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

Lesson 11 Semi-autonomous Control Mode Design Experiment

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Outline

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

Preliminary

□ Three Modes of SAC

Generally, according to the degree of autonomous control of the autopilot, the multi rotor under SAC is divided into three modes:

- **Stabilize Mode**
- **Altitude-Hold Mode**
- **Loiter Mode**

Preliminary

Three Modes of SAC

- **Stabilize Mode**
- **Altitude-Hold Mode**
- **Loiter Mode**

The *stabilize mode* allows a remote pilot to fly the multicopter manually, but self-levels the roll and pitch axis. When the remote pilot releases the roll and pitch control sticks, the multicopter automatically switches itself to AC. Then, its attitude will be stabilized, but the position drift will occur. During this process, the remote pilot will need to regularly give roll, pitch, and throttle commands to keep the multicopter in place as it is pushed around by wind. The throttle command controls the average motor speed to maintain the altitude.

If the remote pilot puts the throttle control stick completely down, then the motors will operate at their minimum rate, and if the multicopter is in the air, it will lose altitude control and tumble. In addition, when the remote pilot releases the yaw control stick, the multicopter will maintain its current heading.

Preliminary

◻ Three Modes of SAC

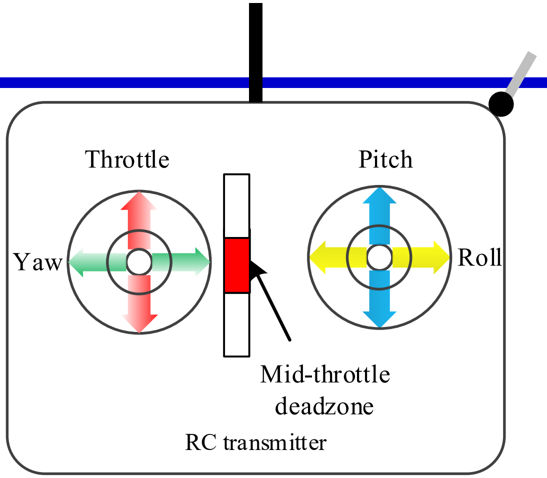


Figure: Stick function and dead zone in RC transmitter

- Stabilize Mode
- Altitude-Hold Mode
- Loiter Mode

As shown in the figure. When the throttle control stick is in the mid-throttle dead zone (40–60%), the multicopter automatically switches itself to AC. Then, the throttle command is automatically given to maintain the current altitude, but the horizontal position drift will occur. The remote pilot will need to regularly give roll and pitch commands to keep the multicopter in place.

Going outside of the mid-throttle dead zone (i.e., below 40% or above 60% for example), the multicopter will enter RC, that is, the multicopter will descend or climb depending upon the deflection of the throttle control stick. The altitude hold mode needs the support of height sensors, such as barometers or ultrasonic rang finders.

Preliminary

☐ Three Modes of SAC

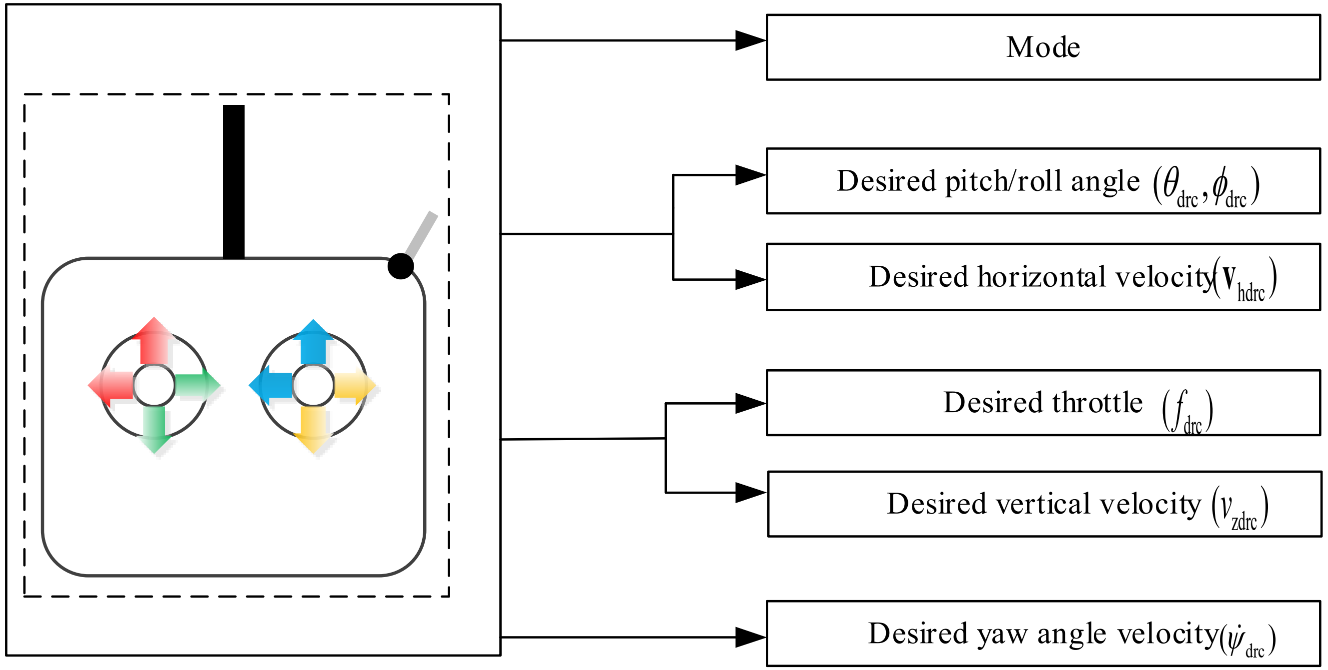
- Stabilize Mode
- Altitude-Hold Mode
- Loiter Mode

When the remote pilot releases the roll, pitch, and yaw control sticks and pushes the throttle control stick to the mid-throttle dead zone, the multicopter will automatically switch itself to AC and maintain the current location, heading and altitude. Precise GPS position, low magnetic interference on the compass, and low vibrations are all important in achieving a good hovering performance.

The remote pilot can control the multicopter's position once by pushing the control sticks out of the midpoints. The loiter mode needs the support from both the height sensors and position sensors such as GPS receiver and cameras.

Preliminary

The output of RC



- CH5 is a three-position switch, it can output three modes (Stabilize Mode, Altitude-hold Mode and Loiter Mode).
- The output of CH1,CH2 channel can convert into the desired attitude angle and horizontal velocity.
- The output of CH3 channel can convert into desired throttle and vertical velocity.
- The output of CH4 channel can convert into the desired yaw angle rate. Further, the desired yaw angle is obtained.

The Realization of the SAC in Autopilot

（1）Stabilize Mode

In the stabilize mode, $\theta_{\mathrm{drc}},\phi_{\mathrm{drc}},\psi_{\mathrm{drc}}$ generate the desired torque and desired throttle f_{drc}. According to $\mathbf{\Theta}_{\mathrm{d}}=[\theta_{\mathrm{drc}}\quad\phi_{\mathrm{drc}}\quad\psi_{\mathrm{drc}}]^{\mathrm{T}}$, design a controller $\lim_{t\to\infty}\left\|\mathbf{e}_{\Theta}(t)\right\|=0$ where $\mathbf{e}_{\Theta}\triangleq\mathbf{\Theta}-\mathbf{\Theta}_{\mathrm{d}}$ .To satisfy this, according to

$$\dot{\mathbf{\Theta}}=\boldsymbol{\omega}$$

The designed angle rate is $\boldsymbol{\omega}_{\mathrm{d}}$

$$\boldsymbol{\omega}_{\mathrm{d}}=-\mathbf{K}_{\Theta}\mathbf{e}_{\Theta}$$

where $\mathbf{K}_{\Theta}\geq0$. The equations above consist velocity control loop.

Preliminary

The Realization of the SAC in Autopilot

（1）Stabilize Mode

According to

$$\mathbf{J}\dot{\boldsymbol{\omega}} = \boldsymbol{\tau}$$

the desired torque ： $\boldsymbol{\tau}_{\mathrm{d}}$

$$\boldsymbol{\tau}_{\mathrm{d}} = -\mathbf{K}_{\omega_{\mathrm{p}}}\mathbf{e}_{\omega} - \mathbf{K}_{\omega_{\mathrm{i}}}\int \mathbf{e}_{\omega} - \mathbf{K}_{\omega_{\mathrm{d}}}\dot{\mathbf{e}}_{\omega}$$

where $\mathbf{e}_{\omega} \triangleq \boldsymbol{\omega} - \boldsymbol{\omega}_{\mathrm{d}}$, $\mathbf{K}_{\omega_{\mathrm{p}}}, \mathbf{K}_{\omega_{\mathrm{i}}}, \mathbf{K}_{\omega_{\mathrm{d}}} \in \mathbb{R}^{3\times 3}$. The equations above consist angle rate loop.

Preliminary

□ The Realization of the SAC in Autopilot

（2）Altitude-Hold Mode

In altitude-hold mode, the desired throttle is not specified by the RC transmitter directly, instead, it is specified by the output of the altitude channel in position controller. While the desired torque is still given by the input of the RC transmitter, which is similar to stabilize mode.

Given the desired altitude, according to

$$\dot{p}_{\mathrm{z}} = v_{\mathrm{z}}$$

The desired velocity is

$$v_{\mathrm{z_d}} = \mathrm{K}_{p_{\mathrm{z}}}\left(p_{\mathrm{z_d}} - p_{\mathrm{z}}\right) + v_{\mathrm{z_{drc}}}$$

Preliminary

□ The Realization of the SAC in Autopilot

（2） Altitude-hold Mode

According to

$$\dot{v}_z = g - \frac{f}{m}$$

The desired acceleration:

$$\dot{v}_{z_d} = -K_{v_z p} e_{v_z} - K_{v_z i} \int e_{v_z} - K_{v_z d} \dot{e}_{v_z}$$

Where $e_{v_z} = v_z - v_{z_d}$

Further, the desired throttle

$$f_d = m(g + K_{v_z p} e_{v_z} + K_{v_z i} \int e_{v_z} + K_{v_z d} \dot{e}_{v_z})$$

Preliminary

◻ The Realization of the SAC in Autopilot

（2） Altitude-hold Mode

The time, denoted by t_{d} , is recorded when the throttle control stick turns back to the midpoint, and then, the altitude estimate $\hat{p}_z\left(t_{\mathrm{d}}\right)$ is saved as $p_{z_{\mathrm{dold}}} = \hat{p}_z\left(t_{\mathrm{d}}\right)$. At the same time, the altitude hold mode starts to hold the multicopter's altitude at $p_{z_{\mathrm{d}}} = p_{z_{\mathrm{dold}}}$.

When the throttle control stick is out of the dead zone, the multicopter enters

manual control mode $p_{\mathrm{z_d}} = \hat{p}_{\mathrm{z}} \quad v_{\mathrm{z_d}} = v_{\mathrm{z_{drc}}}$

In this mode, the throttle channel controls tity along z-axis. Just like the stabilize mode, the altitude hold mode cannot make the multicopter hover for lack of feedback in the horizontal position. The altitude hold mode is often used when the height sensors are available while position sensors or electronic compasses are unavailable.

The Realization of the SAC in Autopilot

（3）Loiter Mode

In Loiter mode, the desired throttle is given by the output of the altitude channel in position controller, which is same as that in the altitude-hold mode. The desired torque is given by the value generated by the attitude controller using the desired attitude angle generated in horizontal position channel of the position controller.

Given the desired horizontal position, according to

$$\dot{\mathbf{p}}_{\mathrm{h}} = \mathbf{v}_{\mathrm{h}}$$

The desired velocity is

$$\mathbf{v}_{\mathrm{hd}} = \mathbf{K}_{\mathrm{Ph}}(\mathbf{p}_{\mathrm{hd}} - \mathbf{p}_{\mathrm{h}}) + \mathbf{v}_{\mathrm{hdrc}}$$

□ The Realization of the SAC in Autopilot

（3）Loiter Mode

According to

$$\dot{\mathbf{v}}_{\mathrm{h}} = -g\mathbf{A}_{\psi}\mathbf{\Theta}_{\mathrm{h}}$$

the desired acceleration can be

$$\dot{\mathbf{v}}_{\mathrm{hd}} = -\mathbf{K}_{\mathbf{v}_{\mathrm{h}}\mathrm{p}}\mathbf{e}_{v_{\mathrm{h}}} - \mathbf{K}_{\mathbf{v}_{\mathbf{h}}\mathrm{i}}\int \mathbf{e}_{\mathbf{v}_{\mathrm{h}}} - \mathbf{K}_{\mathbf{v}_{\mathbf{h}}\mathrm{d}}\dot{\mathbf{e}}_{v_{\mathrm{h}}}$$

where $\mathbf{e}_{\mathbf{v}_{\mathrm{h}}} = \mathbf{v}_{\mathrm{h}} - \mathbf{v}_{\mathrm{hd}}$

Further, the desired attitude angle can be obtained.

$$\mathbf{\Theta}_{\mathrm{hd}} = -g^{-1}\mathbf{A}_{\psi}^{-1}\left(-\mathbf{K}_{\mathbf{v}_{\mathrm{h}}\mathrm{p}}\mathbf{e}_{v_{\mathrm{h}}} - \mathbf{K}_{\mathbf{v}_{\mathbf{h}}\mathrm{i}}\int \mathbf{e}_{\mathbf{v}_{\mathrm{h}}} - \mathbf{K}_{\mathbf{v}_{\mathbf{h}}\mathrm{d}}\dot{\mathbf{e}}_{v_{\mathrm{h}}}\right)$$

Preliminary

□ The Realization of the SAC in Autopilot

（3）Loiter Mode

The time, denoted by t_d , is recorded when the throttle control stick turns back to the midpoint, and then, the horizontal estimate $\hat{\mathbf{p}}_h(t_d)$ is saved as $\mathbf{p}_{hdold} = \hat{\mathbf{p}}_h(t_d)$, $\mathbf{v}_{hdrc} = 0$. At the same time, the loiter mode starts to hold the multicopter's altitude at .

$$\mathbf{p}_{hd} = \mathbf{p}_{hdold}$$

When the pitch/roll control stick is out of the dead zone, the multicopter enters manual control mode $\mathbf{p}_{hd} = \hat{\mathbf{p}}_h$ $\mathbf{v}_{hd} = \mathbf{v}_{hdrc}$

At this time, the pitch/roll channel controls the horizontal position velocity. When the multicopter is in the loiter mode or the altitude-hold mode, i.e., the control sticks all turns back to the midpoint, the multicopter will keep hovering.

Preliminary

In order to make this chapter self-contained, the experiment preliminary is from Chapter. 11 of "**Quan Quan. *Introduction to Multicopter Design and Control*. Springer, Singapore, 2017**"。

Basic Experiment

☐ Experimental Objectives

■ Things to prepare

（**1**）Hardware: Multicopter System, Pixhawk Autopilot System;

（2）Software: MATLAB 2017b and above, Simulink-based Controller Design and Simulation Platform, HIL(Hardware in the loop) Simulation Platform, Experiment Instruction Package “e7.1”（https://flyeval.com/course）.

■ Objectives

(1) On the Simulink-based controller design and simulation platform, repeat the given code and compare the desired attitude with the attitude response during flight in the stabilize mode; Then, record the position when the desired attitude is set to 0; finally, record the position response when the throttle stick is returned to the middle position;

(2) Perform the HIL simulation.

Basic Experiment

□ Simulation procedure

（1） Step1:SIL simulation

1） Parameter Initialization

Run the file “e7/e7.1/SIM/Init_control.m” to initialize the parameters. Next, the file “Stabilize-Control_Sim.slx” will open automatically as shown on the right. To simulate some uncertainties, a constant disturbance has been added to the output of the attitude angle.

