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

Lesson 07 Seneor Calibration Experiment

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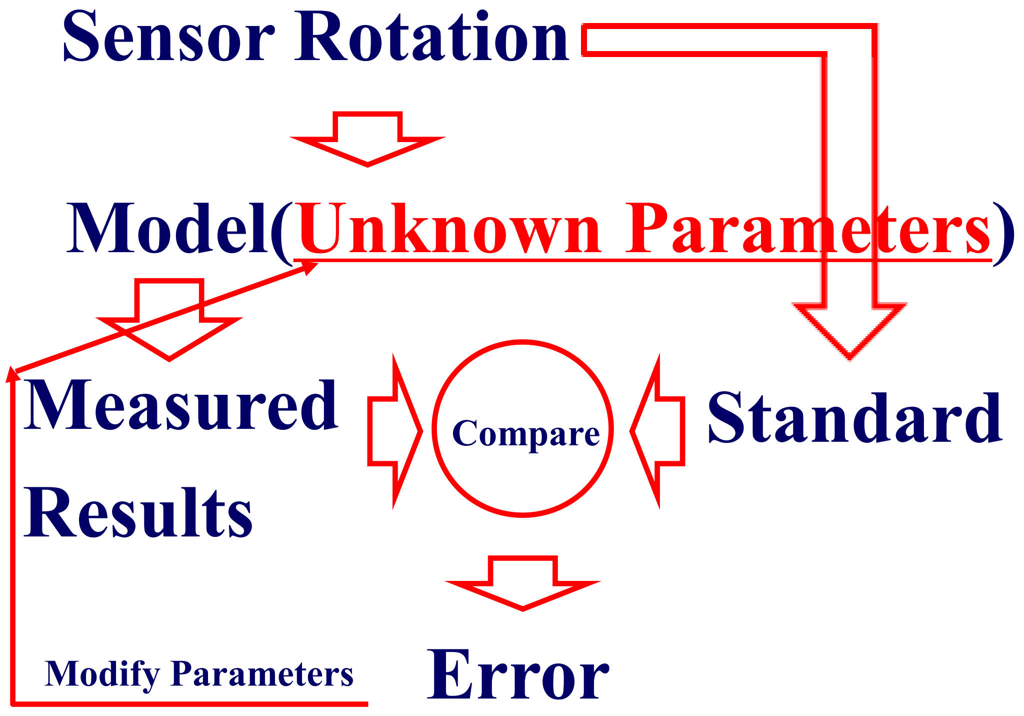
Outline

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

Preliminary

□ Calibration

(1) Calibration



(2) Automatic calibration

- General calibration:

  need external calibration equipment, but accurate.

- Automatic calibration:

  do not require external calibration devices, simple, slightly poor precision

Preliminary

◻ Three-Axis Accelerometer

(1) Error Model

There are always some deviations in the three-axis accelerometer during production and installation. Therefore, the relationship between the calibrated specific force and the specific force without calibration needs to be established. The error model is as follows

$$ {}^{b}\mathbf{a}_{m} = \mathbf{T}_{a}\mathbf{K}_{a}\left({}^{b}\mathbf{a}'_{m} + \mathbf{b}'_{a} \right) $$

The calibrated specific force

$$ \mathbf{T}_{a} = \begin{bmatrix} 1 & \Delta\psi_{a} & -\Delta\theta_{a} \\ -\Delta\psi_{a} & 1 & \Delta\phi_{a} \\ \Delta\theta_{a} & -\Delta\phi_{a} & 1 \end{bmatrix} $$

The tiny tilt in the process of mounting sensors

$$ \mathbf{K}_{a} = \begin{bmatrix} s_{ax} & 0 & 0 \\ 0 & s_{ay} & 0 \\ 0 & 0 & s_{az} \end{bmatrix} $$

The scale factor

The specific force without calibration

$$ \mathbf{b}'_{a} = \begin{bmatrix} b'_{ax} \\ b'_{ay} \\ b'_{az} \end{bmatrix} $$

The bias

Preliminary

☐ Three-Axis Accelerometer

(2) Calibration Principle

To calibrate an accelerometer, the following unknown parameters need to be estimated

$$\Theta_{\mathrm{a}}=\left[\Delta\psi_{\mathrm{a}} \quad \Delta\theta_{\mathrm{a}} \quad \Delta\phi_{\mathrm{a}} \quad s_{\mathrm{ax}} \quad s_{\mathrm{ay}} \quad s_{\mathrm{az}} \quad b'_{\mathrm{ax}} \quad b'_{\mathrm{ay}} \quad b'_{\mathrm{az}}\right]^{\mathrm{T}}$$

Then, it can be written as a function, as follows

$${}^{\mathrm{b}}\mathbf{a}_{\mathrm{m}}=\mathbf{h}_{\mathrm{a}}\left(\Theta_{\mathrm{a}},{}^{\mathrm{b}}\mathbf{a}'_{\mathrm{m}}\right)=\mathbf{T}_{\mathrm{a}}\mathbf{K}_{\mathrm{a}}\left({}^{\mathrm{b}}\mathbf{a}'_{\mathrm{m}}+\mathbf{b}'_{\mathrm{a}}\right)$$

Principle: The calibration principle is that the magnitude of specific force keeps constant with different attitude of accelerometers, i.e. the local gravity, denoted as g.

The calibration principle is that the magnitude of specific force keeps constant with different attitude of accelerometers, i.e. the local gravity, denoted as g.

$$\Theta_{\mathrm{a}}^{*}=\arg\min_{\Theta_{\mathrm{a}}}\sum_{k=1}^{M}\left(\left\|\mathbf{h}_{\mathrm{a}}\left(\Theta_{\mathrm{a}},{}^{\mathrm{b}}\mathbf{a}'_{\mathrm{m},k}\right)\right\|-\mathrm{g}\right)^{2}$$

arg min {} denotes the minimum value of the variable in the objective function

Preliminary

□ Three-Axis Magnetometer

(1) Error Model

There are always some deviations in the three-axis magnetometer during production and installation. Therefore, the relationship between the magnetic induction value after calibration and he magnetic induction value without calibrationneeds to be established. The error model is as follows

$$ {}^{\mathrm{b}}\mathbf{m}_{\mathrm{m}} = \mathbf{T}_{\mathrm{m}}\mathbf{K}_{\mathrm{m}}\left({}^{\mathrm{b}}\mathbf{m}'_{\mathrm{m}} + \mathbf{b}'_{\mathrm{m}}\right) $$

The magnetic induction value after calibration

$$ \mathbf{T}_{\mathrm{m}} = \begin{bmatrix} 1 & \Delta\psi_{\mathrm{m}} & -\Delta\theta_{\mathrm{m}} \\ -\Delta\psi_{\mathrm{m}} & 1 & \Delta\phi_{\mathrm{m}} \\ \Delta\theta_{\mathrm{m}} & -\Delta\phi_{\mathrm{m}} & 1 \end{bmatrix} $$

The tiny tilt in the process of mounting sensors

$$ \mathbf{K}_{\mathrm{m}} = \begin{bmatrix} s_{\mathrm{mx}} & 0 & 0 \\ 0 & s_{\mathrm{my}} & 0 \\ 0 & 0 & s_{\mathrm{mz}} \end{bmatrix} $$

The scale factor

The magnetic induction value without calibration.

$$ \mathbf{b}'_{\mathrm{m}} = \begin{bmatrix} b'_{\mathrm{mx}} \\ b'_{\mathrm{my}} \\ b'_{\mathrm{mz}} \end{bmatrix} $$

The bias

Preliminary

☐ Three-Axis Magnetometer

(2) Calibration Principle

Principle: In normal, the magnetic induction keeps constant with different attitude of magnetometer. Here, the magnetic induction value is normalized $\left\|{}^{\mathrm{b}}\mathbf{m}_{\mathrm{m},k}\right\|^2 = 1, k = 1, 2, \ldots, \mathrm{M}$.

To calibrate a magnetometer, the following unknown parameters need to be estimated.

$$\boldsymbol{\Theta}_{\mathrm{m}} \triangleq \begin{bmatrix} \Delta\psi_{\mathrm{m}} & \Delta\theta_{\mathrm{m}} & \Delta\phi_{\mathrm{m}} & s_{\mathrm{mx}} & s_{\mathrm{my}} & s_{\mathrm{mz}} & b'_{\mathrm{mx}} & b'_{\mathrm{my}} & b'_{\mathrm{mz}} \end{bmatrix}^{\mathrm{T}}$$

Then, it can be written as a function, as follows

$$\mathbf{h}_{\mathrm{m}}(\boldsymbol{\Theta}_{\mathrm{m}}, {}^{\mathrm{b}}\mathbf{m}'_{m}) \triangleq \mathbf{T}_{\mathrm{m}}\mathbf{K}_{\mathrm{m}}({}^{\mathrm{b}}\mathbf{m}'_{\mathrm{m}} + \mathbf{b}'_{\mathrm{m}})$$

According to this principle, the following optimization is given

$$\boldsymbol{\Theta}^*_{\mathrm{m}} = \arg\min_{\boldsymbol{\Theta}_{\mathrm{m}}} \sum_{k=1}^{M} \left(\left\| \mathbf{h}_{\mathrm{m}}\left(\boldsymbol{\Theta}_{\mathrm{m}}, {}^{\mathrm{b}}\mathbf{m}'_{\mathrm{m},k}\right) \right\| - 1 \right)^2$$

Preliminary

The experiment preliminary is from Chapters. 7 of *Introduction to Multicopter Design and Control*.

