Introduction to Multicopter Design and Control

Lesson 12 Position Control Based On Semi-Autonomous Autopilot

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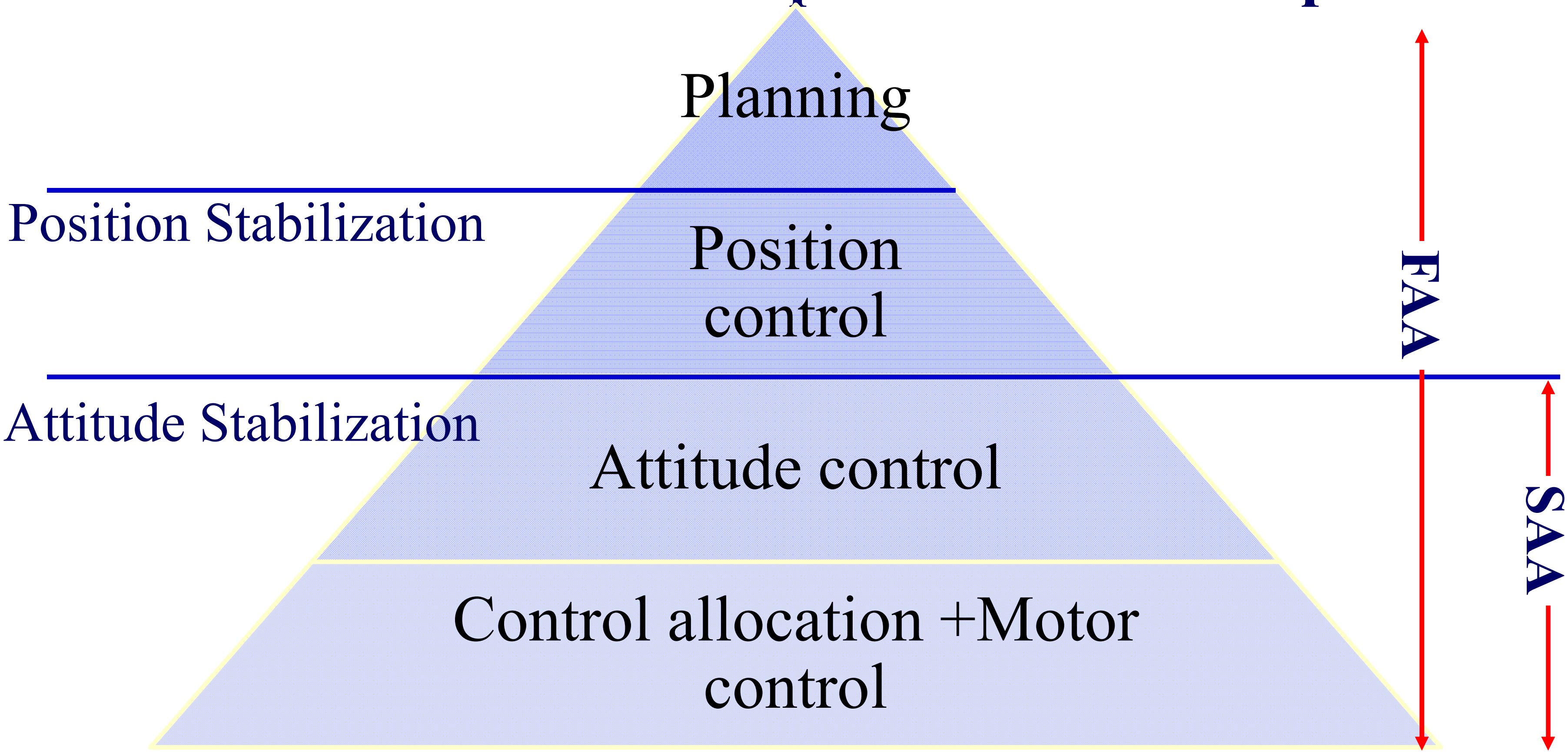
How is a multicopter controlled based on the Semi-Autonomous Autopilots to track a given target position?

Outline

1. Problem Formulation
2. System Identification
3. Position Controller Design
4. Simulation

1. Problem Formulation

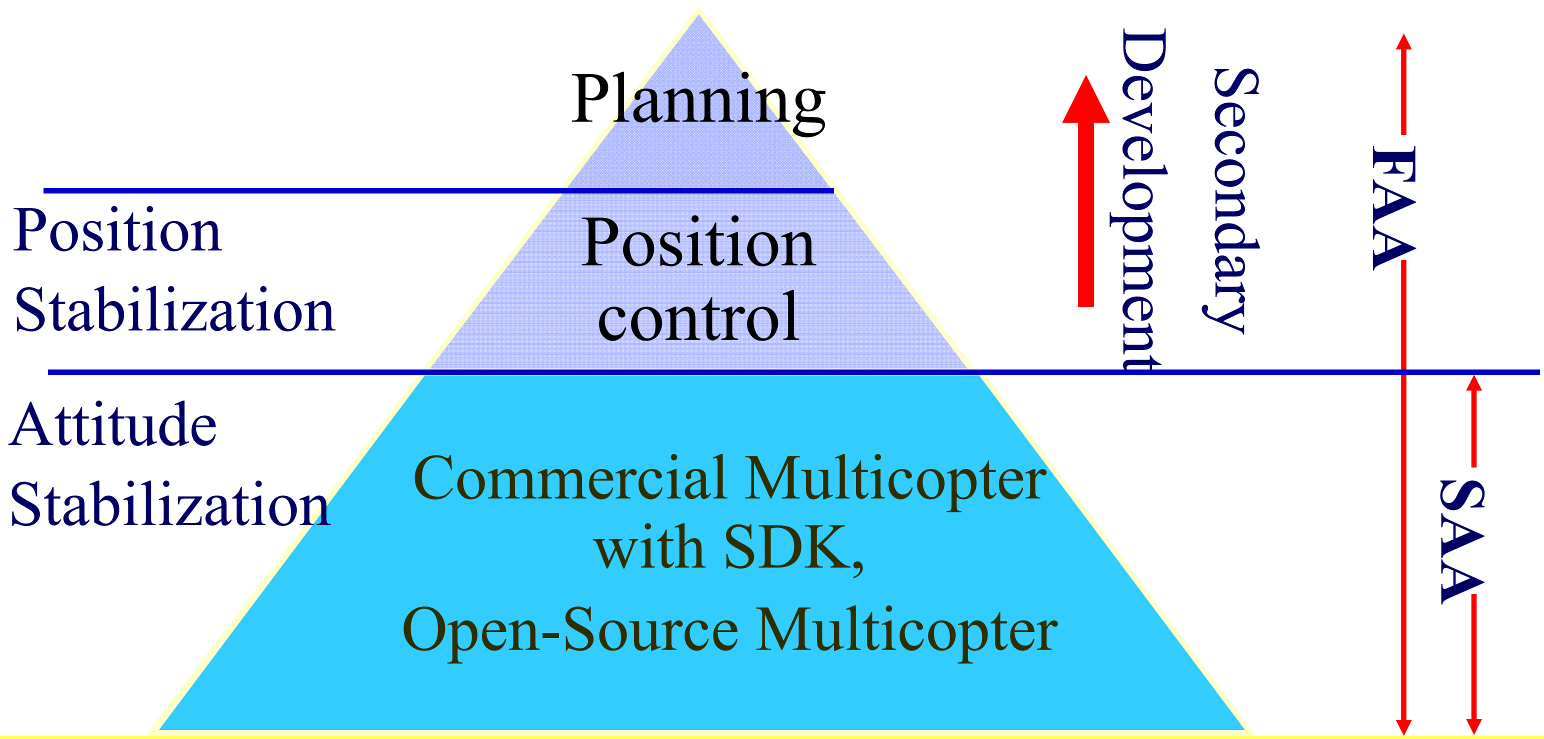
Semi-Autonomous Autopilot Based Development



SAA: Semi-Autonomous Autopilot, FAA: Fully-Autonomous Autopilot

1. Problem Formulation

☐ Semi-Autonomous Autopilot Based Development



Not only can it avoid the trouble of modifying the low-level source code of autopilots, but also it can utilize commercial reliable autopilots to achieve targets.

1. Problem Formulation

Semi-Autonomous Autopilot Based Development

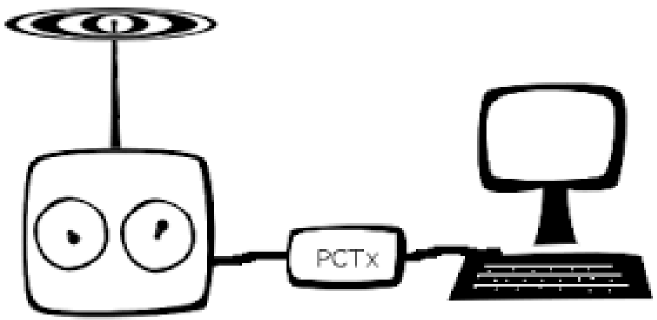
Table 1.1 Major open source Projects

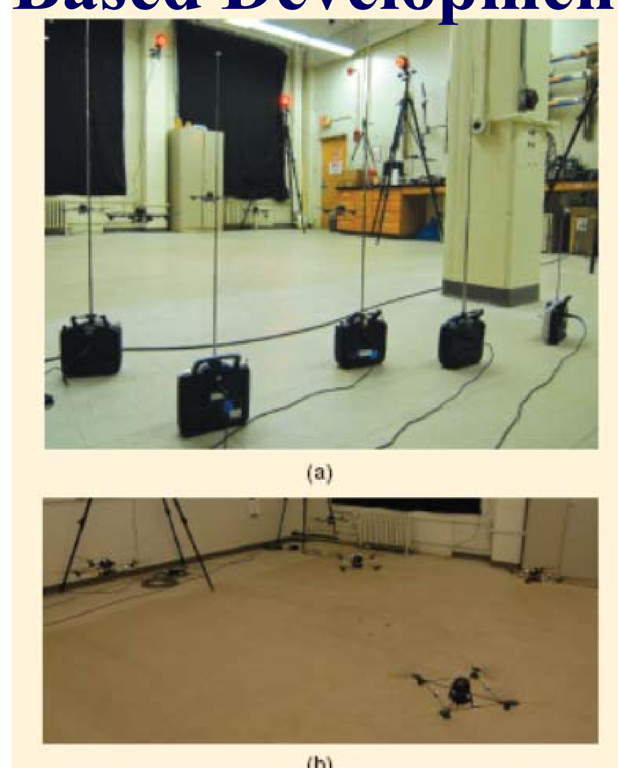
Open-Source Projects	Web site URL
Ardupilot	http://ardupilot.com
Openpilot	http://www.openpilot.org/
Paparazzi	http://paparazziuav.org
Pixhawk	https://pixhawk.ethz.ch/
Mikrokopter	http://www.mikrokopter.de
KKmulticopter	http://www.kkmulticopter.kr/
Multiwii	http://www.multiwii.com/
Aeroquad	http://www.aeroquadstore.com/
Crazyflie	https://www.bitcraze.io/category/crazyflie/
CrazePony	http://www.crazepony.com/
DR. R&D	http://www.etootle.com/
ANO	http://www.anotc.com/
Autoquad	http://autoquad.org/
MegaPirate	http://megapiratex.com/index.php
Erlerobot	http://erlerobotics.com/
MegaPirateNG	http://code.google.com/p/megapirateng

