ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

A VTOL DRONE WITH ONLY TWO PROPELLERS

Team #5

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1 Introduction

1.1 Objectives

With the breakthroughs in wireless communication, sensor technology, computer technology and lithium battery technology in the 21st century, there is evidence that a new era of flying vehicles is upon us. Electric and hybrid powered aircraft are taking an increasing share of the market. Traditional vertical takeoff and landing (VTOL) aircraft like the V-22 have complex internal combustion machines, and complex mechanical arrangements. [1] In contrast, electric VTOL aircraft have a simpler mechanical structure, which increases the fault tolerance and improves the safety issues of traditional VTOL aircraft. [1] At the same time, the relatively simple structure of e-VTOL reduces production costs, and the use of electricity also reduces noise and air pollution well. From a market perspective, e-VTOL also demonstrates very significant growth potential. According to the International Air Transport Association (IATA) 2022 annual report, international air travel is recovering from the low point of COVID-19, now is a good time to develop aircraft. [2] In addition, Jet fuel and crude oil prices have risen to 2.2 times last year's level because of the war in Ukraine and the international economic situation, which further demonstrates the advantages of electric aircrafts like our VTOL aircraft. [2]

1.2 Function and Requirement

- The two propellers combined must provide a force greater than 15N to ensure that the aircraft can take off vertically. Also ensure that the gravitational force on the aircraft itself is less than 15N.
- The wings need to provide at least 15N of lift to ensure that the aircraft can fly horizontally at the preset speed.
- The development board needs to reach approximately 2 kHz flight control loop rate to receive the attitude changes from the sensors in time and react quickly.

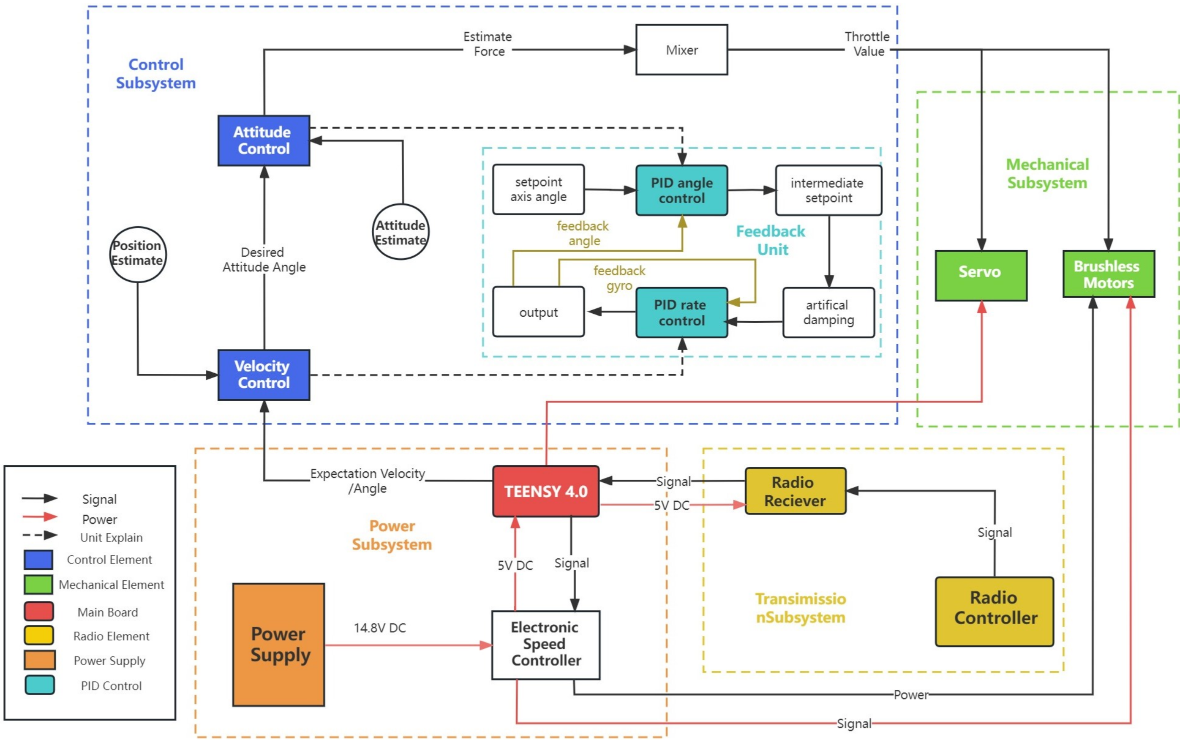
Our goal is to design a small e-VTOL with a wingspan of about one meter to achieve both vertical takeoff and landing and horizontal flight like a fixed-wing aircraft by means of only two rotatable propellers located at the ends of the mean wings. Such two flight modes and the transition between them require a very precise perception and adjustment of the aircraft's attitude compared with drones with 4 motors[3]. To do this, we need a high-frequency motherboard and some gyroscopic sensors to receive and process the aircraft's attitude information and make feedback adjustments. This places high demands on the control section, and on the mechanical side to ensure structural rigidity, reduce unpredictable jitter in the wings and other components. What's more, for the rotatable propeller section. It is important to reduce the inertia of the rotating part while reducing the complexity of the structure and making it more reliable. While designing the aircraft structure with sufficient strength. We also consider the arrangement of the location of each electronic component, the heat dissipation of electronic components, sufficient storage space, certain water resistance, easier maintenance, etc.

1.3 High Level Requirements

- The two propellers combined must provide a force greater than 15N to ensure that the aircraft can take off vertically. Also ensure that the gravitational force on the aircraft itself is less than 15N.
- The wings need to provide at least 15N of lift to ensure that the aircraft can fly horizontally at the preset speed.
- The development board needs to reach approximately 2 kHz flight control loop rate in order to receive the attitude changes from the sensors in time and react quickly.

1.4 Block Diagram & Subsystem Overview

Our VTOL Drone basically includes four subsystems as shown in the Figure 1 below: Power Subsystem, Control Subsystem, Transmission Subsystem and Mechanical Subsystem. The 14.8V DC battery in the power subsystem offers the electricity needed for the control subsystem through an electronic speed controller, which will transfer the 14.8V into 5V DC. The Teensy 4.0 board in the control subsystem will receive the signal from the radio receiver and the MPU-6050 and it will complete the PID controls through the code and send the signal to motors and servos. The transmission subsystem includes the radio controller and radio receiver, and the radio receiver will send the signal from the radio controller into the board. The mechanical subsystem contains servo motors and brushless motors, through the linkage of PLA 3d printed parts, stepper motors control the directional rotation of brushless motors and propellers to complete the adjustment of aircraft attitude and various directions of movement with the cooperation of two propellers. Meanwhile, the 3d printer body reinforced by carbon fiber tube, and glass fiber sheet has good reliability.



2.1 Block Diagram of Our VTOL Drone

Figure 1: Block Diagram

Power Subsystem

This subsystem supplies power to the whole drone. We use a power supply with 14.8V DC and we use ESC to power the TEENSY 4.0 of the Control Subsystem and the motors in the Mechanical Subsystem.

Control Subsystem

This system consists of two PID controls, one for angle control and another one for velocity control. The board will send commands to the motor through the control subsystem.

Transmission Subsystem

This subsystem consists of a radio controller and radio receiver; the receiver will receive the signal from the controller and send it to the main board.

Mechanical Subsystem

This subsystem consists of a few different small modules

- 1. Brushless motor and propeller module

There will be two sets of brushless motor and propeller module on each end of the wings. The motor with propeller will provide different thrust with different efficiency corresponding to the circuit output.

- 2. Servo and gear set module
  There will be two sets of Servo and gear set module on each end of the wings, the brushless motor and carbon fiber rod is connected by this module. Control the rotation of Brushless motor and propeller module precisely.
- 3. Aircraft body module
  Provide a strong structure to support all other modules, also provide enough space for electronic components and wires. There will be two carbon fiber rods supporting the wings and propellers, and another one connecting to the tailpiece.
- 4. Wings module
  Provide enough lifting force in horizontal flying mode. Choosing suitable airfoil according to our horizontal flying speed.