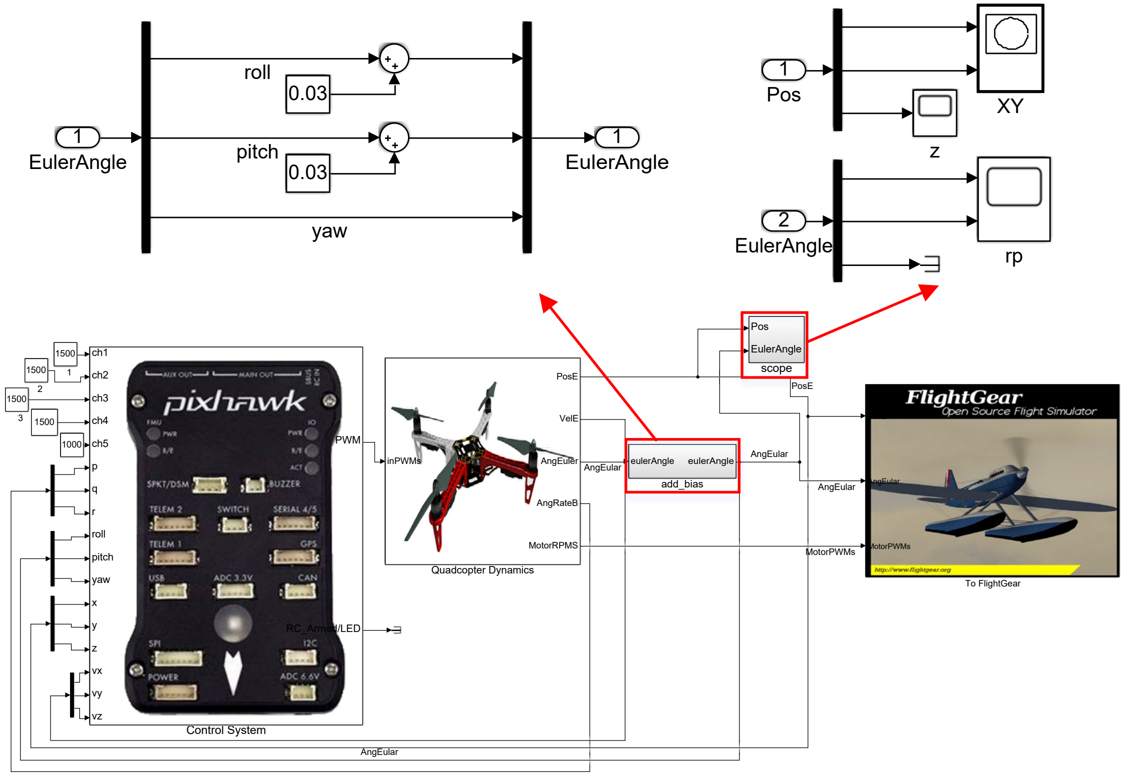


Figure: Simulink file “StabilizeControl_Sim.slx”

In order to observe the output of attitude and position in stabilize mode, set the Scope as shown in the figure to observe the output of attitude and position.

Basic Experiment

□ Simulation procedure

2） Run the simulation and analyze the recorded

experiment results

The desired pitch angle and the roll angle are 0, and the responses of the roll angle and pitch angle are Shown on the right. Because of the added constant disturbance, the initial roll angle is not 0. However, using the attitude controller, the roll/pitch angle approaches the desired roll/pitch angle, finally reaching the desired value.

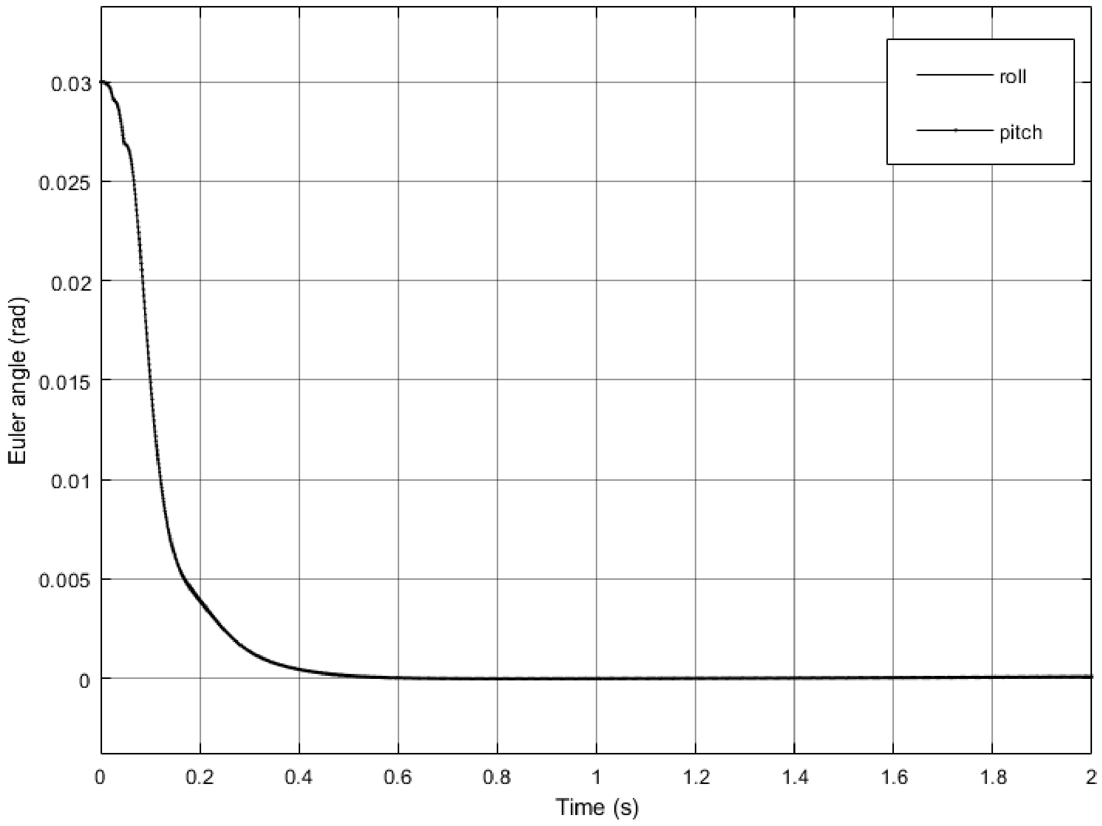


Figure: Response of roll angle and pitch angle

Basic Experiment

Simulation procedure

During the process, a non-zero velocity is generated. It can be observed that the horizontal position drifts because of the disturbance

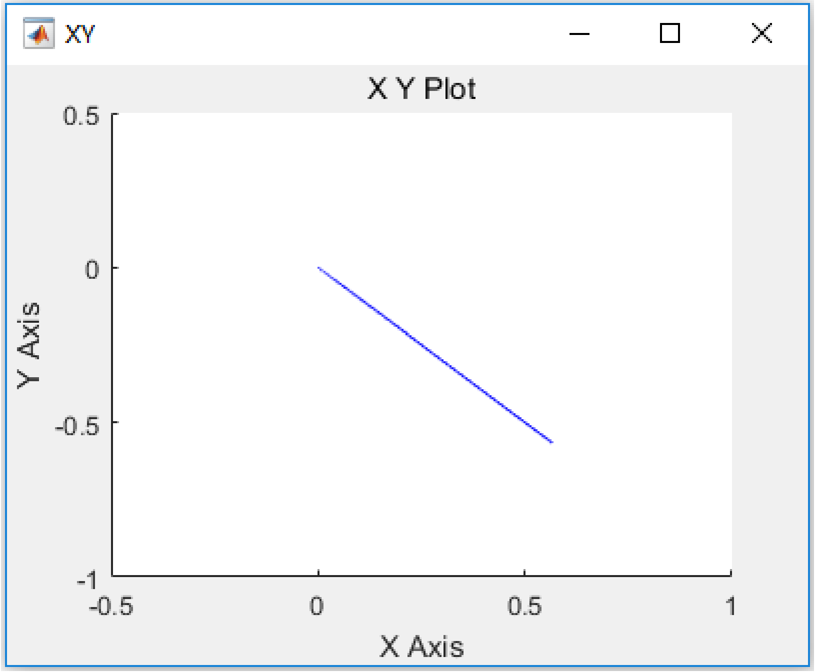


Figure: Horizontal position drifting when control stick in the middle

Basic Experiment

☐ Simulation procedure

In the stabilize mode, the quadcopter can only be stable in attitude and cannot maintain its horizontal position. As for the altitude, it cannot be held either, due to lack of feedback for the altitude.

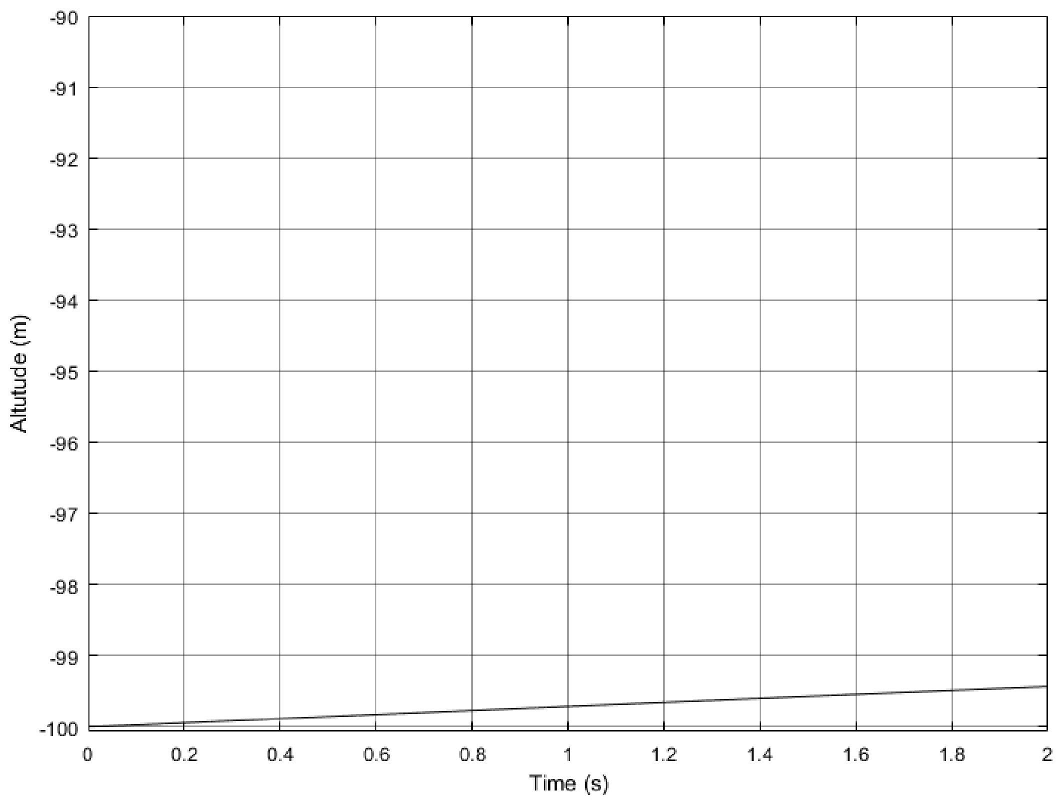


Figure: Altitude response when throttle stick in the middle

Basic Experiment

□ Simulation procedure

（2） Step2: HIL simulation

1） Open Simulink file for HIL

Open the Simulink file“e7/e7.1/HIL/StabilizeControl_HIL.slx”, as shown on the right. It should be noted that “Control System” here is the same as that in the SIL simulation.

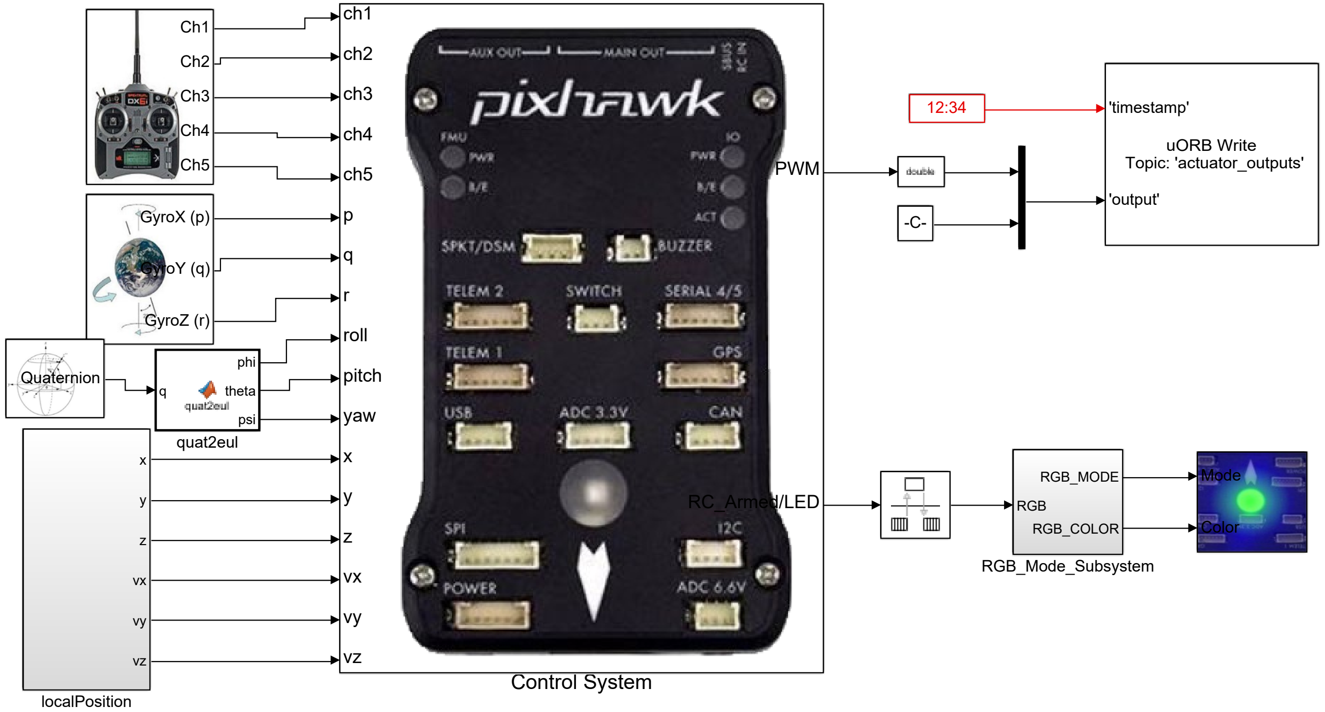


Figure: Simulink model “StabilizeControl_HIL.slx”

◻ Simulation procedure

2） Connect hardware

It should be noted that the airframe type "HIL Quadcopter X" should be selected in HIL simulation.

Figure: Connection between Pixhawk hardware and RC receiver

Basic Experiment

□Simulation procedure

3） Compile and upload code

Compile the HIL simulation model and upload the file to the given Pixhawk autopilot. Later, the designed attitude control program can be run on Pixhawk autopilot.