Open-Source Projects	Web site URL
Taulabs	http://forum.taulabs.org/
Flexbot	http://www.flexbot.cc/
Dronecode	https://www.dronecode.org/
Percepto	http://www.percepto.co/
Parrot API(SDK)	https://projects.ardrone.org/embedded/ardrone-api/index.html
3DR DRONEKIT(SDK)	http://www.dronekit.io/
DJI DEVELOPER(SDK)	http://dev.dji.com/cn
DJI MATRICE 100+ DJI Guidance	https://developer.dji.com/cn/matrice-100/
SDK for XMission(SDK)	http://www.xaircraft.cn/en/xmission/developer
EHANG GHOST SDK(SDK)	http://dev.ehang.com/

1. Problem Formulation

Semi-Autonomous Autopilot Based Development



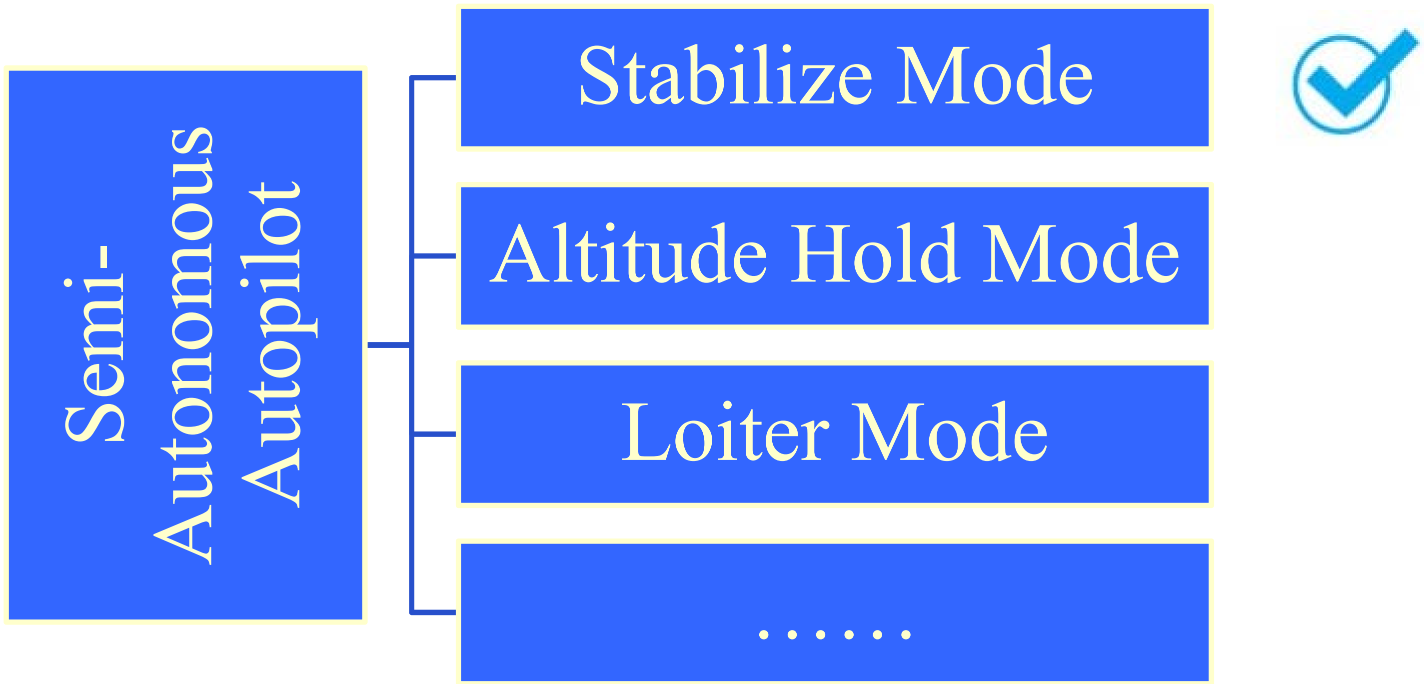


Real-Time Indoor Autonomous
Vehicle Test Environment，MIT

[1] How J P, et al. Real-time indoor autonomous vehicle test environment. IEEE Transaction on Control Systems, 2008, 28(2): 51-64.

1. Problem Formulation

☐ Structure of Multicopter with SAA



A position controller is designed based on the stabilize mode, which is the most basic mode among the three commonly-used modes.

1. Problem Formulation

Structure of Multicopter with SAA

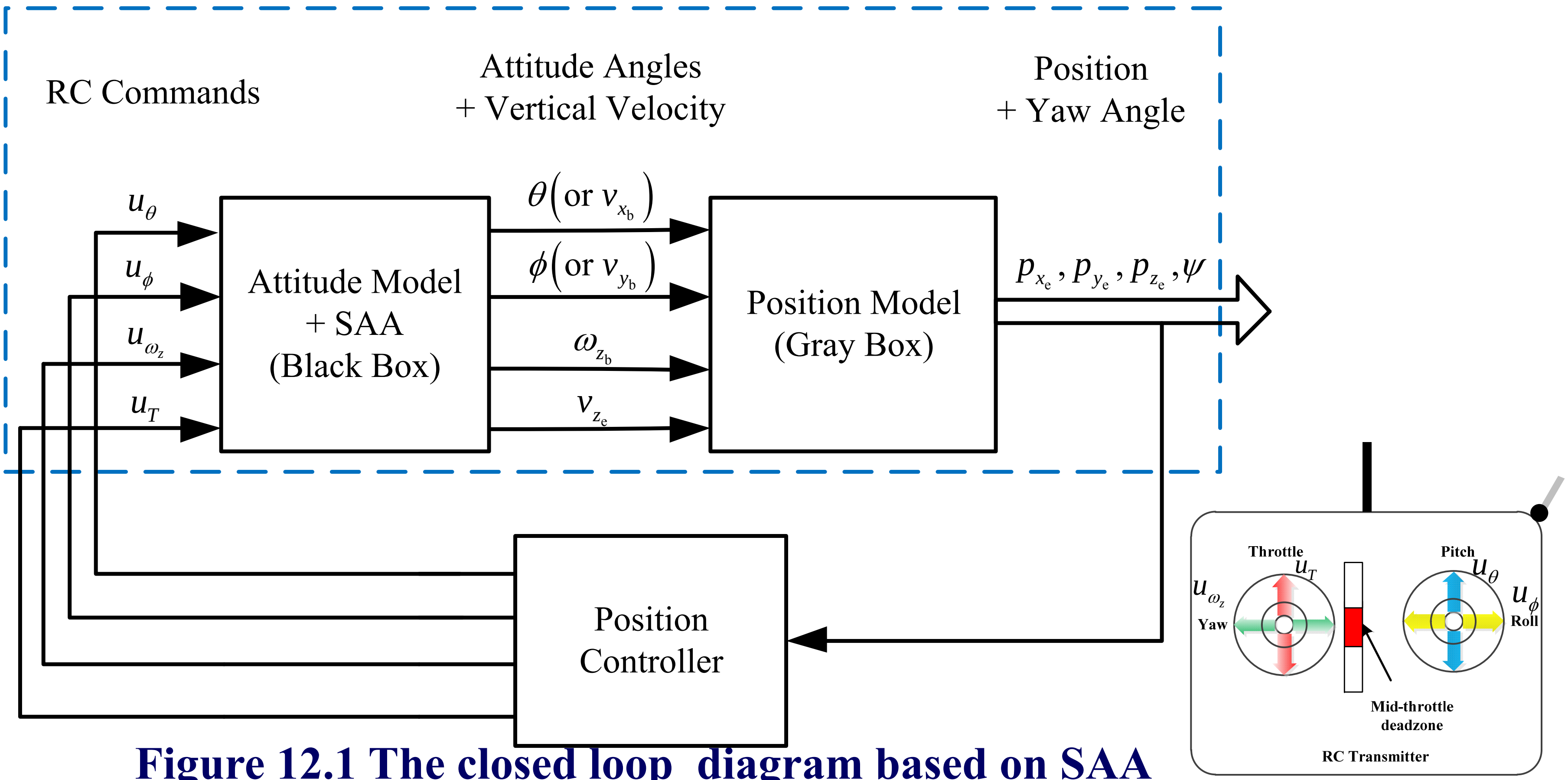
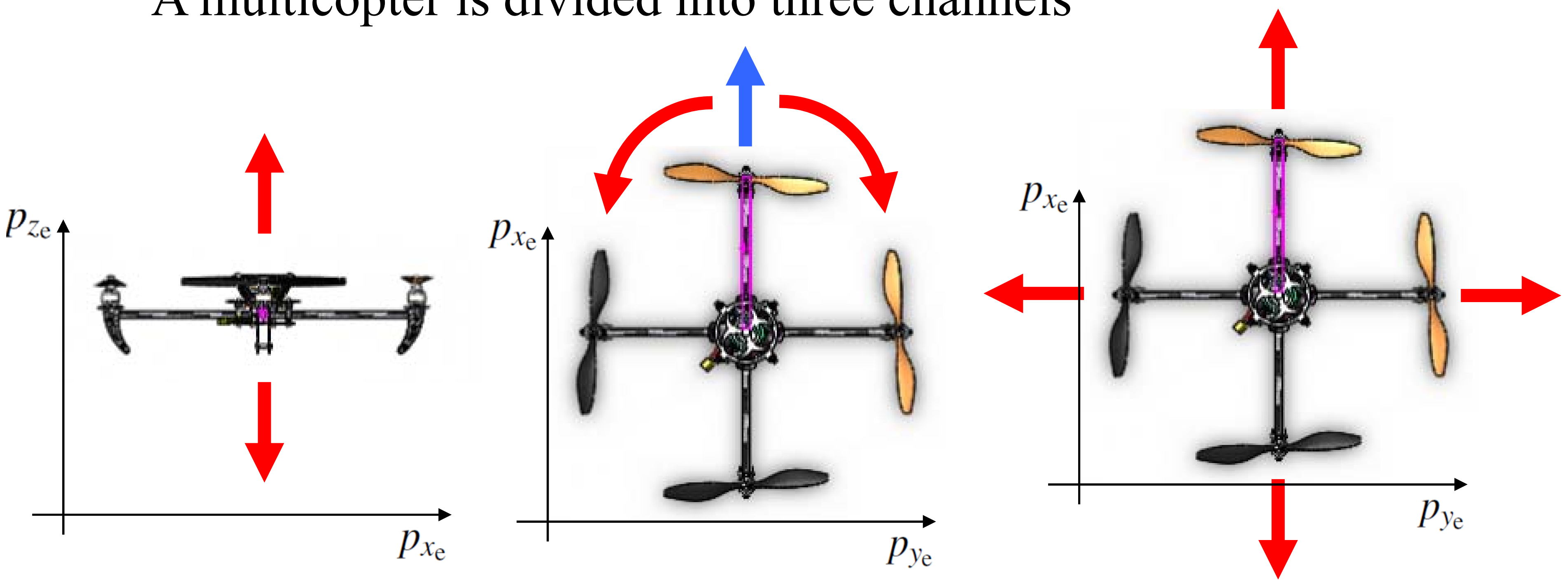