2 Design

2.1 Power Subsystem

Power Subsystem basically consists of two main modules: power supply module and power transmission module. The power supply module offers electricity to the whole system and the power transmission module will adjust the 14.8V DC power supply into 5V output for the use of Teensy board, servos and IMU. The overview of the power subsystem is shown below:

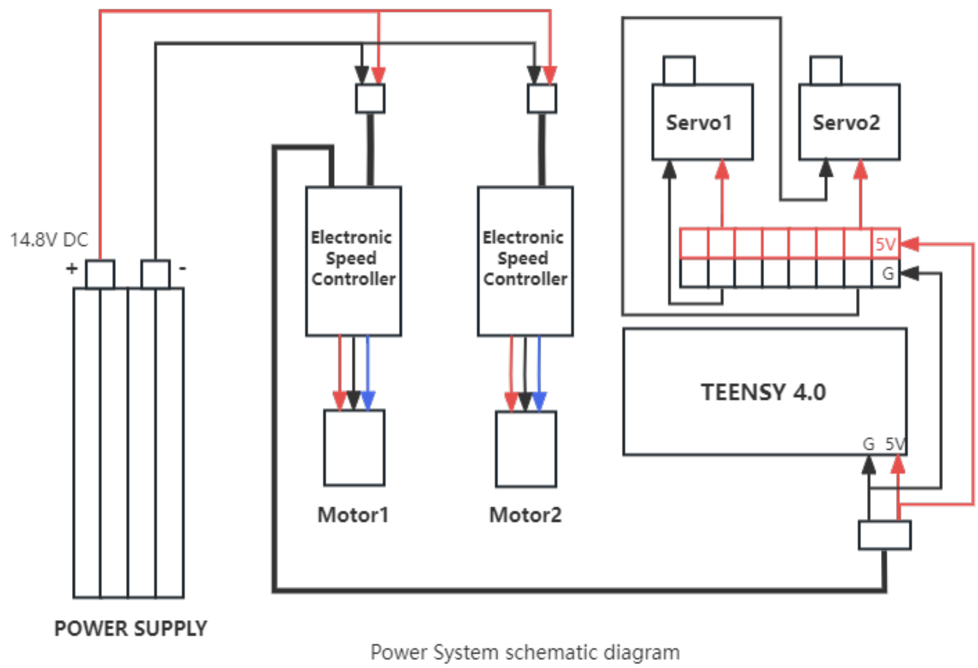


Figure 2: Power Subsystem Schematic

2.1.1 Power Supply module

Design Procedure & Alternatives

We use a 2400mAh Li-Po battery. The Li-Po battery must be able to keep the circuit continuously powered when the drone is flying. Since we need it to power the ESCs, we have selected a Li-Po Battery which satisfies the basic needs of the ESC. For Lithium Battery, we need 2-4 lithium battery packs to supply the power. To make it last long, we select a 4S1P 2400mAh Li-Po battery, which satisfied our needs. This battery has a built-in protection circuit covering short circuits, over-charging, and over-discharging. And it passed our safety test of the maximum temperature.

For the alternatives of the power supply module, we can choose any rechargeable 4S battery to keep it fit for our design. The only requirement of the battery selection is the size of it, the maximum size of the battery is 40mm*30mm*125mm as shown in the figure below.

Design Details

The battery is designed to be placed in the front of our drone, which can help to balance the center of mass of our drone. We reserved a hole for the hook and loop fasteners to fix the battery, and we used a split wire to connect the output of the battery with two electronic speed controllers.

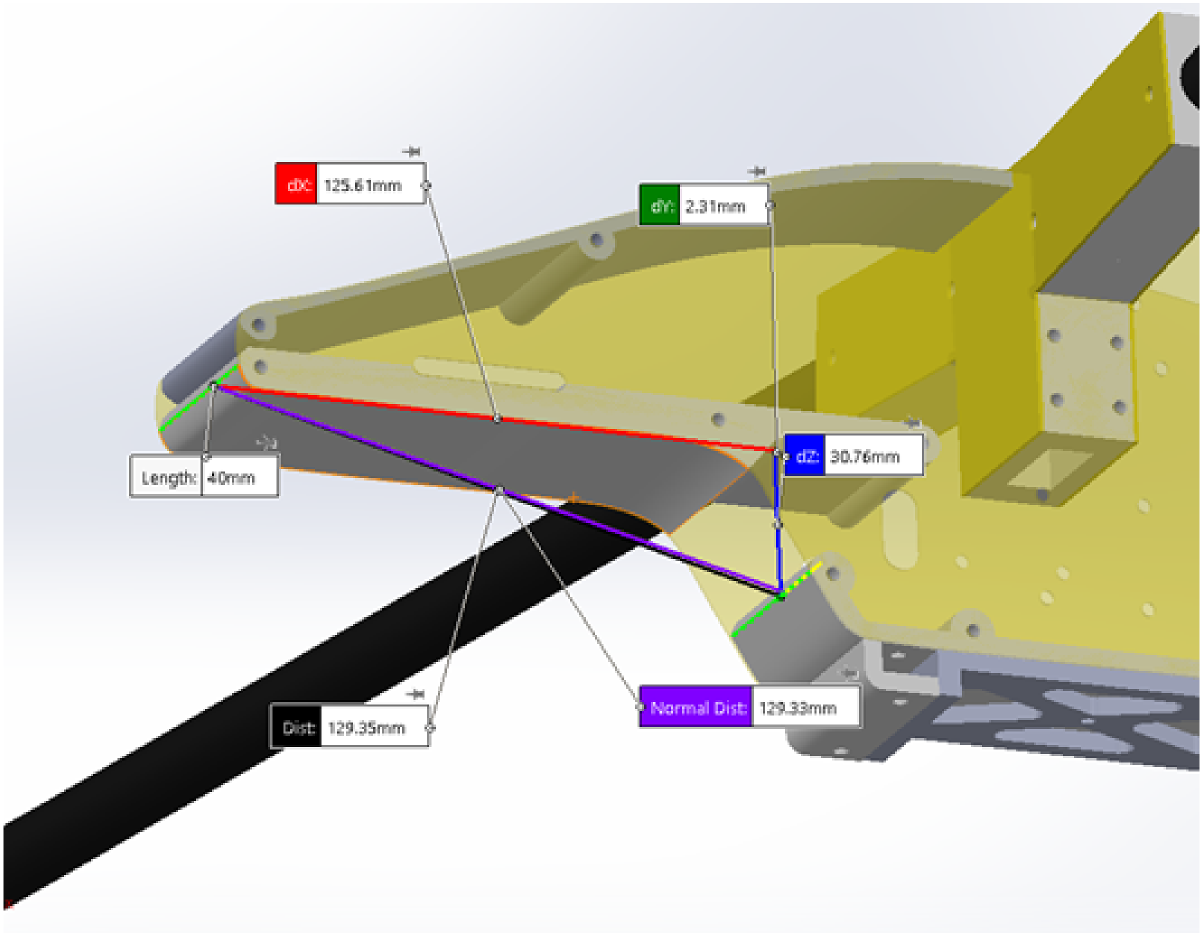


Figure 3: Position of Battery

2.1.2 Power Transmission Module

Design Procedure & Alternatives

We use two electronic speed controllers to adjust the voltage. The two electronic speed controllers (ESCs) are placed in the body of our drone, which are powered by the battery directly. They will output a 5V DC output, which will power the Teensy board, IMU and servos. In addition, the two ESCs will output command voltage of the two brushless motors with the input signal from the Teensy board.

For the alternatives to the power transmission module, we have two main choices. First, we can select the electronic speed controllers that can support more powerful motors, but the motors we select are enough to lift our drone up. In addition, we can use a DC transformer module to help lower the voltage.

Design Details

To regulate all the wires, we used a small breadboard in the power transmission module. The 5V DC output from the electronic speed controllers is connected to the breadboard, and the IMU, Teensy board and servos are powered from the breadboard. The input wires of the ESCs are also fixed with the battery together by the hook and loop fasteners. The breadboard is fixed to the body of our drone through glue and tape.

2.2 Control Subsystem

The control subsystem consists of IMU, TEENSY4.0, receiver, remote control, two servos and two motors. The automatic control part and the manual control part constitute the whole control subsystem. The automatic control part, in other words, feedback unit, consists of IMU,TEENSY4.0, servos and motors.TEENSY4.0 receives and processes data from gyroscope IMU and sends commands to the actuators (two servos and two motors). To adjust the altitude, speed, direction and other flight parameters, manual control part provides a link between the drone and remote controller using PWM wave. The overview of the control subsystem is shown below:

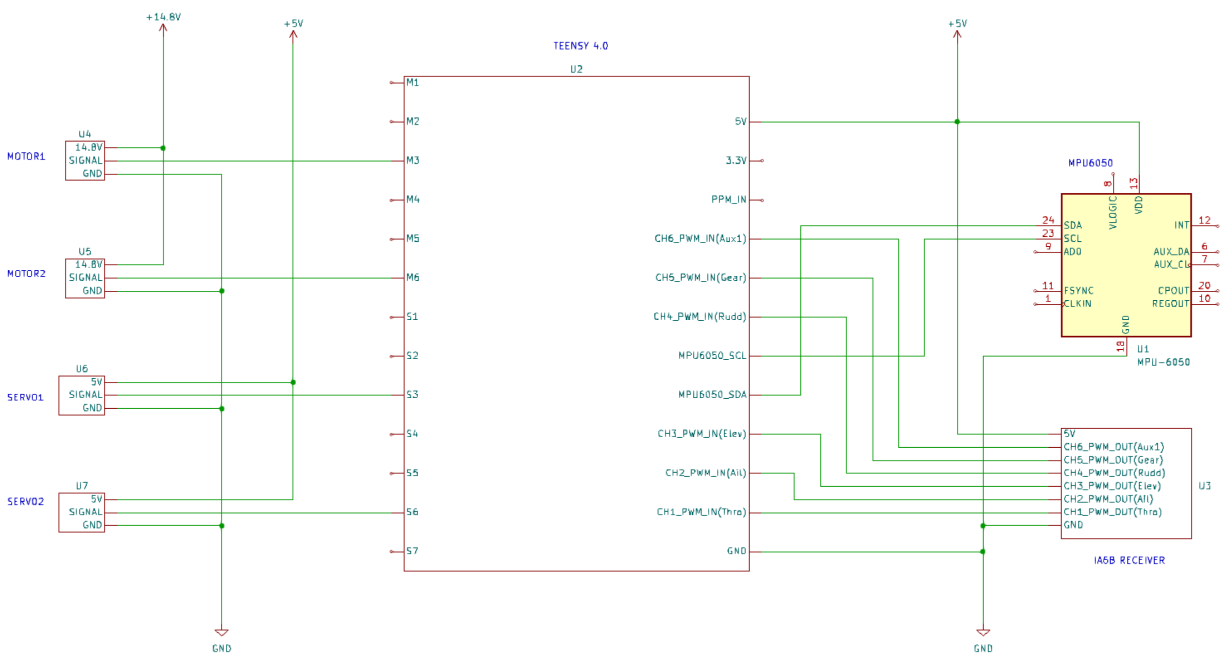


Figure 4: Control Subsystem Schematic

2.2.1 Automatic Control Module

The feedback unit receives data from the sensors on the drone, such as gyroscopes in the IMU, and sends this data to the flight controller TEENSY4.0. The PID control method in the feedback unit assists the flight controller in making decisions to control and stabilize the drone during flight. The basic control logic is shown below:

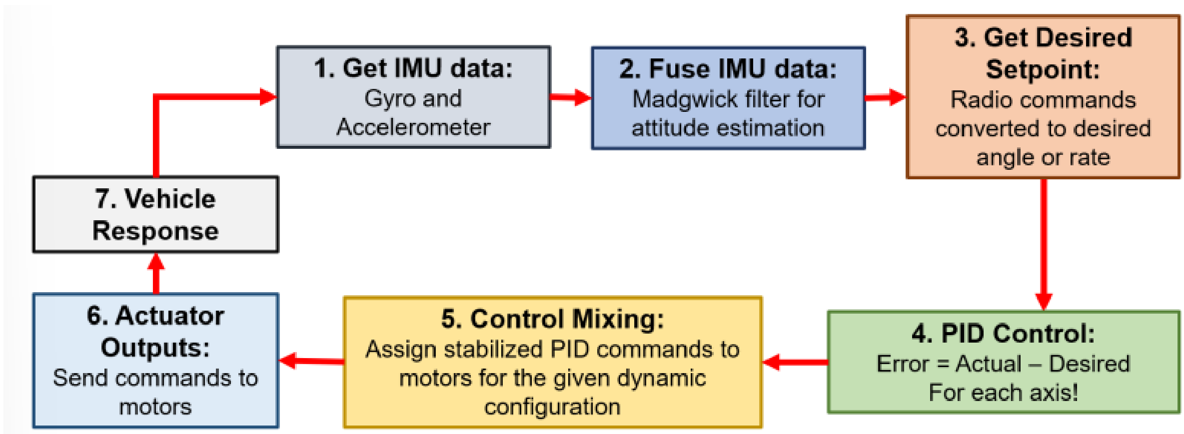


Figure 5: General overview of a flight control loop allowing stabilization of a small aerial vehicle[4]

Design Details

Feedback control of a drone involves continuously measuring its position and orientation, comparing that data to the desired position and orientation, and adjusting the drone's actuators to correct any discrepancies. The design detail of feedback control for our drone includes the following steps.

- We chose IMU which includes gyroscope and accelerometers to measure the drone's position, orientation and velocity.
- We calculate and estimate drone's state through the data received from IMU.
- We use the PID control method to compare the state of our drone to a desired setpoint (target orientation) to minimize the error between drone's actual orientation and the target orientation.
- we choose proper gain to determine the commands for servos and motors.
- Continuously update the estimated drone state in the data rate of 400 HZ, calculate the control law, apply the control action, and repeat this process to maintain the desired control.

The picture below shows the code of our PID controls:

```
//Roll
error_roll = roll_des - GyroX;
integral_roll = integral_roll_prev + error_roll*dt;
if (channel_1_pwm < 1060) {   //Don't let integrator build if throttle is too low
  integral_roll = 0;
}
integral_roll = constrain(integral_roll, -i_limit, i_limit); //Saturate integrator to prevent unsafe buildup
derivative_roll = (error_roll - error_roll_prev)/dt;
roll_PID = .01*(Kp_roll_rate*error_roll + Ki_roll_rate*integral_roll + Kd_roll_rate*derivative_roll); //Scaled by .01 to bring within -1 to 1 range

//Pitch
error_pitch = pitch_des - GyroY;
integral_pitch = integral_pitch_prev + error_pitch*dt;
if (channel_1_pwm < 1060) {   //Don't let integrator build if throttle is too low
  integral_pitch = 0;
}
integral_pitch = constrain(integral_pitch, -i_limit, i_limit); //Saturate integrator to prevent unsafe buildup
derivative_pitch = (error_pitch - error_pitch_prev)/dt;
pitch_PID = .01*(Kp_pitch_rate*error_pitch + Ki_pitch_rate*integral_pitch + Kd_pitch_rate*derivative_pitch); //Scaled by .01 to bring within -1 to 1 range

//Yaw, stablize on rate from GyroZ
error_yaw = yaw_des - GyroZ;
integral_yaw = integral_yaw_prev + error_yaw*dt;
if (channel_1_pwm < 1060) {   //Don't let integrator build if throttle is too low
  integral_yaw = 0;
}
integral_yaw = constrain(integral_yaw, -i_limit, i_limit); //Saturate integrator to prevent unsafe buildup
derivative_yaw = (error_yaw - error_yaw_prev)/dt;
yaw_PID = .01*(Kp_yaw*error_yaw + Ki_yaw*integral_yaw + Kd_yaw*derivative_yaw); //Scaled by .01 to bring within -1 to 1 range
```

Figure 6: PID Controls

2.2.2 Manual Control Module

The communication system allows the drone to communicate with the remote controller in the area. This system facilitates real-time control of the UAV and provides a link for the transmission of data.

Design detail

To make sure that we can control the drone at any moment, we should consider several aspects, such as Range, Latency, Data rate.

- **Data rate**

  Our communication system must have a high data rate to transmit real-time data to the drone, which gives the aircraft flexibility to take instructions quickly.

- **Range**

  The range of the communication system should be sufficient to maintain a stable connection between the UAV and the remote controller, even when the UAV is beyond visual range.

- **Latency**

  The latency of the communication system must be kept as low as possible to provide real-time control of the UAV.

  Both these two components work together to ensure that the drone can be controlled and piloted safely and efficiently. The feedback unit provides the necessary data to allow the control system to adjust in real-time, while the communication system allows pilots to monitor the drone's behavior, even from remote locations.

2.3 Transmission Subsystem

Design Procedure & Alternatives

Our transmission subsystem mainly refers to the radio connection part of our drone, which includes FS-i6 radio controller and FS-iA6B radio receiver. Since the FS-iA6B has 6 PWM channels for control output, we will set the controller's channels corresponding to the receiver, then we can simply use the controller to realize the control commands after the receiver and controller matches successfully.

For the alternatives to the transmission subsystem, we just need a paired remote controller and a receiver. The requirement of the radio receiver is that it should have at least 6 PWM channels.

Design Details

1. Radio controller

The FS-i6 is an entry-level transmitter built for fixed-wing / glider / helicopter modes. Featuring the AFHDS 2A protocol, upgradeability up to 10 channels as well as Chinese and English firmware versions [5]. It has totally 6 channels which is enough for our use.

2. Radio receiver

FS-iA6B is a radio receiver with 6 PWM channels. The wireless frequency is 2.4GHz and can work in the range of 500-1500m. We use the 5V DC to power it and it will receive the signals from the FS-i6.

2.4 Mechanical Subsystem

2.4.1 Brushless motor and propeller module

Design Procedure

To make sure that this module could provide enough lift for the entire drone to take off, we analyzed and estimated the weight of the whole model, as shown in Appendix C.