Basic Experiment

□ Experimental Objectives

- **Things to prepare**

（1）Hardware: Pixhawk autopilot system;

（2）Software: MATLAB 2017b and above, Pixhawk Support Package（PSP）toolbox, QGround-Control（QGC）, Experiment Instruction Package “e3.1”（https://flyeval.com/course);

（3）With respect to data, readers could directly use the data in the experiment instruction package e3.1 if without hardware.

- **Objectives**

Repeat the given calibration steps to calibrate an accelerometer in the given Pixhawk autopilot system. Subsequently, make a comparison between the calibrated results and uncalibrated results.

◻ Accelerometer Calibration Procedure

（1）Step1：Obtain accelerometer data via the Pixhawk autopilot system

1）Hardware connection

The connection between the RC receiver and the Pixhawk autopilot is shown in

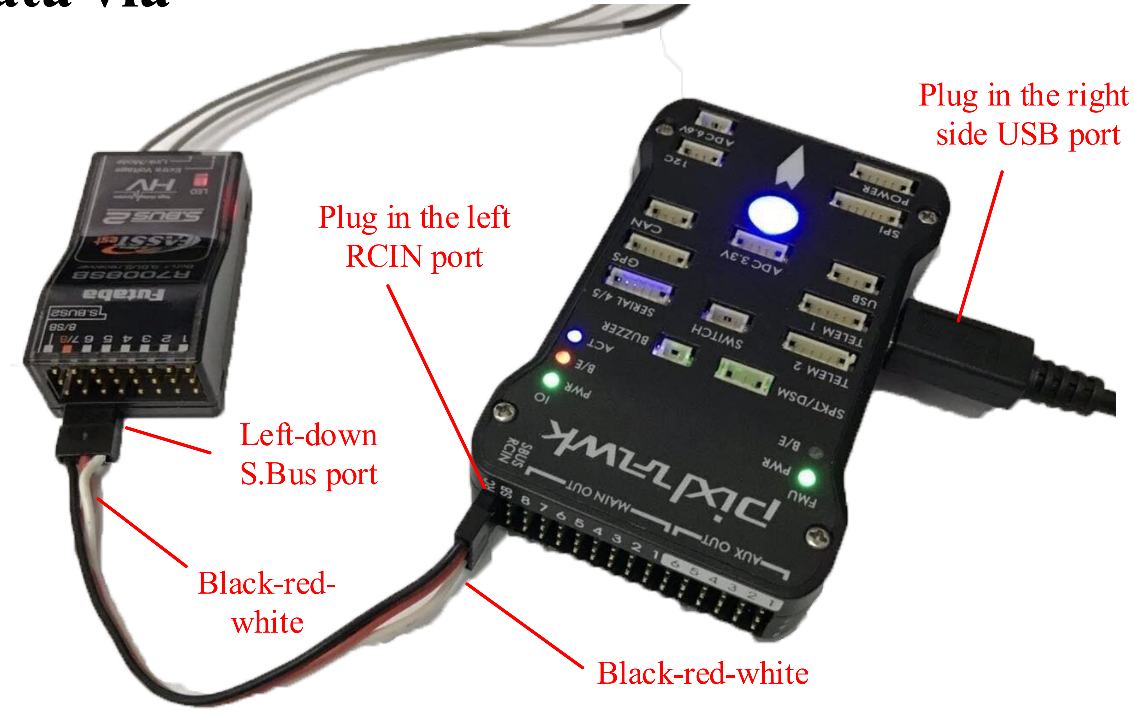


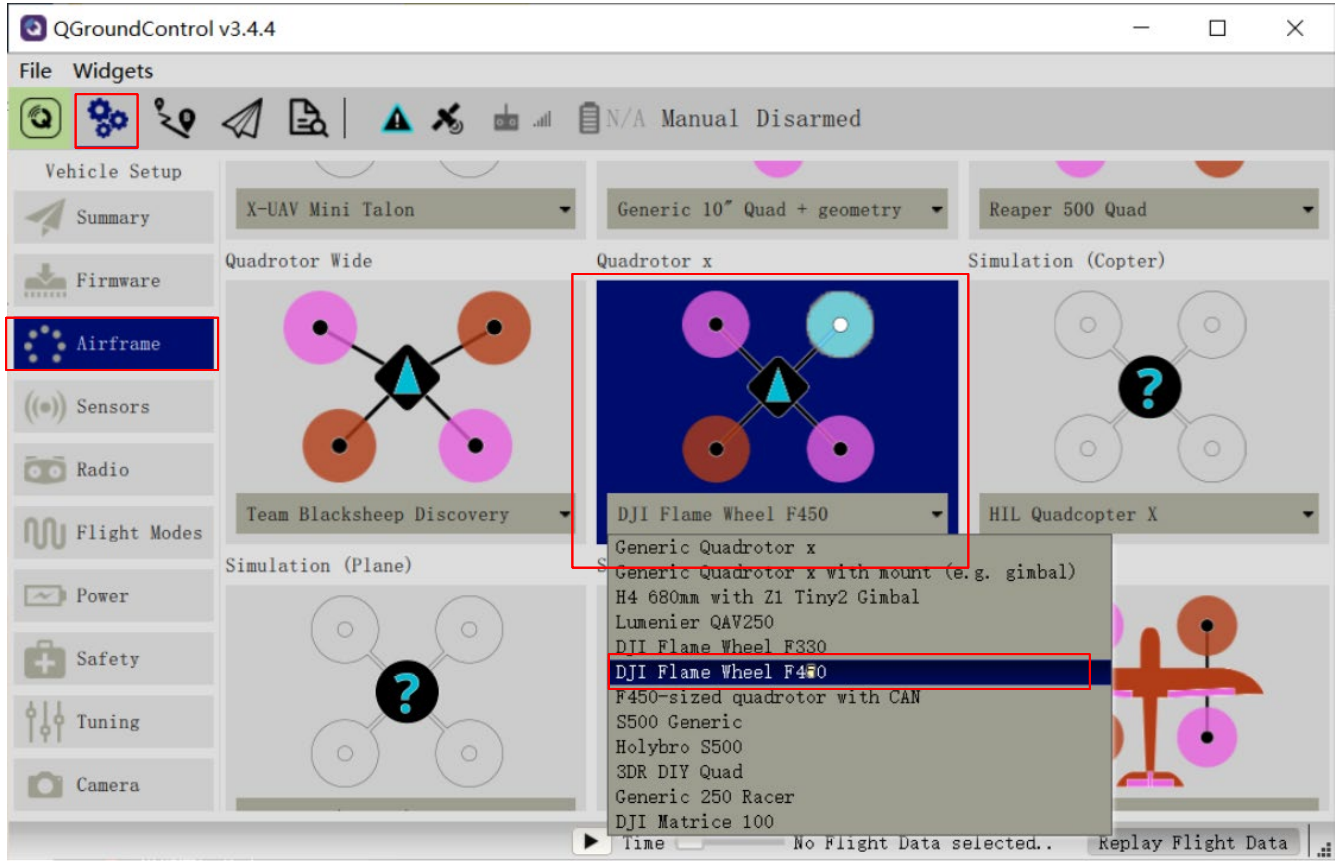
Figure. Pixhawk and RC transmitter connection

Basic Experiment

（1）Step1：Obtain accelerometer data via the Pixhawk autopilot system

1）Hardware connection

Open the QGC, as shown in the right figure and then select “Vehicle Setup” – “Airframe” –“Quadcopter x” – **“DJI Flame Wheel F450”.**