Figure 12.1 The closed loop diagram based on SAA

1. Problem Formulation

□ Models of Three Channels

A multicopter is divided into three channels



Altitude Channel   Yaw Channel   Horizontal position channel

1. Problem Formulation

Models of Three Channels (Assumptions)

Altitude Channel

$$\dot{p}_{z_e} = v_{z_e}$$

$$\dot{v}_{z_e} = -\boxed{k_{v_z}} v_{z_e} - \boxed{k_{u_T}} u_T$$

Yaw Channel

$$\dot{\psi} = \omega_z$$

$$\dot{\omega}_z = -\boxed{k_{\omega_z}} \omega_z + \boxed{k_{u_{\omega_z}}} u_{\omega_z}$$

Horizontal position channel

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

$$\dot{\mathbf{v}}_{\mathrm{h_b}} = -\boxed{\mathbf{K}_{\mathbf{v}_{\mathrm{h_b}}}} \mathbf{v}_{\mathrm{h_b}} - g \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \mathbf{\Theta}_{\mathrm{h}}$$

$$\dot{\mathbf{\Theta}}_{\mathrm{h}} = \boldsymbol{\omega}_{\mathrm{h_b}}$$

$$\dot{\boldsymbol{\omega}}_{\mathrm{h_b}} = -\boxed{\mathbf{K}_{\mathbf{\Theta}_{\mathrm{h}}}} \mathbf{\Theta}_{\mathrm{h}} - \boxed{\mathbf{K}_{\boldsymbol{\omega}_{\mathrm{h_b}}}} \boldsymbol{\omega}_{\mathrm{h_b}} + \boxed{\mathbf{K}_{\mathbf{u}_{\mathrm{h}}}} \mathbf{u}_{\mathrm{h}}$$

Parameters depending on Multicopter and Autopilot are Unknown.

1. Problem Formulation

□ Objective of Position Control

Given a reference trajectory， it consists two parts:

$$\boxed{\mathbf{p}_{\mathrm{d}}(t) \quad \text{and} \quad \psi_{\mathrm{d}}(t)}$$

Objective is to design extra position controller satisfying

$$\boxed{\left\|\mathbf{x}(t)-\mathbf{x}_{\mathrm{d}}(t)\right\| \to 0 \quad \text{or} \quad \mathbf{x}(t)-\mathbf{x}_{\mathrm{d}}(t) \to \mathcal{B}(\mathbf{0}_{4\times 1},\delta)}$$

$$\mathbf{x}=\begin{bmatrix}\mathbf{p}^{\mathrm{T}} & \psi\end{bmatrix}^{\mathrm{T}} \qquad\qquad \mathbf{x}_{\mathrm{d}}=\begin{bmatrix}\mathbf{p}_{\mathrm{d}}^{\mathrm{T}} & \psi_{\mathrm{d}}\end{bmatrix}^{\mathrm{T}}$$

$\mathcal{B}(\mathbf{0}_{4\times 1},\delta)$ Is a ball with the center at zero and radius δ 。

2. System Identification

☐ Objective

The purpose of the identification is to obtain the parameters of the transfer functions. This will facilitate the controller design.

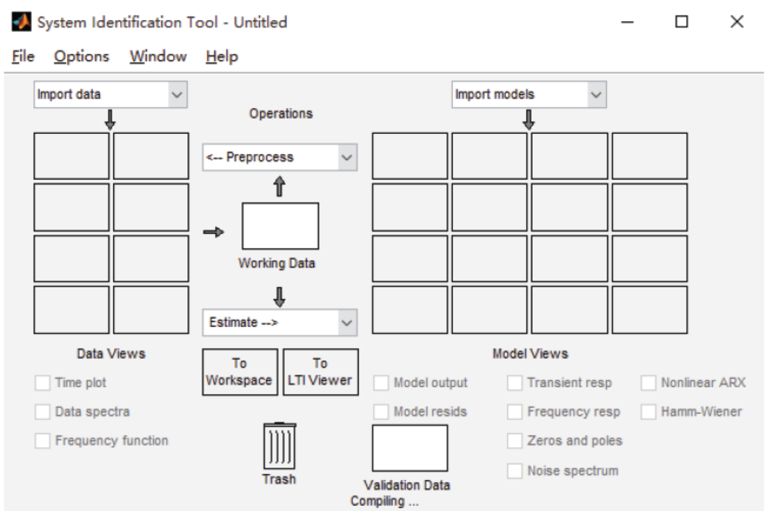


Figure 12.2 System Identification Toolbox of MATLAB.

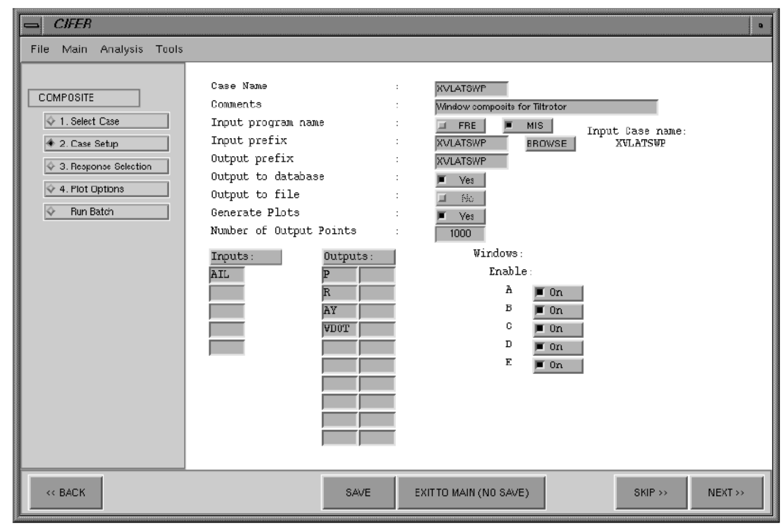


Figure 12.3 Comprehensive Identification from FrEquency Responses(CIFER) toolbox.

2. System Identification

□ Procedure

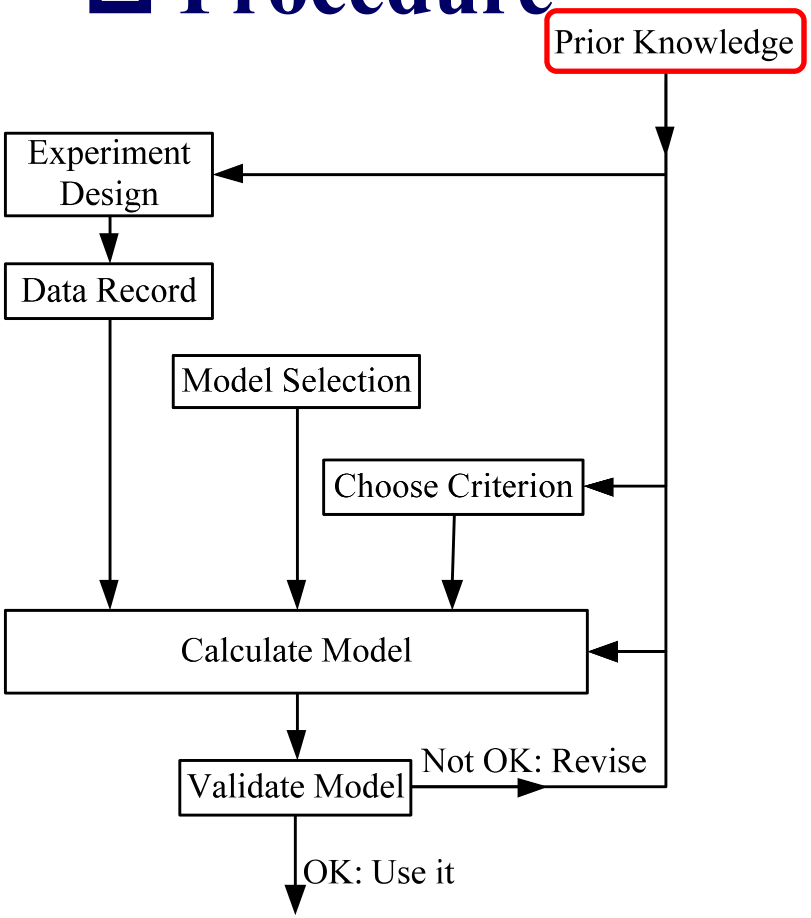


Figure 12.4 The procedure of system identification

1. Prior Knowledge. The prior knowledge means the existing knowledge about the characteristics of the system, the data recording methods and other aspects of the system. This knowledge is very helpful to choose the candidate models, design the experiment, and determine the calculation method and the criterion of validation. Because of the different goals of identifications, the required prior knowledge may be very different, even for the same system.