According to the weight of each part, we could calculate that the overall weight of the entire drone and the center of mass of the flight:

$$M = \sum_{1}^{n} m_i N_i = 1376.52g$$

$$x_{center} = \frac{\sum_{1}^{n} m_i N_i x_i}{M} = 70.07$$

Thus, considering the errors in weight estimates and potential weather effects, we estimate that the propellers should provide a total of at least 2kg thrust. After comparing the detailed operation data of several motors such as X2216 KV800, V2216 KV800, X2212 KV1400, we finally decide to use brushless motor V2216 KV800.

Design Details

The detailed data for the brushless motor V2216 KV800 are shown in Appendix A. To reach the highest possible thrust, we choose the propellers APC1047 and use 14.8V Li-po battery as our power supply. Because our drone only has two propellers and each propeller would produce torque, the rotation direction of them should be opposite to offset them. As a result, we need a symmetrical pair of propellers.

2.4.2 Servo and gear set module

Design Procedure

We use SolidWorks to do CAD design and PLA 3D printing to manufacture this module. This module is where we changed most during our project, there are several versions of designs to solve the problems occur in assembling and testing.

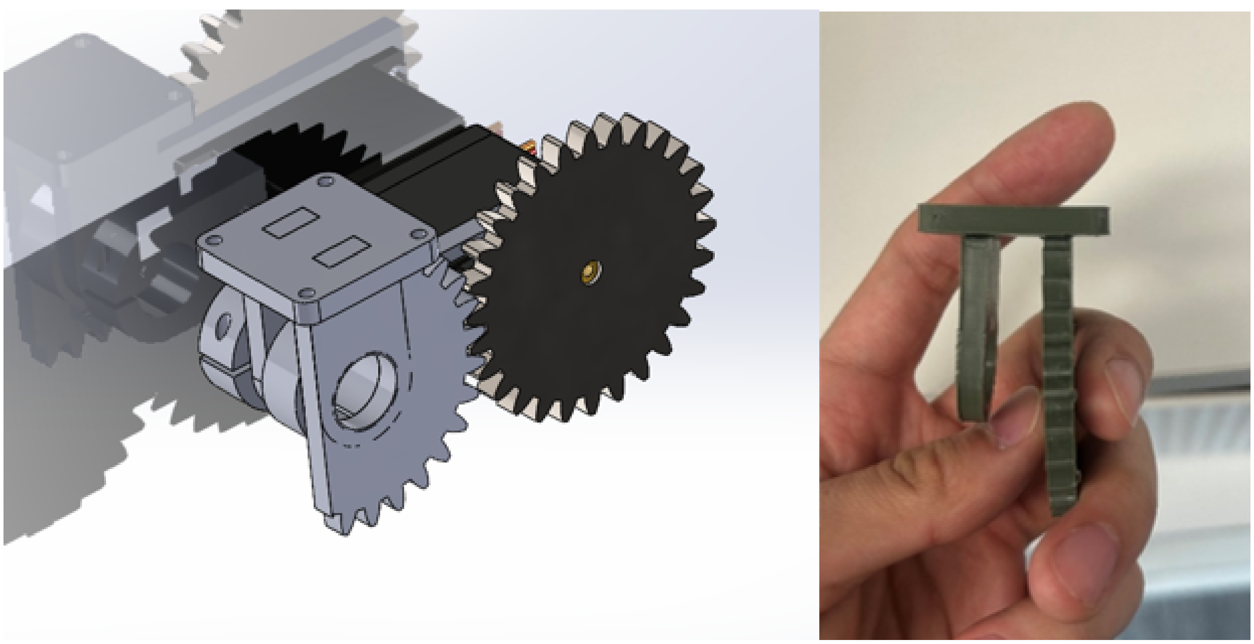


Figure 7: First Version of servo and gear set

The first version of servo and gear set was shown above. The top square plate with four screw holes on each corner was connected to the semi-circular gear with rectangular hole. In CAD model it looks fine, but after 3D printed and assemble, we found that the tolerance was not good, and we need to use a hammer to smash the parts in. What's more, the two vertical pieces below was not parallel with each other.

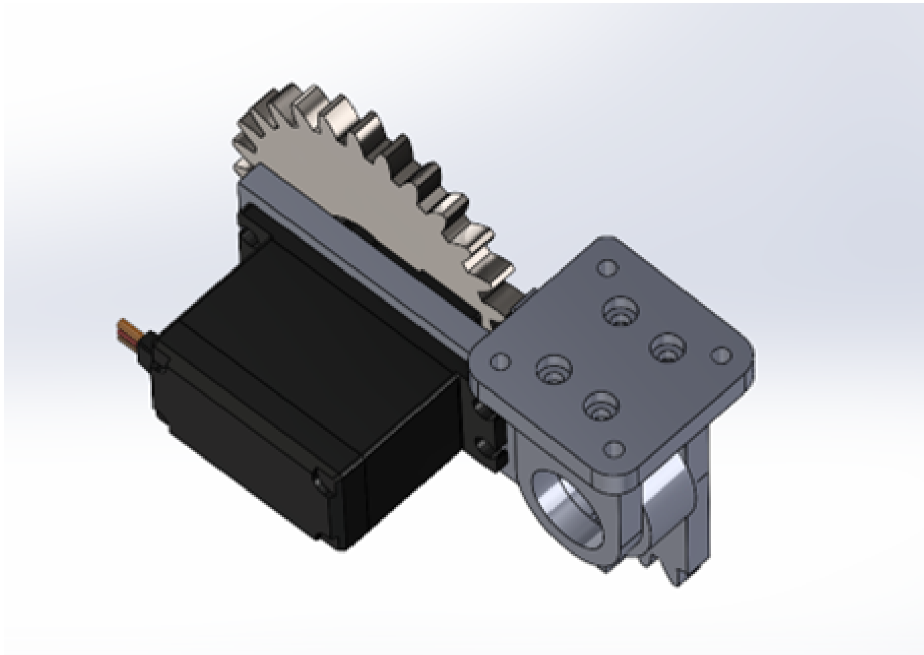


Figure 8: Second Version of servo and gear set

In this version we deleted one unnecessary design and improve the connection method between pieces. Instead of rectangular holes, we decided to use screws to connect parts. This version works well in assembling process. However, the exposed gear set causes this structure to be easily damaged during testing.

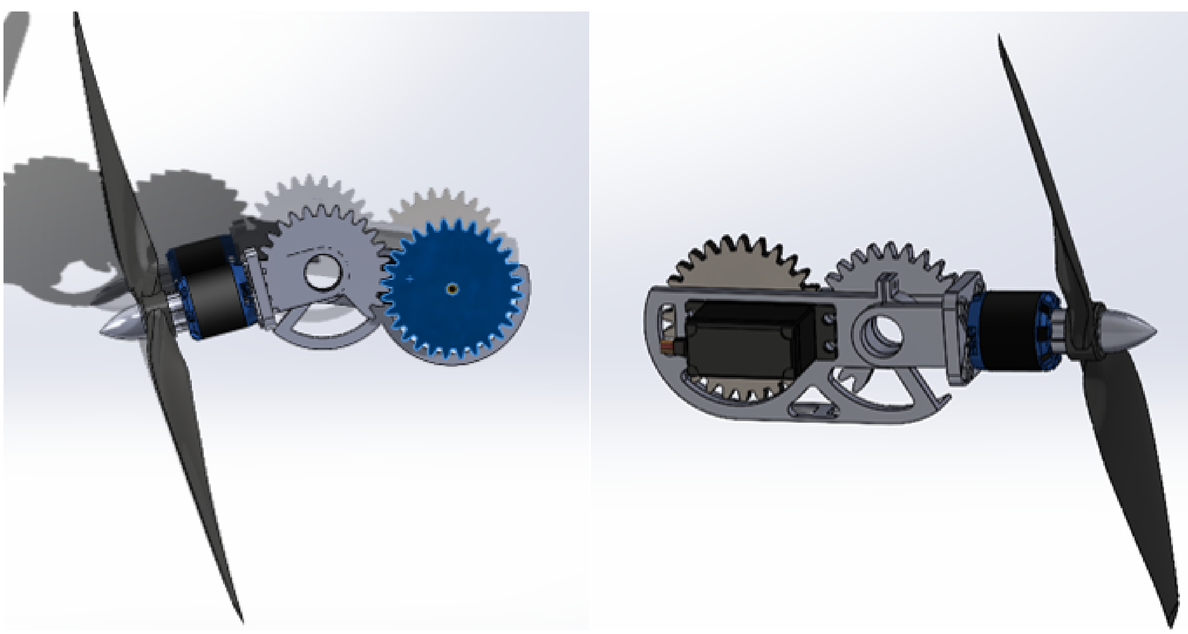


Figure 9: Third and Fourth Version of servo and gear set

In the left above was the third version which increased the tooth number of one gear to prevent the falling around the horizontal flying mode. We also extended the servo connection part to cover the area of gears to provide some protection to gears.

In the right above was the fifth version, the servo connection part was further extended below to provide better protection and motor angle limitation. This new design only added a few grams to the first version.