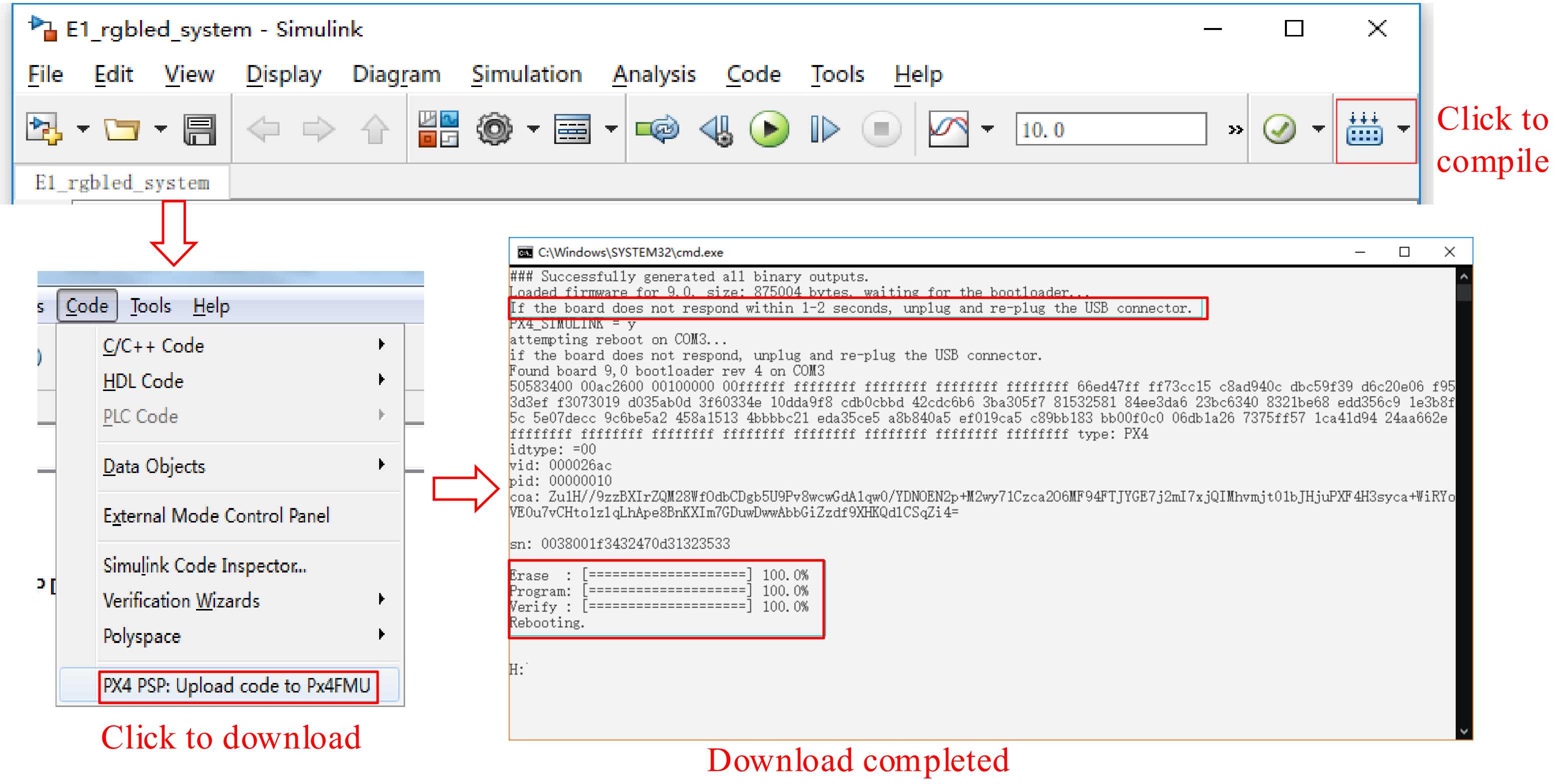


Figure: Code compilation and upload process

Basic Experiment

◻ Simulation procedure

4） Configure CopterSim

Double-click on the desktop shortcut CopterSim to open it. Readers can choose different propulsion systems using the following procedure. Click on “Model Parameters” to customize the model parameters and, then click on “Store and use the parameters” to make them available. The software will automatically match the serial port number. Readers would click the“Run”button to enter the HIL simulation mode. After that, readers could see the message returned by the Pixhawk autopilot in the lower-left corner of the interface.

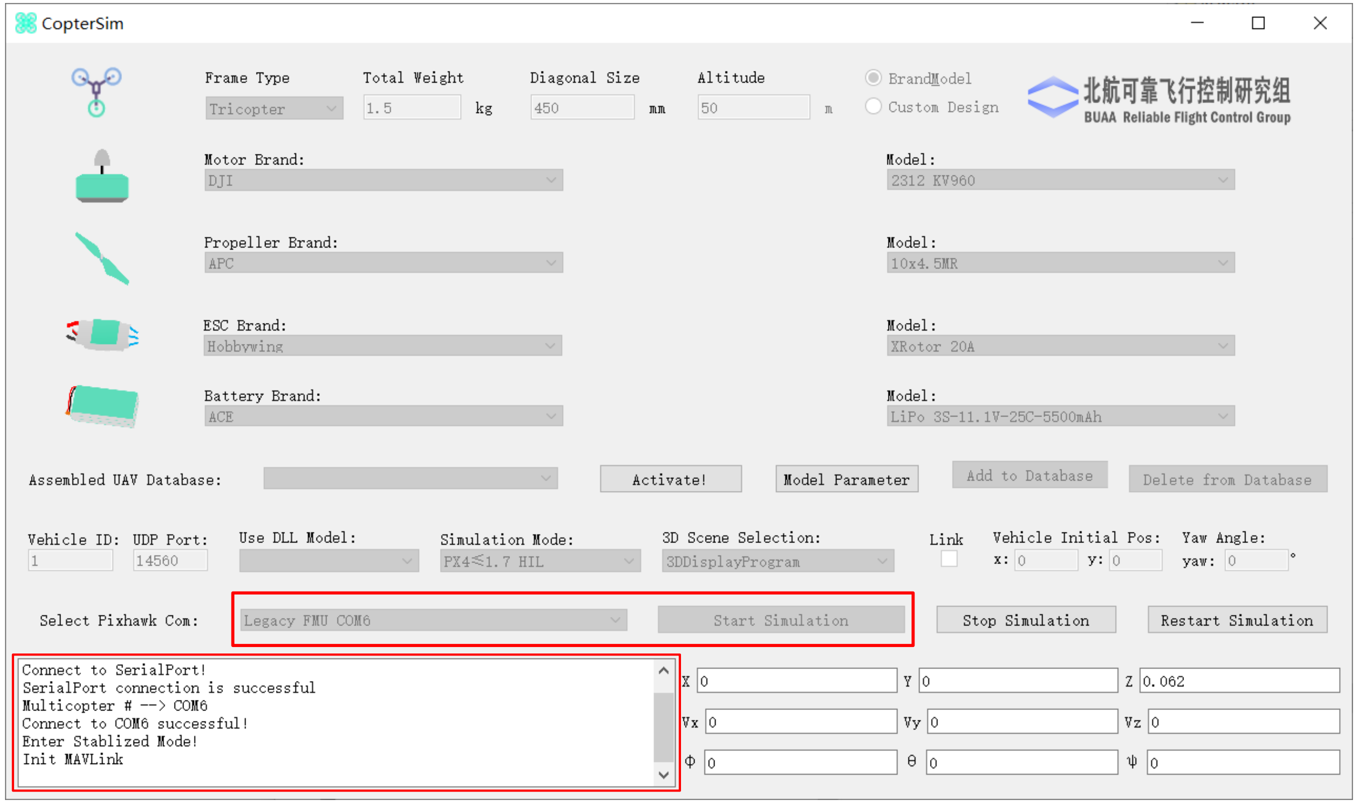


Figure: User interface of CopterSim

Basic Experiment

□Simulation procedure

5）Open 3DDisplay

Double-click on the desktop shortcut 3DDisply to open it.

6）Simulation performance

Arm the quadcopter for manual control using the given RC transmitter1. Given a desired attitude by the remote control, the quadcopter can quickly track the desired attitude.

When all the sticks are in the middle, the attitude is basically horizontal, but the position in the lower right corner of the 3DDisplay software interface is still moving, indicating that the quadcopter is drifting..

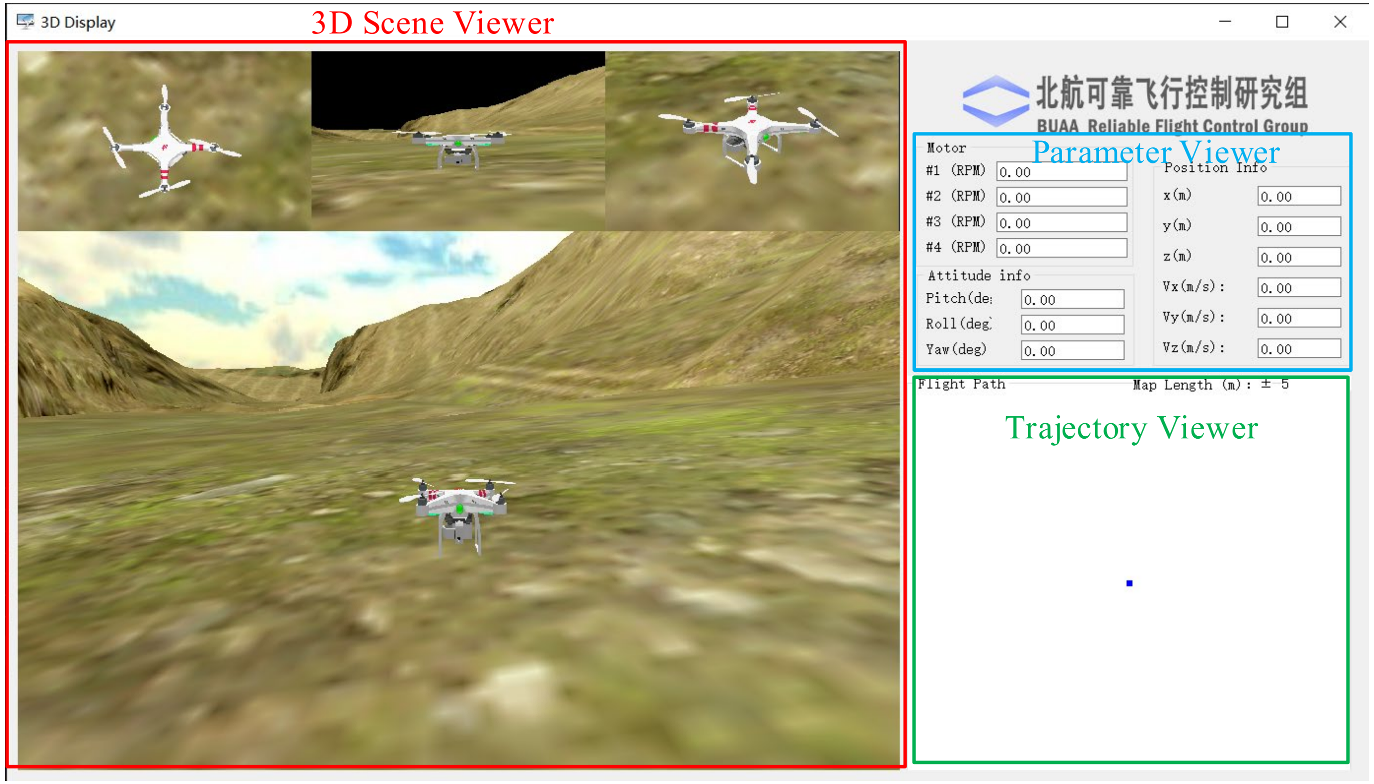


Figure: User interface of 3DDisplay

Analysis Experiment

□ Experiment Objectives

■ **Things to prepare**

（1）Hardware: Multicopter System, Pixhawk Autopilot System;

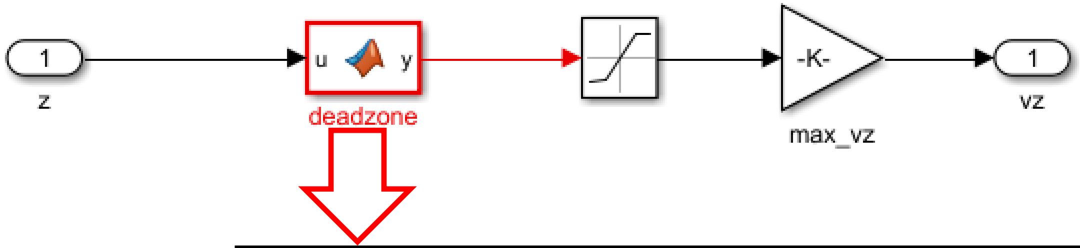
（2）Software: MATLAB 2017b and above, Simulink-based Controller Design and Simulation Platform, HIL Simulation Platform, Experiment Instruction Package “e7.2”（https://flyeval.com/course）.

■ **Objectives**

(1) Design the altitude hold mode based on the stabilize mode. Through the experiment data, compare the attitude and position in the altitude hold mode with those in the stabilize mode;

(2) Perform the HIL simulation.

Analysis Experiment



☐ Simulation procedure

（1） Step1: SIL simulation

1） Add the dead zone to the input signal of RC transmitter

```
function [y] = fcn(u)
RCMin = 1100;
RCMax = 1900;
RCMid = (RCMin+RCMax)/2;
deadZoneRate = 0.05;
deadZone = deadZoneRate*(RCMax-RCMin);
k=1/(RCMax-RCMid-deadZone);
if(u < RCMin)
    u = RCMin;
elseif(u > RCMax)
    u = RCMax;
end
if(u > RCMid+deadZone)
    y = (u-RCMid-deadZone)*k;
 elseif(u < RCMid-deadZone)
    y = (u-RCMid+deadZone)*k;
 else
    y = 0;
 end

 end
```

If the input "u" is a ramp signal whose range is [1000, 2000], after normalization, the range of the output signal amplitude is [-1,1].

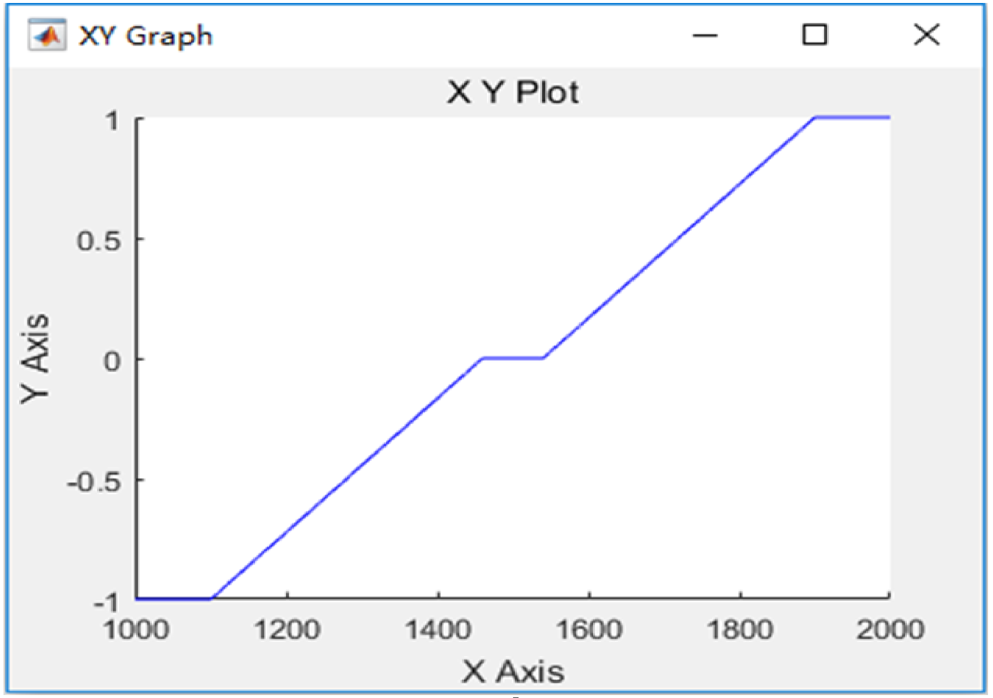


Figure: Relationship of RC transmitter's input and output

Analysis Experiment

□ Simulation procedure

2）Determine the desired position

When the throttle control stick deviates from the middle position, i.e., out of the dead zone range, the desired altitude is changed to be the current altitude. With such a desired altitude, the altitude feedback does not work anymore because the altitude error is always zero. Only altitude velocity feedback works for the altitude controller. On the other hand, when the throttle control stick is within the middle dead zone range, i.e., within the dead zone, the desired altitude is the altitude at the moment. When the control stick just returned back to the dead zone. If the control stick is always in the middle position, the desired altitude remains the same.

```
function [vx_d,vy_d,vz_d,x_d,y_d,z_d] = fcn(vzd,x,y,z,vx,vy,vz)
persistent z1;
if isempty(z1)
   z1=z;
end
persistent hold_z_flag;
if isempty(hold_z_flag)
   hold_z_flag=0;
end

if abs(vzd)<0.001&&abs(vz)<6
   hold_z=1;
else
   hold_z=0;
   hold_z_flag = 0;
end
if (hold_z>0.5)&&(hold_z_flag<0.5)
   z1=z;
   hold_z_flag=1;
end
if hold_z<0.5
   z1=z;
   hold_z_flag = 0;
end
x_d=x;y_d=y;z_d=z1;
vx_d=vx;vy_d=vy;vz_d=vzd;
```