2. System Identification

☐ Procedure

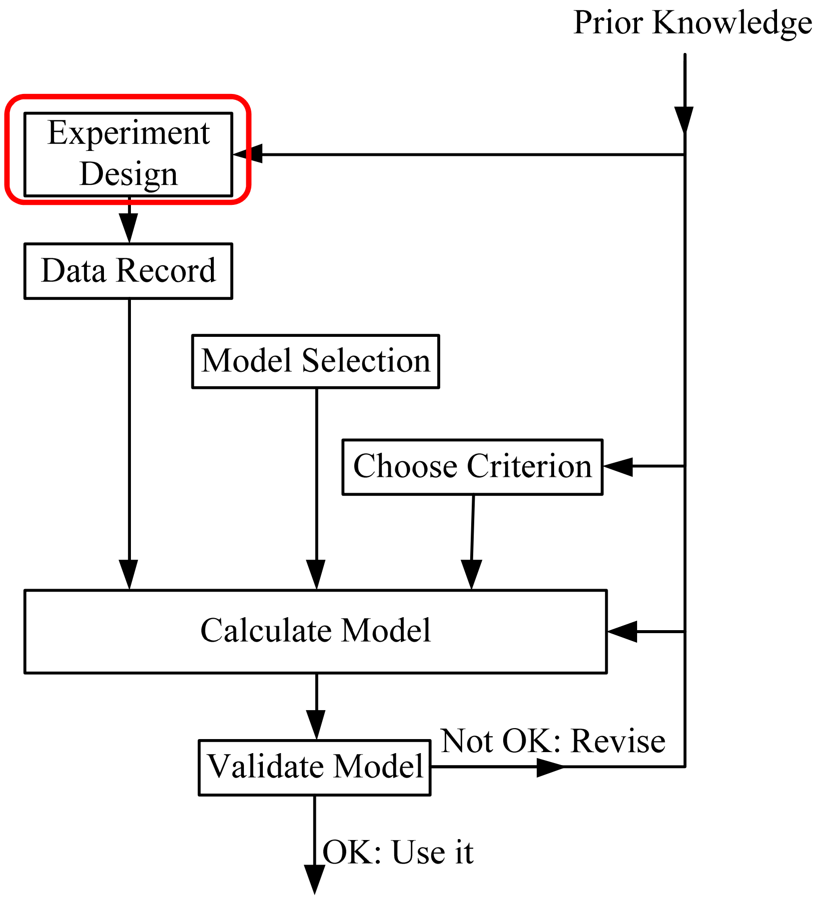


Figure 12.4 The procedure of system identification

2. Experiment design. The purpose of the experiment design is to obtain the input-output data of the system, which can reveal the system performance as much as possible under known conditions. The input-output data are sometimes recorded during a specifically designed identification experiment, where the user may determine which signals to measure and when to measure them.

2. System Identification

□ Procedure

There are two kinds of experiments for system identification: open-loop experiments and closed-loop experiments, which are shown in Figure 12.3(a)(b), respectively.

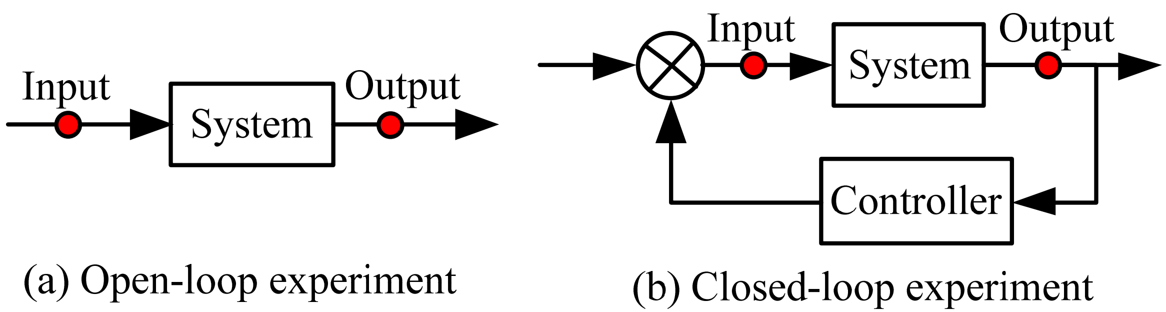


Figure 12.5 Two kinds of experiments for system identification

- The excitation for open-loop experiments are richer than that of closed-loop experiments, because any input signal can be selected in open-loop experiments. Obviously, if systems can work without controllers, open-loop experiments are the better choices.
- Some systems are unstable, and they must work with feedback controllers. As a result, the input signals are decided by the controllers.

2. System Identification

☐ Procedure

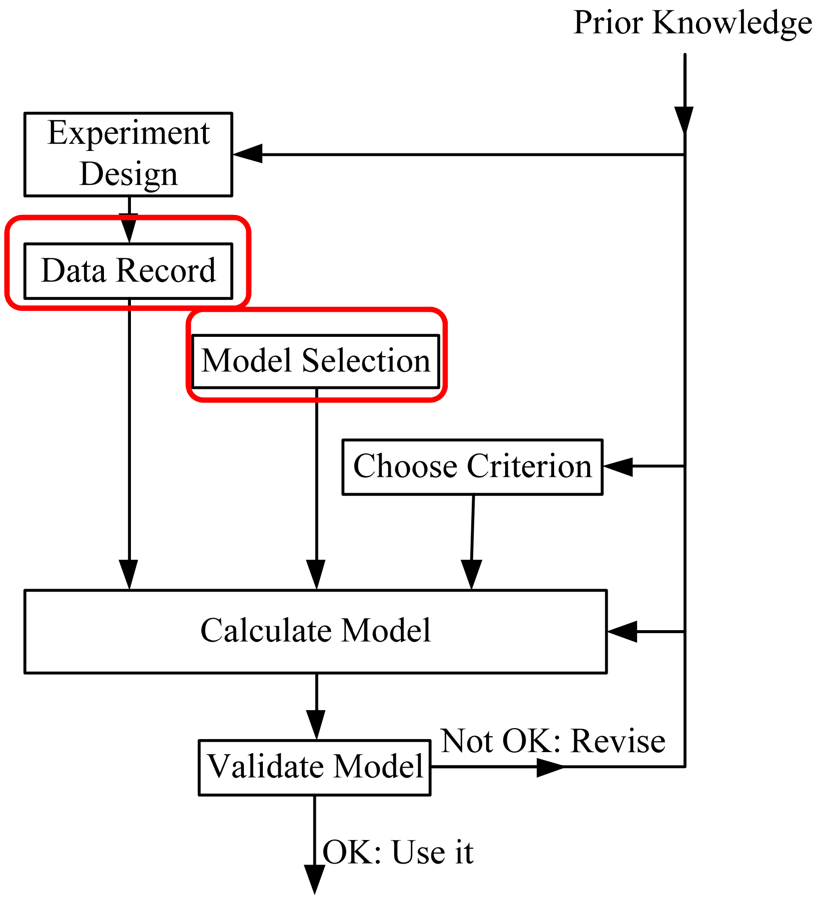


Figure 12.4 The procedure of system identification

3. Data record. Observe the input-output data through the designed experiment.

4. Model selection. Choose a set of candidate models and determine which one of them is the most suitable model through the validation. Through the mathematical modeling, a parametric model with unknown parameters can be obtained. Then, the unknown parameters can be calculated by parametric identification methods.

2. System Identification

□ Procedure

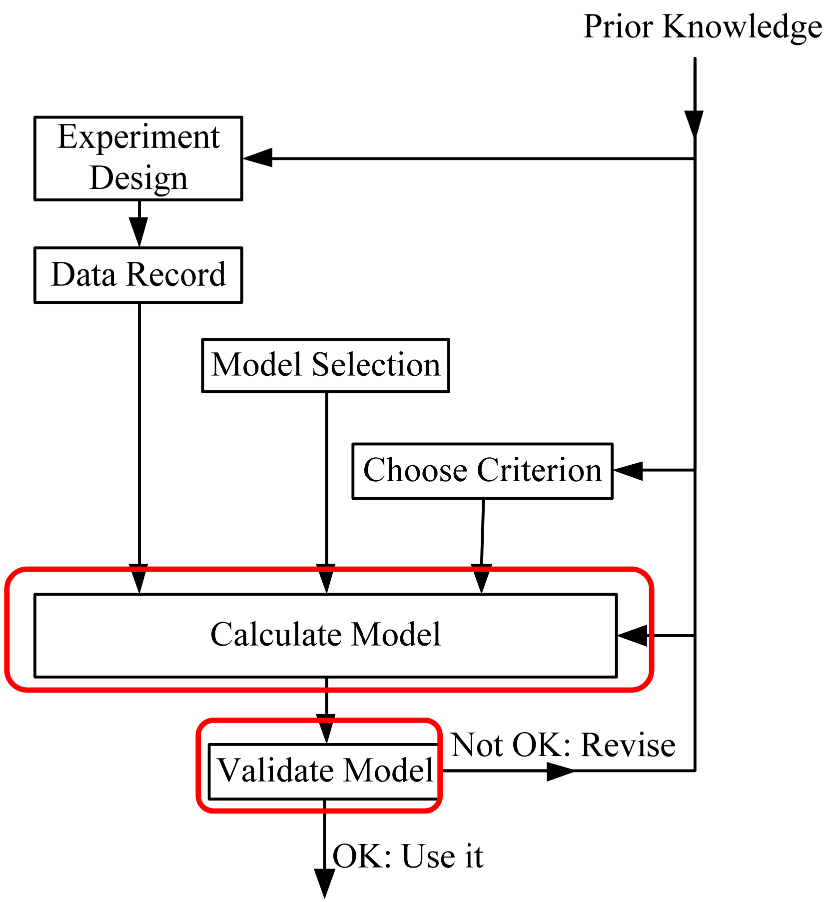


Figure 12.4 The procedure of system identification

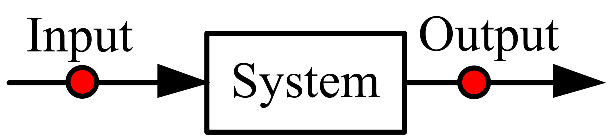
5. Model calculation. The model calculation means that the unknown parameters of the candidate model are determined by appropriate optimization methods.

6. Model validation. A criterion is determined to test whether the candidate model with the calculated parameters is valid for the designed purpose. In general, this criterion relies on the observation data, the prior knowledge, and the application of the identified model. If the model with the parameters passes the validation, it will be chosen as the final model. If not, the previous steps need to be revised.

2. System Identification

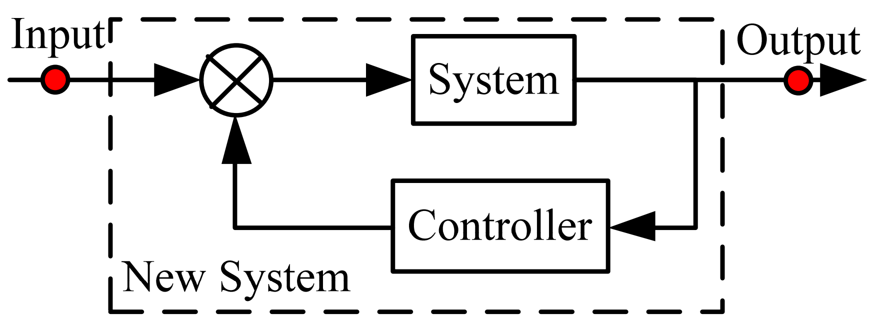
□ Model used in System Identification

1. Altitude Channel



The modification can be used for identification on new systems. But, the original system is still unknown.

