north, east, just above corresponding to X, Y, Z axis.

Attitude calculation: referred to as attitude algorithm and gesture fusion. Attitude resolution refers to the gyroscope, accelerometer, compass and other data together to get the aircraft's air posture.

2.2.The structure of quadrotor aircraft

The rotors of Quadrotor aircraft are cross-shaped arrangement, driving four paddle rotation to produce upward thrust. Four motor wheelbase geometric center of the same distance, when the diagonal two shafts producing the same lift to ensure the balance of

the torque, the four axes will not be tilted in any direction. The four motors work in pairs, one rotates forward, and the other rotates reversal so that the rotation around the vertical axis of the anti-torque balance, to ensure the stability of the four-axis heading.

Compared with the traditional helicopter, the four rotorcraft has the following advantages: the rotor of the fuselage applied by the anti-torque and the rotor in the opposite direction of rotation, so when the motor 1 and motor 3 counterclockwise rotation at the same time, motor 2 and motor 4 Clockwise rotation, you can balance the rotor on the fuselage of the anti-torque.

2.3.Aerodynamic principle

A quadrotor aircraft has a total of six degrees of freedom (respectively, along the three axes for the translation and rotation), the control of these six degrees of freedom can be adjusted by different motor speed to achieve. The basic motion states are:

- Vertical movement
- Forward and backward movement
- Lateral movement
- Pitching movement
- Rolling movement
- Yaw movement

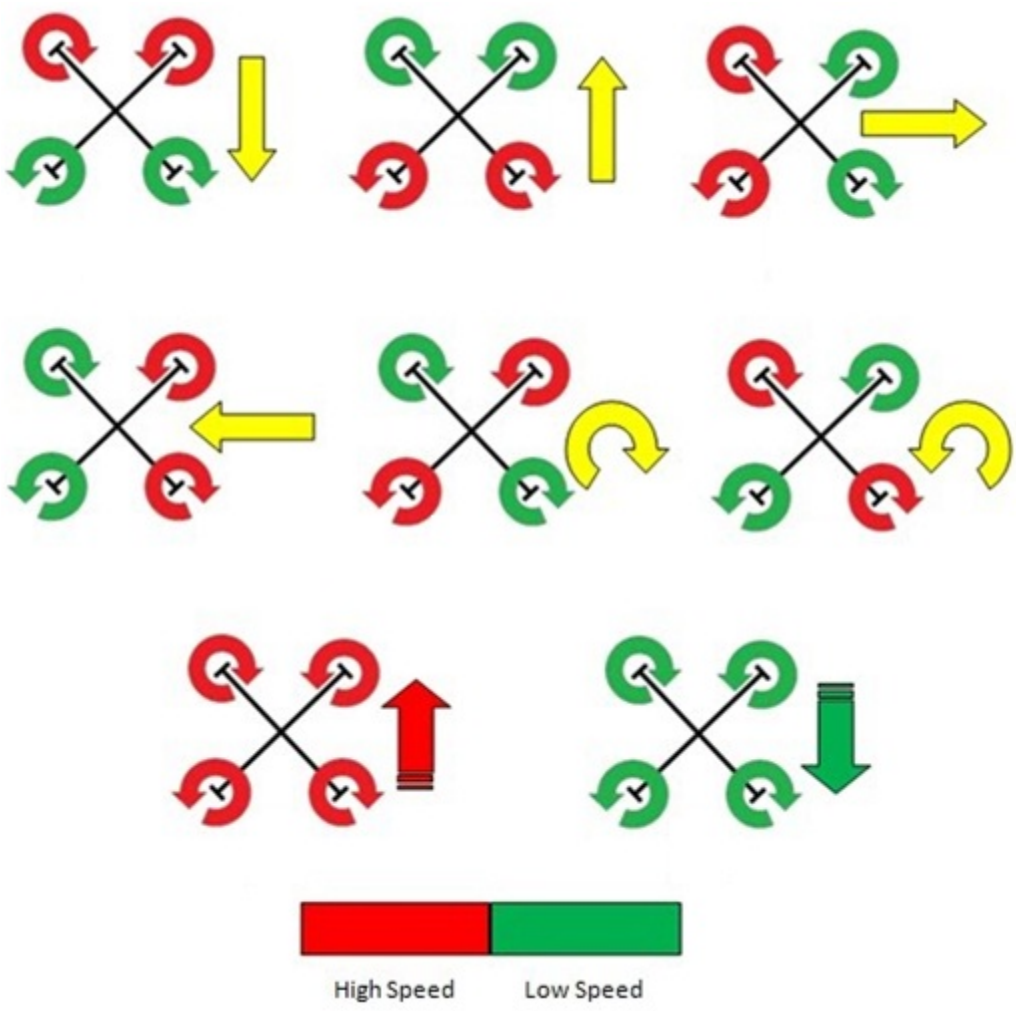

Figure 2 the relationship between rotors speed and attitude

Vertical movement: vertical movement is relatively easy. In the figure, because there are two pairs of motors to the opposite, you can balance its anti-torque on the fuselage, while increasing the output power of the four motors, the rotor speed increases the total tension increases, when the total pull enough to overcome the machine Weight, the four rotorcraft will rise vertically from the ground; the other hand, while reducing the output power of the four motors, the four rotorcraft is vertical down until the balance of landing, to achieve the vertical movement along the z axis. When the external disturbance is zero, the lift is maintained when the lift is equal to the weight of the aircraft. Ensuring that the four rotor speeds are simultaneously increased or decreased is the key to vertical motion.

Forward and backward movement: in order to achieve the aircraft moving in the horizontal forward and backward, the force must be in the horizontal plane to impose the aircraft. Increase the speed of the motor in front left, so that the tension increases, the corresponding reduction the speed of back right, so that the tension is reduced, while maintaining the other two motor speed unchanged, anti-torque still to maintain balance.

The aircraft need a certain degree of tilt, so that the rotor tension to produce horizontal force, so you can achieve the aircraft fly forward. The backward flight is just the opposite of the forward flight.

Lateral movement: Because of the symmetry of the structure, the working principle of the Lateral movement is exactly the same as forward and backward movement.

Pitching motion: In order to remove the rotational speed of the rotor caused by the quadrotor aircraft when the overall torque and total tension change, the diagonal rotor speed should be equal. As the lift of one rotor rises and the lift force of the diagonal rotor decreases, the unbalanced moment is generated to rotate the fuselage around the y-axis. This can achieve the aircraft's pitching movement.

Rolling motion: the theory of rolling motion is similar with pitching motion.

Yaw motion: quadrotor aircraft's yaw movement can be achieved by means of the rotor to produce anti-torque. In order to overcome the influence of the anti-torque, two rotations in the four rotors, two inversions, and the rotation of the respective rotors on the diagonal line, in order to overcome the anti-torque effect due to the air resistance during the rotation of the rotor. The same direction. The size of the counter torque is related to the rotor speed. When the four motor speeds are the same, the four rotor's counterbalances are balanced and the quadrotor aircraft does not rotate. When the quadrotor aircraft speeds are not exactly the same, the unbalanced anti- Causing the quadrotor aircraft to rotate.

3. Basic components

Quadrotor aircraft has many components, most of them can be classified into power part, control part and structure part.

3.1.Structure part

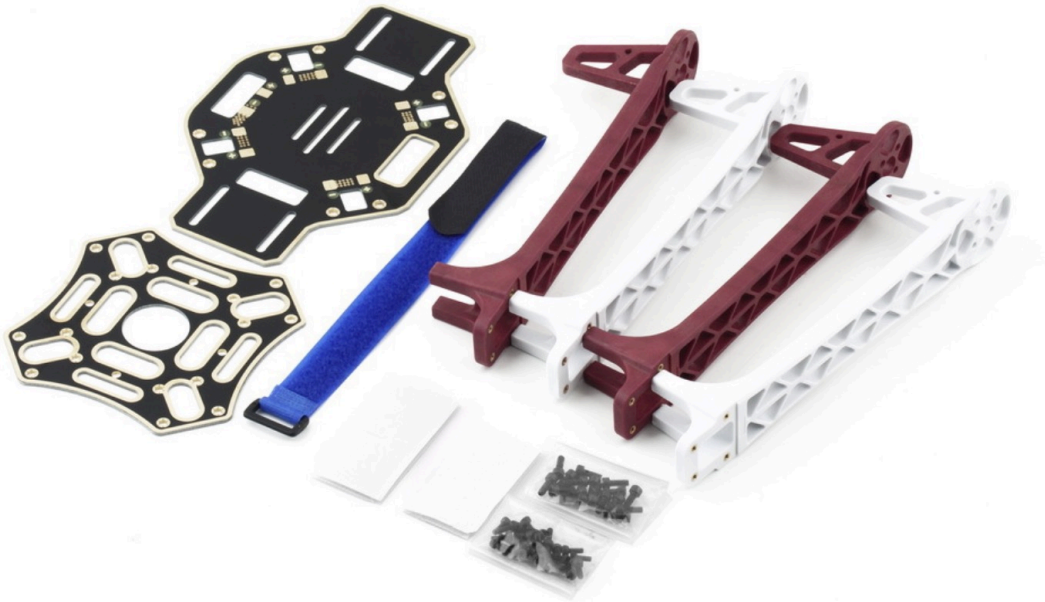

Figure 3 structure part of quadrotor aircraft

The main components of structure parts are shown above. They should be able to carry all of other parts. The length of fuselage will determine the size of propeller which significant influence the carrying capacity. In addition, the power circuit has already been drawn on the fuselage, which means power wires can be soldered on fuselage instead of on another circuit board.

The structure part cannot provide power or other function, thus the main requirement for structure components is weight. The weight of fuselage will directly determine the power consumption during flight, hence, the structure should be as light as possible.

3.2.Power part

Motors, electronic speed controller, and propellers are main components of power part. The parameter of them will determine the available power and control range.

3.2.1. Motor

The motor has brush and brushless type. Structurally, brushless motor and brush motor have similarities, both of them have the rotor and stator, but the structure of them is reverse. The rotor of brush motor is the coil winding, and the power output shaft connected to the stator is permanent magnetism Steel. The rotor of brushless motor is a permanent magnet which welded with the shell and output shaft. The stator is the winding coil, removing the brush used to alternately change the electromagnetic field in brush motors, so this type of motor called brushless motor.