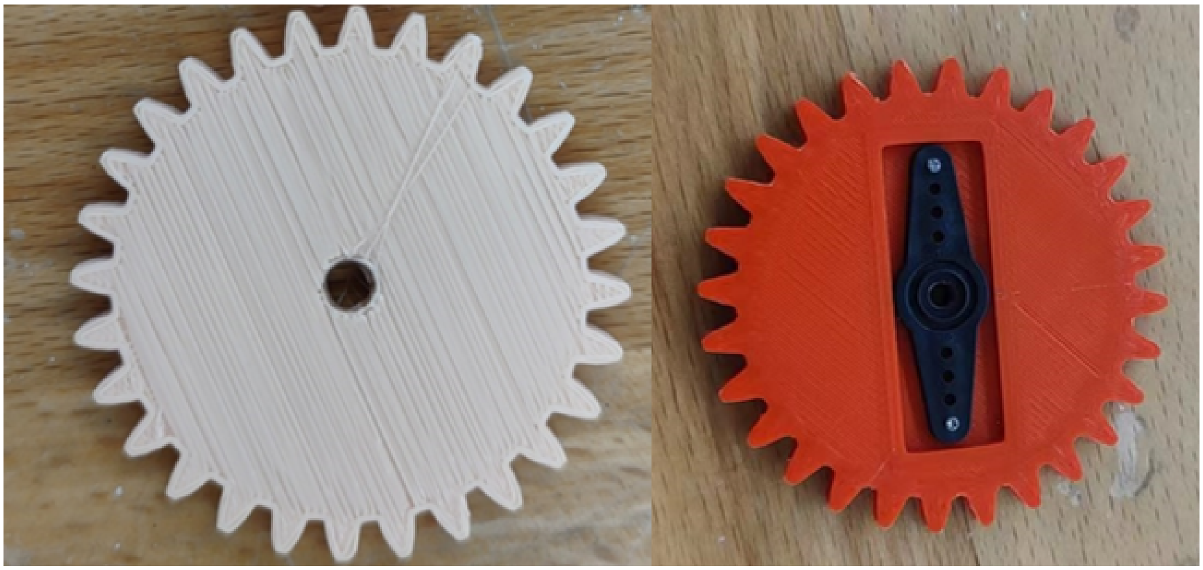


Figure 10: First and Second version of gear connect to the servo directly

On the left is the first version of the gear, which we heated to create the internal pinion shape to connect to the servo. Since this design easily wears out the interior, we changed the design and decided to use the official black fittings. This ABS material is very strong and perfect for our module.

Design Details

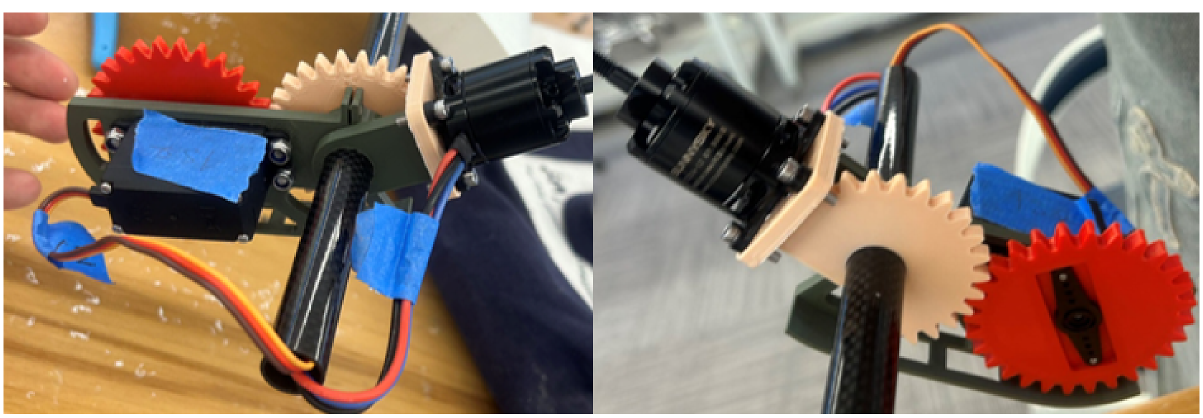


Figure 11: Final version of servo and gear set design

In this module, the servo is fixed on the 3d printed plates, which is fixed on the carbon tube.

As shown in Figure, the shaft of the servo is connected to the spur gear on the left. Because the servo could rotate in 180-degree range and the radius of the pitch circle of the two gears are the same, the output gear could also rotate in 180-degree range. Thus, the plate that holds the motor could rotate and the output direction control is realized. However, to limit the output to a desired range, we extended the servo connection part. This extension also prevents the gearset from hitting the ground.

2.4.3 Aircraft body module

Design Procedure

When designing this part, we need to consider several things: strength, storage space, weight balance and lightweight. In the brainstorming we plan to use carbon fiber to make the whole-body part of body part. But after considering the price and manufacturing difficulties, we finally decide to use PLA, glass fiber plate of 1 mm and carbon fiber rod to make this module.

Design Details

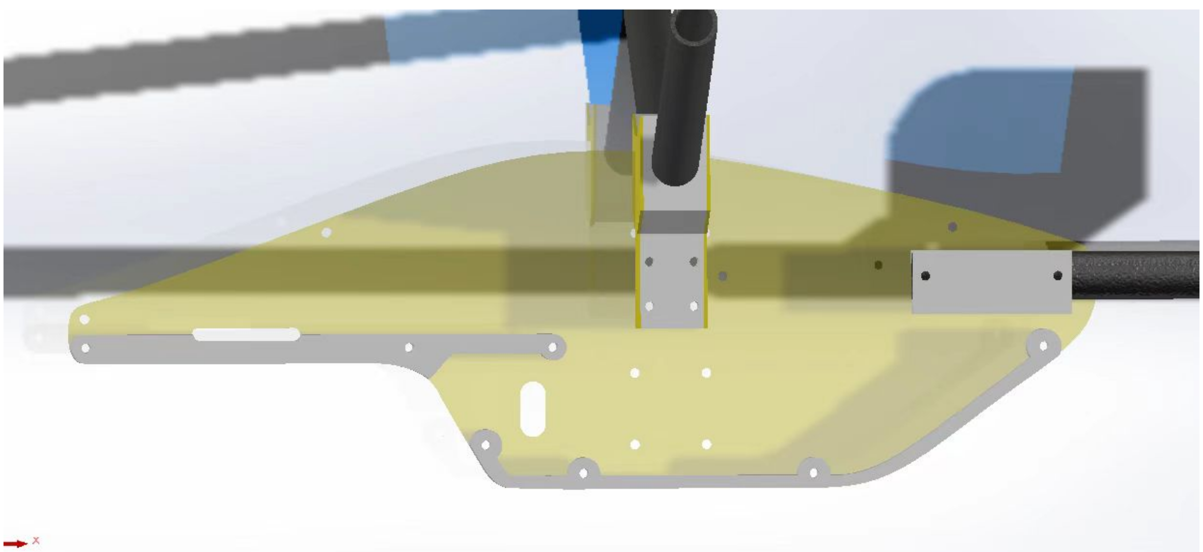


Figure 12: Aircraft body module

We use PLA material to 3D print a suitable size connector to link the 15mm carbon fiber

tube to the fuselage. In order to ensure the strength and lightweight 3d printed parts, we chose a wall thickness of 1.2mm and top layer thickness and used a 5% fill rate. We also sandwiched the 3D printed part with a 1mm thick glass fiber plate to enhance its strength. At the same time, the connectors need intermediate penetrations to ensure the passage of wires.

For the fuselage we also used a combination of 3d printed parts and fiberglass panels. In this part, we will use the fiberglass plate as the main material, PLA material 3d printing suitable size of the connector to link the fiberglass plate on both sides of the fuselage, and reasonable separation of the different functional areas of the aircraft fuselage. At the same time, we set aside space for the front of the aircraft to place the battery, using Velcro to fix the battery, to more easily adjust the center of gravity of the aircraft. The body also needs to ensure sufficient heat dissipation to prevent the electronic components from accumulating heat to melt or soften the 3d printed parts.

2.4.4 Wing Module

Design Procedure

In designing the wings, we first need to know the lift required by the aircraft, which is calculated in Section 2.4.1. We also need to estimate the horizontal flight speed of the aircraft, we assume that the horizontal flight speed of our aircraft is 40 m/s. From the speed we calculate the Reynolds number, and from the experimental data of various airfoils on the website we get various wing coefficients. Then we calculate the lift from the wing dimensions. When the lift force is greater than the gravity, the requirement is satisfied, and then we need to print the wing with light weight PLA. In this process, we design a reasonable internal filling structure to achieve the purpose of light weight and high strength.

Alternative Airfoil: NACA 2412

The Cl vs Alpha, Cd vs Alpha curves for NACA 2412 are similar to NACA 4412, all of which can meet the flight requirements of our aircraft. But at low Reynolds number, NACA 4412 has more linearity and Cl than NACA 2412, so NACA 4412 is a better choice for us.