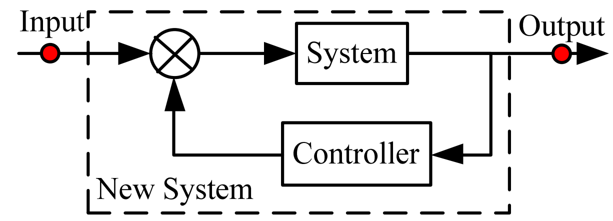
A trade-off open-loop system identification



2. System Identification

□ Model used in System Identification

1. Altitude Channel



Unstable

$$\dot{p}_{z_e} = v_{z_e}$$

$$\dot{v}_{z_e} = -k_{v_z} v_{z_e} - k_{u_T} u_T$$

Controller redesign

$$u_T = k_{p_z} p_{z_e} + u_{p_z}$$

Stable

$$\dot{p}_{z_e} = v_{z_e}$$

$$\dot{v}_{z_e} = -k_{u_T} k_{p_z} p_{z_e} - k_{v_z} v_{z_e} - k_{u_T} u_{p_z}$$

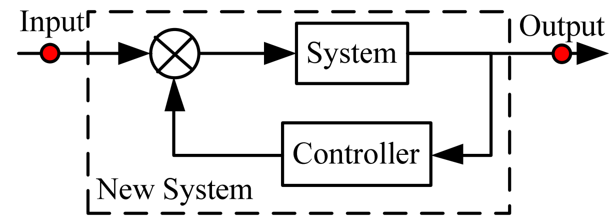
Candidate Model

$$\boxed{p_{z_e}(s)} = G_{p_z u_{p_z}}(s) \boxed{u_{p_z}(s)}$$

2. System Identification

□ Model used in System Identification

2. Yaw Channel



Unstable

$$\dot{\psi} = \omega_z$$

$$\dot{\omega}_z = -k_{\omega_z}\omega_z + k_{u_{\omega_z}} u_{\omega_z}$$

$$u_{\omega_z} = -k_\psi \psi + u_\psi$$

Stable

$$\dot{\psi} = \omega_z$$

$$\dot{\omega}_z = -k_{u_{\omega_z}} k_\psi \psi - k_{\omega_z}\omega_z + k_{u_{\omega_z}} u_\psi$$

Candidate Model

$$\boxed{\psi(s)} = G_{\psi u_\psi}(s)\boxed{u_\psi(s)}$$

Model used in System Identification

3. Horizontal Position Channel

The horizontal position channel is identified after the other two channels are well controlled. In this situation, under the controller of the yaw channel, $\psi \approx \psi_{\mathrm{d}}$ is satisfied. Then, $\mathbf{R}_{\psi}$ is a constant matrix. The transfer function of horizontal position channel is expressed as follows

$$\begin{aligned}\mathbf{p}_{\mathrm{h_e}}(s) &= \mathrm{diag}\left(\frac{1}{s},\frac{1}{s}\right)\mathbf{R}_{\psi}\mathbf{G}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathrm{h}}}(s)\mathbf{u}_{\mathrm{h}}(s)\\ &= \mathbf{R}_{\psi}\mathrm{diag}\left(\frac{1}{s},\frac{1}{s}\right)\mathbf{G}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathrm{h}}}(s)\mathbf{u}_{\mathrm{h}}(s)\end{aligned}$$

This channel is harder to control than the other two channels because of the influence of $\mathbf{R}_{\psi}$. Thus, the horizontal velocity controller is designed in the following part.

2. System Identification

□ Model used in System Identification

3. Horizontal Position Channel

For the SAA which contains a velocity feedback controller, $\mathbf{K}_{\mathbf{v}_{\mathrm{h}}}$ is reasonable. The transfer function $\mathbf{G}_{\mathbf{v}_{\mathrm{b}}\mathbf{u}_{\mathbf{v}_{\mathrm{h}}}}(s)$ is stable in channel and it can be identified directly. Otherwise

$$\dot{\mathbf{v}}_{\mathrm{h_b}} = -\mathbf{K}_{\mathbf{v}_{\mathrm{h_b}}}\mathbf{v}_{\mathrm{h_b}} - g\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\boldsymbol{\Theta}_{\mathrm{h}}$$

$$\dot{\boldsymbol{\Theta}}_{\mathrm{h}} = \boldsymbol{\omega}_{\mathrm{h_b}}$$

$$\dot{\boldsymbol{\omega}}_{\mathrm{h_b}} = -\mathbf{K}_{\boldsymbol{\Theta}_{\mathrm{h}}}\boldsymbol{\Theta}_{\mathrm{h}} - \mathbf{K}_{\boldsymbol{\omega}_{\mathrm{h_b}}}\boldsymbol{\omega}_{\mathrm{h_b}} + \mathbf{K}_{\mathbf{u}_{\mathrm{h}}}\mathbf{u}_{\mathrm{h}}$$

$$\mathbf{u}_{\mathrm{h}} = -\mathbf{K}'_{\mathbf{v}_{\mathrm{h_b}}}\mathbf{v}_{\mathrm{h_b}} + \mathbf{u}_{\mathbf{v}_{\mathrm{h}}}$$

$$\dot{\mathbf{v}}_{\mathrm{h_b}} = -\mathbf{K}_{\mathbf{v}_{\mathrm{h_b}}}\mathbf{v}_{\mathrm{h_b}} - g\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\boldsymbol{\Theta}_{\mathrm{h}}$$

$$\dot{\boldsymbol{\Theta}}_{\mathrm{h}} = \boldsymbol{\omega}_{\mathrm{h_b}}$$

$$\dot{\boldsymbol{\omega}}_{\mathrm{h_b}} = -\mathbf{K}_{\mathbf{u}_{\mathrm{h}}}\mathbf{K}'_{\mathbf{v}_{\mathrm{h_b}}}\mathbf{v}_{\mathrm{h_b}} - \mathbf{K}_{\boldsymbol{\Theta}_{\mathrm{h}}}\boldsymbol{\Theta}_{\mathrm{h}} - \mathbf{K}_{\boldsymbol{\omega}_{\mathrm{h_b}}}\boldsymbol{\omega}_{\mathrm{h_b}} + \mathbf{K}_{\mathbf{u}_{\mathrm{h}}}\mathbf{u}_{\mathbf{v}_{\mathrm{h}}}$$

$$\boxed{\mathbf{v}_{\mathrm{h_b}}(s)} = \mathbf{G}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathbf{v}_{\mathrm{h}}}}(s)\boxed{\mathbf{u}_{\mathbf{v}_{\mathrm{h}}}(s)}$$

3. Position Controller Design

PID Controller

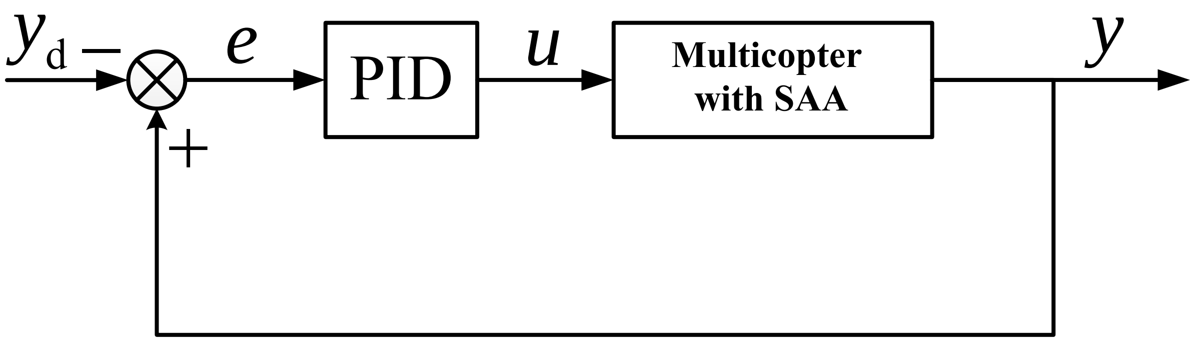


Figure 12.5 PID controller

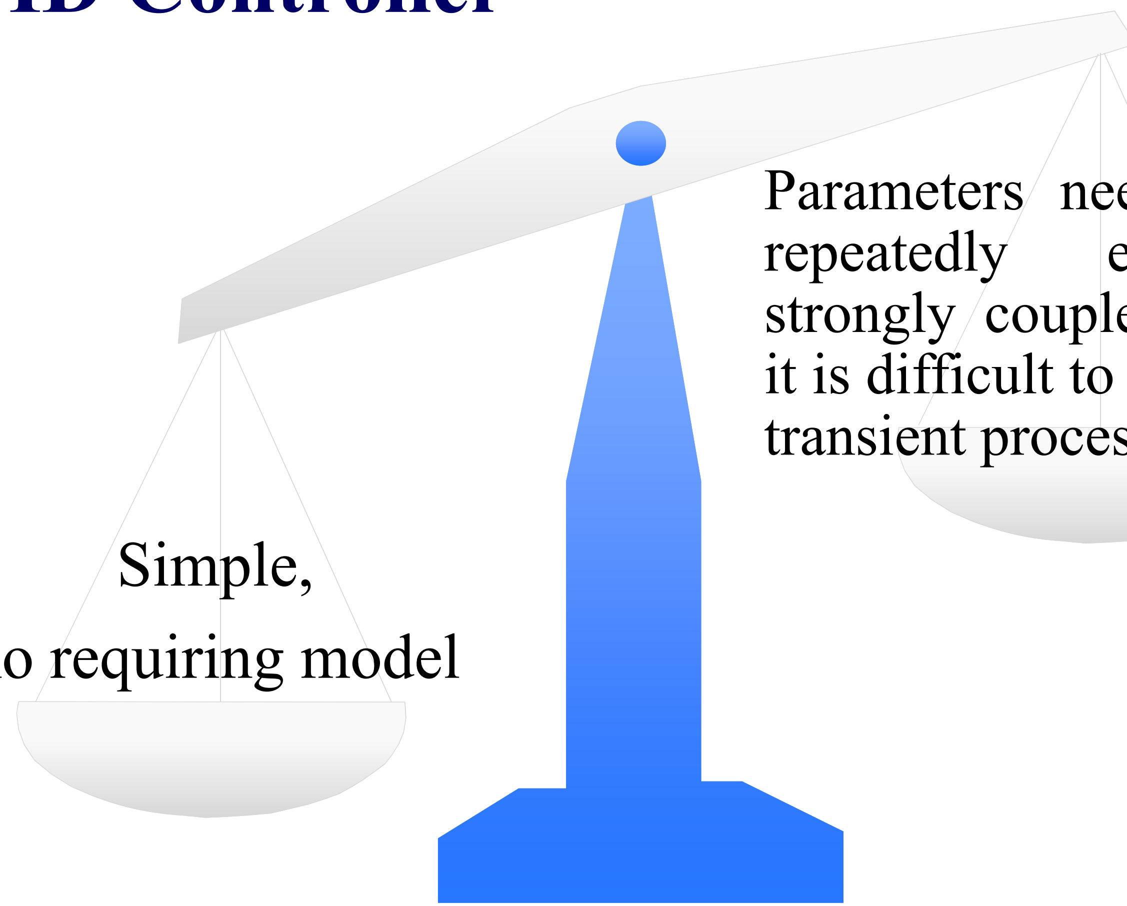
$$u_T = -k_{p_z\mathrm{p}}\left(p_{z_e} - p_{z_e\mathrm{d}}\right) - k_{p_z\mathrm{d}}\left(\dot{p}_{z_e} - \dot{p}_{z_e\mathrm{d}}\right) - k_{p_z\mathrm{i}}\int\left(p_{z_e} - p_{z_e\mathrm{d}}\right)$$