Analysis Experiment

□ Simulation procedure

3）Realize the controller for the altitude hold mode

Add the dead zone module and the desired position module designed in the previous two steps to the controller. Besides, change the input of mode type from 0 to 1, indicating that the altitude hold mode is available,

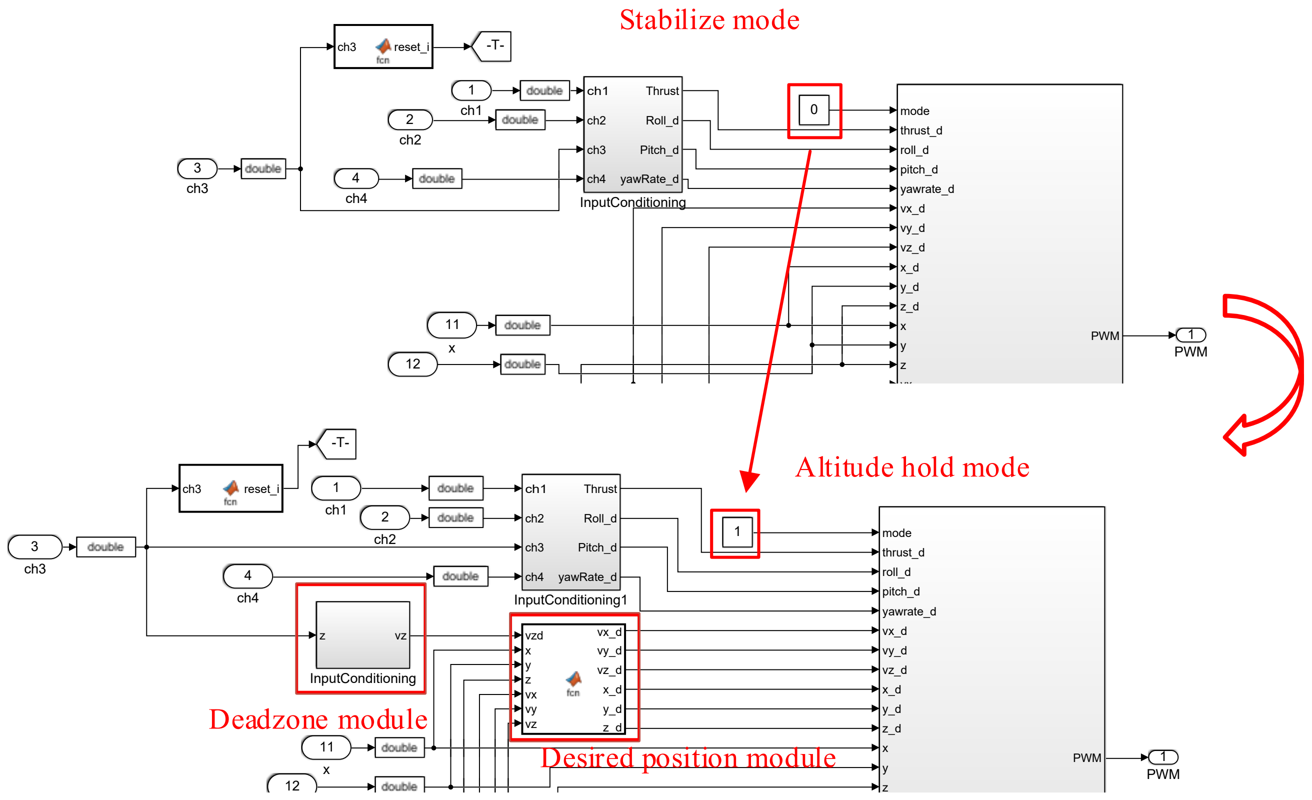


Figure: Difference between stabilize mode and altitude hold mode

Analysis Experiment

□ Simulation procedure

4） Run the simulation and analyze the test results

The attitude and horizontal position response are the same as that in the stabilize mode which means that the attitude can remain stable, whereas the horizontal position cannot remain stable,

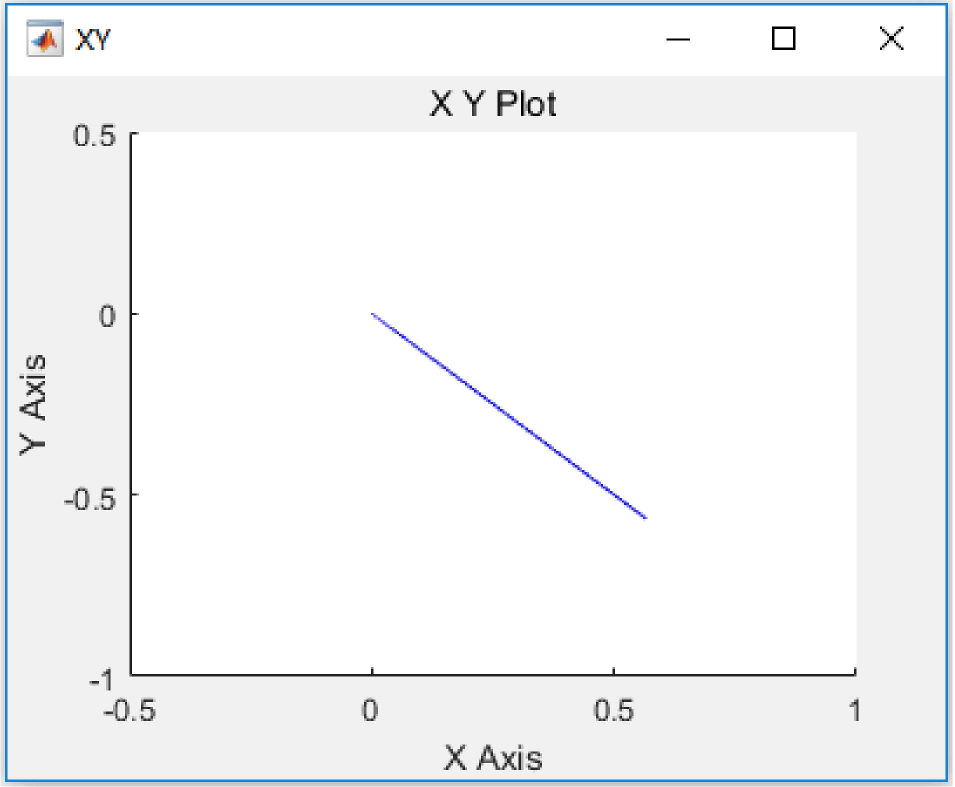


Figure: Position response in altitude hold mode

Analysis Experiment

□ Simulation procedure

4） Run the simulation and analyze the test results

When the altitude input is between 1460 and 1540, meaning the throttle control stick is within middle dead zone range.

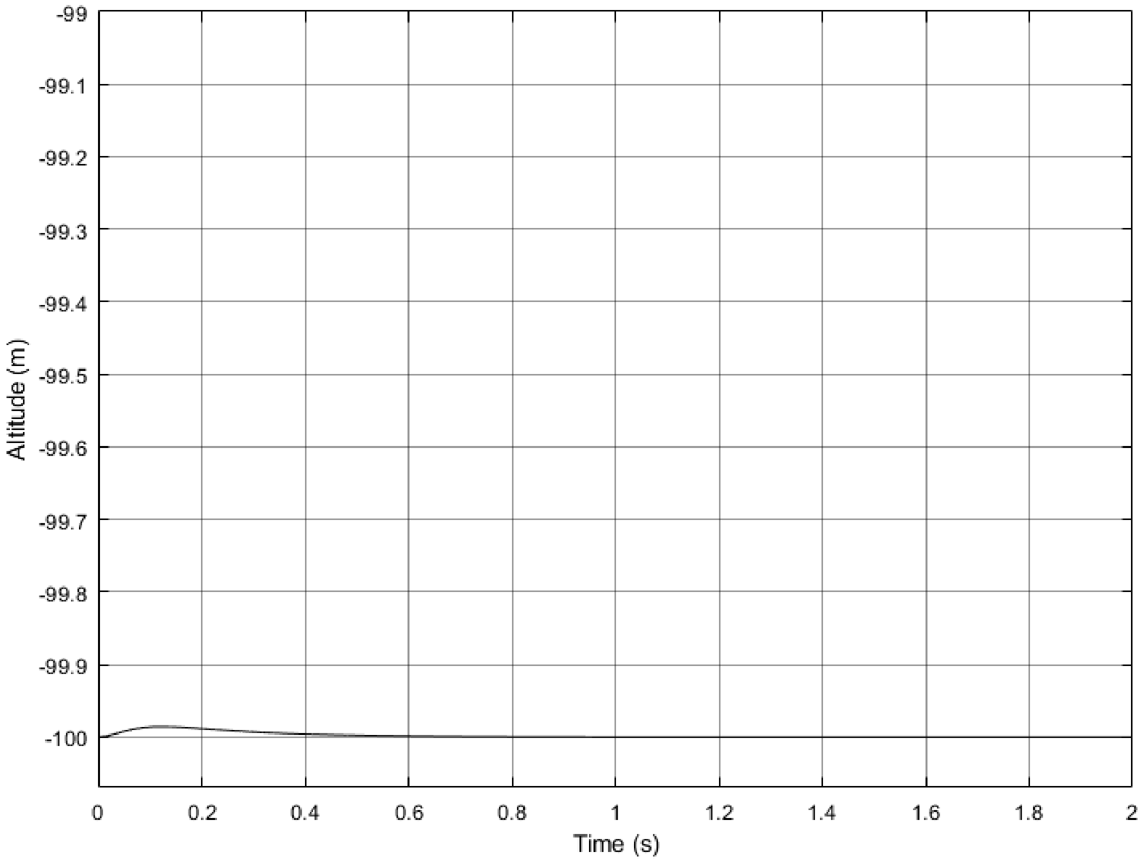


Figure: Altitude response when throttle control stick is in dead zone

Analysis Experiment

□ Simulation procedure

4） Run the simulation and analyze the test results

When the throttle exceeds the dead zone, such as the throttle input is 1600, the altitude velocity follows the desired velocity steadily while the altitude continues to increase.

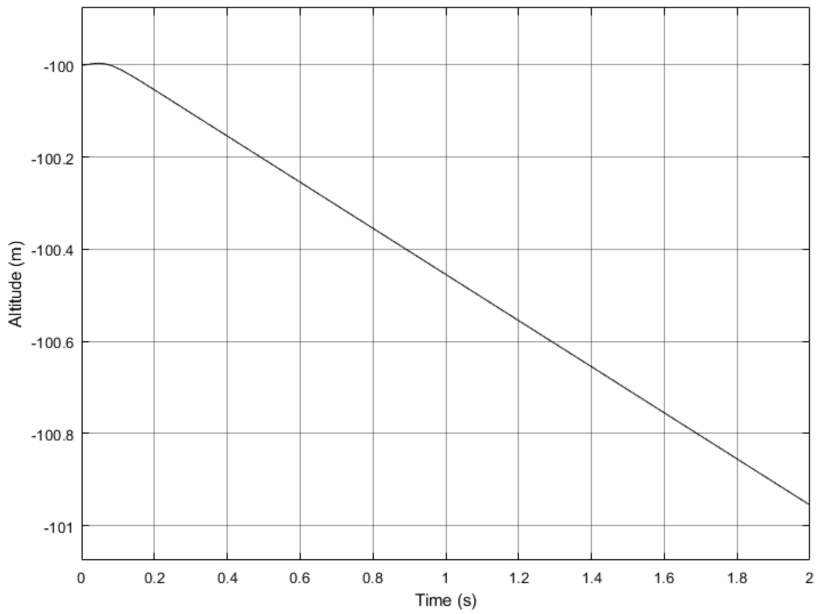


Figure: Altitude response when the PWM value of “ch3” is 1600

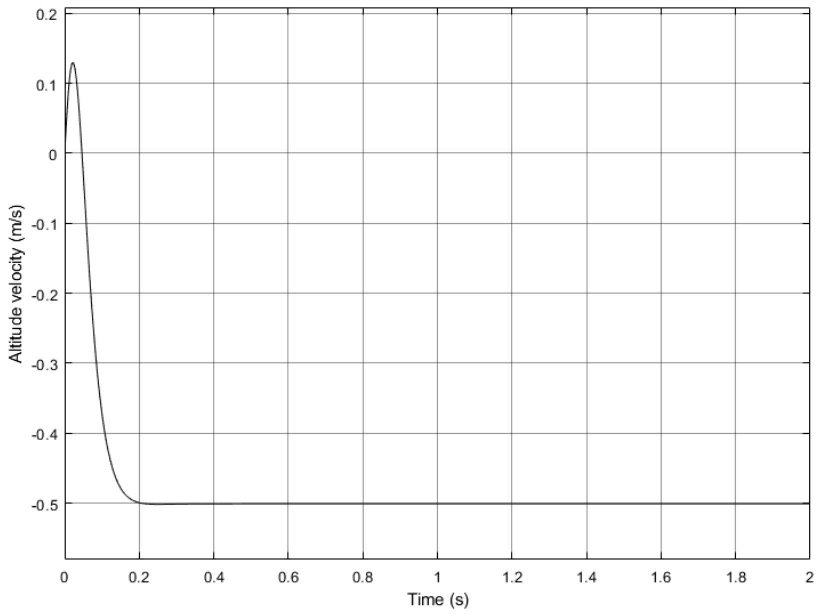


Figure: Altitude velocity response when PWM value of “ch3” is 1600

Analysis Experiment

□ Simulation procedure

（2） Step2: HIL simulation

1） Open the Simulink file for HIL

Open the file "e7/e7.2/HIL/HeightControlHIL.slx". It should be noted that "Control System" in the attitude hold mode SIL simulation is the same as that in the HIL simulation.

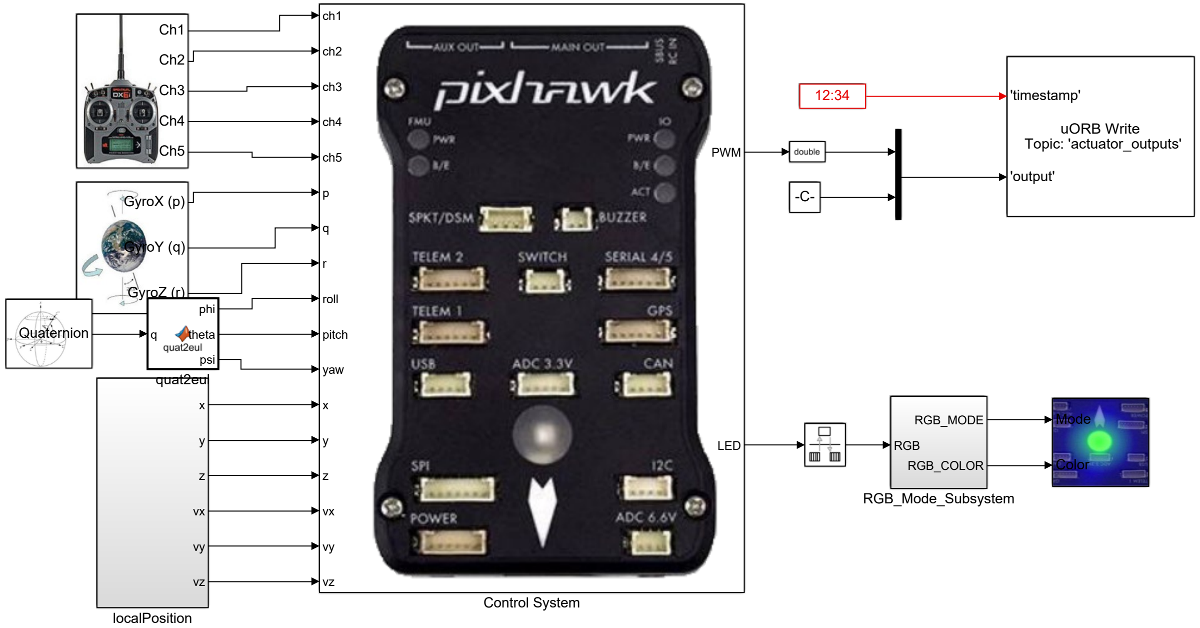


Figure: Simulink file "HeightControl_HIL.slx"

Analysis Experiment

◻ Simulation procedure

2）Connect hardware

It should be noted that the airframe type "HIL Quadcopter X" should be selected in HIL simulation.