Brushless motor has some advantages such as strong dynamic power, long life and high efficiency, so, the most quadrotor aircraft use brushless motor. The brushless motor appearance is as follows. Different from the brush motor, the most obvious differential is the brushless motor has three lines, and need to use with electronic speed controller （ESC）

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Figure 4 brushless motor

The most important parameter of brushless motor is KV value. This value is a unique performance parameters of brushless motor. it is of an important data used to judge the characteristics of brushless motor performance. The KV value is defined as speed per volt, which means when the input voltage increases by 1 volt, the speed of brushless motor increase the certain value (rpm). From the definition of KV value, we can know that the brushless motor voltage input and motor speed is to follow the strict linear proportional relationship.

3.2.2. Electronic speed controller(ESC)

ESC is used to control the motor rotation, stop and the speed of rotation. In addition, brushless motor must be used with ESC.

Figure 5 Electronic speed controller(ESC)

The input of ESC is direct current, usually directly connected to the module battery. The output is 3 wires that drive the brushless motor. In addition, brushless ESC has three signal lines which general input PWM signal, used to control the motor speed.

3.2.3. Propeller

The propeller model is represented by four digits, such as 8045, 1038, representing two important parameters of the blade. The diameter of the paddle is the diameter of the

circle formed by the rotation of the paddle. For the double-paddle (two blades, which is the most commonly used paddle), the length of the two blades is exactly the same as the preceding two digits, 80 and 10 in inches. The paddle pitch represents the distance that the propeller rotates forward for one week, expressed by the last two digits, as above 45 and 38. The greater the diameter and pitch of the paddle, the greater the pull (push) force that the paddle can provide.

The balance of the blades

The blade will rotate with the motor at high speed, so its rotation balance is a very important indicator. If one side of blade is heavier than the other or other imbalance, then the rotation will produce left and right or forward and backward force and other issues. This is not only the power efficiency is low, but also may damage the motor and even cause the aircraft broken.

The combination of motor and propeller

If the winding turns of brushless motor is large, the KV value is low and the maximum output current is small, but the torque is large. To achieve the same thrust, comparing with the high KV value motor, it is energy saving, so the quadrotor aircraft to use a small KV motor.

In general, when using the same battery, the motor with large KV values should use small propellers and the motor with small KV values should use large propellers. Relatively speaking, if the propeller is too small, the motor cannot generate the maximum thrust. In addition, if the propeller is too large, the motor will overheat which will demagnetize the motor, resulting in a permanent decline in motor performance.

3.3.Control part

The control parts are flight controller, sensor and remoter. Quadrotor aircraft must be equipped with gyroscope, which is the most basic requirements. In addition, all of 3-axis must contain gyroscope. On this basis, supplemented by 3-axis acceleration sensor, the six degrees of freedom constitutes the basic part of the flight attitude stability, but also the key part of the inertial navigation module, referred to as IMU. Attitude in the flight depend on the IMU, and can be seen that it is the core part of the whole model.

3.3.1. Sensor

The sensor is used to measure the attitude and motion of a quadrotor. In this project, using MPU6050 as the sensor. This sensor has two main function: G-sensors and Gyros.

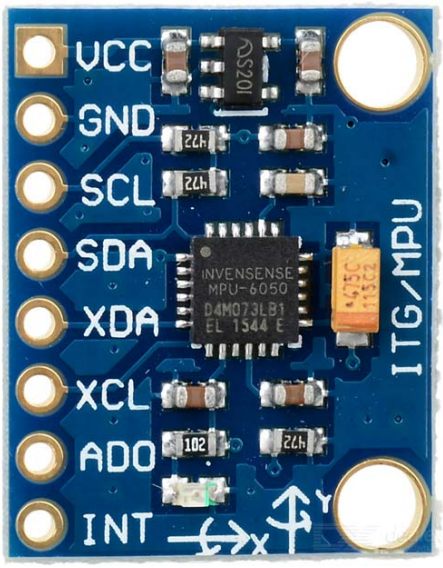


Figure 6 MPU6050

G-sensors

The accelerator can be used to sense the linear acceleration and tilt angle, and the single or multi-axis accelerator can sense the amplitude and direction of the linear by using gravitational acceleration. Contains accelerator products that provide limited motion sensing. For example, the accelerator-containing product can be moved in a fixed orientation, inductive direction to the transverse direction, so that the accelerator is

mainly used in sensing products related to the direction of gravity, such as turning the phone into a lateral direction.

Gyros

The gyroscope is an angular motion detection device that utilizes the momentum moment sensitive housing to measure the rotation about one or both axes orthogonal to the axis of rotation. The use of other principles made of angular motion detection device from the same function, also known as gyroscope.

The gyroscope can sense the rotational angular velocity for one or more axes, and can accurately detect the complex movement in free space. Therefore, the gyroscope becomes the necessary motion sensor to track the moving direction and rotation of the object. Unlike accelerators and electronic compasses, the gyroscope does not have to use any external force, such as gravity or magnetic field, to function autonomously.

3.3.2. Flight controller

Flight controller is the most important part of quadrotor aircraft. In this project, Raspberry Pi 3 model B is the flight controller. It is a single chip computer with Linux OS. It also has wireless function, 4 USB ports and more than 20 pins with I2C function. The input voltage is 5V and the current is 2.1A. If the current cannot satisfy the demand, The system will breakdown, thus a stable and reliable power supply is critical.

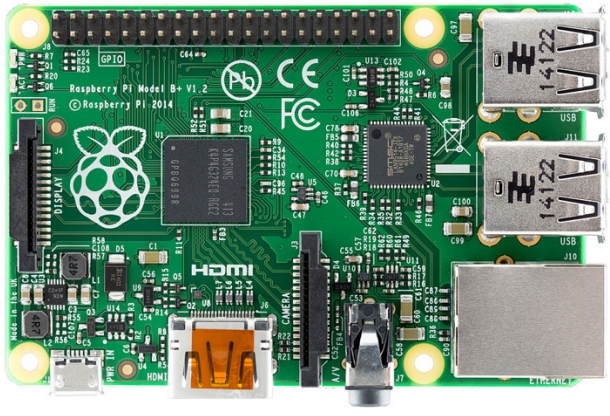


Figure 7 Raspberry Pi 3

The main function of flight controller is to deal with the measure statistics from sensors, response to instructions from remoter and send appropriate orders to ESC. To achieve these functions, a control program is needed. In this project, the program is based on JAVA and the details will be in followed chapter.

3.3.3. Remoter

Common wireless remote control in accordance with the use of different technologies, mainly infrared remote control and 2.4G remote control. Infrared remote control has a narrow range, the distance is short, so the model remote control is basically using 2.4G wireless remote control.

Traditional quadcopter aircraft need a specialized remoter as followed, thus users need the receiver and remoter from same company. However, because Raspberry Pi 3 model B has wireless function, in this project, using Android phone as a remoter.

Figure 8 quadcopter remoter

3.3.4. Pulse Width Modulation(PWM) generator

To drive ESC，a PWM signal is necessary. it is a simulation of the signal into a pulse wave technology, the general conversion pulse cycle is fixed, but the pulse of the duty cycle will be based on the size of the analog signal changes.

PWM signal

Unlike analog circuits, the digital circuit takes values within a predetermined range. At any time, the output may only be in either ON or OFF states, so the voltage or current will be applied to the analog load by repeating the pulse sequence. The PWM technique is a digital coding method for analog signal levels that modulates the level of an analog signal by modulating the duty cycle of the square wave using a high-resolution counter

(modulation frequency). The biggest advantage is that all signals from the processor to the controlled object are in digital form, eliminating the need for a digital-to-analog conversion process; and the ability to resist noise is greatly enhanced (noise is only existing when it is strong enough to change logic value, it can have a real impact on the digital signal), which is the main reason that PWM signal transmission industry in the communications industry has been a large number of applications.

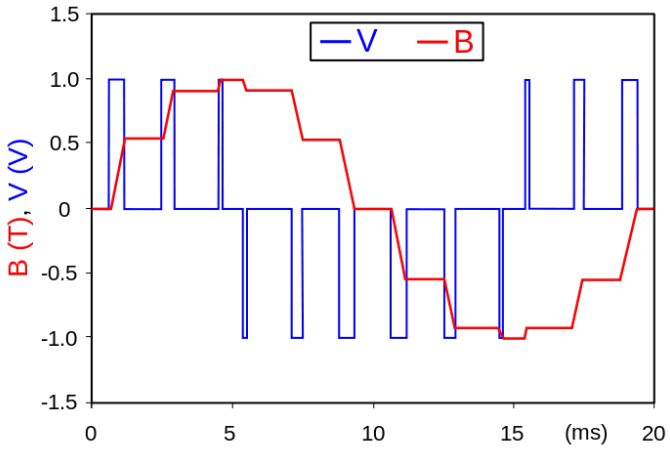


Figure 9 PWM signal

However, Raspberry Pi only has one PWM pin, and if use software to simulate PWM signal, it will consume too much resources. Thus, a PWM generator is necessary. In this project, use Tennsy as the generator.

Tennsy

Tennsy is a small single chip computer. It does not have OS; thus, it need to program in C language and use serial port to write program into Tennsy. Tennsy 3.6 has more than 10 PWM I/O pins, and the frequency can be more than 10000Hz. In addition, the resolution is also more than 10000.

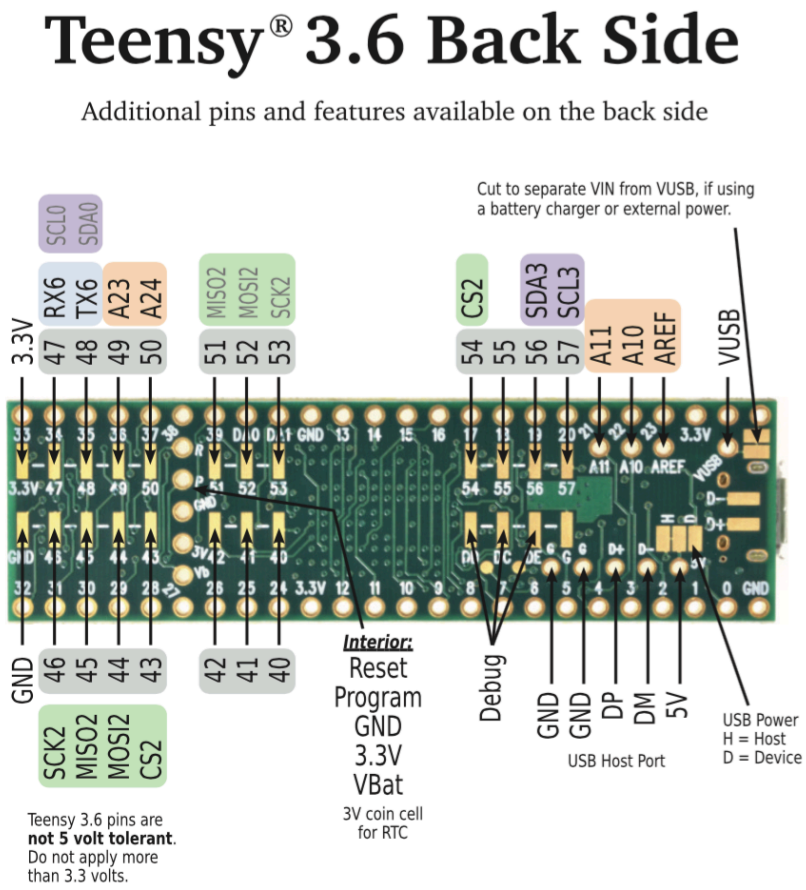


Figure 10 Teensy 3.6

4. Programming language

4.1.JAVA

Java is an object-oriented programming language, not only absorb the various advantages of the C + + language, but also to abandon the C++ difficult to understand function such as multi-inheritance, pointer and other concepts, so the Java language has a powerful and easy to use two features. Java language as a static object-oriented programming language representatives, an excellent realization of the object-oriented theory, allowing programmers to elegant way of thinking for complex programming.