$$u_{\omega_z} = -k_{\psi\mathrm{p}}\left(\psi - \psi_\mathrm{d}\right) - k_{\psi\mathrm{d}}\left(\omega_z - \dot{\psi}_\mathrm{d}\right) - k_{\psi\mathrm{i}}\int\left(\psi - \psi_\mathrm{d}\right)$$

$$\mathbf{u}_\mathrm{h} = -\mathbf{K}_\mathrm{hp}\mathbf{R}_\psi^{-1}\left(\mathbf{p}_\mathrm{h} - \mathbf{p}_\mathrm{hd}\right) - \mathbf{K}_\mathrm{hd}\mathbf{R}_\psi^{-1}\left(\dot{\mathbf{p}}_\mathrm{h} - \dot{\mathbf{p}}_\mathrm{hd}\right) - \mathbf{K}_\mathrm{hi}\int\mathbf{R}_\psi^{-1}\left(\mathbf{p}_\mathrm{h} - \mathbf{p}_\mathrm{hd}\right)$$

3. Position Controller Design

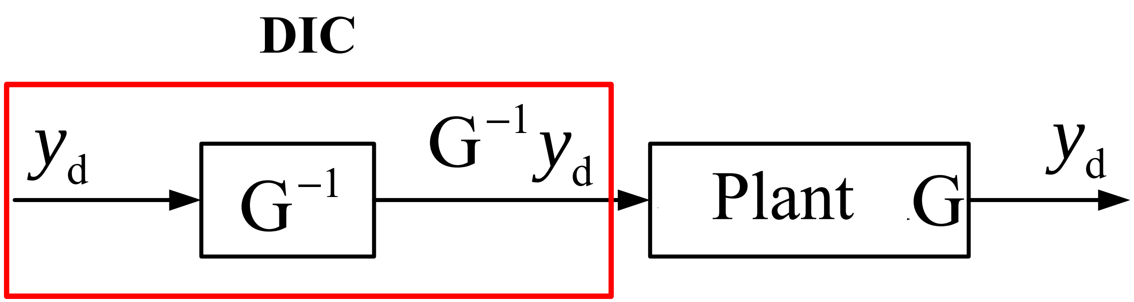
□ PID Controller



3. Position Controller Design

□ AOD-Based DIC

1. Idea of DIC



1. In practice, G is unknown, but it can be identified as $\hat{G}$ approximately
2. There have differences between G and $\hat{G}$. How to deal with?

AOD: Additive Output Decomposition, DIC: Dynamic Inversion Control

3. Position Controller Design

□ AOD-Based DIC[2]

1. Idea of DIC

$$\dot{x} = f(t,x,u)$$
$$y = h(t,x)$$

$$y(t) = y_p(t) + y_s(t)$$

$$\dot{x}_p = f_p(t,x_p,u_p)$$
$$y_p = h_p(t,x_p)$$

$$+$$

$$\dot{x}_s = f_s(t,x_s,u_s)$$
$$y_s = h_s(t,x_s) - h_p(t,x_p)$$

AOD for transfer functions：

$$y = Gu + d \xrightarrow{y_s \triangleq y - y_p} y_p = G_p u_p + y_s = Gu + d - G_p u_p$$

[2] Quan Quan, Kai-Yuan Cai. Additive-Output-Decomposition-Based Dynamic Inversion Tracking Control for a Class of Uncertain Linear Time-Invariant Systems. The 51st IEEE Conference on Decision and Control, 2012, Maui, Hawaii, USA, 2866-2871.

3. Position Controller Design

AOD-Based DIC

2. Altitude channel

$$\boxed{p_{z_e}(s)=G_{p_z u_{p_z}}(s)u_{p_z}(s)} \xrightarrow{\text{Identification}} p_{z_e\mathrm{p}}(s)=\hat{G}_{p_z u_{p_z}}(s)u_{p_z\mathrm{p}}(s)$$

AOD:

$$p_{z_e\mathrm{p}}(s)=\hat{G}_{p_z u_{p_z}}(s)u_{p_z\mathrm{p}}(s)$$

$$p_{z_e\mathrm{s}}(s)=G_{p_z u_{p_z}}(s)u_{p_z}(s)-\hat{G}_{p_z u_{p_z}}(s)u_{p_z\mathrm{p}}(s)$$

$$d_{p_z1}=\left(G_{p_z u_{p_z}}(s)-\hat{G}_{p_z u_{p_z}}(s)\right)u_{p_z}(s)$$

$$|||$$

$$\hat{d}_{p_z1}=p_{z_e}(s)-\hat{G}_{p_z u_{p_z}}(s)u_{p_z}(s)$$

$$p_{z_e\mathrm{p}}(s)=\hat{G}_{p_z u_{p_z}}(s)u_{p_z}(s)$$

$$p_{z_e}(s)=p_{z_e\mathrm{p}}(s)+d_{p_z1}(s)$$

AOD-Based DIC

2. Altitude channel

AOD-Based DIC: $u_{p_z}(s) = \hat{G}^{-1}_{p_z u_{p_z}}(s)\left(p_{z_e\mathrm{d}}(s) - d_{p_z 1}(s)\right)$

Unrealizable, so a low-pass filter is adopted $Q_{p_z u_{p_z}}(s)$

$Q_{p_z u_{p_z}}(s)\hat{G}^{-1}_{p_z u_{p_z}}(s)$ is realizable, and $Q_{p_z u_{p_z}}(0) = 1$

$$u_{p_z}(s) = Q_{p_z u_{p_z}}(s)\hat{G}^{-1}_{p_z u_{p_z}}(s)\left(p_{z_e\mathrm{d}}(s) - d_{p_z 1}(s)\right)$$

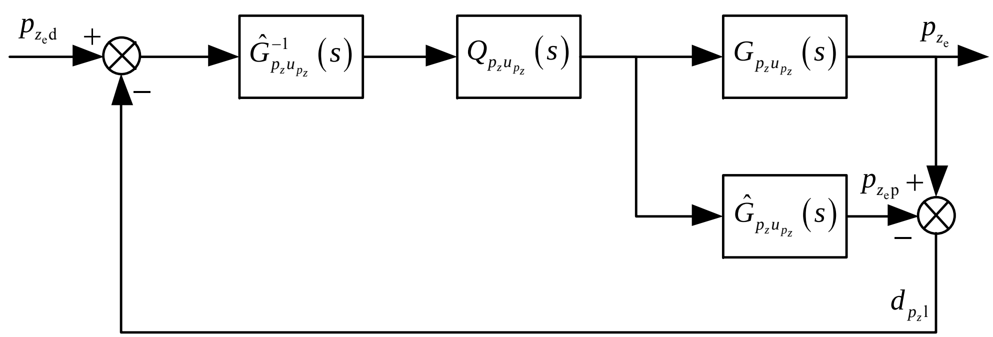


Figure 12.6 The closed-loop system based on AOD-based DIC

3. Position Controller Design

□ AOD-Based DIC

2. Altitude channel

Stability analysis, theorem:

Suppose (1) $\hat{G}_{p_z u_{p_z}}(s)$ is minimum phase;

(2) $Q_{p_z u_{p_z}}(s)$ and $G_{p_z u_{p_z}}(s)$ are stable, and $Q_{p_z u_{p_z}}(0)=1$;

(3) $\sup_{\omega}\left|\left(1-G_{p_z u_{p_z}}(j\omega)\hat{G}^{-1}_{p_z u_{p_z}}(j\omega)\right)Q_{p_z u_{p_z}}(j\omega)\right|<1$;

(4) $p_{z_{\mathrm{e}}\mathrm{d}}$ is constant。

Then u_{p_z} is bounded and $\left|e_{p_z}(t)\right|\to 0$ as $t\to\infty$, where $e_{p_z}\triangleq p_{z_{\mathrm{e}}}-p_{z_{\mathrm{e}}\mathrm{d}}$

Quan Quan, Kai-Yuan Cai. Additive-Output-Decomposition-Based Dynamic Inversion Tracking Control for a Class of Uncertain Linear Time-Invariant Systems. The 51st IEEE Conference on Decision and Control, 2012, Maui, Hawaii, USA, 2866-2871.