Figure: Connection between Pixhawk hardware and RC receiver

Analysis Experiment

□Simulation procedure

3）Compile and upload code

Compile the HIL simulation model and upload the file to the given Pixhawk autopilot. Later, the designed attitude control program can be run on Pixhawk autopilot.

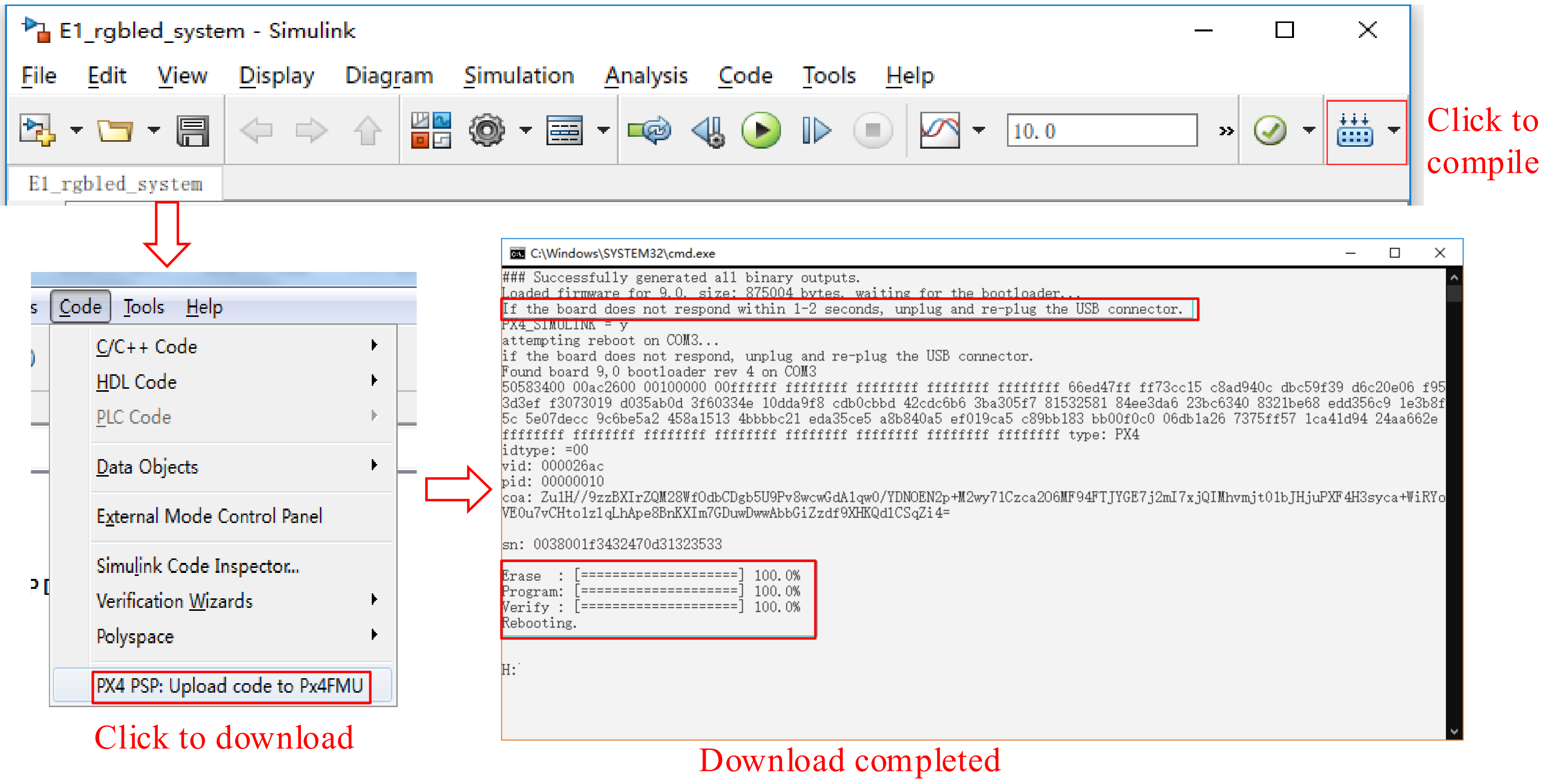


Figure: Code compilation and upload process

Analysis Experiment

□ Simulation procedure

4） Configure CopterSim

Double-click on the desktop shortcut CopterSim to open it. Readers can choose different propulsion systems using the following procedure. Click on “Model Parameters” to customize the model parameters and, then click on “Store and use the parameters” to make them available. The software will automatically match the serial port number. Readers would click the“Run”button to enter the HIL simulation mode. After that, readers could see the message returned by the Pixhawk autopilot in the lower-left corner of the interface.

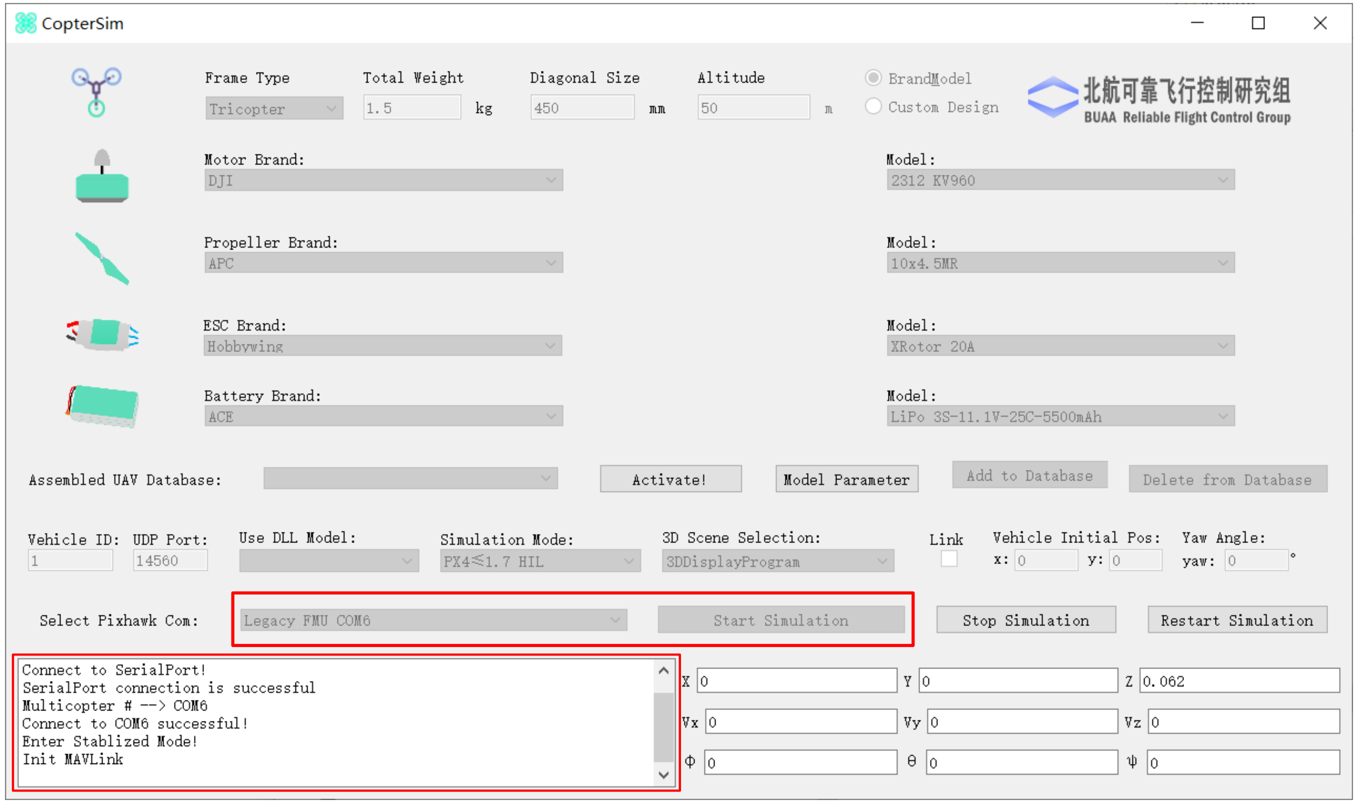


Figure: User interface of CopterSim

Analysis Experiment

□Simulation procedure

5） Open 3DDisplay

Double-click on the desktop shortcut 3DDisply to open it.

6） Simulation performance

Arm the quadcopter for manual control using the given RC transmitter. Given a desired attitude by the remote control, the quadcopter can quickly track the desired attitude. When all the sticks are in the middle, the attitude is basically horizontal, but the position in the lower right corner of the 3DDisplay software interface is still moving, indicating that the quadcopter is drifting.

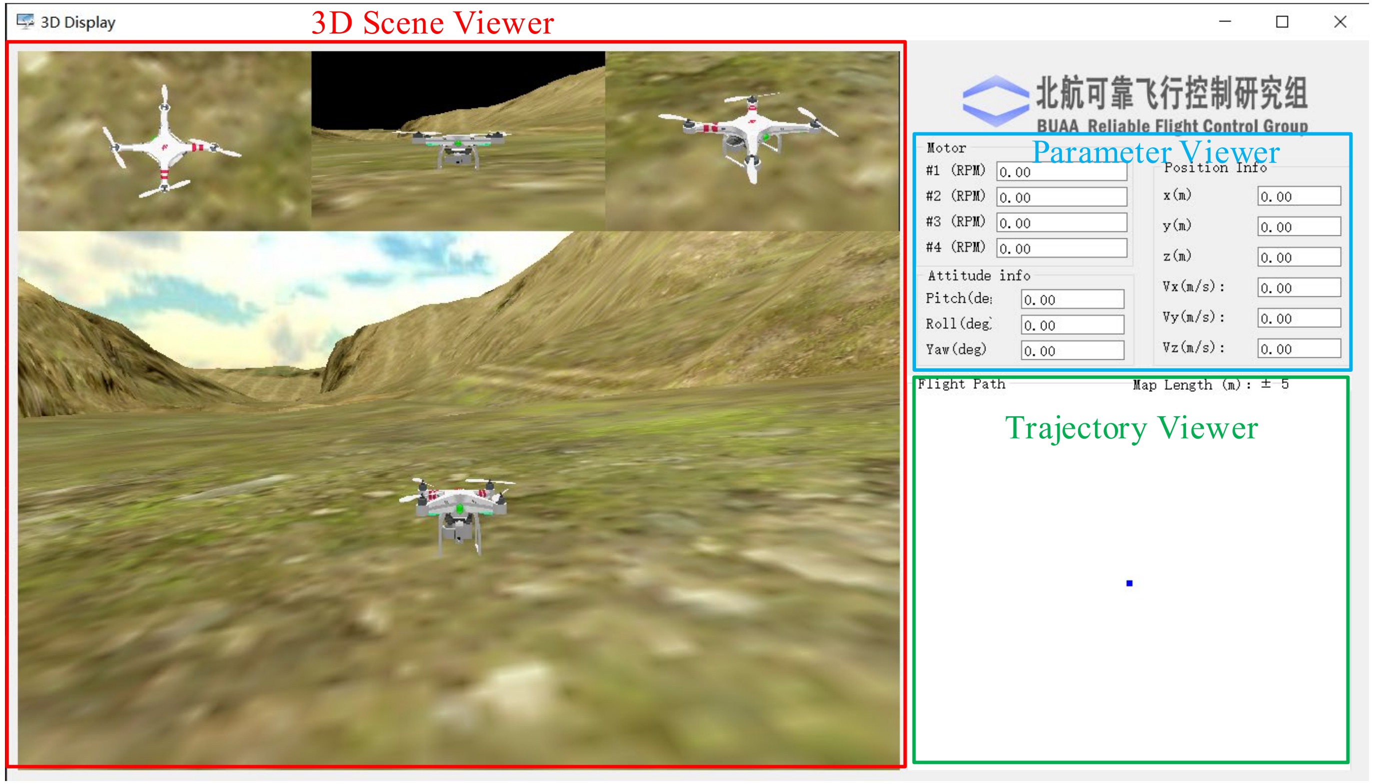


Figure: User interface of 3DDisplay

Design Experiment

□ Experiment Objectives

■ **Things to prepare**

(1) Hardware: Multicopter Hardware System, Pixhawk Autopilot System;

(2) Software: MATLAB 2017b and above, Simulink-based Controller Design and Simulation Platform, HIL Simulation Platform, Experiment Instruction Package “e7.3” (https://flyeval.com/course)

■ **Objectives**

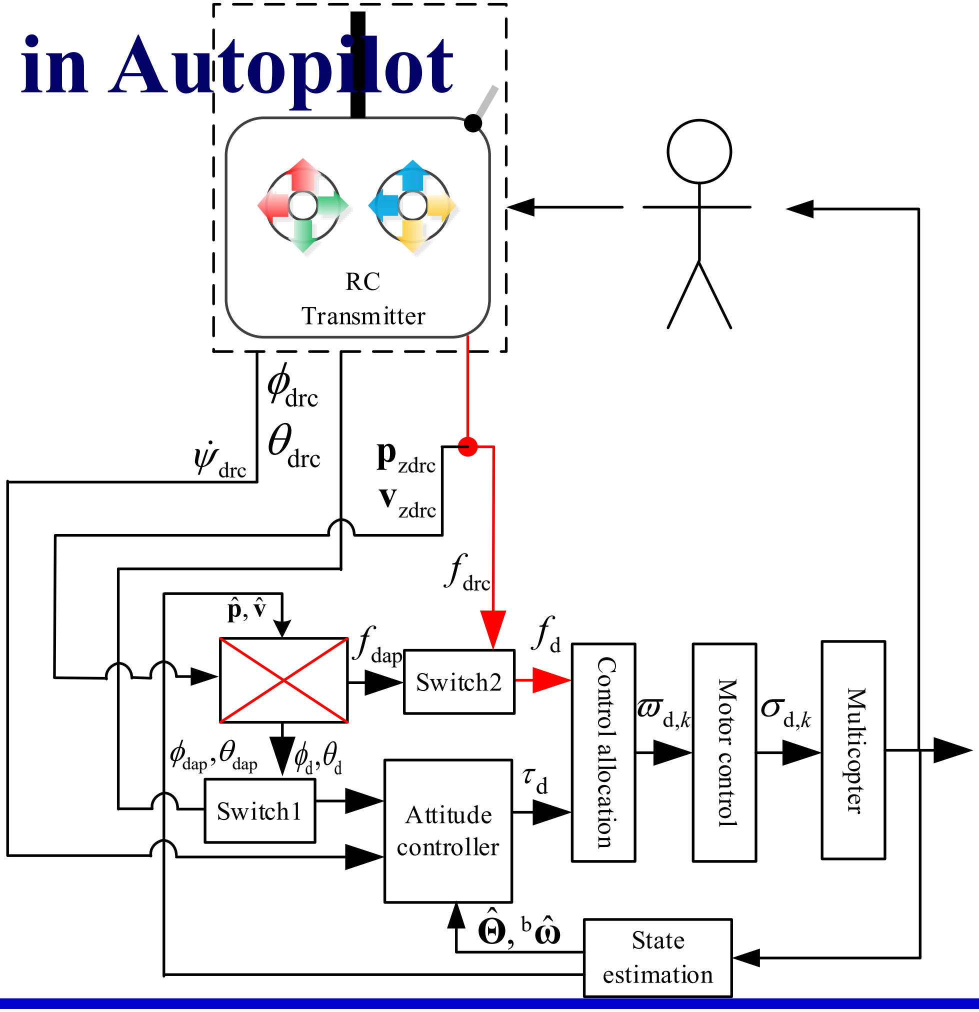
(1) Design and realize the loiter mode based on the stabilize mode. Through the experimental data, compare the attitude and position in the loiter mode with those in the stabilize mode.