Alternative Manufacturing methods

We tested the print with normal PLA and light PLA, which is heavier but has a smoother surface. By setting 50% inlet and higher extrusion temperature, light weight PLA can also achieve exceptionally good results. Also, we tried to design many kinds of internal fillings and chose a version with good strength and weight.

Design Details

After our VTOL drone turns into horizontal flight mode, we need to calculate the drag force and lift force in typical speed. Here we assume after totally horizontal flight, the horizontal speed (V) for our drone is around 40 m/s.
Reynold number: $Re = \frac{\rho V l}{\mu}$
At standard atmospheric pressure, 15 degrees Celsius, $\rho = 1.225 \frac{kg}{m^3}$
Characteristic length: $l = 0.2m$

Dynamic viscosity at standard atmospheric pressure, 15 degrees Celsius:

$$\mu = 18\mu Pa \cdot s = 18 \cdot 10^(-6)\frac{kg}{m \cdot s}$$

Thus we can get the Reynold number for $V = 40m/s$ is $Re = \frac{\rho V l}{\mu} = 544444$
From Airfoil Tools' website (NACA 4412 (naca4412-il) (airfoiltools.com)) We can get the Dat file of airfoils, wing drag coefficient, wing lift coefficient. They record the coefficients at $Re = 500000$, where $V = 37m/s$.

When the angle of attack$\alpha = 0deg$, we can read from the plots that $C_L = 0.5, C_D = 0.007$. To calculate the drag force(D) and lift force(L):

$$D = C_D \cdot \frac{1}{2}\rho V^2 S_{ref}$$

$$L = C_L \cdot \frac{1}{2}\rho V^2 S_{ref}$$

Where S_{ref} is the wing reference area, $S_ref = 2 \cdot d \cdot L = 0.1623m^2$, where $L = 0.8m$ is the wing Length at one side and wing thickness from the front view and

$$d = \frac{\Delta y}{\Delta x}L = \frac{y_{max} - y_{min}}{x_{max} - x_{min}}L = \frac{0.0980 - (-0.0228)}{1.0 - 0} \cdot 0.8 = 0.10144m$$

Thus, for wing at $V = 37m/s, \alpha = 0deg$,

$$D = C_D \cdot \frac{1}{2}\rho V^2 S_{ref} = 0.9526N$$

$$L = C_L \cdot \frac{1}{2}\rho V^2 S_{ref} = 68.04N$$

For other components on the plane, they also provide drag forces, based on the equivalence surface area and drag force of wings, we can get:

$$D_{total} = D + D_{other} \approx 4N < F_{motor} = 24.8N$$

From the previous analysis, the Gravity force of the drone is $G = 13.7652N < L$ which means that at $V = 37m/s$, ur drone can still go upwards using only 15% of motor forces. The calculation above proves that our drone will work well in horizontal flight mode.

3 Cost & Schedule

3.1 Cost Analysis

3.1.1 Labor

According to UIUC public data [6], the average starting salaries for computer engineering is $105352 per year from 2020 to 2021. Without average working time, we just simply assume that the working time is 8 hours per day, 5 days per week and 52 weeks per year. Thus, our fixed labor costs are estimated to be $50/hour, 10 hours/week for four people. Neglecting the cost of others' potential help that may need to be calculated, the labor costs are shown below.

Name	Hourly Rate	Hours	Total	Total $\times 2.5$
Yanzhao Gong	$50	160	$8000	$20000
Jinke Li	$50	160	$8000	$20000
Tianqi Yu	$50	160	$8000	$20000
Qianli Zhao	$50	160	$8000	$20000
Total	$80000			

3.1.2 Parts

Part	Manufacturer	Description	Quantity	Cost
Brushless motor	SUNNYSKY	V2216, KV800	2	$37.67
Servo	XUANTEJIA	MG996R	2	$4.93
Battery	GREPOW	14.8V 2400mah	1	$25.79
ESC	HOBBYWING	50A, XT60	2	$22.03
Receiver	FLYSKY	FS-iA6B	1	$8.55
Audio adapter board	SPARKFUN	Teensy 4.0	1	$67.82
Carbon tube	HONGWANGXIN	15*13*1000mm	3	$14.78
Fiberglass plate	CHUANGYIFU	500mm*500mm*1mm	2	$3.62
IMU	TELESKY	GY521 MPU6050	1	$1.67
Cords	70cm motor extension cords, servo cords and so on			$14.3
TOTAL	$201.16			

3.1.3 Grand Total

The grand total is:

$\$80000(Labor) + \$201.16(Part) = \$80201.16$

3.2 Schedule

See schedule in Appendix B.

4 Requirements and Verification

4.1 Power Subsystem

4.1.1 Battery

Requirements

The Li-Po battery must be able to keep the circuit continuously powered when the drone is flying. For Lithium Battery, we need 2-4 lithium battery packs to supply the power. In order to make it last long, we select a 4S1P 2400mAh Li-Po battery, which will satisfy our needs.

- Can store > 2400mAh of charge.
- Should not reach $60°C$ when working a long time.

Verification & Quantity results

- A. We Charged the Li-Po Battery with the charger until it's fully charged(16.8V).
  B. Then we discharged the battery at 300mA for 6 hours. And used a voltmeter to ensure the voltage is above 14.8V(4x cell voltage)
- We observed the temperature if the discharging cycle and used an IR thermometer to test the temperature that the battery doesn't reach the temperature of $60°C$ [7].

4.1.2 ESCs

Requirements

We use two electronic speed controllers in our drone. They should be supplied with 14.8V DC from the Li-Po battery and they will transfer the voltage into 5V DC for the use of the Teensy board and the servos. In addition, they should create a changing output voltage for the motors according to the signal from the Teensy board.

- Should output a 5V±5%from a 14.8V-16.8V battery
- Should be under $65°C$ when working

Verification & Quantity results

- We measured the output voltage using an oscilloscope, finding that the output voltage stays within 5% of 5V.
- We observed the temperature if the discharging cycle and used an IR thermometer, finding that the battery doesn't reach the temperature of $65°C$ [8].

4.2 Control Subsystem

4.2.1 MPU-6050

Requirements

- The IMU should be able to provide accurate and precise measurements of the drone's orientation, velocity, and acceleration.
- The IMU should be able to provide measurements at a sufficiently high rate to enable the drone's flight controller to make real-time decisions and adjustments.

Verification

- Connect the IMU to TEENSY4.0, plug in the Teensy 4.0 using a micro-USB cable. Print out the data from IMU on the Arduino serial monitor. Rotate IMU on three different spatial axes to simulate different attitudes of drone during flight. Observe the data shown on the serial monitor.
- Utilizing the baud rate of serial monitor and determine whether the IMU provide a high-rate measurements.

Quantity result

Arduino serial plotter showing proper IMU gyro data and the curve of IMU is shown as below:

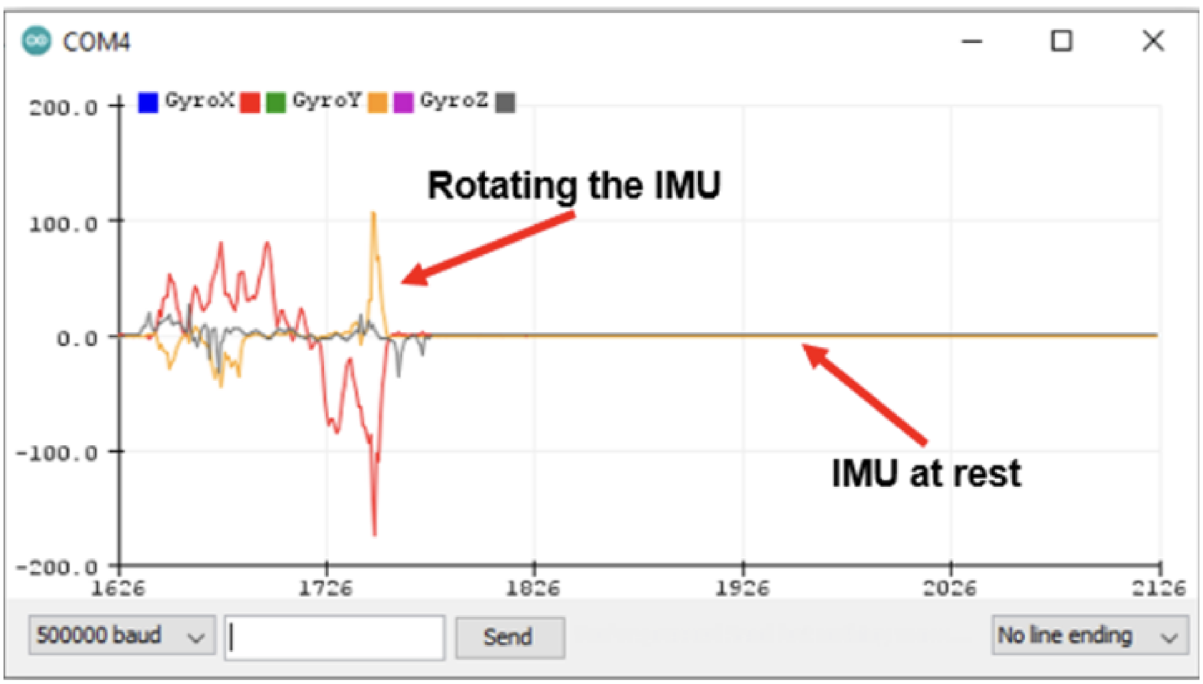


Figure 13: Arduino serial plotter showing proper IMU gyro data

4.2.2 TEENSY 4.0 Board

Requirement

- The TEENSY4.0 should have sufficient processing power to calculate flight trajectories, stabilize the drone, process sensor data in real-time, and execute flight commands quickly.