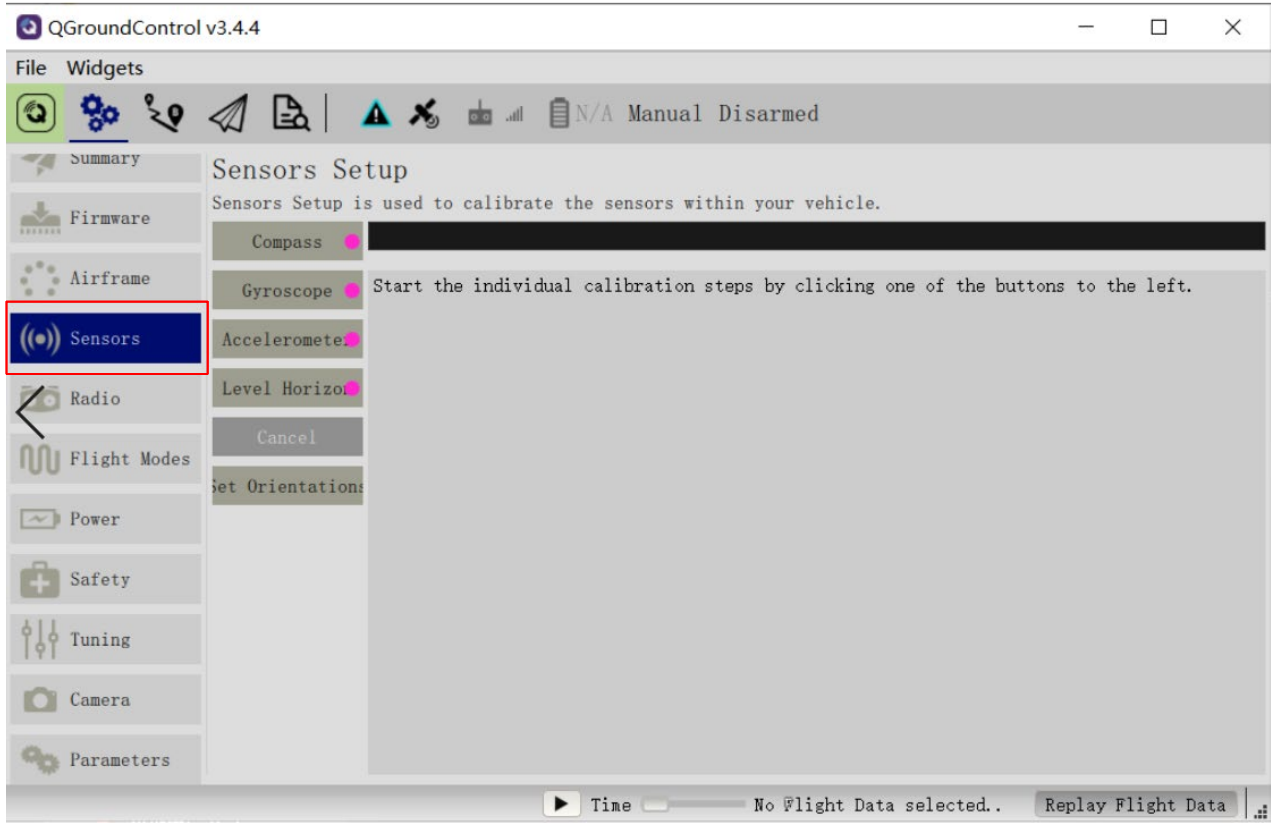


Basic Experiment

(1) Step1: Obtain accelerometer data via the Pixhawk autopilot system

1) Open the data collection model

Finally, click the "Apply" button and the autopilot will automatically reboot to make the adopted configuration available. If the adopted configuration is modified, the system will require another re-calibration of the sensor data, as shown in the figure.



□ Accelerometer Calibration Procedure

（1）Step1：Obtain accelerometer data via the Pixhawk autopilot system

2）Open the data collection model

To record the sensor and Remote Controller (RC) data in the Pixhawk microSD card, a file “acquire_data_ag.slx” is created, as shown in the right figure.

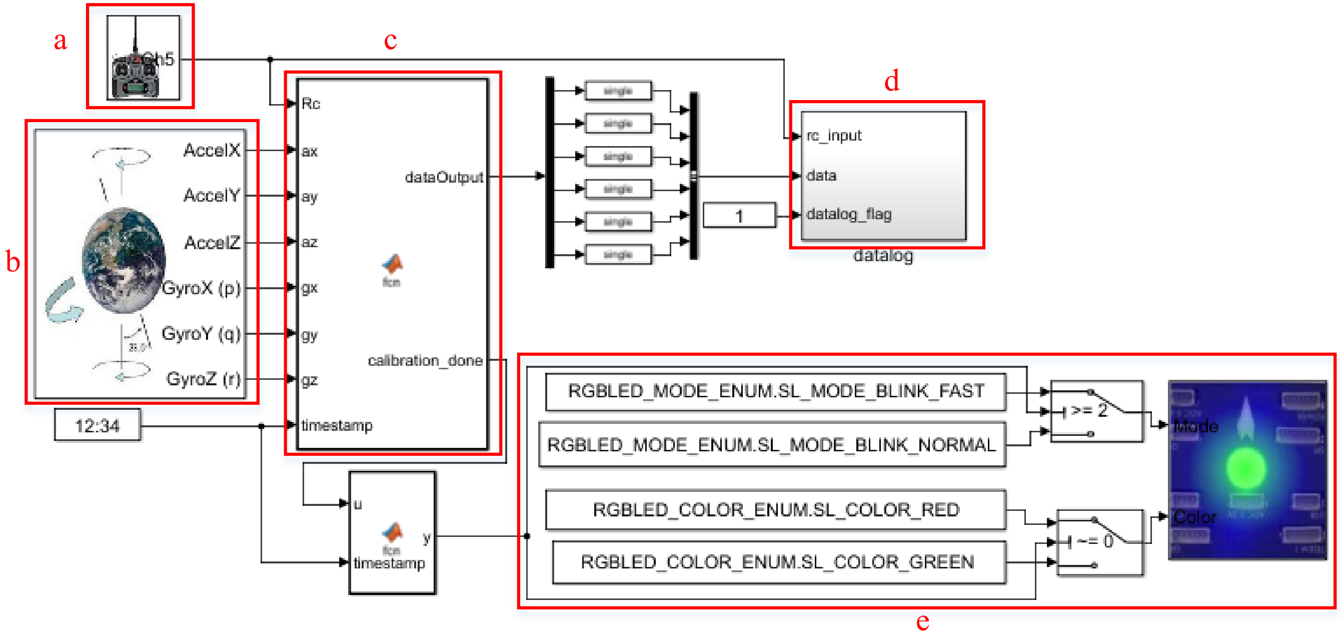


Figure. Hardware-in-the-loop (HIL) test for accelerometer data logging, Simulink model “acquire_data_ag.slx”

Basic Experiment

（1） Step1： Obtain accelerometer data via the Pixhawk autopilot system

2） Open the data collection model

Write data to the microSD card. Double-click block "binary_logger", as shown in the right figure. The first three path names of "fs/microsd/log/e3" cannot be changed, whereas the last path name "e3" is the name of the file to the log data, and can be changed as desired.

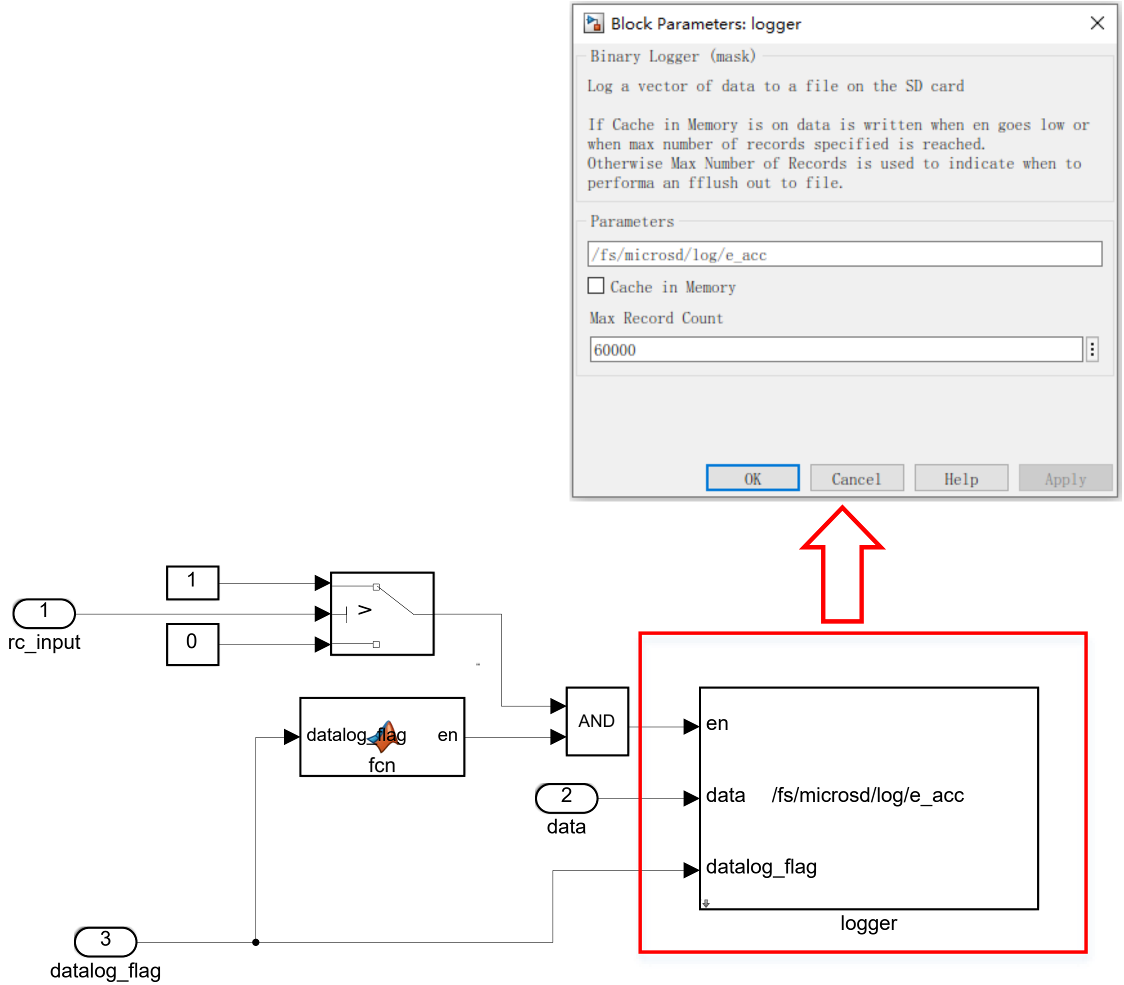


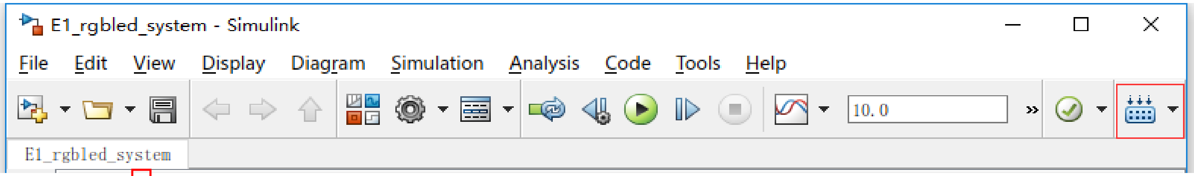
Figure. Binary logger block in Simulink model "acquire_data_ag.slx"Click