(2) Realize switching among three modes by the three-position switch. Then, perform the HIL simulation and flight test.

Design Experiment

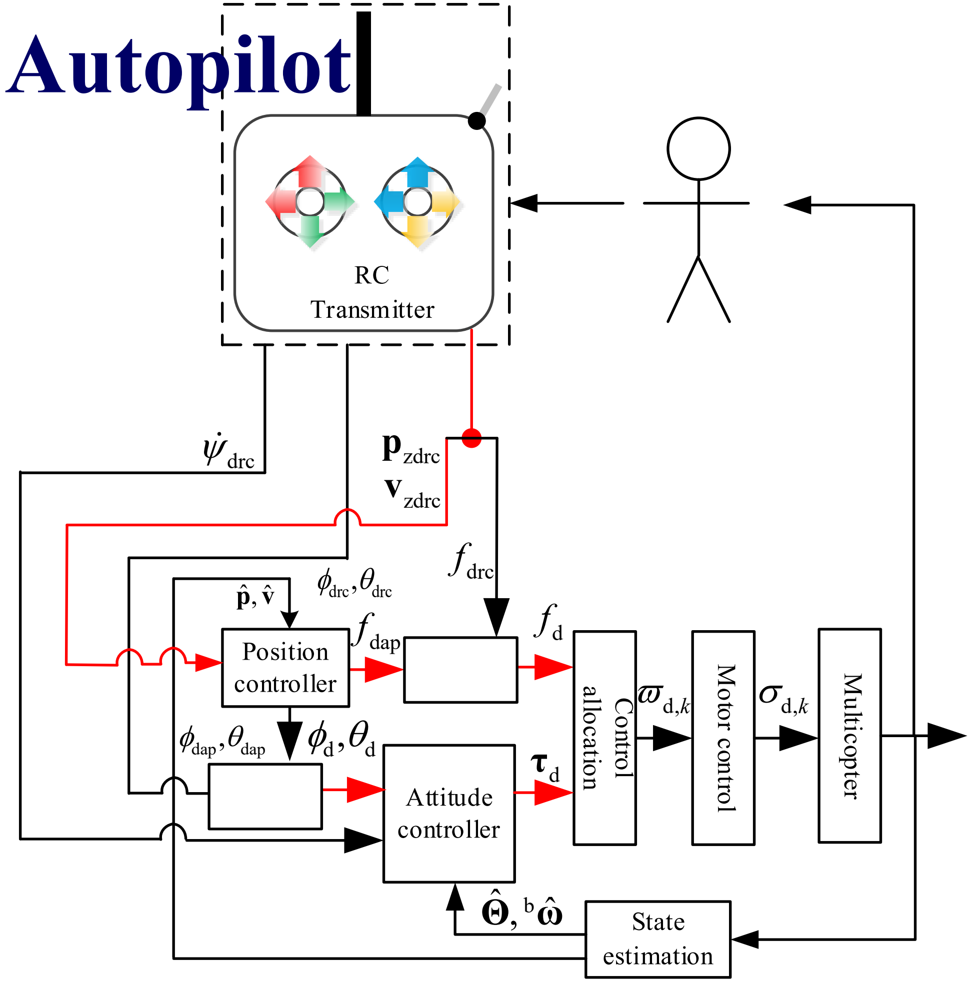
◻ The Realization of three modes in Autopilot

Stabilize mode: Through “Switch1”, $\theta_{\mathrm{drc}}, \phi_{\mathrm{drc}}$ are selected as the desired attitude angles (the expected yaw angle is the same in all three modes); through “Switch2”, f_{drc} is selected as the desired throttle.



Design Experiment

◻ The Realization of three modes in Autopilot



Altitude-hold mode: In the altitude hold mode, through "Switch1", $\theta_{\mathrm{drc}},\phi_{\mathrm{drc}}$ are selected as the desired attitude angles; and through "Switch2", f_{dap} is selected

as the desired throttle,

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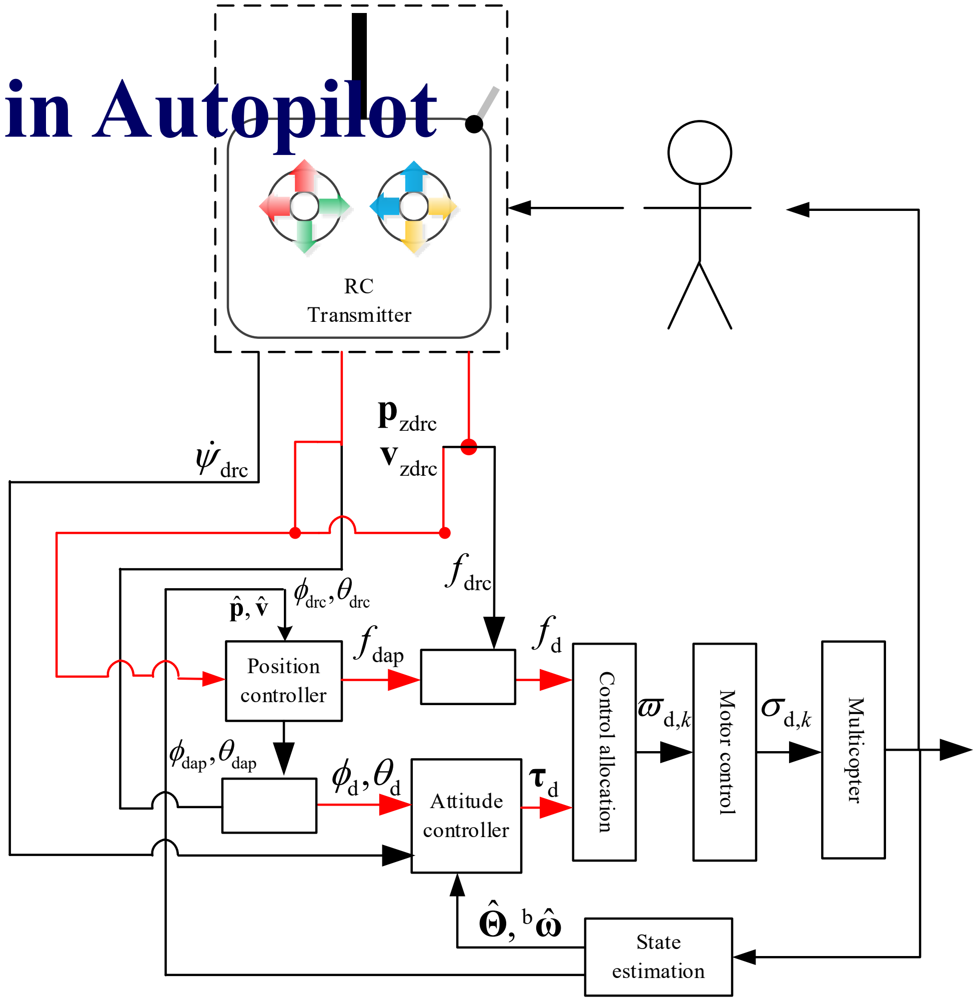
□ The Realization of three modes in Autopilot

Loiter mode: $\theta_{\mathrm{dap}}, \phi_{\mathrm{dap}}$ are selected as the desired attitude angle through "Switch1"; and f_{dap} is selected as the desired throttle through "Switch2",



Design Experiment

☐ Simulation Procedure

（1） Step1. SIL Simulation

1） Design dead zone for loiter mode

The dead zone configuration for the loiter mode is the same as that for the altitude hold mode. If the input of “u” is a ramp signal, whose range is within [1000,2000], while the input signal is normalized at the same time, the range of the output signal amplitude is within [-1, 1].

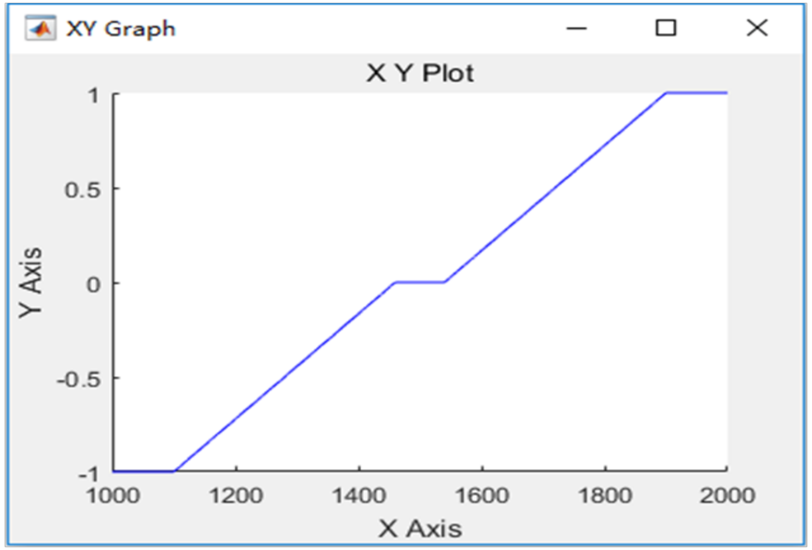


Figure: response of the RC signals

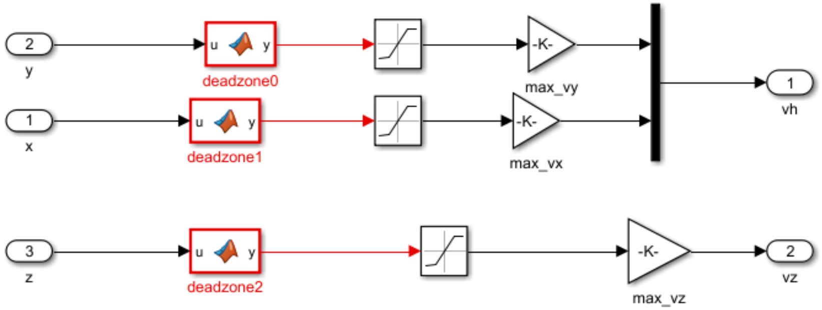


Figure: Dead zone configuration for loiter mode

Design Experiment

□ Simulation Procedure

2） Determine the desired horizontal position

When the RC sticks (CH1,CH2 or CH3) deviates from the middle dead zone range, the desired position for AC is always the current position. As a result, the position feedback of AC does not work. There is only desired velocity by RC, which is calculated and then transmitted to the AC controller. When the RC stick (CH1,CH2 or CH3) is in the middle, the desired position is the position at the moment when the stick comes back to the middle. If the control stick is always in the middle, the desired position remains the same.

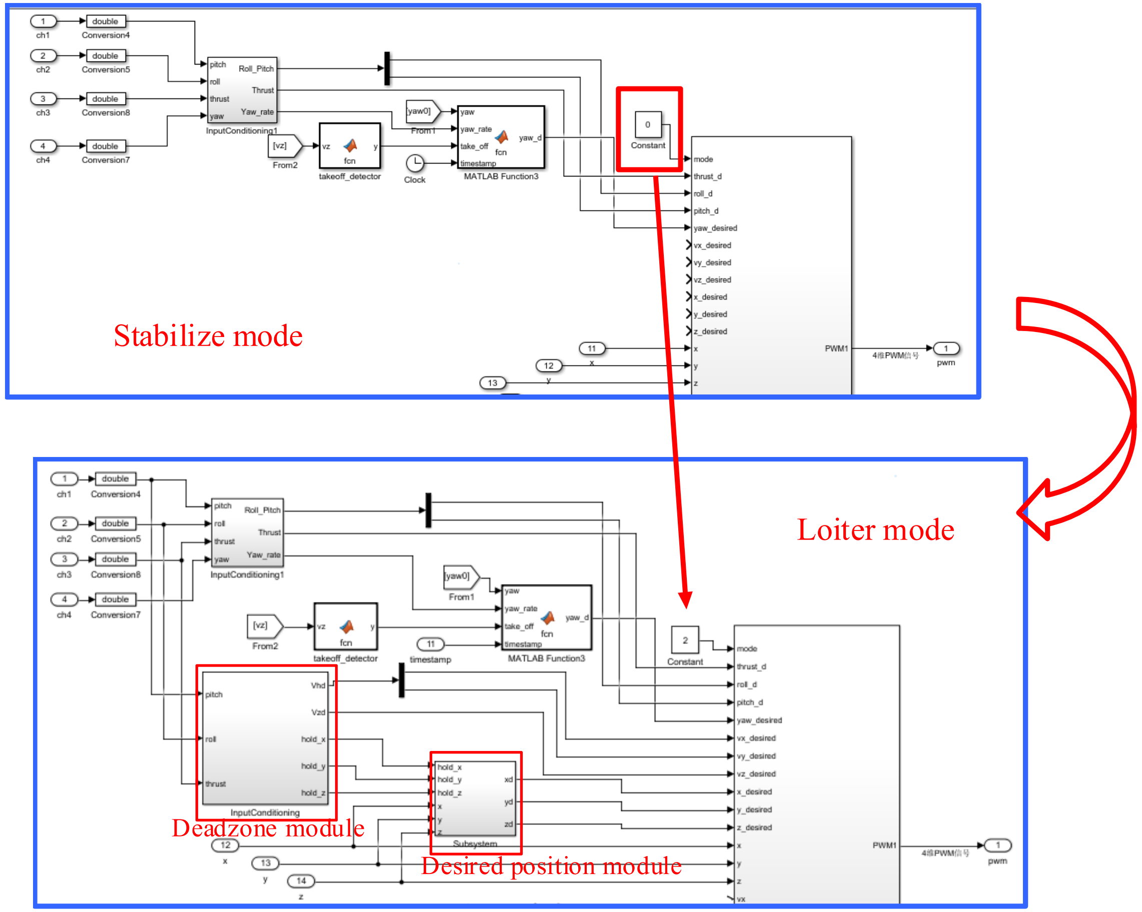
```
function [vx_d,vy_d,vz_d,x_d,y_d,z_d]  = fcn(vxd,vyd,vzd,x,y,z,vx,vy,vz)
persistent x1;
if isempty(x1)
   x1=0;
end
…
persistent hold_x_flag;
if isempty(hold_x_flag)
   hold_x_flag=0;
end
…
if abs(vxd)<0.001&&abs(vx)<8 %
   hold_x=1;
else
   hold_x=0;
end

if (hold_x>0.5)&&(hold_x_flag<0.5
   x1=x;
   hold_x_flag=1;
end

if hold_x<0.5%
   x1=x;
   hold_x_flag = 0;
end
x_d=x1;y_d=y1;z_d=z1;
vx_d=vxd;vy_d=vyd;vz_d=vzd;
```

Design Experiment

◻ Simulation Procedure

3） Write a position control model

Add the dead zone and the position controller designed before in the model of stabilize model.



Design Experiment

☐ Simulation Procedure

4） Run the simulation and analyze test results

The altitude response is the same as that in the altitude hold mode, which means that the altitude can remain stable.