- The TEENSY4.0 should support various sensors such as the IMU and provide accurate data to enable the drone to navigate and maintain stability[9].
- The TEENSY4.0's firmware should be upgradable and programmable, allowing the operator to modify the system's behavior or add new features.

Verification

Plug in the TEENSY4.0 to computer using micro-USB cable and test the power supply circuits, I/O ports, signal and data processing capabilities, communication interfaces, and other critical components and subsystems of the mainboard.

4.3 Transmission Subsystem

4.3.1 Remote Controller

Requirements

- The remote control should have a sufficient range to receive the data transmitted by the UAV from a reasonable distance.
- The remote controller should also provide a remote-control interface for the operator to control the UAV's movements as needed.

Verification

- Test the physical buttons, joysticks, antennas, LCD screens, and communication modules. The verification process may involve simulation, firmware testing, and system-level testing to ensure the remote controller functions correctly under various operating conditions.
- Test the maximum range of the signal transmission and reception.

Quantity result

The maximum range of signal transmission and reception is 500 meters.

4.3.2 Radio Receiver

Requirements

- The receiver should have low latency to ensure that the UAV accurately responds to the control commands in real-time.
- The receiver should be compatible with the remote controller to ensure seamless communication between the two.

Verification

Connect the receiver to TEENSY4.0, plug in the Teensy 4.0 using a micro-USB cable to computer. Print out the data from receiver on the Arduino serial monitor. We can see that when the receiver receives the commands from controller, the data it sends to TEENSY4.0 changed.

Quantity result

Arduino serial monitor showing radio data where the radio is properly connected and all channels have been adjusted correctly, the figure is shown below.

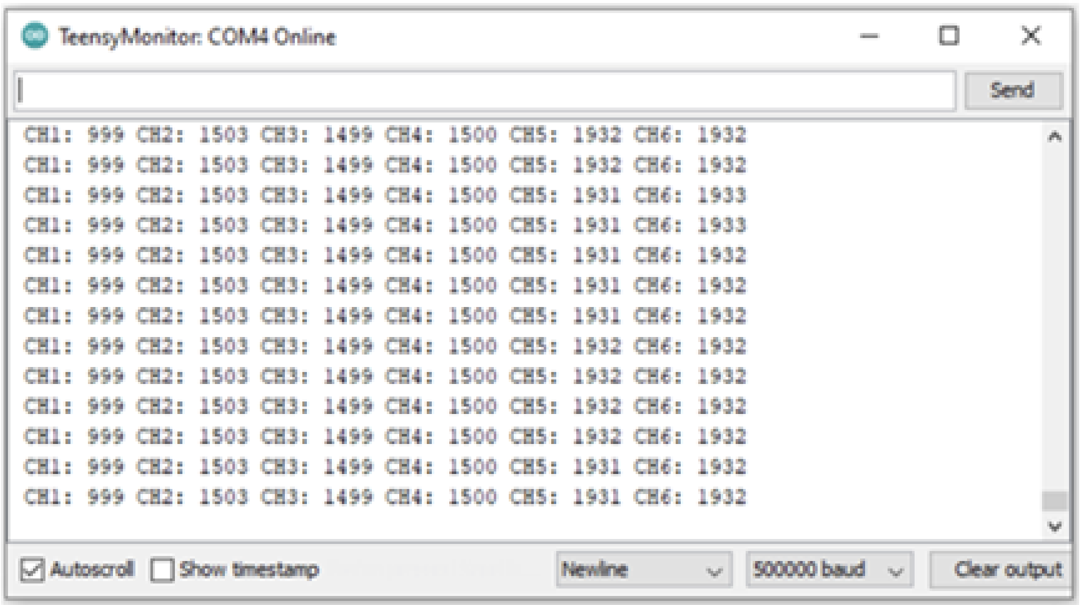


Figure 14: Radio data on serial monitor

4.4 Mechanical Subsystem

4.4.1 Brushless motor and propeller module

Requirements

- When powered by a 14.8V supply, the brushless motor is capable of producing a maximum thrust of 1150g.
- After running continuously for 5 minutes, the motor's highest temperature should remain below 75°C.

Verification

- Fixed the brushless motor in the six-component balance and connected it to the ESC, which relates to the 14.8V battery and receiver. Use the remote control to directly control the ESC to maximize the power and observe the display.
- Use the infrared thermometer to keep monitoring the temperature during the 5-minutes operation and record the highest temperature.

Quantity Results

The display of the six-component balance is 1223g, which is higher than our estimation and the highest temperature is 65°C during the 5-minutes operation.

4.4.2 Servo and gear set module

Requirements

- The servo could rotate in a range of 180°.
- The servo could provide a maximum torque of 5kg/cm.

Verification

Connect the brown and the red wire to the positive and negative terminals of a 5V power supply. Connect the orange wire of the servo to a function signal generator. Adjust the machine so that its output signal period is 20ms PWM signal. Adjust pulse width between 0.5ms and 2.5ms. Ensure the rotation degrees of the servo could reach 0 degrees and 180 degrees. Then attach shaft to a 1cm-radius gear with 4kg weight hanging at the edge. Ensure the servo could still rotate smoothly

Quantity Results

The servo could rotate in a range of 181 degrees measured by the protractor. And the servo could even work properly if the weight adds to 4.5kg.

4.4.3 Aircraft body module

Requirements

- The space is set up in such a way that the center of gravity of the aircraft is directly below the center of the wing attachment.
- The connecting part must be able to withstand a torque of 20 Nm in the x, y, and z directions.

Verification

Complete assembly of all aircraft components. And use a marker to draw the wing carbon tube connectors and the plane where the carbon tubes are located on the aircraft's shell. Find a roller to place on the bottom of the aircraft and roll it back and forth until a position where the aircraft is no longer tilted forward or backward. Adjust the position of the battery until the point where the roll is tangent to the bottom of the aircraft falls on the mark of the marker. Record the position of the battery at the next time.

Fix the bottom of the aircraft on the vise. Measure and record the coordinates from the screw holes of the connectors to the bench vise with a vernier caliper. Apply a force of 25 N perpendicular to the carbon tubes with a tensiometer at the end of the principle connector of the other carbon tubes. Observe the PLA connector for deformation visible to the naked eye and measure and record the coordinates from the screw holes of the connectors to the bench vise with a vernier caliper. Compare the deformation of the screw holes of the connector before and after the applied force is greater than 2mm. Repeat steps for both wing connectors and back connector in the other directions.

Quantity Results

After proper adjustment of the battery, the position of the mass center falls on the mark of the marker. And the deformation is 1.2mm, 0.5mm and 1.6mm in three directions, which satisfies the limit. The MG996R servos, powered directly by the radio receiver and controlled by the Teensy 4.0, should be able to rotate in a range of 180 degrees and thus, change the output angle of the brushless motors. And the brushless motors should be able to supply enough lift force, which is higher than the total weight (about 1.5 kg) of the plane, during the VTOL process and thrust during level flight.

4.4.4 Wings module

Requirements

- The drag force of the wing is no larger than 10N at speed 40m/s.
- The lift force provided by the wing is larger than 20N.

Verification

Use 3d printing technology to construct a y-section wing with a chord length of 0.2m and a main length of 0.3m and fix it vertically on a sextant balance with a rotatable base. Then use the wind tunnel to generate different wind speeds to simulate real flight conditions and rotate the base to verify the conditions at different pitch angles. Record the force and torque under various conditions with the sextant balance.

Quantity Results

According to the display of the sextant balance, the drag force is only 3N and the lift force is 60N, which generally matches our calculation and satisfies the requirements.

5 Conclusion

5.1 Accomplishment

We have successfully met all the high-level requirements that we set before beginning our project. The two motors and servos in our drone are controlled by a combination of both the remote control and PID control. With the help of PID control, our drone is capable of self-adjusting to maintain stability in all three rotational directions during flight. When combined with the commands from the remote control, our drone can take off smoothly and soar through the air with ease.