Basic Experiment

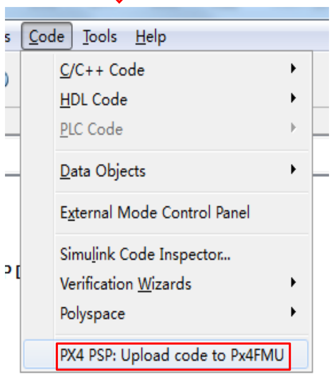
（1）Step1： Obtain accelerometer data via the Pixhawk autopilot system

3）Compile the file “acquire_data_ag.slx” and upload it to the Pixhawk autopilot.

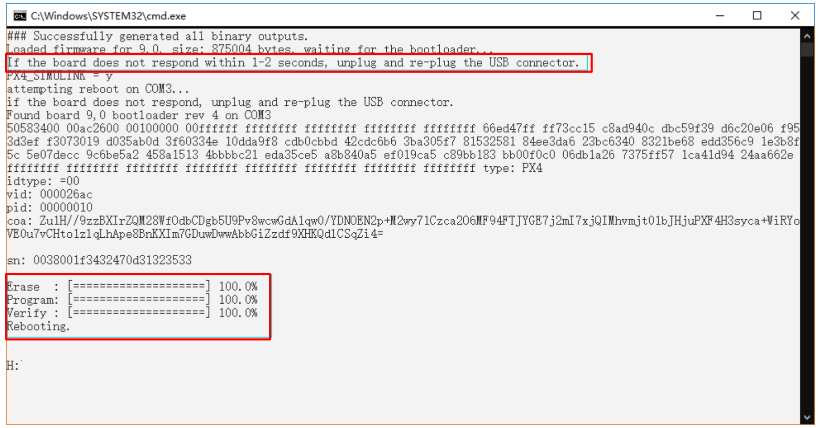
Data can be logged automatically, by placing the upper-left stick (CH5) in the corresponding position.



Click to build



Click to download



Download completed

Basic Experiment

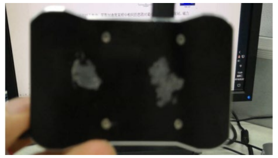
（1）Step1：Obtain accelerometer data via the Pixhawk autopilot system

4）Rotate the Pixhawk autopilot to log data

Pull back the upper-left switch corresponding to CH5>1500 , to start writing data to the microSD card. Place the Pixhawk autopilot as guided by the right figure and hold the Pixhawk autopilot still with each orientation for a period of time. Meanwhile, the Pixhawk autopilot logs data to a file called “e3_A.bin” on the microSD card. Once a feature point is collected, the Pixhawk LED status light will slowly blink in red. By recalling the feature point collection method, one feature point corresponds to one orientation that the Pixhawk is placed in. Repeat the logging process for all orientations. Once ten feature points corresponding to ten orientations are collected, the Pixhawk LED status light will begin quickly blinking in red. Then, pull forward the upper-left.


①Upward


②Down


③Left


④Right


⑤Forward


⑥Backward


⑦45° to the left


⑧45° to the right


⑨45° to the forward


⑩45° to the backward

Figure. Ten different orientations of Pixhawk autopilot

Basic Experiment

（1）Step1：Obtain accelerometer data via the Pixhawk autopilot system

5）Read data

Take out the microSD card, read the data by a card reader, copy the file “e3_A.bin”to the folder “/e3/e3.1” and save it. Use the function

[datapoints, numpoints] = px4_read_binary_file(‘e_acc1_A.bin’)

to read data saved in “datapoints”. The number of data is saved in “numpoints”. The x-axis accelerometer sampling data and feature data are shown in the right figure.

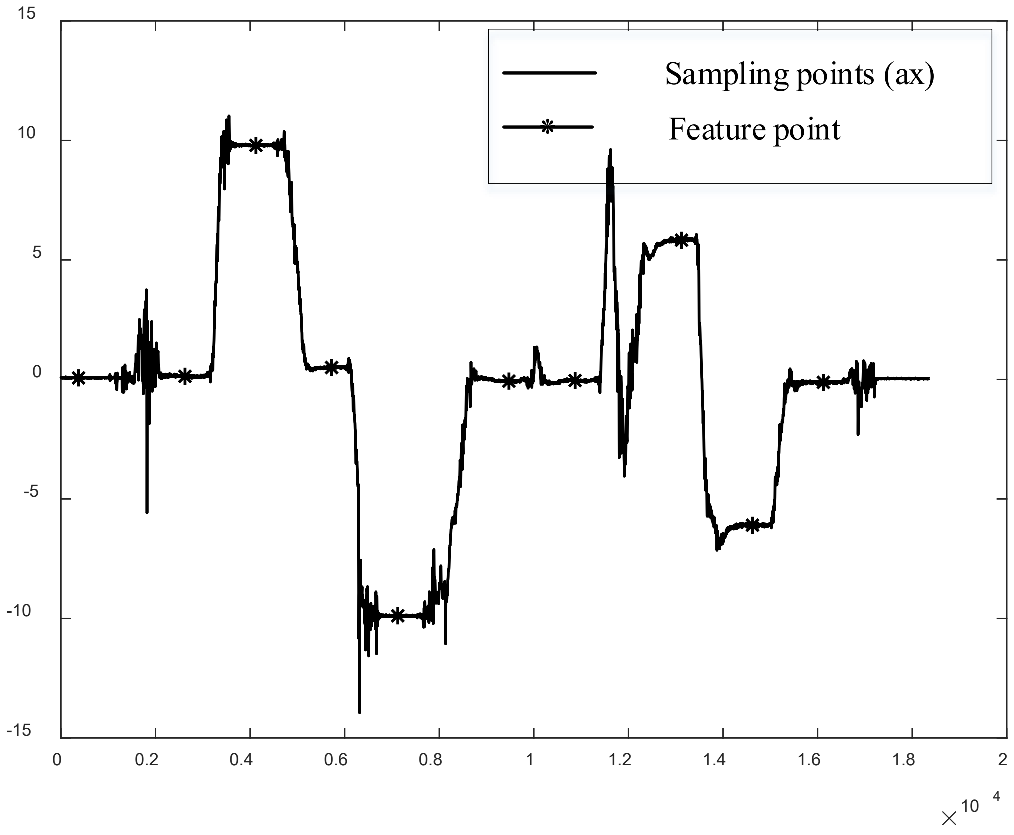
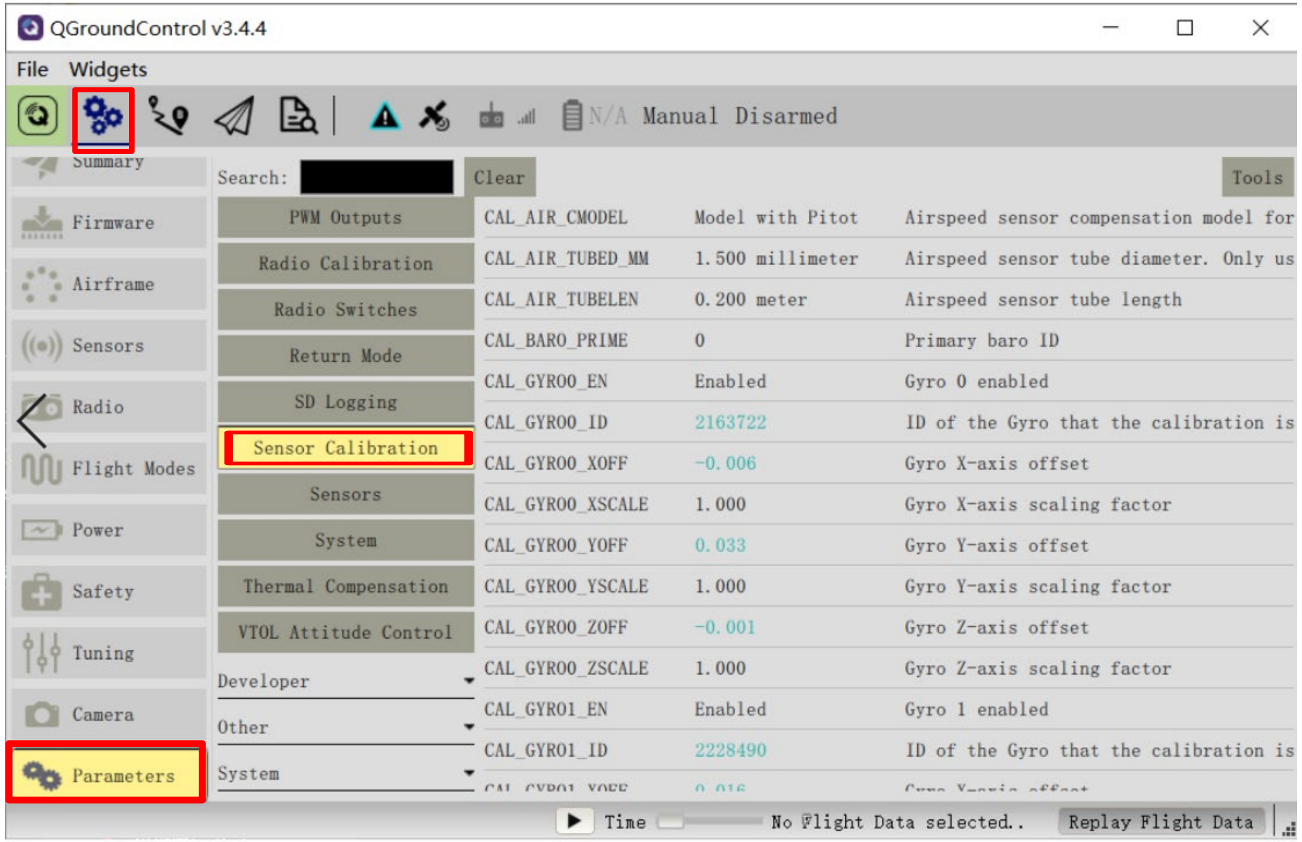