Java has the characteristics of simplicity, object-oriented, distributed, robustness, security, platform independence and portability, multi-threading, and dynamic. Java

can write desktop applications, Web applications, distributed systems, and embedded system applications.

4.1.1. Pi4J

To control the pin and Wi-Fi model in Raspberry Pi, an Application Programming Interface(API) is essential. PI4J is very powerful and can control almost all the equipment on the raspberry GPIO including I/O pins, PWM, serial, I2C, SPI, system, and the most important, Pi4J use Java control, very convenient, very fast running speed.

Pi4j is designed to provide a friendly and object-oriented API for java developers to manipulate raspberry factions. Pi4j on the underlying interface to achieve the package, so that developers will be more energy on their own business logic.

4.1.2. Maven

Maven is a project management and building automation tool. It can conveniently add dependencies to JAVA projects, and it can easily compile program. Maven has many advantage:

- Provide a unified version management for the third-party dependent library
- Unify the structure of project catalog
- Unify software building stage
- Support multiple plug-in function
- Automatically generate project website

4.2.C language

C language is a common programming language which widely uses in system software and application software. C language is highly efficient, flexible, feature-rich, expressive and high portability and other characteristics, popular among programmers to become the most widely used programming language in the last 25 years.

The design goal of C language is to provide a programming language that can be compiled in a simple way, processing low-level memory, producing a small amount of mechanical code, and without executing any environmental support. C language is also very suitable for using with assembly language. Although the C language provides many low-level processing functions, but still maintain a good cross-platform features, a standard specification to write the C language program can be compiled on many computer platforms, and even contains some embedded processors (microcontrollers or MCU), super computer and other operating platforms. In this project, C language is use to control Teensy which is the PWM signal generator.

4.3.Android

Android is an open source operating system based on the Linux kernel. The Open Handset Alliance (OHA), based in Google, continues to lead and develop, designed primarily for touch-screen mobile devices such as smartphones and tablets and other Portable devices.

Android OS has a high compatibility and support various languages. However, the main programming language is JAVA. In Android OS, it provides plenty of API to achieve the functions to control devices.

4.4.Linux

Linux is a free and open source UNIX operating system. As long as developers follow the GNU General Public License, any individual and organization is free to use all of the underlying Linux source code, and can freely modify and redistribute.

The world's top 500 supercomputers run more than 90 percent of Linux distributions or variants, including the fastest 10 top supercomputers running on Linux-based operating systems. Linux is also widely used in embedded systems, such as mobile phones, tablet

computers, routers, televisions and video games. The Android operating system, which is widely used on mobile devices, is built on top of the Linux kernel. In this project, Raspberry Pi is using Ubuntu, a variant of Linux, as its operation system.

5. Integrated Development Environment(IDE)

This project mainly use 2 programming in 3 platforms. To program, compile and run in different platforms, disparate software is essential.

5.1.Arduino IDE

Arduino IDE is an open-source software. It was originally designed for compiling and running C language for Arduino (a single chip computer). To compile control orders for Teensy, a plug-in should be installed, and to rewrite and cover the original context, the Teensy should use a USB wire to connect to a computer.

This IDE is quite awful, it cannot complete code and the debug function is terrible as well. But because it is the only IDE for Teensy, thus the best option is use another IDE to program and only use Arduino IDE to compile for Teensy.

5.2.Eclipse

Eclipse is an open source, Java-based extensible development platform. For its part, it's just a framework and a set of services for building a development environment through plug-in components. Fortunately, Eclipse comes with a standard set of plug-ins, including Java development tools. This IDE is mainly use for the program in Raspberry pi.

The advantage of Eclipse:

- Provide consistent set of features on most platforms
- Not only support Java but also any single language

- Open source and free, and fully supported
- Truly scalable and configurable
- The shortcut keys are designed to be the best

But it also has some disadvantage:

- bug (some bug cannot be fixed all year round, sometimes updated to the new version will introduce new bugs),
- Large project index is slow
- Accounting for memory
- Code completion function is immature

5.3.Android studio

Android Studio is an IDE for Android platform development. Published on Google I/O for free use by developers at May 16, 2013. Android Studio is based on IntelliJ IDEA, specifically customizable for Android and runs on Windows, OS X and Linux platforms.

The current versions have some functions as below:

- Visual layout: WYSIWYG editor - Real-time encoding - Real-time program interface preview;
- Developer Console: Optimize tips to assist in translation, source tracking, promotion and marketing graphs;
- Beta version for test, and stage display;
- Based on Gradle build support;
- Android specific code refactoring and quick fix;
- The Lint hint tool provides better control over program performance, availability, version compatibility, and other issues;
- Support for ProGuard and application signatures;
- Template-based wizards to generate common Android application designs and components;

- Comes with a layout editor that allows developers to drag and drop UI components and preview UI displays on different sizes of devices, and so on.
- Support building Android Wear apps
- Built-in Google Cloud Platform support for Google Cloud Messaging and App Engine integration.

Because the functions above, Android Studio is the best IDE for Android software development. In this project, the mobile remoter is designed in this IDE.

6. Integral structure

The integral structure of whole aircraft is shown below.

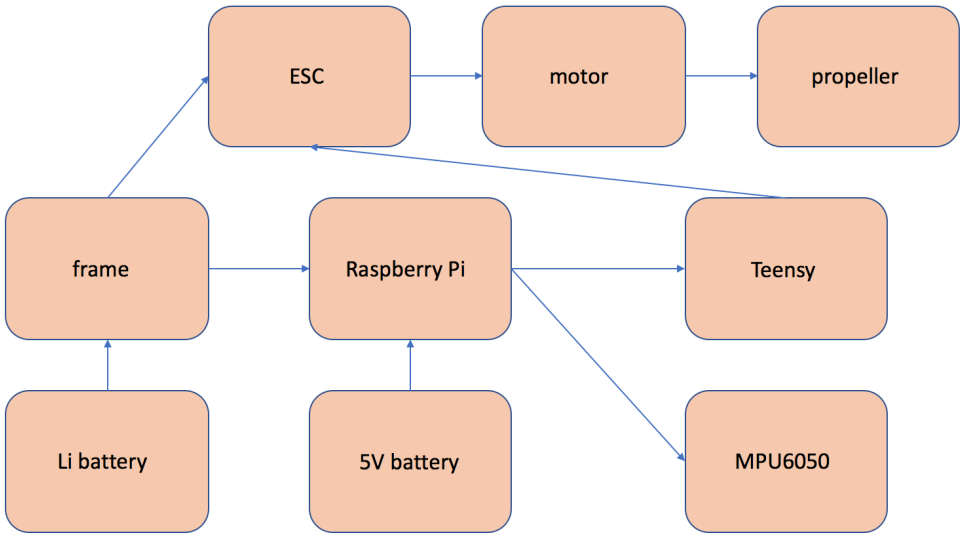


Figure 11 integral structure of whole aircraft

6.1. Power system

From the figure above, there are two power input in this system. The first one is Li battery.

the core of structure is frame. All of components are fixed on the frame, and to reduce vibration, all components are fixed on it by using different methods. Because the frame

has circuit on board, thus the Li battery as the main power for motor can directly connect to the frame which can disperse power to motors.

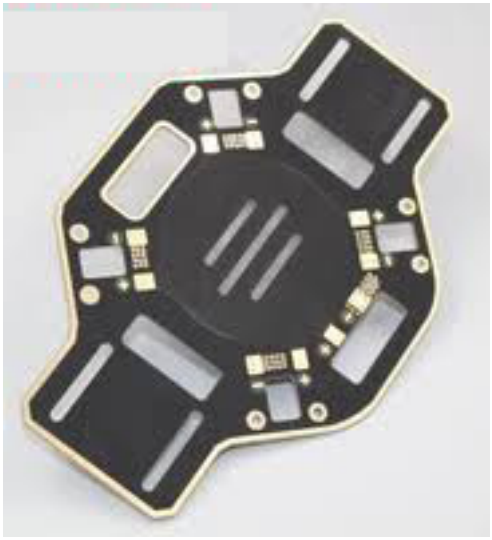


Figure 12 frame circular board

As for 5V power, because the Raspberry pi is the key of whole system, a stable power supply is important, thus, use an individual 5V battery to supply power for Raspberry Pi. But this method also cause the airplane has to bring more weight which increase the difficulty of control and decrease the flight time.

6.2. Data transmit

6.2.1. Reading from MPU6050

Raspberry Pi is the core of control system. It read attitude statistics from MPU6050. The communication method is I2c and the wire connection is shown below.