3. Position Controller Design

□ AOD-Based DIC

3. Other two channels

$$u_{\psi}(s)=Q_{\psi u_{\psi}}(s)\hat{G}_{\psi u_{\psi}}^{-1}(s)\left(\psi_{\mathrm{d}}(s)-d_{\psi 1}(s)\right)$$

$$d_{\psi 1}(s)=\psi(s)-\hat{G}_{\psi u_{\psi}}(s)u_{\psi}(s)$$

and

$$\mathbf{u}_{\mathbf{v}_{\mathrm{h}}}(s)=\mathbf{Q}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathrm{v_h}}}(s)\hat{\mathbf{G}}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathrm{v_h}}}^{-1}(s)\left(\mathbf{v}_{\mathrm{h_b d}}(s)-\mathbf{d}_{\mathbf{v}_{\mathrm{h}}1}(s)\right)$$

$$\mathbf{d}_{\mathbf{v}_{\mathrm{h}}1}(s)=\mathbf{v}_{\mathrm{h_b}}(s)-\hat{\mathbf{G}}_{\mathbf{v}_{\mathrm{h_b}}\mathbf{u}_{\mathrm{v_h}}}(s)\mathbf{u}_{\mathrm{v_h}}(s)$$

□ AOD-Based DIC

3. Other two channels

The desired horizontal velocity needs to be transformed from the desired horizontal position. First, the transient process is expected as follows

$$\dot{\mathbf{p}}_{\mathrm{h}} - \dot{\mathbf{p}}_{\mathrm{hd}} = -\mathbf{K}_{\mathbf{p}_{\mathrm{h}}}(\mathbf{p}_{\mathrm{h}} - \mathbf{p}_{\mathrm{hd}})$$

where $\mathbf{K}_{\mathbf{p}_{\mathrm{h}}} \in \mathbb{R}^{2\times 2} \cap \mathcal{D} \cap \mathcal{P}$. If so, then $\lim_{t\to\infty}\left\|\mathbf{p}_{\mathrm{h}}(t) - \mathbf{p}_{\mathrm{hd}}(t)\right\| = 0$. Since

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

the desired horizontal velocity should satisfy

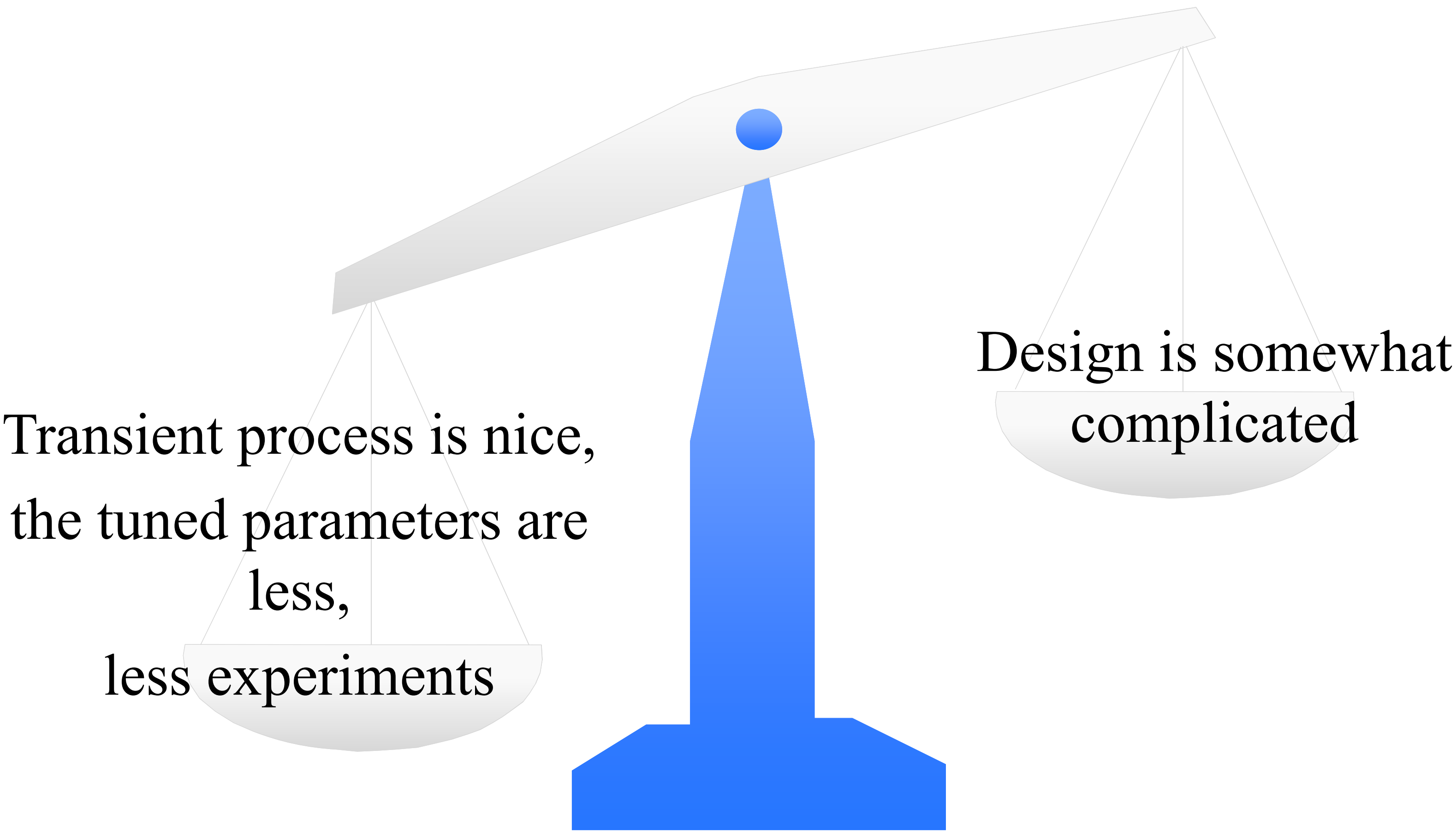
$$\mathbf{R}_{\psi}\mathbf{v}_{\mathrm{h_b d}} = \dot{\mathbf{p}}_{\mathrm{hd}} - \mathbf{K}_{\mathbf{p}_{\mathrm{h}}}(\mathbf{p}_{\mathrm{h}} - \mathbf{p}_{\mathrm{hd}}).$$

Then

$$\mathbf{v}_{\mathrm{h_b d}} = -\mathbf{R}_{\psi}^{-1}\mathbf{K}_{\mathbf{p}_{\mathrm{h}}}(\mathbf{p}_{\mathrm{h}} - \mathbf{p}_{\mathrm{hd}}).$$

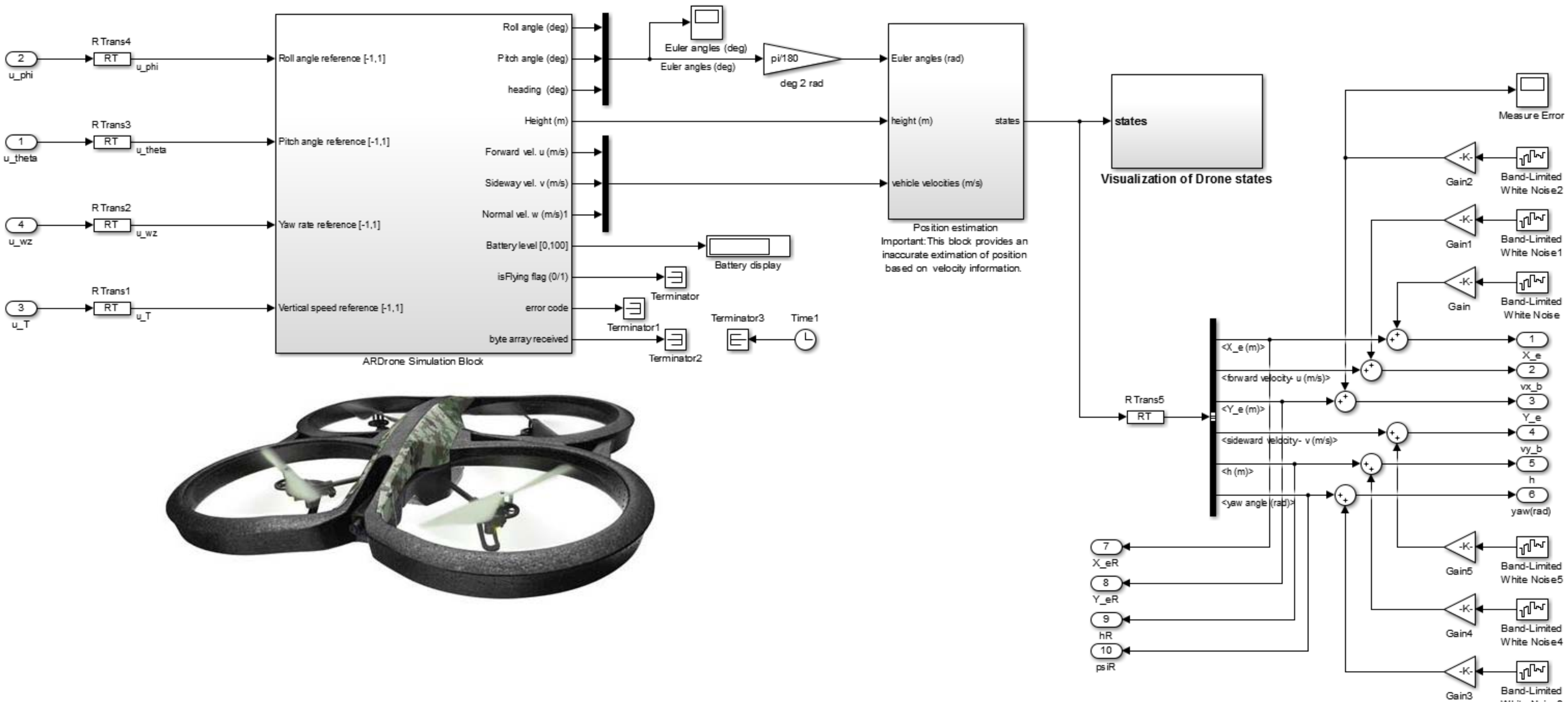
3. Position Controller Design

□ AOD-Based DIC



4. Simulation

□ Plant



Zander J (2013) AR Drone Simulink. https://github.com/justynazander/AR Drone Simulink. Accessed 20 Jan 2016

4. Simulation

□ System Identification

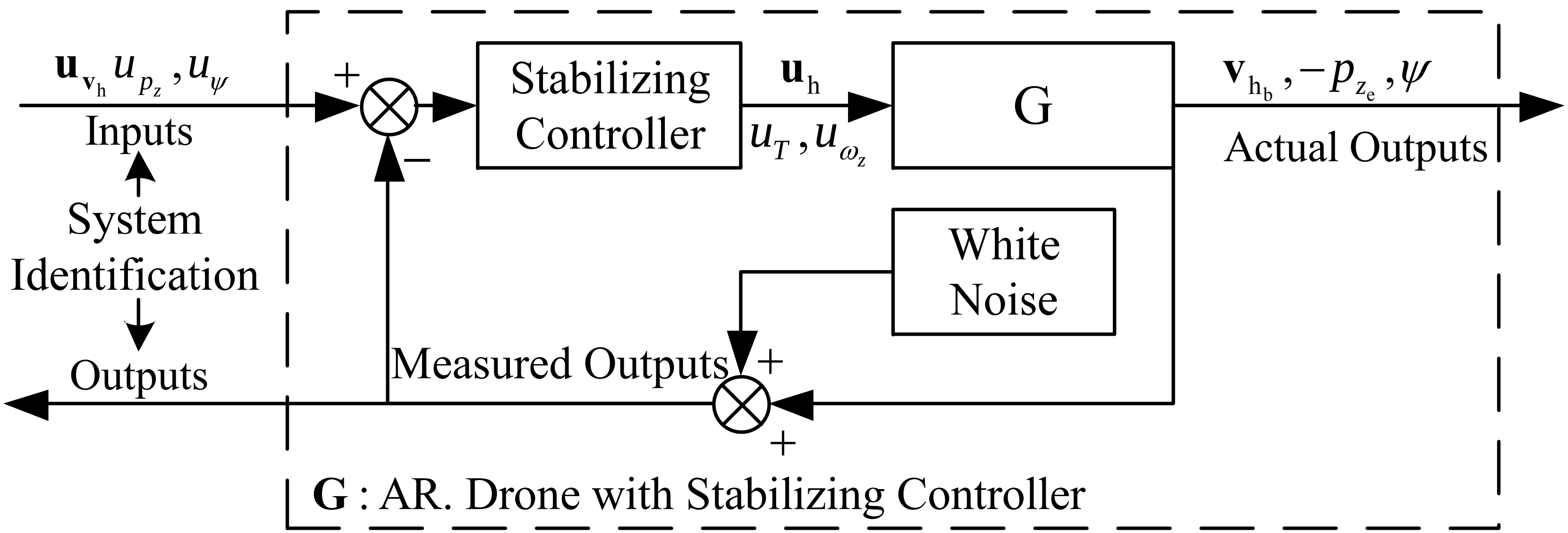


Figure 12.7 The simulation for the system identification

4. Simulation

□ System Identification

1. Prior Knowledge

The models of multicopters are established above are the prior knowledge.