Figure. x-axis accelerometer sampling data and feature data

Basic Experiment

（2）Step2：Parameter calibration

To obtain uncalibrated original data, the accelerometer calibration parameters in the Pixhawk autopilot are first read by QGC. In QGC, select “Parameters” – “Sensor Calibration” to obtain the accelerometer calibration parameters, as shown in the right figure. Then, restore the data to uncalibrated data, based on the obtained accelerometer calibration parameters from QGC.



Basic Experiment

（2）Step2：Parameter calibration

1）Understand LM algorithm and use function

p = lm(func,p,x,y_dat,dp,p_min,p_max)

- Input parameters：
- func function name y_hat = func(x,p)， the functional relationship is $\left\| \mathbf{T}_a \mathbf{K}_a \left({}^{b}\mathbf{a}'_m + \mathbf{b}'_a \right) \right\|$, and let $\mathbf{T}_a = \mathbf{I}_3$.
- p: the initial value of the parameter to be estimated, which denotes initial value in optimization;
- x: feature points;
- dp:related to the Jacobian matrix;
- p_min： the minimum norm of the unknown parameter, the default is -100*abs(p);
- p_max: the maximum norm of the unknown parameter, the default is 100*abs(p);

- Output
- p: The unknown parameter value estimated by the algorithm iteration, i.e. $\mathbf{\Theta}_a$

Basic Experiment

（2）Step2：Parameter calibration

2）Calibrate the accelerometer by the LM algorithm. The main code is shown in following table.

```
%File Description:
% According to the accelerometer error model, the accelerometer error model parameters are calculated using the lm optimization algorithm.
close all
clc
clear

load AccRaw  %Load uncalibrated accelerometer data
g = 9.8;
m = length(AccRaw);

y_dat = g*ones(m, 1);  %Expected gravitational acceleration data
p0 = [1 1 1 0 0 0]';
p_init = [1.0 1.0 1.0 0.1 0.1 0.1]';  %Accelerometer error model parameter initial data
y_raw = calFunc(AccRaw, p0);  %2−norm of uncalibrated accelerometer dara
y_raw = y_raw(:);
r_raw = y_dat - y_raw;   %The difference between the uncalibrated gravitational acceleration measured by the accelerometer and the standard gravitational acceleration
p_fit = lm('calFunc', p_init, AccRaw, y_dat);
y_lm = calFunc(AccRaw, p_fit);  %2−norm of calibrated accelerometer value
y_lm = y_lm(:);
r_lm = y_dat - y_lm;
kx = p_fit(1);
ky = p_fit(2);
kz = p_fit(3);
bx = p_fit(4);
by = p_fit(5);
bz = p_fit(6);
Ka9_8 = [kx 0 0; 0 ky 0; 0 0 kz]
ba9_8 = [bx by bz]'
save('calP9_8', 'Ka9_8', 'ba9_8')
```

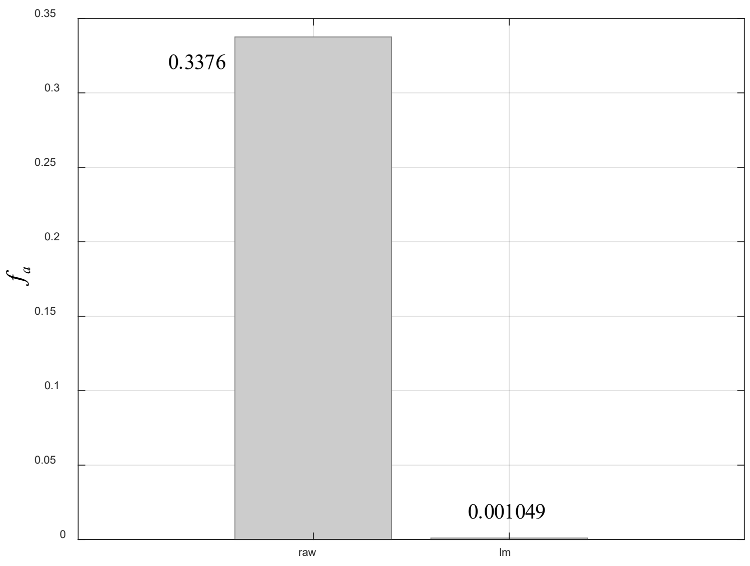
Basic Experiment

（2）Step2：Parameter calibration

Moreover, as shown in the following figure, the optimization objective converges to zero very quickly as the iterative number is increased with the calibrated parameters obtained as

$$\mathbf{K}_{\mathrm{a}}^{*}=\begin{bmatrix}0.9912 & 0 & 0\\ 0 & 0.9974 & 0\\ 0 & 0 & 0.9947\end{bmatrix}$$

$$\mathbf{b}_{\mathrm{a}}^{*}=\begin{bmatrix}0.0168\\ 0.2691\\ 0.1253\end{bmatrix}$$



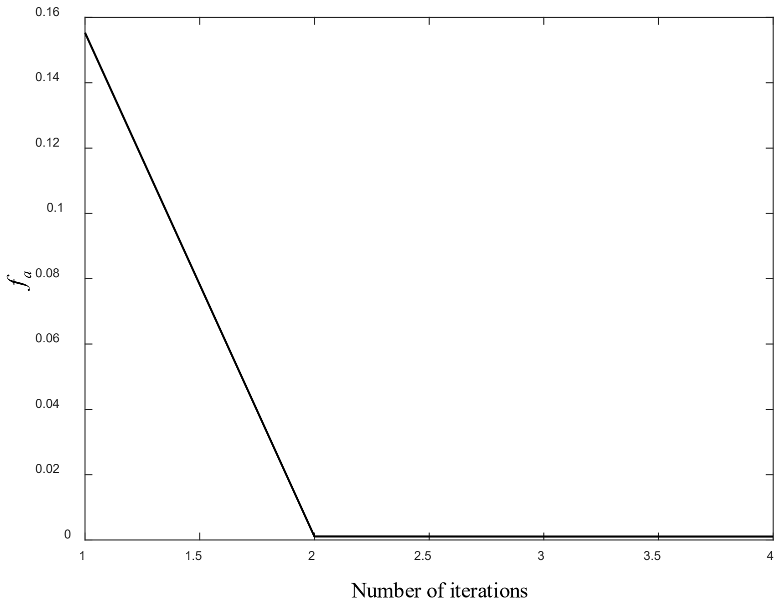


Figure. Value of f_{a} of calibrated and uncalibrated accelerameters

Analysis Experiment

□ Experimental Objectives

- **Things to prepare**

  The acceleration data collected from the basic experiments.

- **Objectives**

  Change the value of the gravitational acceleration from 9.8 to 1. Calibrate the accelerometer parameters again; with the calibrated data, calculate the pitch angle. Compare and analyze the calibration parameters and pitch angles computed from different calibrated parameters when the gravitational acceleration is set from 9.8 to 1.