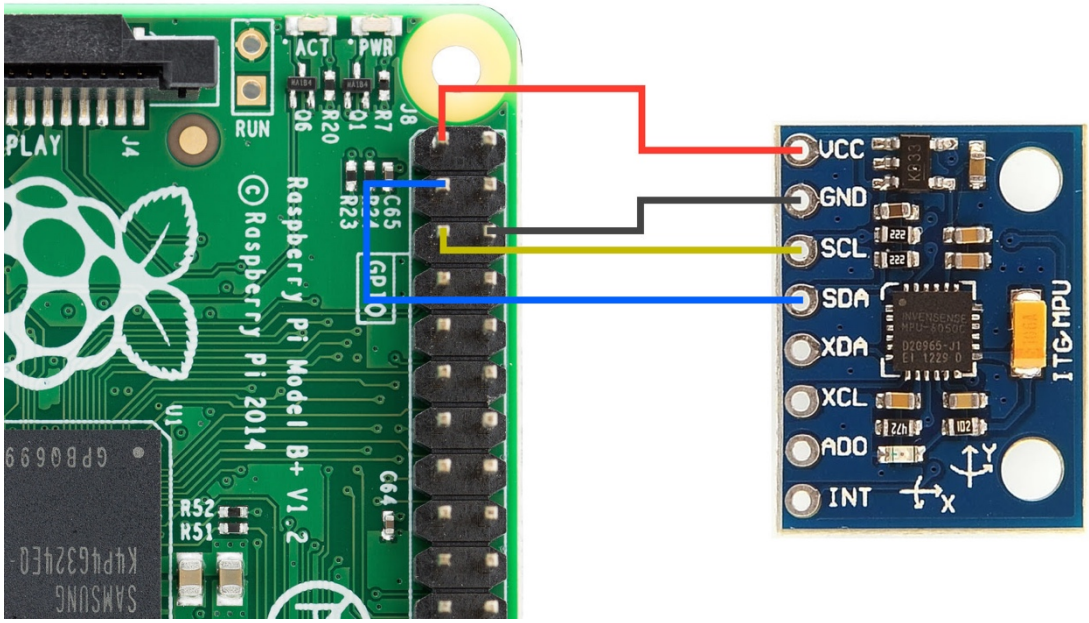


Figure 13 I2c connect between Raspberry Pi and MPU6050

The main advantage of the I2C bus is its simplicity and effectiveness. As the interface directly above the components, so the I2C bus space is very small, reducing the board space and the number of chip pins, reducing the cost of interconnection. The bus can be up to 25 feet in length and can support up to 40 components at a maximum transfer rate of 10Kbps.

Another advantage of the I2C bus is that it supports multi-mastering, where any device that can send or receive and can become the primary bus. A master can control the signal transmission and clock frequency. Of course, there can be only one master at any point in time.

6.2.2. Communicate with Teensy

Tennsy is a power consumption device, and it can only use 3.3V power, however, Raspberry cannot output 3.3V power thus a USB cable is essential to connect them. Because USB port can also transmit data, thus using serial communication method to

control Teensy.

Although universal serial bus (USB) has several disadvantages in terms of communication method for example

- USB communication distance is too short, only 5 meters
- Anti-interference ability is too weak
- USB is not a peer protocol, all requests must be initiated by the host, the device can only be passive control, equipment and equipment cannot communicate directly between each other.

However, as in this project, this communication method is more than enough. Raspberry pi only need to send 15 bytes every 300 milliseconds, and the communication distance is less than 10 centimeters, thus USB communication is suitable in this case.

6.2.3. ESC part

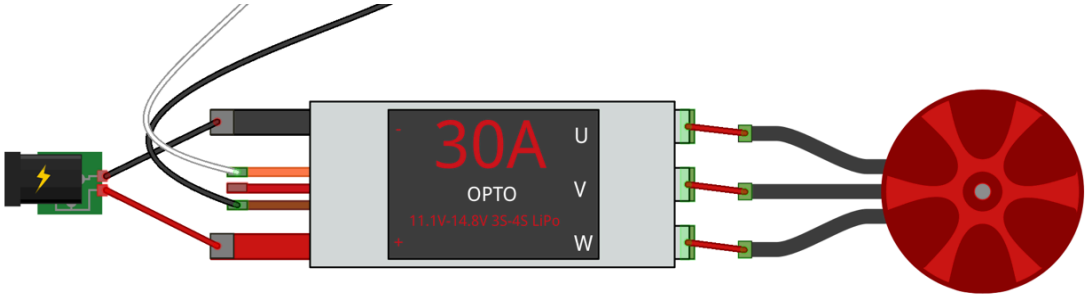


Figure 14 ESC connection method

From the figure, on the left there are totally 5 wires, and from top to bottom they are power-ground, signal-in, signal-VCC, signal-ground, power-VCC. The power wires are soldered on frame and connected to Li battery, and the signal-in wires are connected to the PWM pins on Teensy. In addition, signal-VCC is useless in this case, because it is used to supply power for other 5V devices.

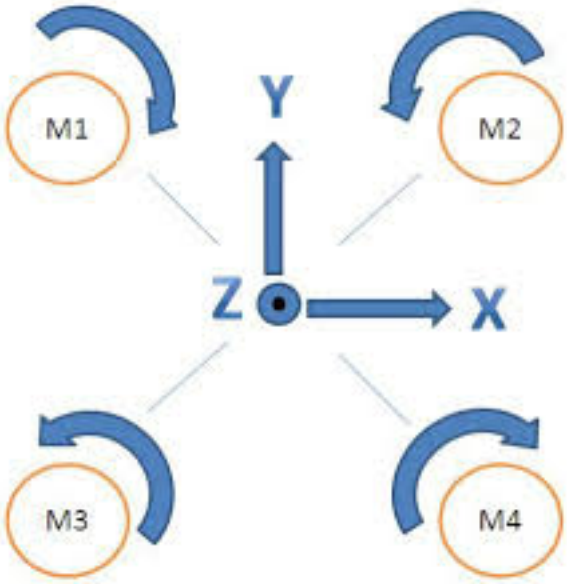


Figure 15 the direction of motor's rotation

On the right, there are 3 wires, all of them connect to brushless motor, and when there is a signal into ESC, the motor will rotate. In addition, swap any two wires can reverse the direction of rotate.

6.2.4. Install propellers

Installing propellers correctly is critical, if any propellers are not fixed, there will be a risk of shoot propellers. In addition, the rotate direction of motor and propeller is important.

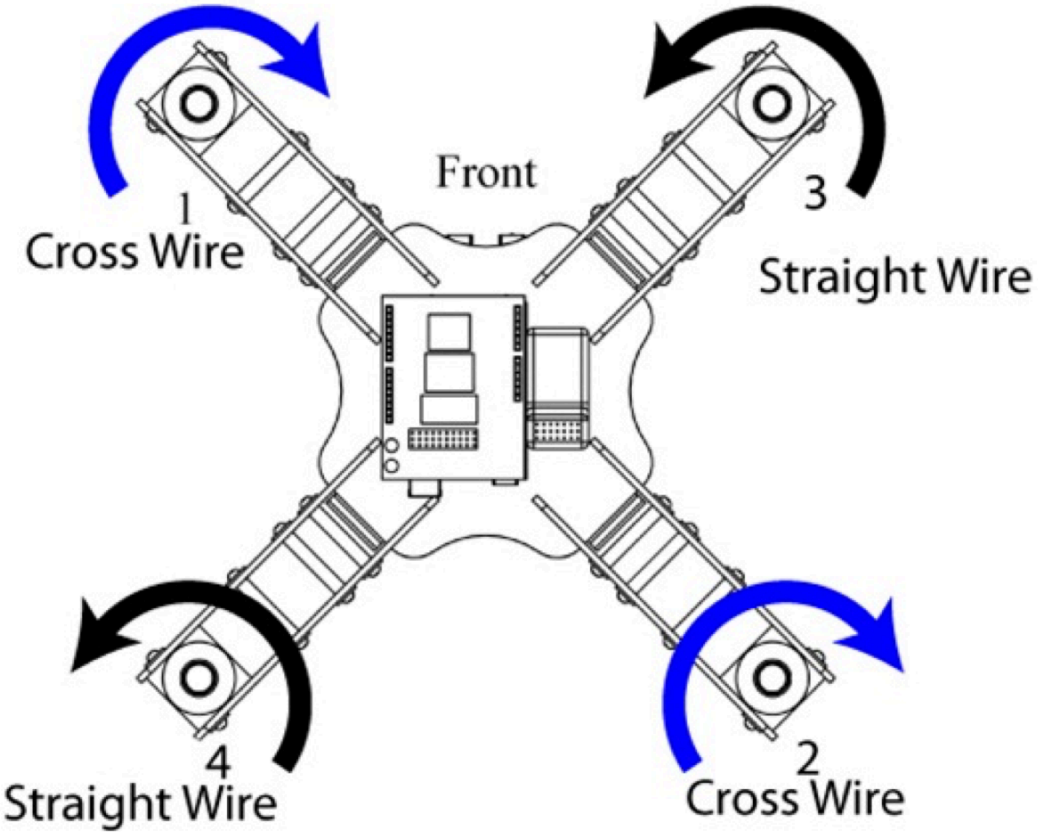


Figure 16 the direction of propellers

From the figure, the motor rotate direction and propeller direction are relative. If the directions incorrect, the aircraft may turn on one side. In addition, the whole control system will breakdown, because it cannot supply correct thrust as it designed.

7. Software structure

7.1. Raspberry Pi

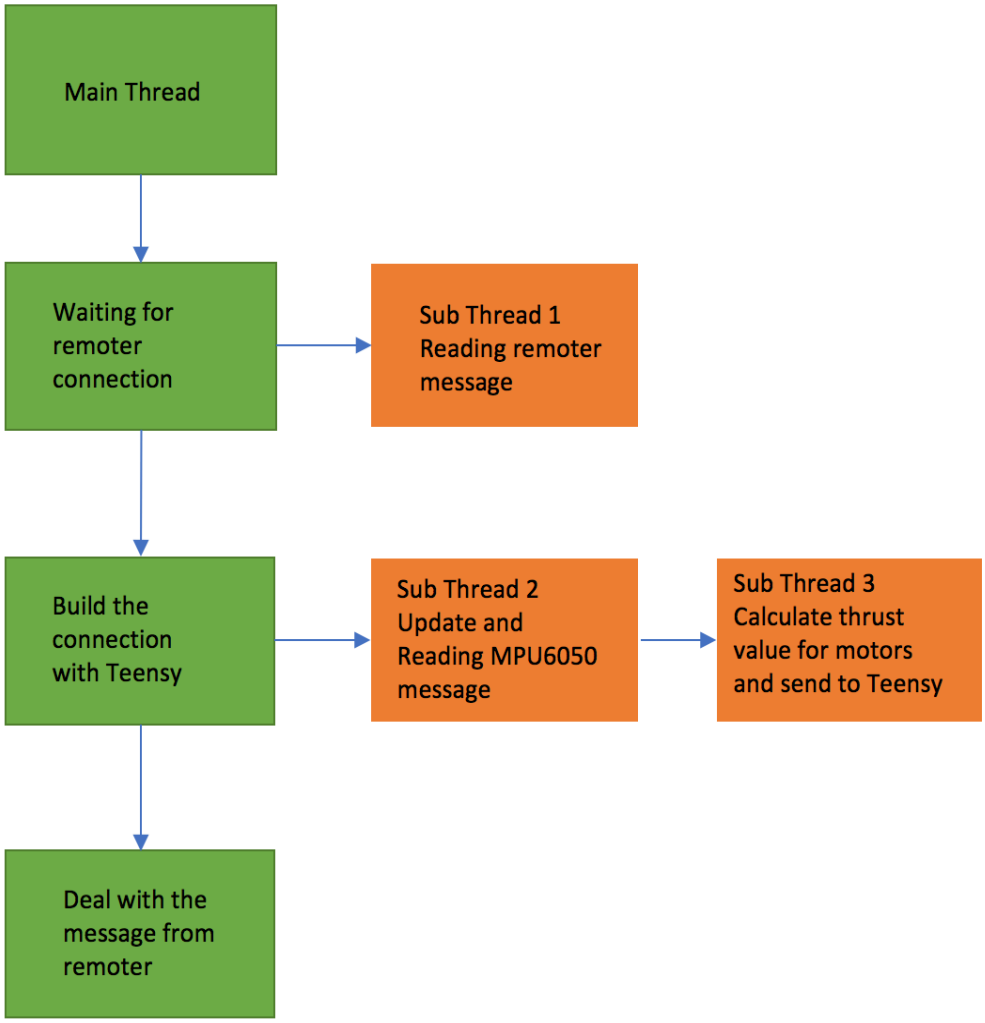


Figure 17 main flow path in Raspberry pi

The figure above shows the main flow path in Raspberry. JAVA can use multithread which has many advantage for example:

- **Play the power of multiprocessor:** Now the multi-processor on the computer becomes very popular, even if the low-end server with the four processors 8 processors have been very common. Because it has become increasingly difficult to improve performance by increasing the clock frequency. So, a lot of chip manufacturers have accelerated the pace of integration of processors to a

single chip. Because in the modern operating system, the thread is the basic scheduling unit, if a process inside only one thread, then if it is a 4-processor computer, there will be 75% of the waste. As the processor increases this waste will become more and more serious.

- **Simpler multitasking modeling:** By using threads, complex and asynchronous workflows can be further broken down into a set of simple and synchronized workflows. Each workflow runs in a separate thread. Synchronize at a specific location.

However, it also has some disadvantage such as:

- **Security issues:** If the same section of the program, the synchronization problem is not good. It is likely to work in a single-threaded environment, but in a multi-threaded environment will produce incorrect results. Because in the multi-threaded environment, race conditions in the case without reasonable synchronization in the implementation of the order is unpredictable. Because unmatched block of code, either the compiler, the hardware, or the runtime, may reorder the instructions, or other optimizations, such as caching variables in registers or processors, for cached variables for other threads Said it is not visible (this is a hardware or virtual machine an optimization means).

- **Programming issues:** An activity problem in a single thread, such as an infinite loop. Multi-threaded activity issues include deadlock, hunger, and live locks.

- **Performance issues:** In a good design, multi-threaded can improve the performance of the program. But in the multi-threaded process, the creation of the destruction of the thread, and the switch between the threads will be time-consuming. Synchronization of shared data will inhibit the compiler to optimize the program will increase the cost of performance

There are three main sub-Threads in this project:

1. Reading remoter message
2. Updating and reading MPU6050 message
3. Calculating thrust value for motor and send to Teensy

To immediate response to orders from the remoter, an individual sub-Thread is essential. In this thread, the program is always waiting for message, and once a message comes, it will send this order to main thread to response the order.

By this method, remoter message will be deal individually, and never disturb other thread. What is more, multi-thread can optimize the program efficient.

In terms of updating and reading MPU6050 message, the attitude of aircraft is critical for control, thus, make sure the attitude accurate and timely is important. By setting an individual thread, the program will make sure the statistics is always the newest and most accurate value.

The last but not the least, calculating thrust value for motor and sending to Teensy is also quite important. This will make sure the value can be sent to Teensy as accurate as possible.

7.1.1. Data processing of MPU6050

The MPU6050 is a very popular space motion sensor chip that captures the current three acceleration components and three rotational angular speeds of the device. Because of its small size, powerful, high precision. It not only is widely used in industry, but also aircraft model enthusiasts' artifact, was installed in various types of aircraft on the blue sky.

The MPU-6050 uses three 16-bit ADCs for the gyroscope and accelerometer, respectively, to convert the measured analog quantity to an output digital quantity. In order to accurately track fast and slow motion, the sensor measurement range is user controllable, gyroscope measurable range of ± 250, ± 500, ± 1000, ± 2000 ° / sec (dps), accelerometer measurable range ± 2, ± 4, ± 8, ± 16g. And all device registers communicate with a 400kHz I2C interface or a 1MHz SPI interface. For applications that require high-speed transmission, read and interrupt registers are available for 20MHz SPI. In addition, the chip also embedded a temperature sensor and in the working environment only ± 1% of the oscillator. Chip size 4 × 4 × 0.9mm, QFN package (no lead square package), can withstand the maximum impact of 10000g, and a programmable low-pass filter. For power supplies, the MPU-6050 supports a VDD range of 2.5V ± 5%, 3.0V ± 5%, or 3.3V ± 5%.

Before setting the MPU6050, we need to know how to calculate roll, pitch and yaw angle, by using gyro and acceleration.

Gyro

Gyroscope, measuring angular velocity, has high dynamic properties, but it is an indirect measurement of the angle of the device, which measures the angle of the derivative, angular velocity, the angular velocity of the time to get points to get the angle.

If the world is ideal, then our problem is resolved, but unfortunately, the reality is cruel, the introduction of error, making the points there is a problem.

Assuming that the gyroscope is fixed, the ideal angular velocity is 0dps (degree per second), but there is a bias of 0.1 dps added to the top, so the measured is 0.1dps, after the integration of one second, the angle is 0.1 degrees, 1 minute Followed by 6 degrees, but also tolerate, after an hour is 360 degrees, turn a circle, that is, gyroscope in a short time there is a great reference value.

The gyroscope is a gyro inside, and its axis is always parallel to the initial direction, so that the actual direction can be calculated by deviating from the initial direction. The sensor MPU6050 is actually a very precise structure of the chip, the internal contains ultra-small gyro. After the gyroscope is running for a while, noise and offset can cause data skew and need to be corrected with other sensors.

Using the gyroscope to obtain the angle, we must consider the problem of integral error.

Accelerometer

The accelerometer can measure the acceleration, including the acceleration of gravity, so when the static or uniform motion, the accelerometer only measure the gravity acceleration, and gravity acceleration is fixed, through this relationship, you can get the angle between the plane and the ground of the accelerometer.

However, if the accelerometer rotates around the axis of gravity acceleration, the measured value does not change, meaning that the horizontal rotation cannot be perceived.

We can imagine the accelerometer as a positive cube box with a ball, the ball is spring fixed in the center of the cube. When the box moves, according to the location of the virtual ball can calculate the current acceleration value. Imagine if in space, the box without any force, the hypothetical ball will be in the center of the position, the acceleration of the three axes are 0. See below

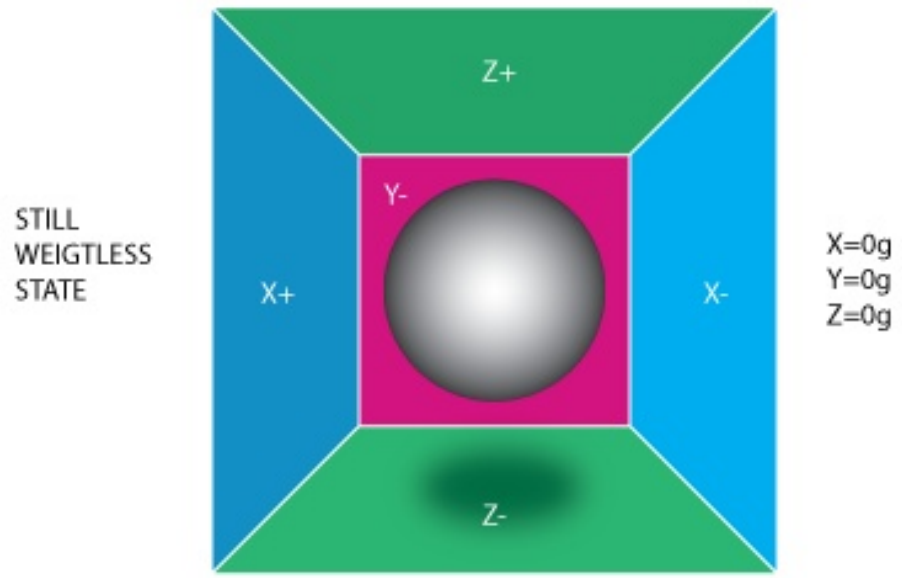


Figure 18 accelerometer without force

If we apply a horizontal leftward force to the box, it is clear that the box will have a leftward acceleration, and the hypothetical ball in the box will be attached to the right side of the box due to inertia. As shown below:

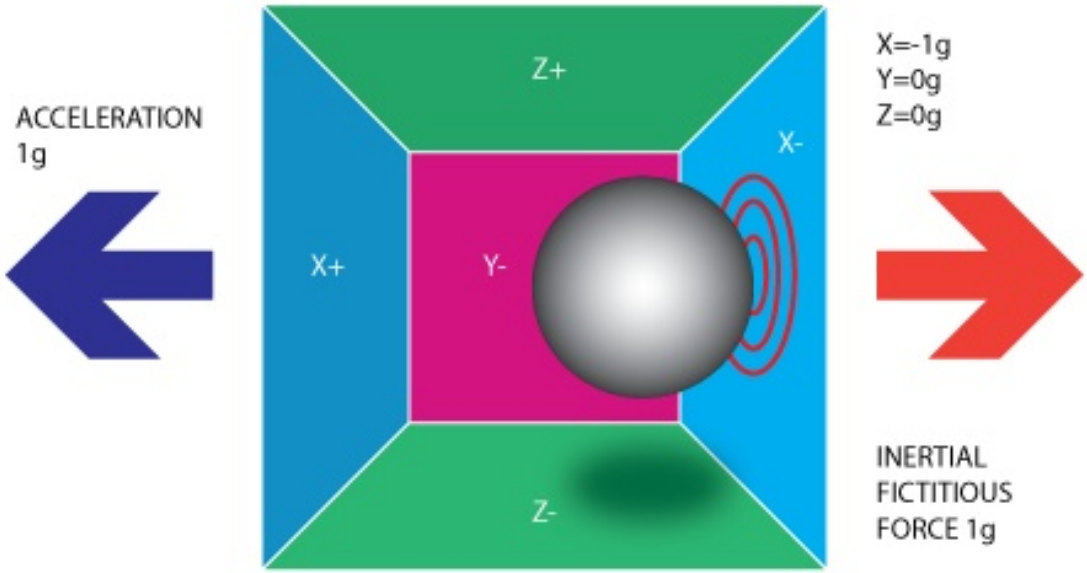


Figure 19 apply force to accelerometer

In order to ensure the physical meaning of the data, MPU6050 accelerometer is the imaginary ball in the three axes on the opposite value as the acceleration value of the three axes. When the position of the virtual ball is biased in the forward direction of an axis, the acceleration reading of the axis is negative and the acceleration reading of the axis is positive when the position of the virtual sphere is biased to the negative direction of one axis.