5.2 Uncertainties

Due to the gyroscope only, our aircraft cannot monitor the displacement and velocity in the three directions x y and z, which makes the actual control not easy, and the drone cannot stay in the air for long. In other word, the drone could theoretically pan in all directions with no rotation even the PID control is working properly. As a result, the exact altitude and direction of flight require human effort and are not precise

Besides, the codes in the Teensy 4.0 are not perfect and our drone couldn't always maintain stable in actual flight. Machining accuracy of each component is another problem and also greatly influences the flight.

5.3 Future work

We will continue to fine-tune our code to ensure that the drone can more accurately execute commands from the remote control. Additionally, we plan to install airspeed meters on the UAV and develop the corresponding code to enable better speed control and achieve our goal of stable hovering.

5.4 Ethical Consideration

5.4.1 Ethics

Our design aims to improve the performance of current ordinary drones, providing the people with more convenient and efficient tools for production and life. After careful consideration of the UAV's functionality and potential range of applications, we promise that we would put the safety, health and welfare of the public first [10], refusing to provide any products or related technology to the wrongdoers in any way and prohibiting the use in espionage or military activities. Besides, in order to avoid "endangering the public and the environment" [10], we guarantee that we would inform relevant people of the possible potential hazards of our UAV products and preventive measures. Privacy concerns arise from the use of cameras mounted on the UAVs, which can capture images of people without their consent. This can be particularly problematic in public spaces, where individuals have a reasonable expectation of privacy. What's more, considering this is a design task, challenge and study process, we would accept honest criticism of our UAV, acknowledge and correct errors in time as well as making statements according to reliable data [10].

5.4.2 Safety

Safety is another critical consideration when it comes to the use of two propeller UAVs. These drones can be dangerous if not handled properly, particularly in crowded or densely populated areas. First, when testing the aircraft, we need to be very careful of the aircraft's high-speed rotating propellers, and to do brushless motor and remote-control power-off at the moment when hands are likely to touch the propellers. Secondly, we need to do a good job of fireproofing the electronic components. Water leakage and exposed wires may lead to short circuits, so we avoid flying on rainy days until we can ensure that the system is completely waterproof. Not only that, we should also try to avoid crowds and various facilities during the flight, so as to reduce the danger caused by the plane crashing. Also, we need to do a good job of heat dissipation of the electronic components to prevent the PLA materials used to build the main part of the aircraft from melting and deforming due to high temperatures. Some of the safety risks associated with two propeller UAVs include loss of control due to environmental factors such as wind, and malfunction or failure of critical components.

To ensure the safety of individuals and property, regulations have been put in place to govern the use of UAVs. These regulations include requirements for operator training, restrictions on where and when UAVs can be flown, and the use of safety features such as fail-safe mechanisms and automatic collision avoidance systems.

In conclusion, while the use of two propeller drones has numerous benefits, the ethics and safety of their use must be given utmost considerations. Ethics and the respect of people's privacy need to be enforced to avoid misusing them, while safety standards are needed to prevent accidents, damages, and injuries they may cause. As regulations for the use of UAVs continue to evolve, it is essential to ensure that their deployment does not interfere with established ethical and safety practices.

Appendix A Comparison Table of Motors

Prop (inch)	Volts (V)	Amps (A)	Thrust(g)	Watts (W)	Efficiency (g/W)	全油门负载温度
APC1038	11.1	0.6	100	6.66	15.01501502	
		1.6	200	17.76	11.26126126	
		2.8	300	31.08	9.652509653	
		4.1	400	45.51	8.789277082	
		5.8	500	64.38	7.766387077	
		7.2	600	79.92	7.507507508	
		9.2	700	102.12	6.854680768	
		10.1	760	112.11	6.779056284	
	14.8	0.5	100	7.4	13.51351351	
		1.2	200	17.76	11.26126126	
		2.2	300	32.56	9.213759214	
		3.3	400	48.84	8.19000819	
		4.5	500	66.6	7.507507508	
		5.9	600	87.32	6.871278058	
		7.4	700	109.52	6.391526662	
		9	800	133.2	6.006006006	
		10.9	900	161.32	5.578973469	
		12.8	1000	189.44	5.278716216	
		14.6	1100	216.08	5.090707146	
		16	1190	236.8	5.025337838	64°
APC1047	11.1	0.6	100	6.66	15.01501502	
		1.6	200	17.76	11.26126126	
		2.7	300	29.97	10.01001001	
		3.9	400	43.29	9.24000924	
		5.6	500	62.16	8.043758044	
		7.3	600	81.03	7.404664939	
		9.3	700	103.23	6.780974523	
		11	790	122.1	6.47010647	
	14.8	0.4	100	5.92	16.89189189	
		1.2	200	17.76	11.26126126	
		2.1	300	31.08	9.652509653	
		3.1	400	45.88	8.718395815	
		4.4	500	65.12	7.678132678	
		5.7	600	84.36	7.112375533	
		7.1	700	105.08	6.661591169	
		8.9	800	131.72	6.07348922	
		10.5	900	155.4	5.791505792	
		12.5	1000	185	5.405405405	
		14.5	1100	214.6	5.125815471	
		16.8	1240	248.64	4.987129987	66°
APC1147	11.1	0.6	100	6.66	15.01501502	
		1.5	200	16.65	12.01201201	
		2.6	300	28.86	10.3950104	
		3.9	400	43.29	9.24000924	
		5.2	500	57.72	8.662508663	
		7	600	77.7	7.722007722	
		8.6	700	95.46	7.33291431	
		10.7	800	118.77	6.73570767	
		12.8	900	142.08	6.334459459	
		13.6	950	150.96	6.293057764	50°

Appendix B Schedule

Week	Tianqi Yu	Yanzhao Gong	Jinke Li	Qianli Zhao
03/06/2023	Brainstorming of aircraft structures and modeling of aircraft fuselage and skeleton structures in CAD design software.	Search related website for information about VTOL drone design, discuss the basic physical structure.	Read related materials to figure out what hardware is needed and understand the basic control logic of a VTOL drone	Consult relevant literature, draw the feedback control schematic with PID method
03/13/2023	Design of rotatable propeller section. Calculate the force and center of gravity.	Collect the information about the components that need to purchase and communicate with related shops.	Consulted relevant literature, found some relevant UAV hardware equipment, and chose our hardware equipment based on the calculated data	Draw a flowchart of the feedback control process. weld the mainboard TEENSY 4.0 and gyroscope.
03/20/2023	3D print the PLA parts and laser cut the glass fiber parts. Add protection part to gear set. Assemble the Drone.	3D print PLA parts and process related components, check the purchased components, assemble the drone.	Assemble the hardware equipment and connect the radio receiver and board	Connect and test the component, make sure that two motors and two servos can work properly

03/27/2023	After installing the first version of the model, we will look for points in the design that needs improvement and tried to improve them.	Search for problems of the drone and improve the entire structure.	Test the receiver through the controller and set the channels and pins of the board	Connect the control system to the power supply system to test whether each part can work properly
04/03/2023	Try vertical takeoff and optimize existing models.	Test the vertical takeoff function, discuss the problems found and try to improve the model.	Modify the code of the control subsystem and test the code	Write the code of feedback unit
04/10/2023	Lightweight slicing design for the wings.	Test light weight PLA printing for wings	Test and adjust the code so that the drone can fly smoothly	Copy our code into mainboard and try to control the drone
04/17/2023	Wing assembly and strength testing	Assemble the wings and test the strength	Test and adjust the code so that the drone can fly smoothly	Test and modify the code so that the drone could fly smoothly
04/24/2023	Test complete flight capability and make improvements.	Evaluate the flight capability of the drone and test.	Prepare for the final presentation	Prepare for final presentation
05/01/2023	Final report and presentation.	Prepare for the final presentation.	Prepare the final report	Prepare the final report
05/08/2023	Final report.	Final report.	Final report	Final report

Appendix C   Weight Estimation

Part	Mass(g/each)	Quantity	X Position
Wing	100	2	74.97
Carbon wing tube	55.98	2	73.83
Body glass fiber	38.29	2	66.04
Body PLA-1	25	1	103.91
Body PLA-2	19	1	-39.95
Body PLA-3	21	2	68
Body PLA-4	11	1	174.56
Servo	55	2	119.42
Brushless motor	77	2	69.98
Spur gear	7	2	128.74
Motor connect-1	2	2	73
Motor connect-2	5	2	78.71
Motor connect-3	4	2	71.75
Servo connect	6	2	94.12
Carbon tail tube	55.98	1	299.56
Tail	7	1	699.14
Li-po battery	250	1	-45
ESC	43	2	102
Extension cord	23	6	73.83
Teensy 4.0	15	1	103.91
Receiver	7	1	102
Propeller	10	2	68.84

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