Analysis Experiment

Theoretical Analysis

The optimization of $\boldsymbol{\Theta}_{\mathrm{a}}^{*}$ is the desired objective. Then

$$\left.\frac{\partial \sum_{k=1}^{M}\left(\left\|\mathbf{T}_{\mathrm{a}}\mathbf{K}_{\mathrm{a}}^{*}\left({}^{\mathrm{b}}\mathbf{a}_{\mathrm{m}}'+\mathbf{b}_{\mathrm{m}}'\right)\right\|-g\right)^{2}}{\partial \boldsymbol{\Theta}_{\mathrm{a}}}\right|_{\boldsymbol{\Theta}_{\mathrm{a}}=\boldsymbol{\Theta}_{\mathrm{a}}^{*}}=\mathbf{0}$$

where $\mathrm{T}_{\mathrm{a}}=\mathbf{I}_{3}$. In that regard, the gravitational acceleration changes. For example, g is changed to $\alpha g, \alpha>0$. Multiplying the left and right sides of The equation by α yields

$$\left.\frac{\partial \sum_{k=1}^{M}\left(\left\|\mathbf{T}_{\mathrm{a}}\alpha\mathbf{K}_{\mathrm{a}}^{*}\left({}^{\mathrm{b}}\mathbf{a}_{\mathrm{m}}'+\mathbf{b}_{\mathrm{m}}'\right)\right\|-\alpha g\right)^{2}}{\partial \boldsymbol{\Theta}_{\mathrm{a}}}\right|_{\boldsymbol{\Theta}_{\mathrm{a}}=\boldsymbol{\Theta}_{\mathrm{a}}^{*}}=\mathbf{0}$$

This implies that, after the gravitational acceleration is changed, the calibration parameters are $\mathrm{K}_{\mathrm{a}}^{*\prime}=\alpha\mathrm{K}_{\mathrm{a}}^{*}$ and $\mathbf{b}_{\mathrm{a}}^{*\prime}=\mathbf{b}_{\mathrm{a}}^{*}$

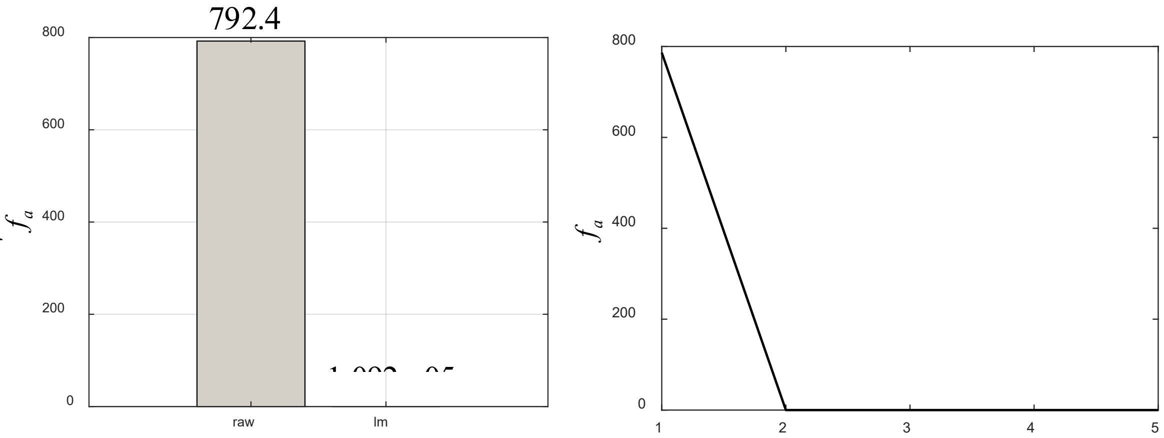
Analysis Experiment

□ Calibration Procedure

（1）Step1: Open the file “calLM.m” and change the value of gravitational acceleration “g” from 9.8 to 1.

（2）Step2: Copy the sensor data obtained in the basic experiment for file “calLM.m”.

（3）Step3: Run the file “calLM.m” to obtain the calibration results and curves.



(a) Value of f_a of calibrated and uncalibrated accelerameters

(b) f_a changes with number of iterations

Figure. Calibration results when “g” is 1

Analysis Experiment

◻ Calibration Procedure

（3）Step3: Run the file “calLM.m” to obtain the calibration results and curves

- g=9. 8

$$\mathbf{K}_a^{*\prime}=\begin{bmatrix}0.9912 & 0 & 0\\ 0 & 0.9974 & 0\\ 0 & 0 & 0.9947\end{bmatrix}\quad \mathbf{b}_a^{*\prime}=\begin{bmatrix}0.0168\\ 0.2691\\ 0.1253\end{bmatrix}$$

- g=1

$$\mathbf{K}_a^{*\prime}=\begin{bmatrix}0.1012 & 0 & 0\\ 0 & 0.1017 & 0\\ 0 & 0 & 0.1014\end{bmatrix}\quad \mathbf{b}_a^{*\prime}=\begin{bmatrix}0.0123\\ 0.2771\\ 0.1456\end{bmatrix}$$

One can conclude that when “g” is 1 and 9.8, $\mathrm{K}_a^{*\prime}$ is reduced to approximately 1/9.8 of K_a^{*}, which is consistent with the theoretical analysis.

Analysis Experiment

☐ Calibration Procedure

（3）Step3: Run the file “calLM.m” to obtain the calibration results and curves

The three-axis accelerometer is fixed to the multicopter and aligned with the aircraft-body coordinate frame. To better illustrate the pitch angle in a continuous process, a set of accelerometer data is logged again when the Pixhawk autopilot is slowly turned, as shown in the right figure. One can conclude that the two calibration solutions result in the same angle. This implies that the pitch angle measurement is independent of different sizes of acceleration of gravity.

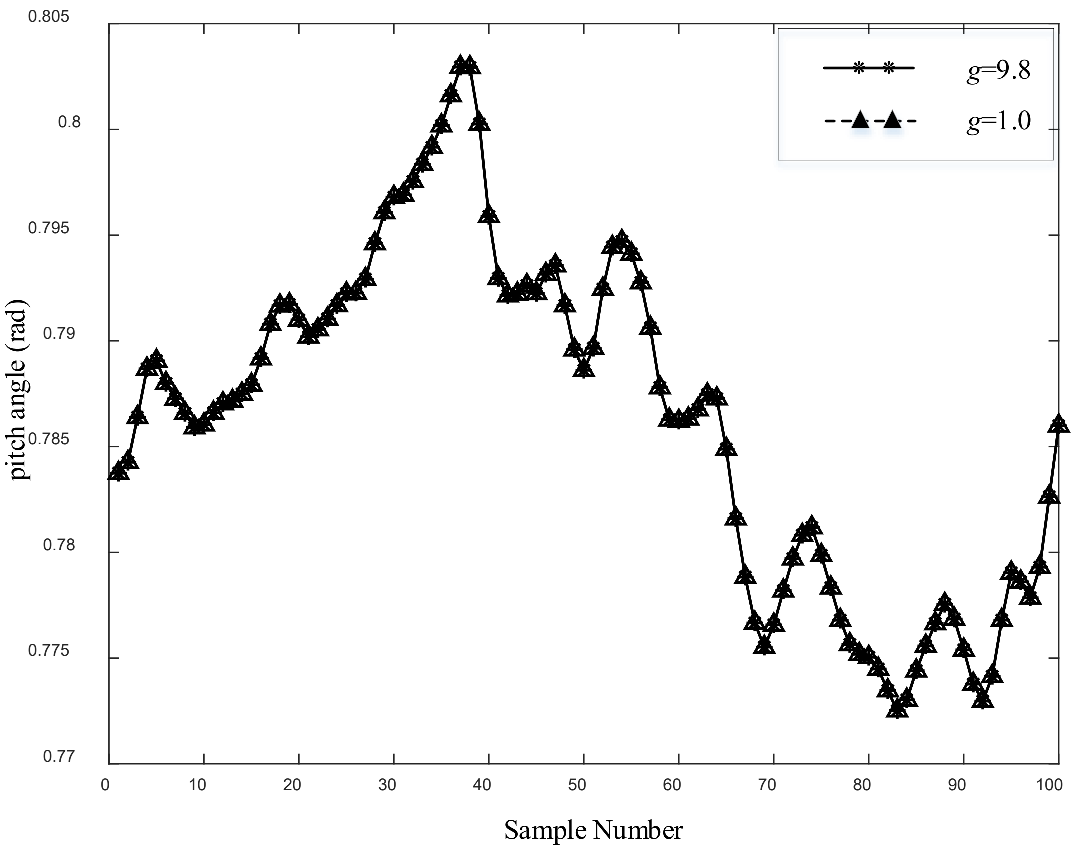


Figure. Pitch angle with respect two different “g” values

Design Experiment

□ Experimental Objectives

- **Things to prepare**

(1) Hardware: Pixhawk Autopilot System;

(2) Software: MATLAB2017b and above, Pixhawk Support Package（PSP）Toolbox, QGroundControl （QGC） and Experiment Instruction Package "e3.3" https://flyeval.com/course);

(3) With respect to data, readers could directly use the data in the experiment instruction package e3.1 if without hardware.