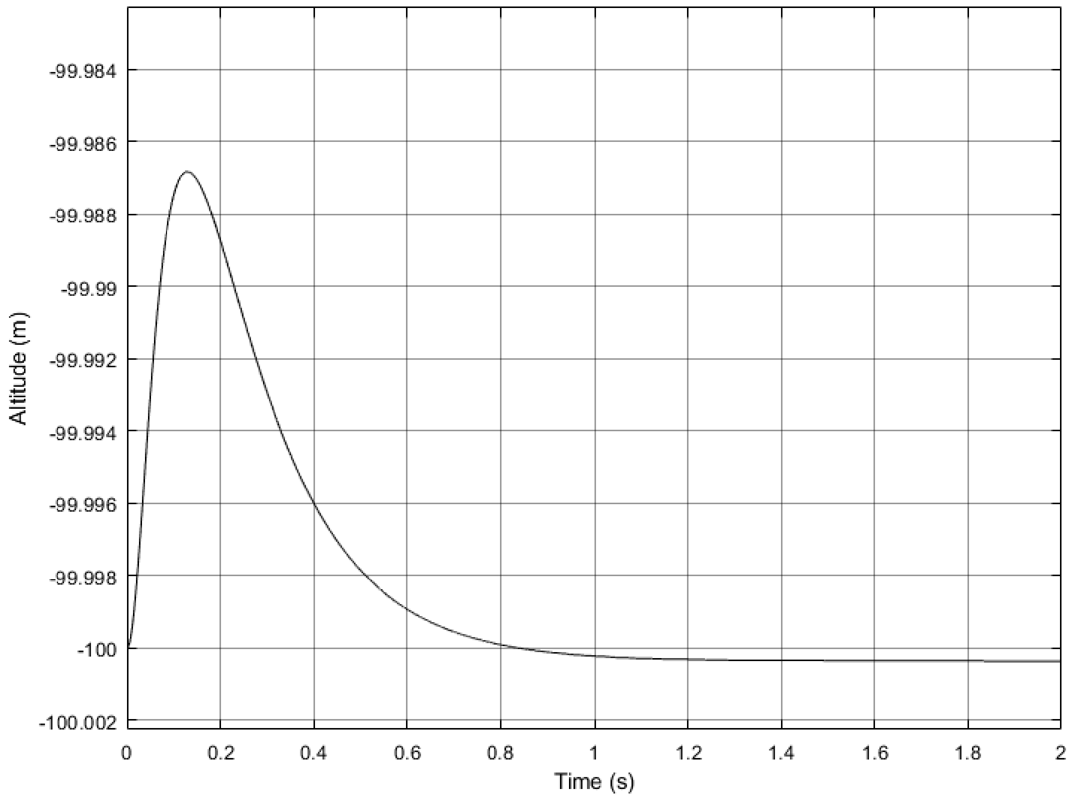


Figure: Altitude response when the throttle control

Design Experiment

Simulation Procedure

4） Run the simulation and analyze test results

When the values of the “ch1” and “ch2”(corresponding to CH1 and CH2 of the RC transmitter) are between 1460 and 1540 for the roll and pitch channels , It can be observed that, in the presence of the fixed disturbance on the roll and pitch channels, the disturbance is well rejected in the loiter mode.

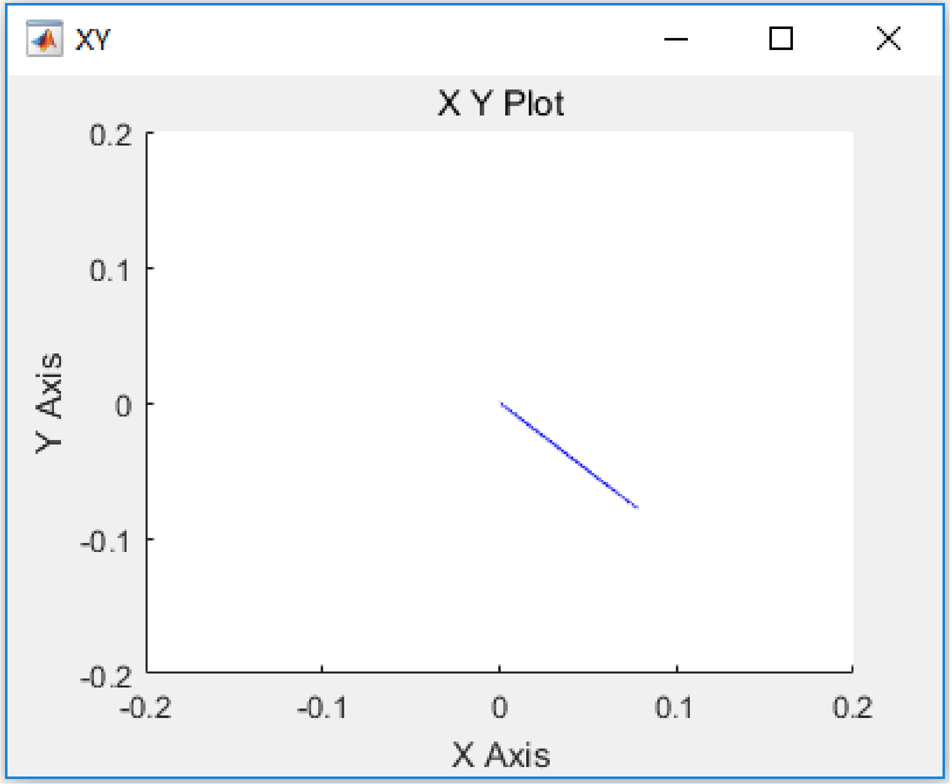


Figure: Horizontal position response when pitch and roll sticks are in the middle

Design Experiment

4） Run the simulation and analyze test results

When the value of “ch2” is 1600 for the pitch channel, the observed velocity along the $o_e x_e$ axis can follow the desired velocity steadily.

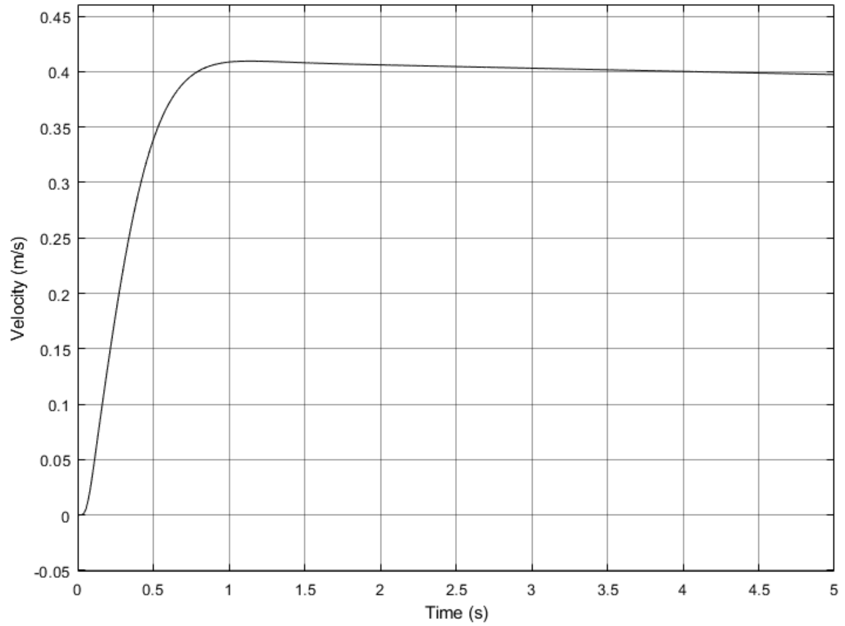


Figure: Velocity response along the $o_e x_e$ axis when PWM value of “ch2” is 1600

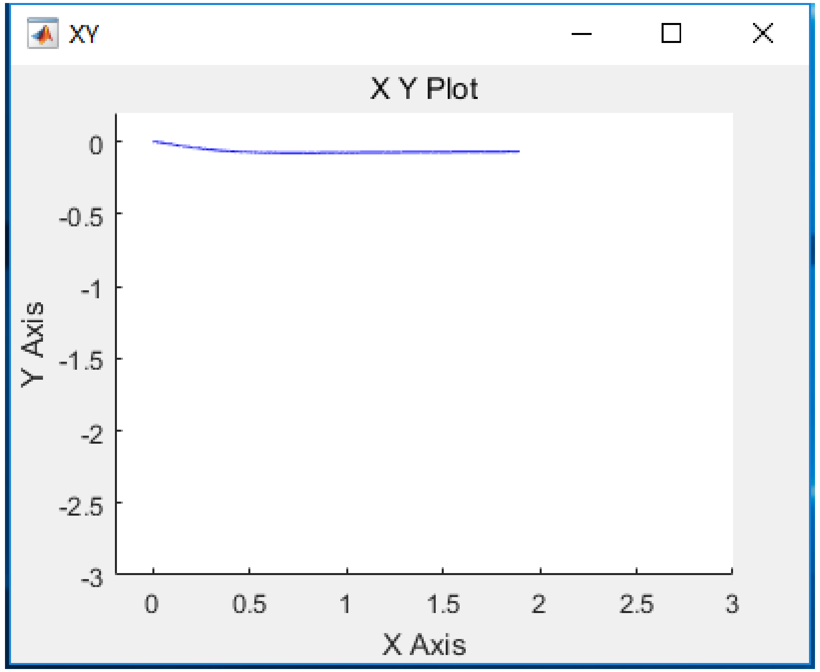


Figure: Horizontal position response when PWM Value of “ch2” is 1600

Design Experiment

□ Simulation Procedure

（2）Step2: HIL simulation

1）Open Simulink file for HIL

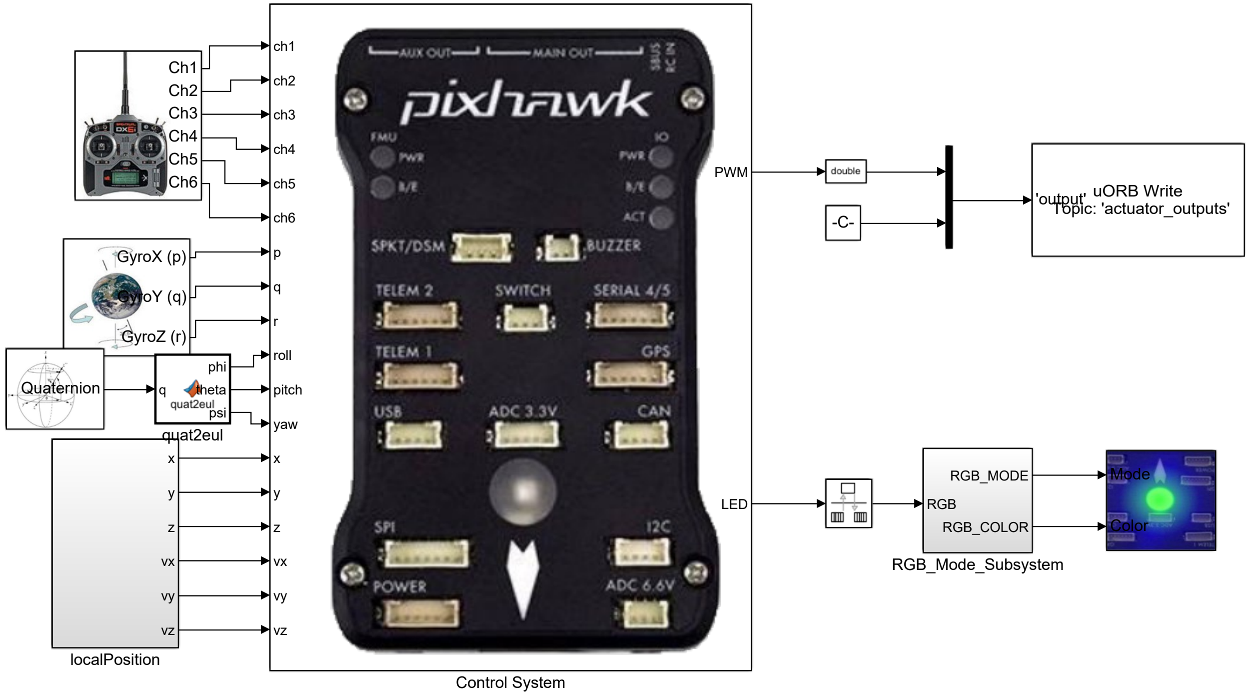


图. ModeSwitch_HIL.slx截图

Open the Simulink file "e7/e7.3/HIL/ModeSwitch_HIL.slx".

Design Experiment

☐ Simulation procedure

2）Connect hardware

It should be noted that the airframe type "HIL Quadcopter X" should be selected in HIL simulation.

Figure: Connection between Pixhawk hardware and RC receiver

Design Experiment

◻Simulation procedure

3）Compile and upload code

Compile the HIL simulation model and upload the file to the given Pixhawk autopilot. Later, the designed attitude control program can be run on Pixhawk autopilot.

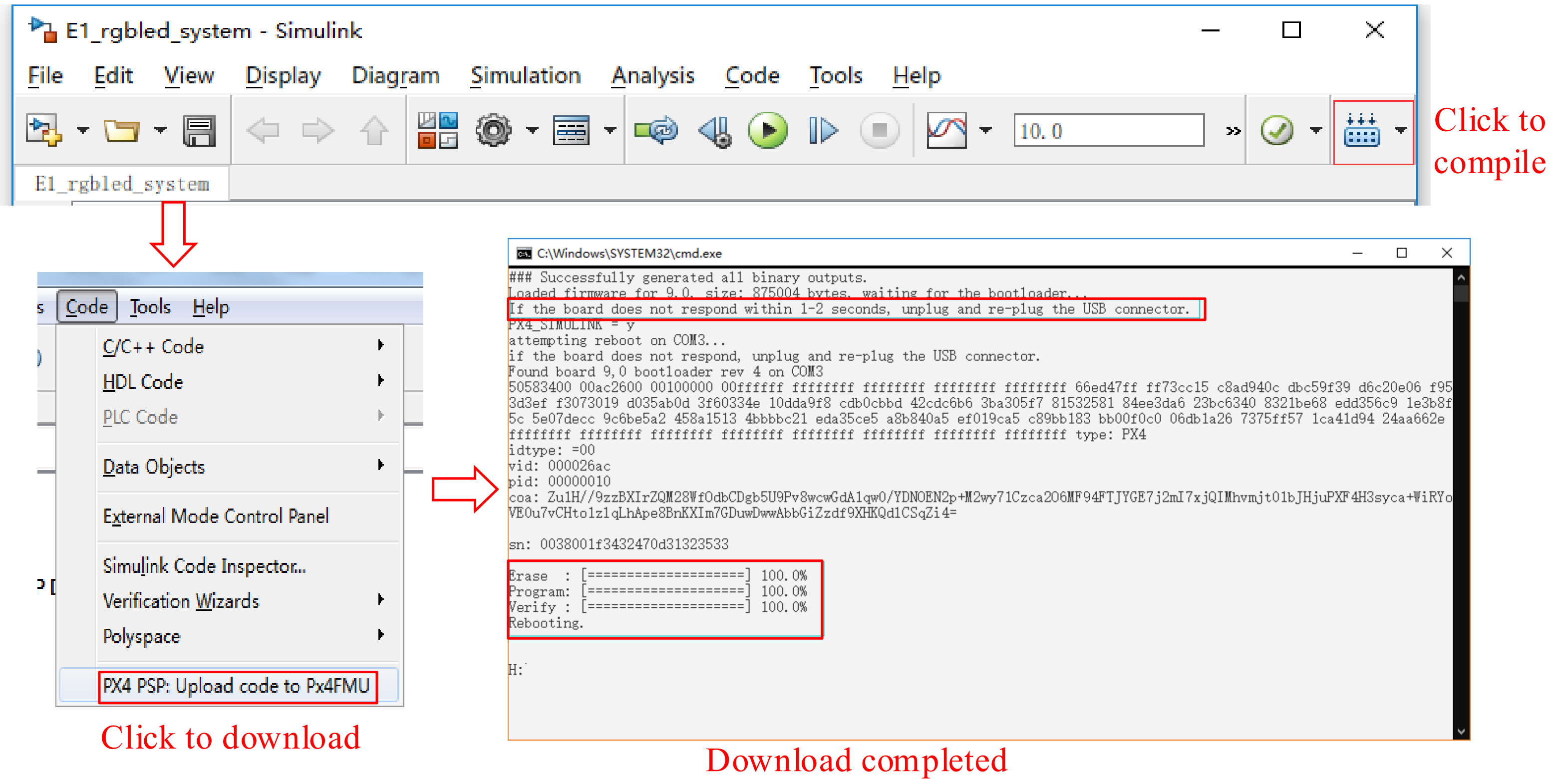


Figure: Code compilation and upload process

Design Experiment

☐ Simulation procedure

4） Configure CopterSim

Double-click on the desktop shortcut CopterSim to open it. Readers can choose different propulsion systems using the following procedure. Click on “Model Parameters” to customize the model parameters and, then click on “Store and use the parameters” to make them available. The software will automatically match the serial port number. Readers would click the“Run”button to enter the HIL simulation mode. After that, readers could see the message returned by the Pixhawk autopilot in the lower-left corner of the interface.