According to the above analysis, when we put the MPU6050 chip level in place, the chip surface toward the sky, at this time due to the role of gravity of the Earth, the virtual ball position bias Z axis of the negative, so the Z axis acceleration reading should be positive, and In the ideal case should be g. Note that the physical meaning of this acceleration is not the acceleration of gravity, but the acceleration of its own motion, it can be understood that: because of its own motion acceleration and gravity acceleration in the same direction, the chip can remain stationary.

Thus, we need an attitude algorithm to show the actual angle.

Attitude algorithm

Attitude algorithm, also known as attitude analysis, attitude estimation, attitude fusion. Attitude resolution refers to the gyroscope, accelerometer, compass and other data together to get the aircraft's air posture.

The aircraft from the three-axis angular velocity of the gyroscope is obtained by the quaternion method of pitch, yaw and roll angle, which is a quick solution, combined with three-axis geomagnetism and triaxle acceleration to obtain drift compensation and depth solution. In this project, using quick solution to get attitude angle.

A common model that represents the current flight attitude of the aircraft is to create the coordinate system shown below and use Roll to represent the rotation around the X axis. The Pitch represents the rotation around the Y axis and Yaw represents the rotation

around the Z axis.

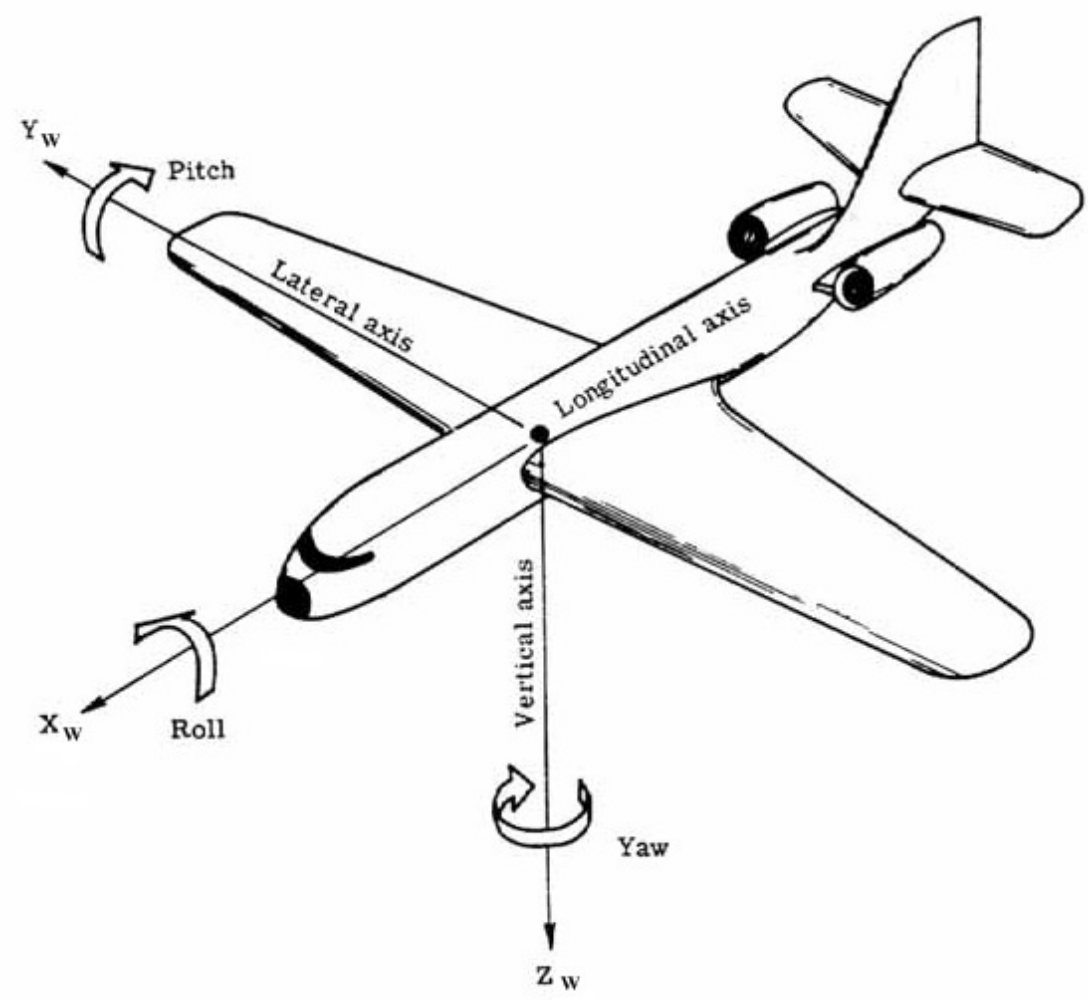


Figure 20 attitude angle

Since the MPU6050 can obtain three axes of acceleration, and the Earth's gravity is long-term and always vertical down, so we can according to the gravity acceleration relative to the chip point of reference for the current attitude.

And the following steps shows how to get data by using program.

1. Write data to MPU6050

To correctly use MPU6050, the first step is write design orders to this chip. The core functions are list below:

- Waking the device up
- Configure sample rate
- Setting global config
- Configure gyroscope
- Configure accelerometer
- Configure interrupts
- Configure low power operations

In terms of waking the device up, configure sample rate, setting global config, configure interrupts and configure low power operations, just need to maintain default. Because the default setting can already satisfy the demand in this project. However, in terms of configure gyroscope and configure accelerometer decreasing the range of accuracy can increasing the performance.

Because the gyroscope measurable range of ± 250, ± 500, ± 1000, ± 2000 ° / sec (dps)，and the accelerometer measurable range ± 2, ± 4, ± 8, ± 16g. thus, setting the gyroscope measurable range to ± 250° / sec and the accelerometer measurable range to ± 2g.

2. Read data from MPU6050

There are 6 main value to determine the attitude angle.

- Acceleration X
- Acceleration Y
- Acceleration Z
- Gyro X
- Gyro Y
- Gyro Z

To get the value, the address should be determined first. From the instruction of MPU6050 we can find, the values are 16bits, thus each value has two address, and the

first address means the first 8bits of actual value.

According to instruction, the address for acceleration is from 59 to 64 and the address for gyro is from 67 to 72. In addition, because the range of measurable value will influence the meaning of value, thus, from the instruction, when the gyroscope measurable range to ± 250° / sec, the gyro sensitive is 131 and when the accelerometer measurable range is ± 2g, the acceleration sensitive is 16384.

In addition, the first bit means the value is negative or positive, thus to avoid noise influence the value too much, add a judgement below.

```
public static int readWord2C(int registerAddress) throws IOException {
    int value = mpu6050.read(registerAddress);
    value = value << 8;
    value += mpu6050.read(registerAddress + 1);

    if (value >= 0x8000) {
        value = -(65536 - value);
    }
    return value;
}
```

Figure 21 read value from MPU6050

3. Initial MPU6050

As already talk about, gyro can integral angle by using angle speed. However, when we need the initial value, the gyro is useless. However, in accelerometer, gravity should always plumb, thus we can calculate current attitude angle by measure the relation shape of gravity.

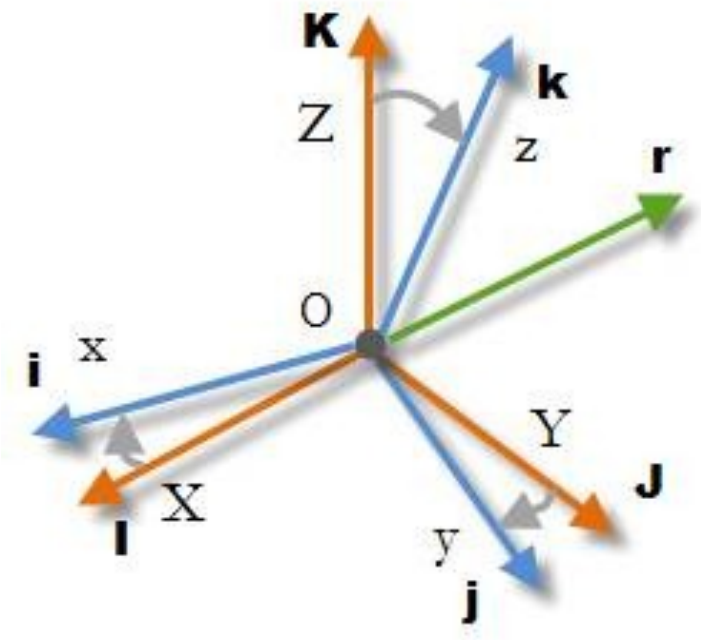


Figure 22 MPU6050 initial angle

4. Updating values

Both gyro and accelerometer can measure the attitude angle, so which one is more accurate?

The figure below shows the accelerometer performance during vibration, and the red line is the average value of acceleration pitch angle. Thus, we can find that vibration make the accelerometer totally useless and only the average value of acceleration value is usable.

On the other hand, gyro is less sensitive to vibration, and during flight, there are plenty of vibration, thus gyro is more useful. However, because of the measure, noise and integral error, the gyro measurement error will be accumulated, thus we need average acceleration value to decrease the error.