- **Objectives**

Design the magnetometer data logging block, following the procedure in the basic experiment. With the obtained data, calibrate the magnetometer and compare the calibrated and uncalibrated results.

Design Experiment

□ Magnetometer Calibration Procedure

（1）Step1: Obtain magnetometer data from Pixhawk Autopilot

1）Data logging block

Create a new Simulink file and drag out the corresponding modules from the Simulink PSP Toolbox, as shown in the right figure. To log data, use the corresponding blocks in “Pixhawk Target Blocks” that log data from the inertial sensor and RC transmitter. That data can be saved into the Pixhawk microSD card.

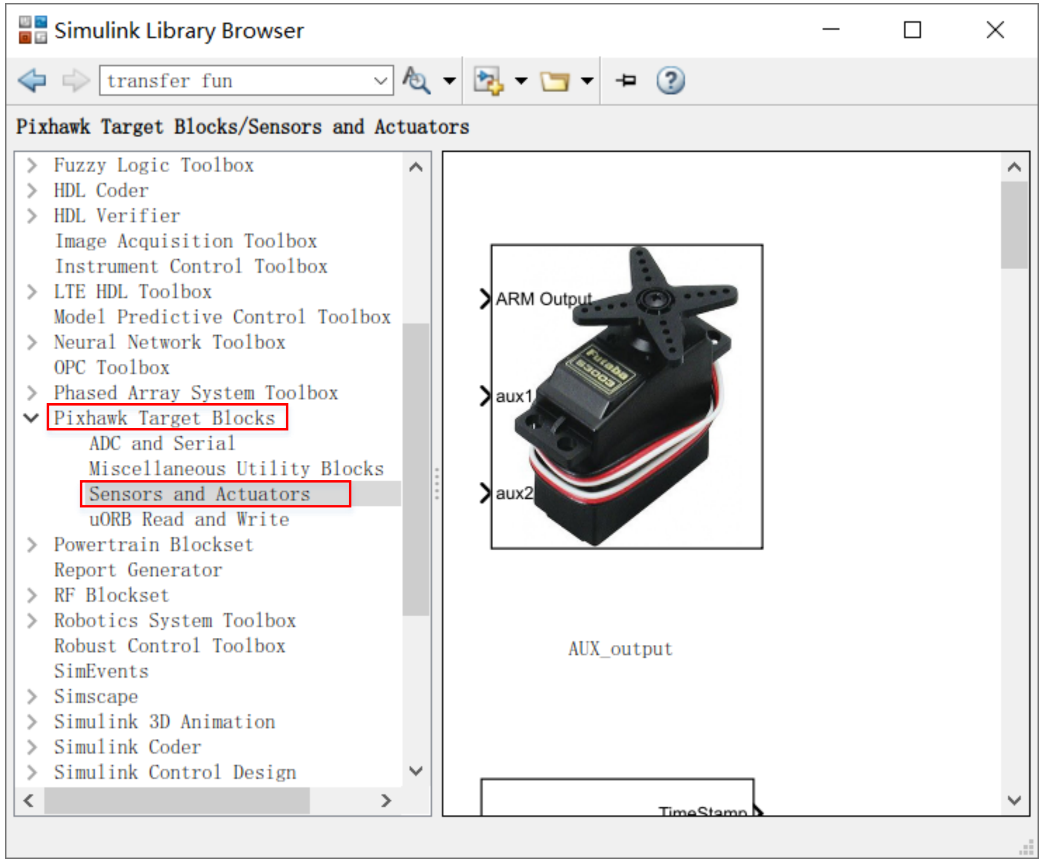


Figure. PSP tool module in Simulink library browser

Design Experiment

□ Magnetometer Calibration Procedure

（1）Step1: Obtain magnetometer data from Pixhawk Autopilot

1） Data logging block

An appropriate model given in the file “acquire_data_mag.slx” is shown in the right figure.

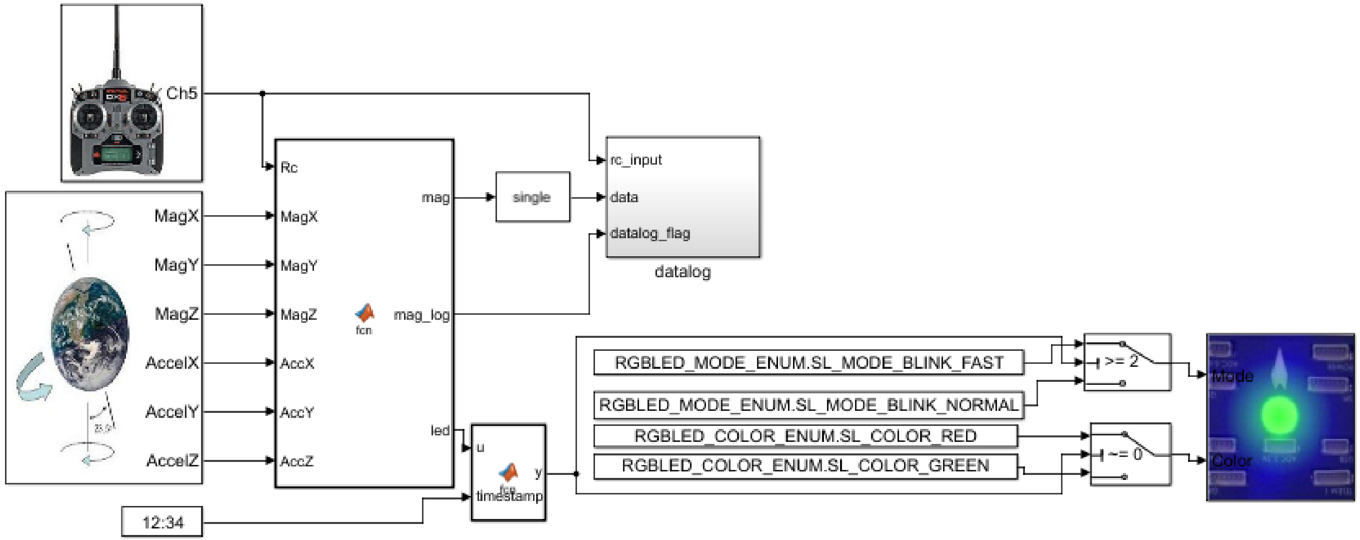


Figure. HIL test for magnetometer data logging, Simulink model “acquire_data_mag.slx”

Design Experiment

□ Magnetometer Calibration Procedure

（1） Step1: Obtain magnetometer data from Pixhawk Autopilot

2）Hardware connection

The connection between the RC receiver and the Pixhawk autopilot can be determined, as is shown in the right figure.

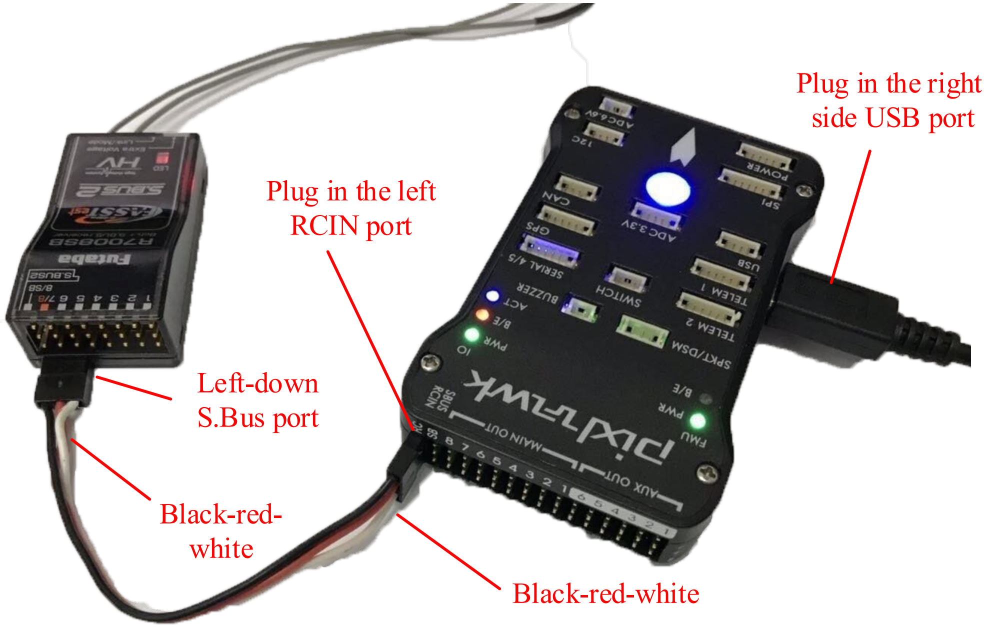


Figure. Pixhawk and RC transmitter connection

□ Magnetometer Calibration Procedure

（1） Step1: Obtain magnetometer data from Pixhawk Autopilot

3）Compile the file “acquire_data_mag.slx” and upload it to the Pixhawk autopilot.

4）Log the data

When the data of the magnetometer is logged, the average data is not used to eliminate data noise; rather, a significant amount of raw data is used to eliminate noise. The reason for this is that when the data of the magnetometer is logged, the Pixhawk autopilot should be shaken, which will cause extra acceleration, but will not change the magnetic field around the autopilot. Thus, to obtain sufficient magnetometer data, the Pixhawk autopilot can be randomly shaken.