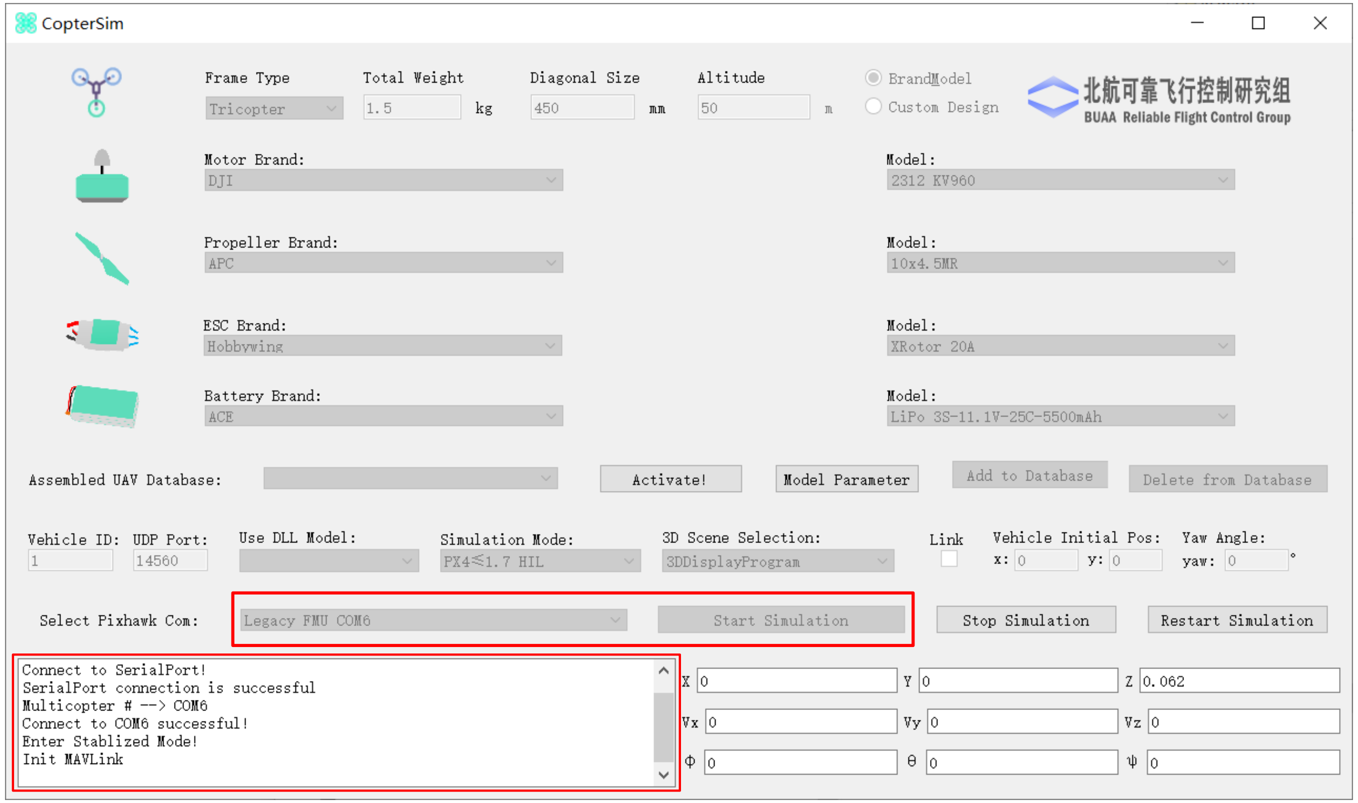


Figure: User interface of CopterSim

Design Experiment

□Simulation procedure

5）Open 3DDisplay

Double-click on the desktop shortcut 3DDisply to open it.

6）Simulation performance

Arm the quadcopter for manual control. Rotate the left-upper switch corresponding to CH5 for mode switching. When the the quadcopter is in the stabilize mode, the response of it is the same asthat in the basic experiment; when it is toggled to the altitude hold mode, the performance is the same as that in the design experiment; when it is toggled to the loiter mode and all the stickers return to the center, the quadcopter stay in the air after adjusting.

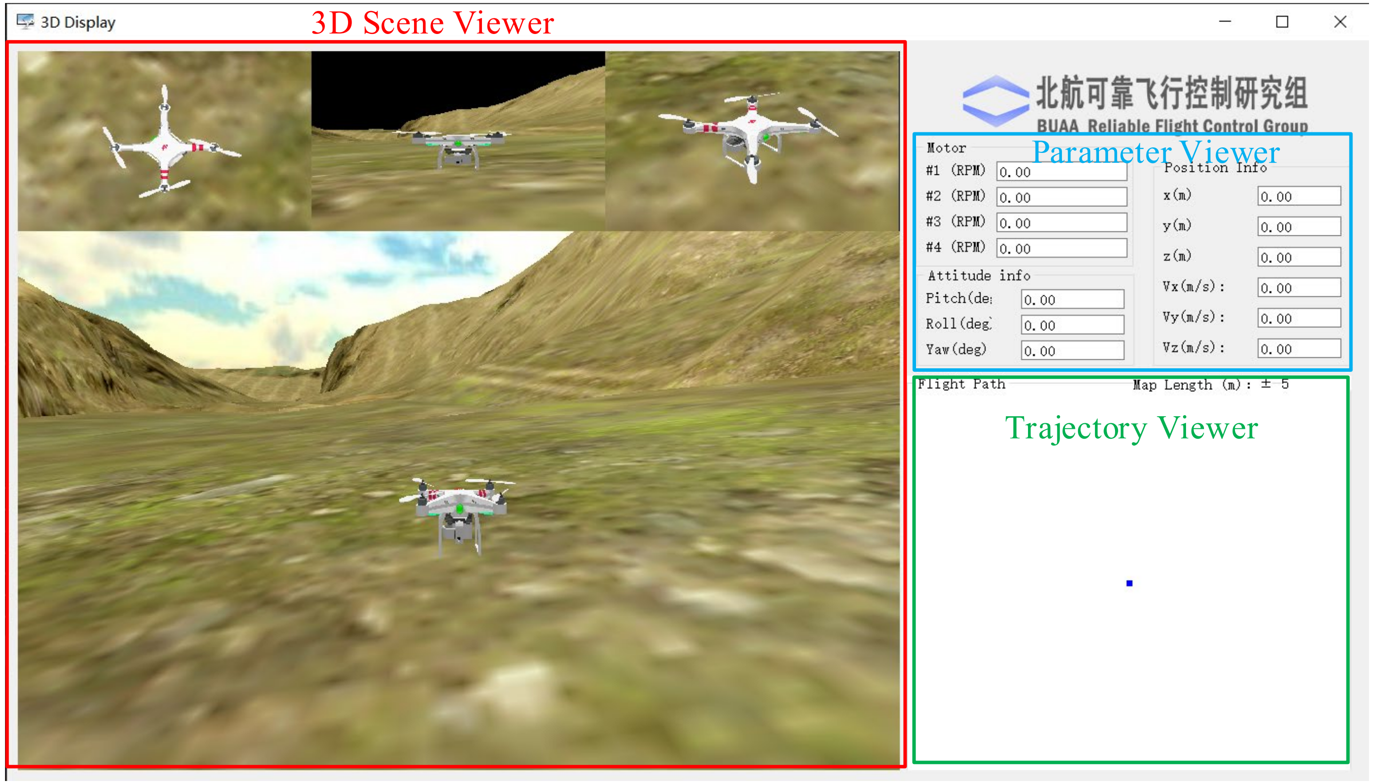


Figure: User interface of 3DDisplay

Design Experiment

□ Flight Test Procedure

（1） Step1: Quadcopter configuration

The multicopter used in the outdoor flight tests is an F450 quadcopter For outdoor flight tests, the airframe of Pixhawk should be changed from “HIL Quadcopter X” to “DJI Flame Wheel F450” in QGC and all sensors should also be calibrated in QGC.

Figure: F450 airframe schematic

Design Experiment

□Flight Test Procedure

（2） Step2: Simulink model for flight test

Replace the PWM output part in HIL Simulink module.

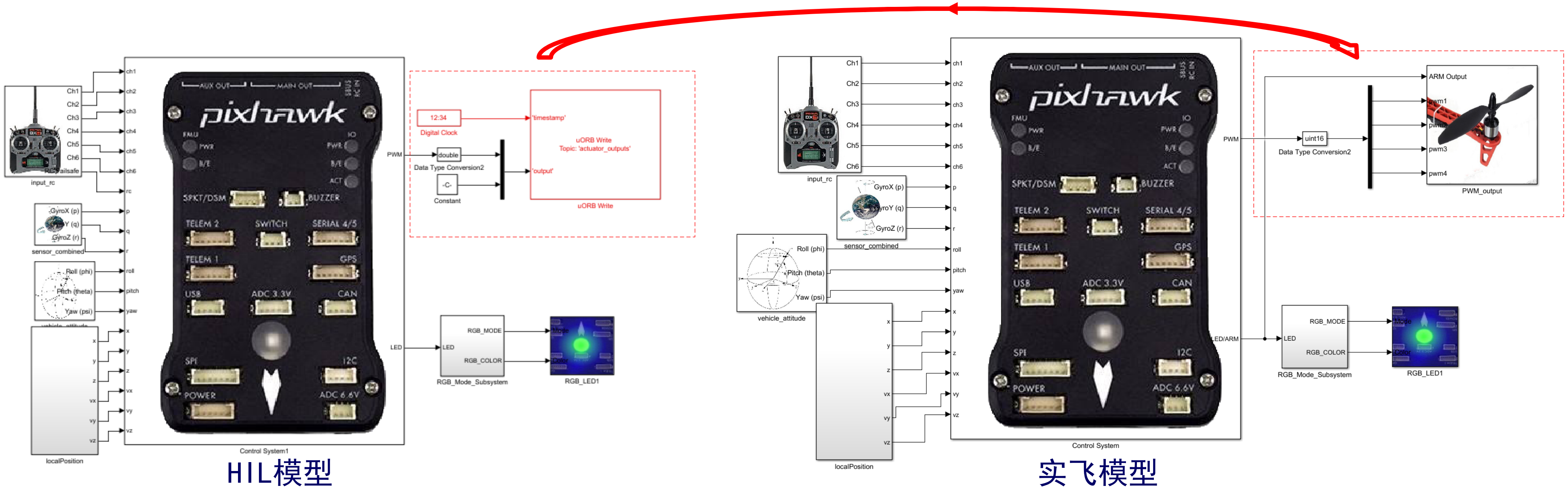


图. 替换PWM输出

Design Experiment

Flight Test Procedure

(3) Step3: Upload code

This process is similar to that used for compiling and uploading the code in HIL simulation.

(4) Step4: Outdoor flight test

To ensure safety, a rope is tethered to the quadcopter, and the other end is tethered to a heavy object. The remote pilot maintains a safe distance from the quadcopter during flight.

Figure: Outdoor flight test

Flight test

（5）Step5. Analyze the data

It can be observed that in the first 60s, the quadcopter is in the stabilize mode, corresponding the phase “a”, and then shifts to the altitude hold mode, corresponding to the phase “b”. Here, the throttle stick is at the middle and the altitude remains the same. Later, it enters the loiter mode where the position remains the same , corresponding to the phase “c”. At the same time, the pitch and roll sticks are at the middle and the throttle stick is centered. The flight performance and data show that the three modes of the quadcopter can be switched correctly .

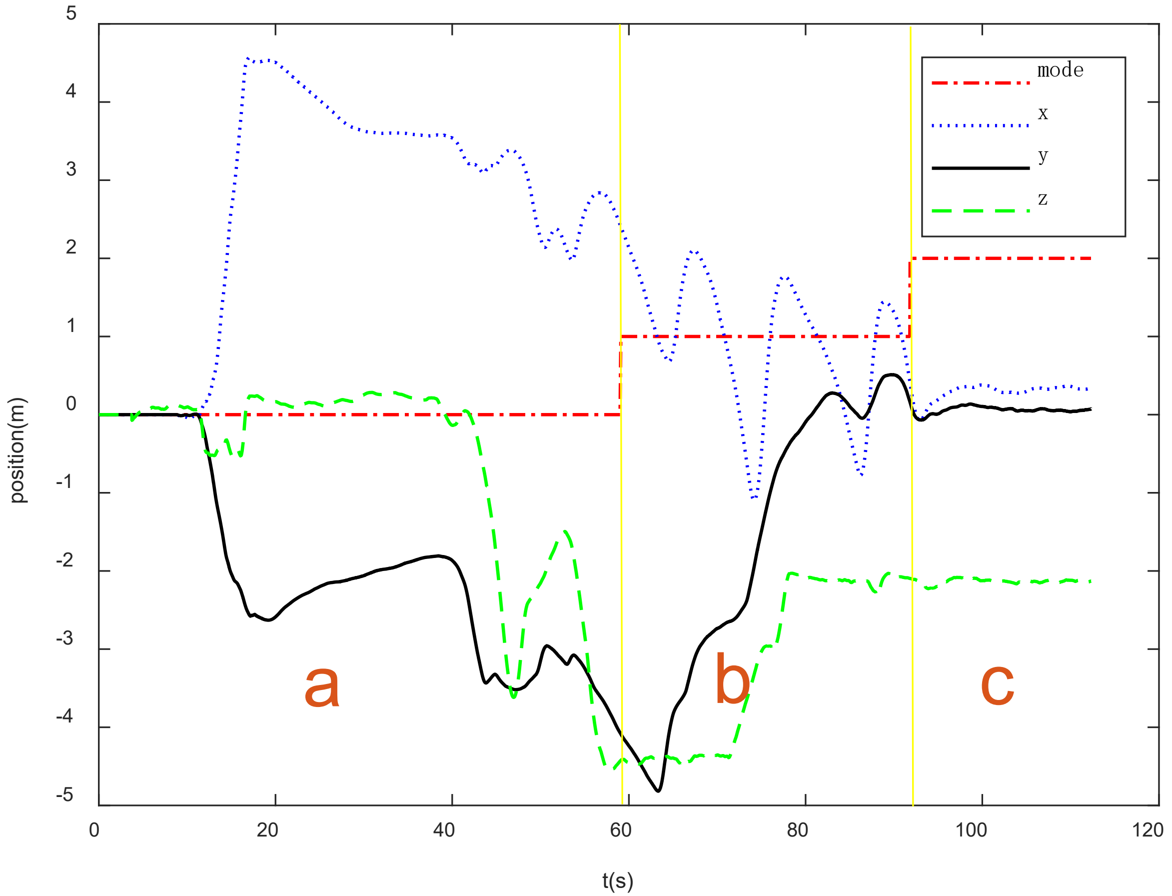


Figure: Flight test data

Summary

（1）In the basic experiment, the quadcopter maintains the desired attitude and position in the "stabilize" mode under ideal conditions, i.e., when no uncertainties exist. However, due to environmental disturbances and measurement errors (similar to disturbances given in the SIL simulation), the position of quadcopter will drift.

（2）In the design of the "stabilize" mode, the PWM inputs of the RC transmitter are converted into desired angles. The key point of the altitude hold mode design is the control logic related to the dead zone. In the dead zone, the altitude feedback of AC works to ensure the altitude remains constant. When the control stick is out of the dead zone, only the velocity feedback of the AC works for tracking with the command from RC in the altitude channel.

（3）In the design experiment, based on the design of the altitude hold mode, the design of the loiter mode is realized; in this mode, the command for horizontal position is from the roll and pitch control stick. For mode switching, using the three-position switch in the RC transmitter, readers can convert the input of the RC transmitter into the corresponding signal to trigger the desired mode.

Thanks