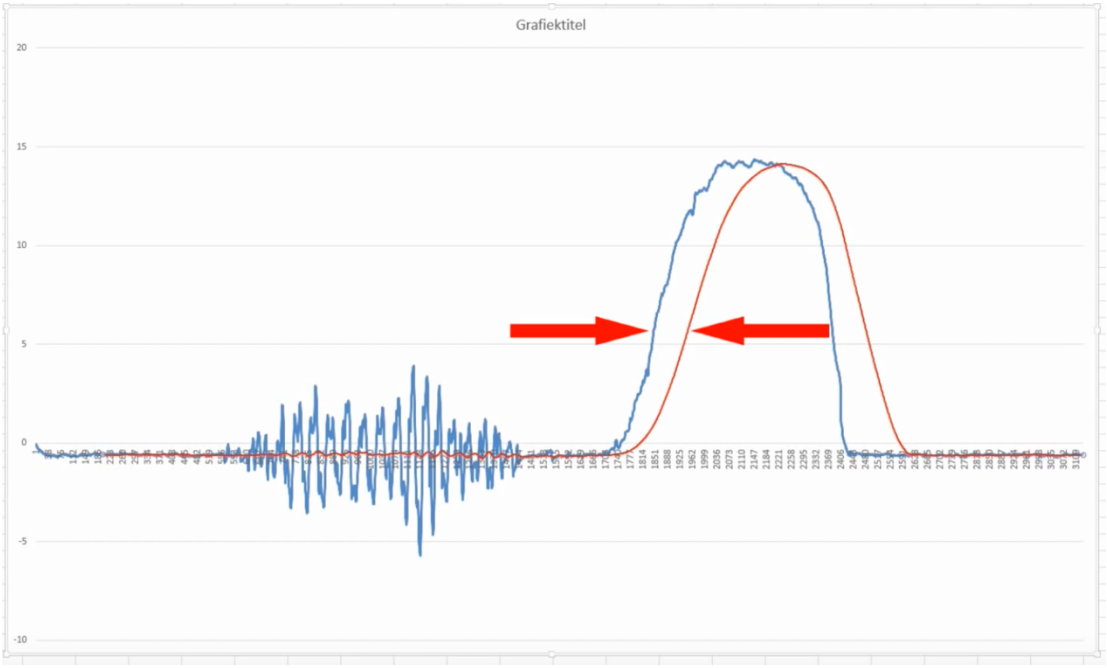


Figure 23 accelerometer pitch angle with vibration

7.1.2. PID control

We first assume that an ideal situation, the four-motor speed is exactly the same, thus, we do not need to control the quadrotor aircraft to maintain the same four-speed motor speed, and when the speed exceeds a critical point (lift just offset the gravity) four-axis can fly it up smoothly.

In fact, due to the difference between the motor and the propeller itself we cannot make the four-motors' speed is exactly the same, thus it is possible after the aircraft took off after the rollover. In general, a control system is necessary.

The PID controller (proportional-integral-derivative controller) consists of a proportional unit (P), an integrating unit (I) and a differential unit (D). Through the Kp, Ki and Kd three parameters set. The PID controller is mainly suitable for systems that are substantially linear and whose dynamic characteristics do not vary with time.

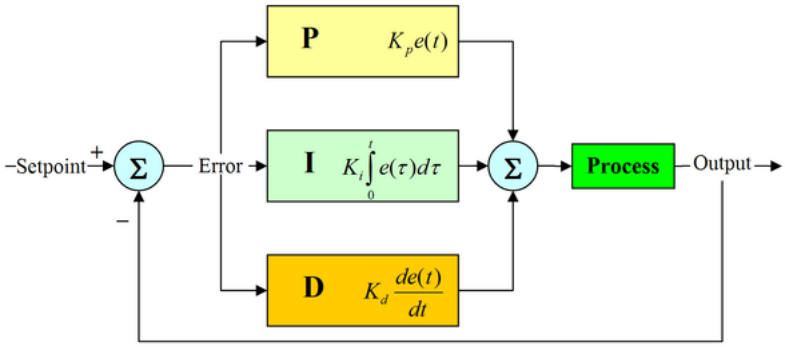


Figure 24 PID control diagram

The proportional unit (P), integral unit (I) and differential unit (D) of the PID controller correspond to the current error, the past cumulative error and the future error respectively. If you do not know the characteristics of the controlled system, PID controller is generally considered the most suitable controller. By adjusting the three parameters of the PID controller, you can adjust the control system and try to meet the design requirements. The response of the controller can be expressed by the controller's response to the error, the degree of overshoot of the controller, and the degree of system shock. However, the use of PID controller does not necessarily guarantee that the system can achieve the best control, nor to ensure system stability.

PID is named with its three correction algorithms. The controlled variable is the result of the addition of three algorithms (proportional, integral, derivative), that is, its output, the input is the error value (the result of the set value minus the measured value) or the signal derived from the error value. If defined u (t) for the control output, PID algorithm can be expressed as follows:

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{d}{dt} e(t)$$

Thus, with this control, aircraft will automatically maintain the ordered attitude.

7.2.Teensy

7.2.1. The limitation of Raspberry Pi

At first, I tried to use Raspberry Pi to generate PWM signals, however, because the Raspberry Pi only has one PWM hardware output, thus I tried to use software simulation. The frequency of PWM signal is quite high which is 50Hz in this project. This means a single circle is only 20ms and the control duty cycle is from 5% to 15% which means 1ms to 3ms. In JAVA program, the common method to get time is "System.currentTimemillis()", however, this command can only get time in milliseconds. Thus, the control range will become 1ms(off), 2ms and 3ms (full power). This control accuracy is too poor.

Another method can get time is "System.nanoTime", this method can return nanoseconds which is 1000000 times more accurate than milliseconds. Although it can increase the control range and accuracy, this method cost too many CPU resource, and if CPU occupancy rate is 100%, the program will breakdown. Thus, use another board to generate PWM signal is essential.

7.2.2. The advantage of Teensy

Teensy 3.6 is a feature-rich lab-friendly development board which can easily use an onboard USB connection for programming without the need for an external programmer. By installing the Teensyduino add-on, Teensy can be programmed in C or Arduino IDE.

The microcontrollers on Teensy are able to simulate any type of USB device, making it ideal for USB-MIDI and other HID projects. 32-bit, 180 MHz microcontrollers also offer multi-channel direct memory access, multiple high-resolution ADCs and I2S digital audio interfaces. It has four independent interval timers, plus a delay timer. All digital pins have interrupt capability and operate at 3.3 V logic levels

All of these features are included on a 62.3 mm x 18.0 mm board with all solder joints located on a 0.1 "test board compatible grid. The board also provides an onboard micro SD card port. Compared to the previous generation Teensy 3.2 product, The main features of this new "teensy" development board include an upgraded ARM® Cortex-MCU (72 MHz to 180 MHz) and more memory (256 K to 1 M), as well as more RAM, EEPROM and accessible pins.

In addition, totally 22 PWM output pins can satisfy this project demand. This board is much stronger than this function needed.

The program in Teensy is quite simple, the main processes are shown below.

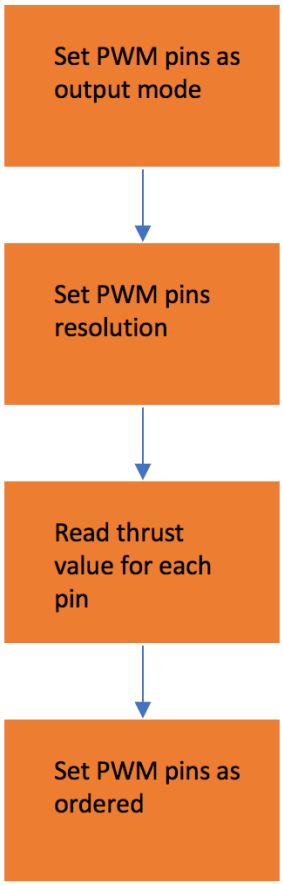


Figure 25 Teensy working flow

From the figure above, there are only 4 steps in Teensy. The only goal for this part is send particular PWM signal to ESCs. It receives control signal from Raspberry Pi and translate into PWM signals.

7.3.Android mobile

The aircraft should be able to achieve some presupposed goal, however, in this project there is no particular goal, thus, a remoter is needed to send command to aircraft.

7.3.1. Model aircraft remoter

To convenience control, most quadrotor aircraft use model aircraft remoter to send orders to aircraft. The model aircraft remoter has 2 main components. They are remote control transmitter and remote control receiver.

Remote control transmitter

Remote control transmitter is the remoter. It is used to control our aircraft. Because it has a long external antenna, remote control instructions are through the outside of the control switch and button, through the internal circuit modulation, coding, and then through the high-frequency signal amplifier circuit from the antenna to launch electromagnetic waves.

Model aircraft remote control according to different ways, divided into the hands of the United States and Japan.

American hand that is the left-hand rocker is responsible for throttle and yaw, right hand rocker is responsible for pitching and roll. Left hand rocker up and down for the throttle control, left and right yaw control; right hand rocker up and down for the pitch control, left and right for the roll control. Corresponding to another remote control for the Japanese hand. Left hand rocker is responsible for pitching and yaw, right hand

rocker is responsible for throttle and roll.

Figure 26 Remote control transmitter

Remote control receiver

The remote control receiver is mounted on a aircraft for receiving a radio signal. It will process the radio signal from the remote transmitter, the received signal amplification, shaping, decoding, and the received control signal into the implementation of the circuit can identify the audio signal or digital pulse signal, transmitted to the electronic parts on the aircraft model.

Figure 27 remote control receiver

7.3.2. Mobile remoter

Smart phones are the essential device in our daily life, and nearly everyone has at least one smart phone, thus using mobile as remoter is convince for users. What's more, Raspberry Pi has a Wi-Fi model on board which can be used as remote control receiver. Therefore, mobile remoter can avoid install a receiver on airplane.

In addition, mobile can also act as a receiver to demonstrate some statistics about the plane, such as attitude angle and thrust of each motor. The designed layout is shown as below.

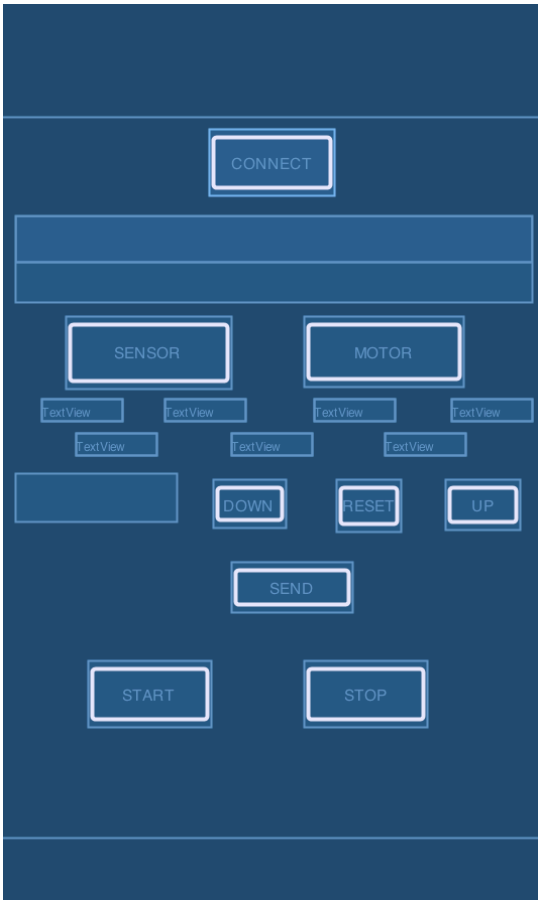


Figure 28 layout of mobile controller

The connect button on the top can set a connection with Raspberry Pi, only after the connection is set up, the program continue working. The textview below shows the aircraft state sent from controller. The sensor and motor button shows the attitude angle and thrust in the textview below.