Design Experiment

□ Magnetometer Calibration Procedure

（1） Step1: Obtain magnetometer data from Pixhawk Autopilot

4） Log the data

Pull back the upper-left switch corresponding to CH5>1500, to start writing data to the microSD card. Place the Pixhawk autopilot as guided by the right figure. Starting at each orientation, rotate the Pixhawk autopilot a circle clockwise or counterclockwise around its principal axes of the moment of inertia, where 40 sampling data are logged. Meanwhile, the Pixhawk autopilot logs data to a file called "e3_m_A.bin" on the microSD card. Once the process of logging is completed for the current orientation, the Pixhawk LED status light will be slowly blinking in red. Then, repeat the logging process for all orientations. Once all data corresponding to all six orientation is collected, the Pixhawk LED status light will be quickly blinking in red and a total 240 sampling data are logged. Then, pull forward the upper-left switch (CH5<1500) to stop writing data to the microSD card.

①Upward ②Down

③Left ④Right

⑤Upward ⑥Down

Figure. Pixhawk autopilot placement facing six different directions

Design Experiment

（1） Step1: Obtain magnetometer data from Pixhawk Autopilot

5）Read the data

First, remove the microSD card from Pixhawk autopilot. Read the data using a card reader. Copy the file “e3_m_A.bin” to the folder “/e3/e3.3” and save it. Use the function

[datapoints, numpoints] = px4_read_binary_file(e3_m_A.bin’)

to read the data saved in “datapoints”, and the number of data is saved in “numpoints”. The logged data is shown in the right figure.

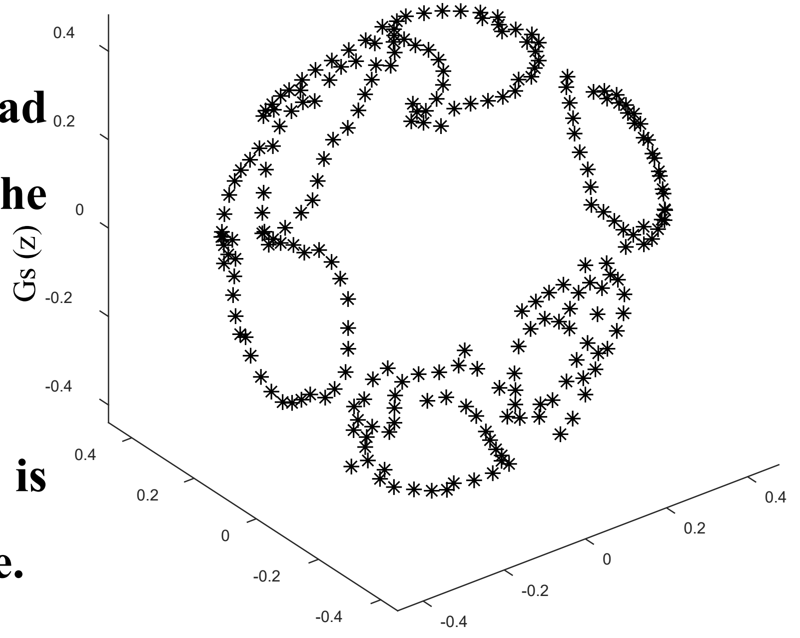


Figure. Magnetometer calibration sampling point

Design Experiment

Calibrate the accelerometer by the LM algorithm. The main code is shown in following table.

```
close all
clc
clear
load MagRaw.mat
CAL_MAG_SCALE = [1, 1, 1]';  %Calibration value in autopilot
CAL_MAG_OFF = [0.064, 0.014, -0.053]';
MagRaw = (mag + CAL_MAG_OFF)./CAL_MAG_SCALE;
%Original magnetometer data
m = length(MagRaw);
MagSum = 0;
for k = 1 : m
   MagSum = MagSum + norm(MagRaw(:, k));
end
MagAver = MagSum/m;  %Estimated magnetic field strength
Vdata = MagRaw/MagAver;  %Normalization

y_dat = ones(m, 1);
p0 = [1 1 1 0 0 0]';

p_init = [1 1 1 0.01 0.01 0.01]';  %Initial value of the parameter to be estimated
y_raw = calFunc(Vdata, p0);  %2−norm of uncalibrated magnetometer
value
y_raw = y_raw(:);
r_raw = y_dat - y_raw;
p_fit = lm('calFunc', p_init, Vdata, y_dat, 0.001);
y_lm = calFunc(Vdata, p_fit);  %2−norm of calibrated magnetometer value
y_lm = y_lm(:);
r_lm = y_dat - y_lm;
y_px4 = calFunc(mag/MagAver, p0);  %2−norm of PX4 Calibrated magnetometer value
y_px4 = y_px4(:);
r_px4 = y_dat - y_px4;
kx = p_fit(1);
ky = p_fit(2);
kz = p_fit(3);
bx = p_fit(4);
by = p_fit(5);
bz = p_fit(6);
Km = [kx 0 0;0 ky 0;0 0 kz]
bm = [bx by bz]'
```

Design Experiment

□ Magnetometer Calibration Procedure

（2）Parameter calibration

As shown in the following figure, the optimization objective becomes smaller than that for uncalibrated parameters, and the optimization objective converges to 0.5 very quickly as the iterative number is increased. Finally, the calibrated parameters are obtained as

$$\mathbf{K}_{\mathrm{m}}^{*}=\begin{bmatrix}0.9853 & 0 & 0\\ 0 & 1.0202 & 0\\ 0 & 0 & 1.0004\end{bmatrix}$$

$$\mathbf{b}_{\mathrm{m}}^{*}=\begin{bmatrix}-0.1448\\ -0.0334\\ -0.0898\end{bmatrix}$$

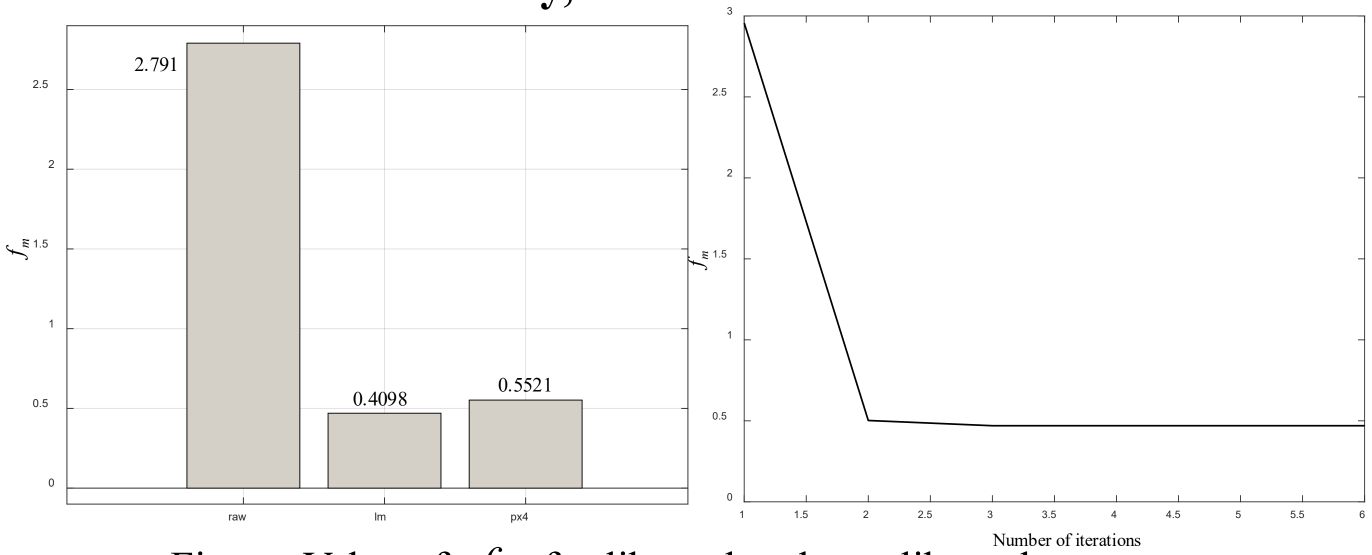


Figure. Value of f_{m} of calibrated and uncalibrated magnetometers

Summary

(1) An accelerometer calibration model and a magnetometer calibration model are illustrated using a multicopter sensor calibration experiment, where the PSP Toolbox is used for data logging.

(2) When recording accelerometer data, to avoid additional non-gravity acceleration, it is necessary to hold the Pixhawk still. To save computation time, some extracted feature points are used for calibration optimization, rather than all sample points. The calibration results are satisfactory.

(3) After the gravity acceleration "g" is changed from 9.8 to 1, the same code from the basic experiment is executed again. The results show that the scale factor K_a narrows 1/9.8, but the attitude angle is consistent with that when "g" is 9.8. This implies that the pitch angle measurement is independent of different sizes of acceleration of gravity.

(4) When recording the magnetometer data, the Pixhawk autopilot is rotated starting from six different orientations. The calibration results are satisfactory.

Thanks