The middle part can adjust the basic thrust of each motor. And at the bottom the start button and stop button is used to active and stop the motors separately. The actual effect as below.

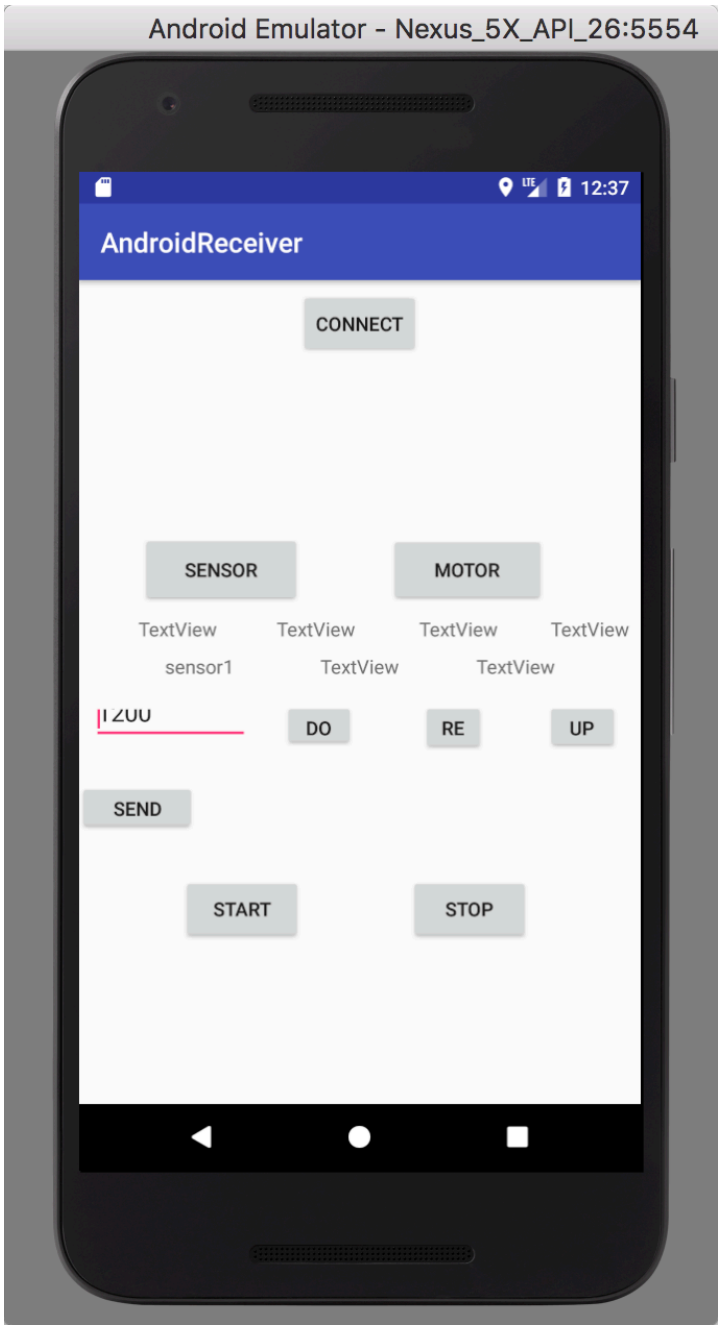


Figure 29 effect picture

8. Hardware structure

The integrated aircraft is shown below,

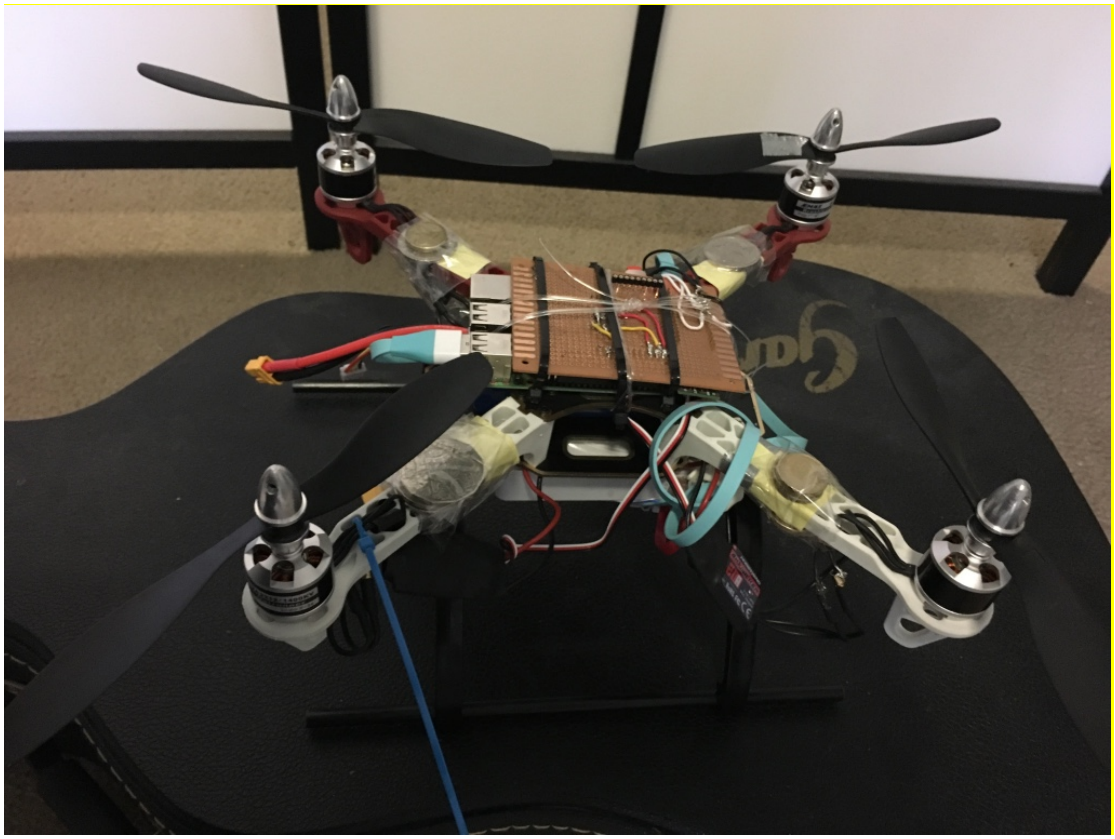
9. Flight preparation

9.1. Propeller dynamic balance

Rotational motion of the parts in the ideal case, no matter rotation and not rotating, the pressure on the bearing should be the same, such a rotating body is a balanced rotation body. But due to uneven material or rough defects, processing and assembly of the errors generated, even when the design has an asymmetric geometry and other factors, making the rotating body unbalance. the centrifugal inertia forces generated by tiny particles cannot cancel by each other, and centrifugal inertial force through the bearing to the mechanical and its basis, causing vibration, noise, accelerate bearing wear, affect performance, increase power consumption, shorten the mechanical life, can cause serious Destructive accident. For this reason, the rotor must be balanced so that it reaches the permissible level of equilibrium accuracy or the resulting mechanical vibration amplitude falls within the allowable range.

Thus, propellers should lead to as less vibration as possible. The benchmark for vibration can be measured by calculating the sum of square yaw angle, pitch angle and roll angle. In addition, because the sensor has noise in itself, thus the result will never be 0.

To measure the result, each propeller should rotate separately. If the result is larger than 20, try to stick some tape on one side. If the result increase, try another side, until the result satisfies the demand.



9.2.Center gravity adjustment

The point when the center of gravity is in the gravitational field, the object in any orientation of all the components of force of gravity through the fulcrum. To rules and density of uniform objects, the center of gravity is its geometric center. The center of gravity of an irregular object can be determined by the suspension method. The center of gravity of the object is not necessarily on the object. In addition, the center of gravity may refer to the center or main part of the matter.

In this project, use fishing line to measure the gravity center. Bond the fishing line to the geometric center and suspend the whole airplane. using the attitude angle as the benchmark of horizontal. Stick several coins on the light side to balance the weight.

10. Possible improvement

10.1. use mobile to replace Raspberry Pi and MPU6050

A smart phone can be used to replace Raspberry pi and MPU6050. Because all mobile have accelerometer and gyroscope to measure the state of mobile. In addition, the performance of mobile is also higher than Raspberry Pi. Thus, smart phone can totally replace Raspberry Pi in this project.

Communication between devices is issued by the USB Host, and USB device can only passive response. Generally, the computer is the host, and U disk, USB keyboard and mouse are slave. In the mobile device, the situation changed. The phone can do host to connect the keyboard and mouse; can also be used as device, put itself on the computer

when the U disk. This is called On The Go standard (OTG).

In addition, Android can run JAVA program, which means the main body of program do not need to change. Only use build-in accelerometer and gyroscope to replace MPU6050 can satisfy the demand.

11.Conclusion

In this project report, first give a short introduction about the history and the classification of quadrotor aircraft. Followed by basic knowledge and basic components such as terminology, structure, aerodynamic principle and some main components of quadrotor aircraft. These knowledge help to understand the function of whole physical structure and components.

Next part is programming language and integrated development environment(IDE). An aircraft need a reasonable software to support its flight, and in this project, use 2 main language together to control this aircraft. Choosing a reasonable IDE will be useful to increase the efficiency of programming.

The chapter 6 talked about the assembling of aircraft. The power system and data transmit system are the core system in the project. In this chapter shows how to assemble separate components and the reason of this assemble method.

The chapter 7 shows the software structure. This part discusses the reason of using this single chip computer and devices. And also talk about the advantage and disadvantage of Raspberry Pi, Teensy and mobile. The specific program will be attached in appendix.

It followed by flight preparation, to make sure the aircraft performance as it designed. The disturb factor should as small as possible. Thus, propeller dynamic balance test and

center gravity adjustment is critical. The first one can decrease vibration during flight and the second one can save energy and increase control effect.

The last part is possible improvement. With the performance of mobile increasing, mobile can do much more job than we think. In this project, it is a potential control board and sensor.

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Appendix

All program can be download from https://github.com/everpast