Altitude Channel

$$\dot{p}_{z_e} = v_{z_e}$$
$$\dot{v}_{z_e} = -k_{v_z} v_{z_e} - k_{u_T} u_T$$

Yaw Channel

$$\dot{\psi} = \omega_z$$
$$\dot{\omega}_z = -k_{\omega_z} \omega_z + k_{u_{\omega_z}} u_{\omega_z}$$

Horizontal position channel

$$\dot{\mathbf{p}}_h = \mathbf{R}_\psi \mathbf{v}_{h_b}$$
$$\dot{\mathbf{v}}_{h_b} = -\mathbf{K}_{\mathbf{v}_{h_b}} \mathbf{v}_{h_b} - g \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \mathbf{\Theta}_h$$
$$\dot{\mathbf{\Theta}}_h = \boldsymbol{\omega}_{h_b}$$
$$\dot{\boldsymbol{\omega}}_{h_b} = -\mathbf{K}_{\mathbf{\Theta}_h} \mathbf{\Theta}_h - \mathbf{K}_{\boldsymbol{\omega}_{h_b}} \boldsymbol{\omega}_{h_b} + \mathbf{K}_{\mathbf{u}_h} \mathbf{u}_h$$

4. Simulation

☐ System Identification

2. Experiment design

Before the identification, stabilizing controllers will be employed if needed. The controllers of the altitude channel (also called as z channel) and the yaw channel (also called as ψ channel) are designed as

$$u_T = k_{p_z} p_{z_e} + u_{p_z} \qquad u_{\omega_z} = -k_\psi \psi + u_\psi$$

Here, the desired yaw angle ψ_d is set to 0, so $\mathbf{R}_\psi \approx \mathbf{I}_2$ under the well-designed yaw channel controller and the horizontal position channel is decoupled into x channel and y channel. This means that u_{v_x} controls velocity v_{x_e} through θ, and u_{v_y} controls the velocity v_{y_e} through ϕ. Then

$$\mathbf{v}_{h_b}(s) = \mathbf{G}_{\mathbf{v}_{h_b}\mathbf{u}_{\mathbf{v}_h}}(s)\mathbf{u}_{\mathbf{v}_h}(s) = \begin{bmatrix} G_{v_x u_{v_x}}(s) u_{v_x}(s) \\ G_{v_y u_{v_y}}(s) u_{v_y}(s) \end{bmatrix}$$

4. Simulation

□ System Identification

2. Experiment design

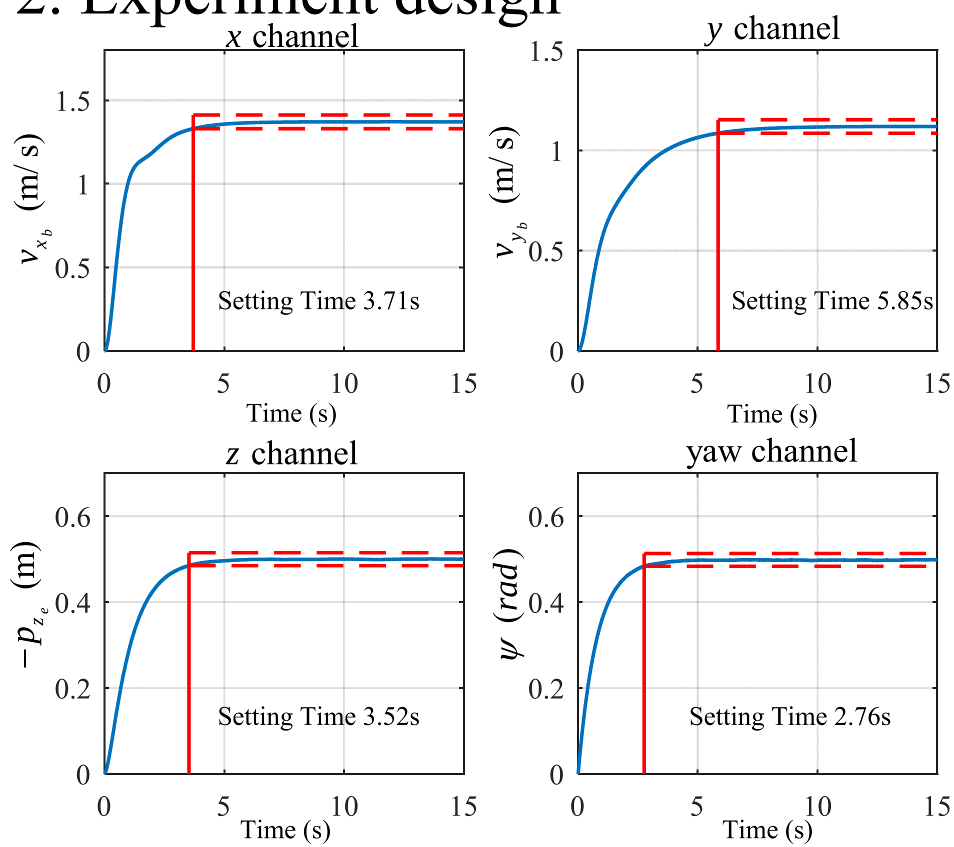


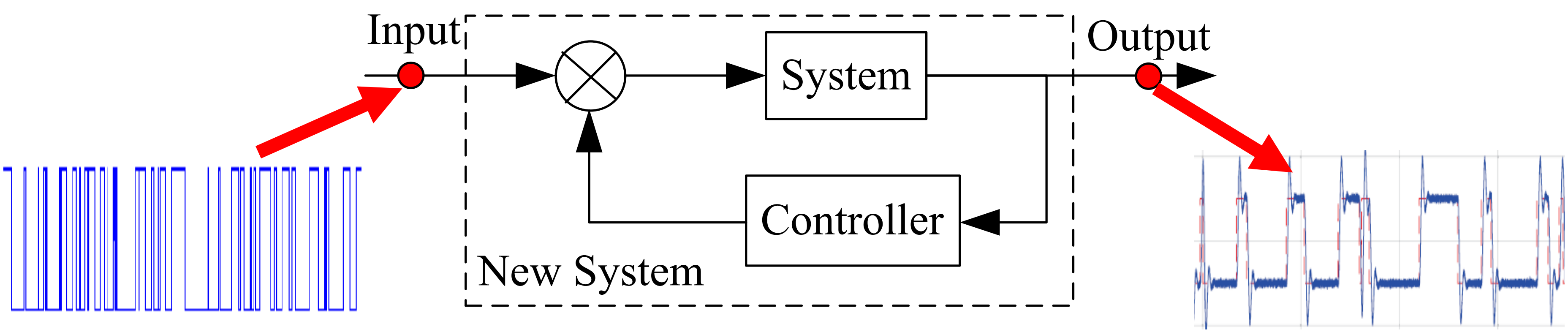
Figure 12.8 The actual step response of each channel under PID controller

Settling time is long!

4. Simulation

System Identification

3. Data record



Pseudo-Random Binary Signals (PRBS) are generated to stimulate these channels.

4. Simulation

☐ System Identification

3. Data record

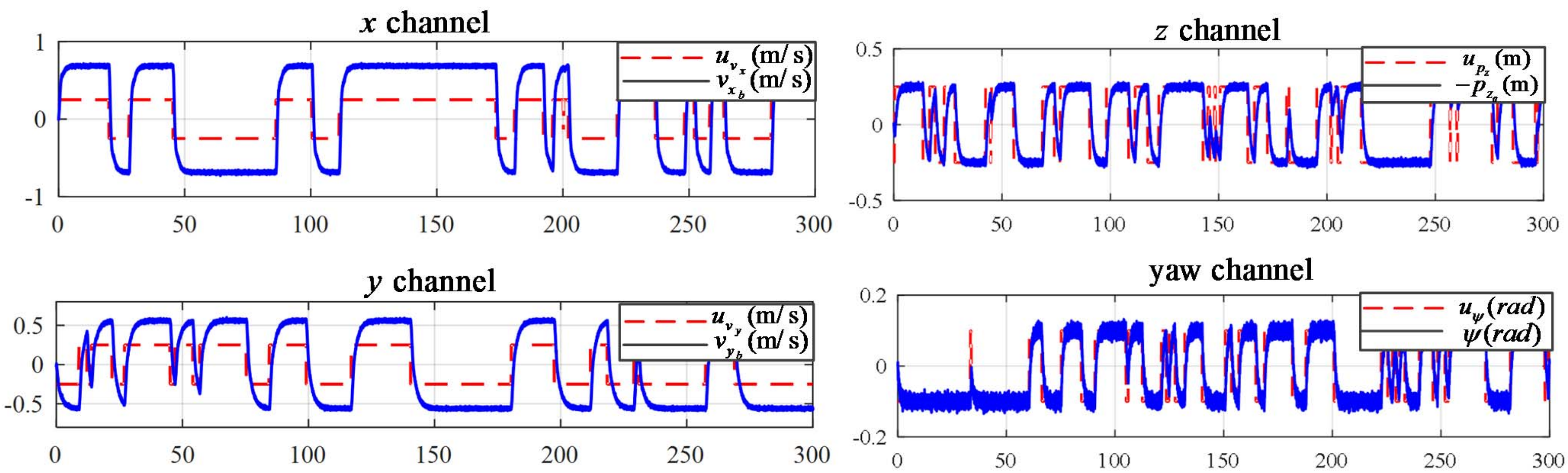


Figure 12.9 The input output data of the four channels used in the identification (The output data are the measured outputs)

4. Simulation

□ System Identification

4. Model selection

The principle of choosing model is

(1) The identification results can pass the model validation and the fitness is used as the criterion.

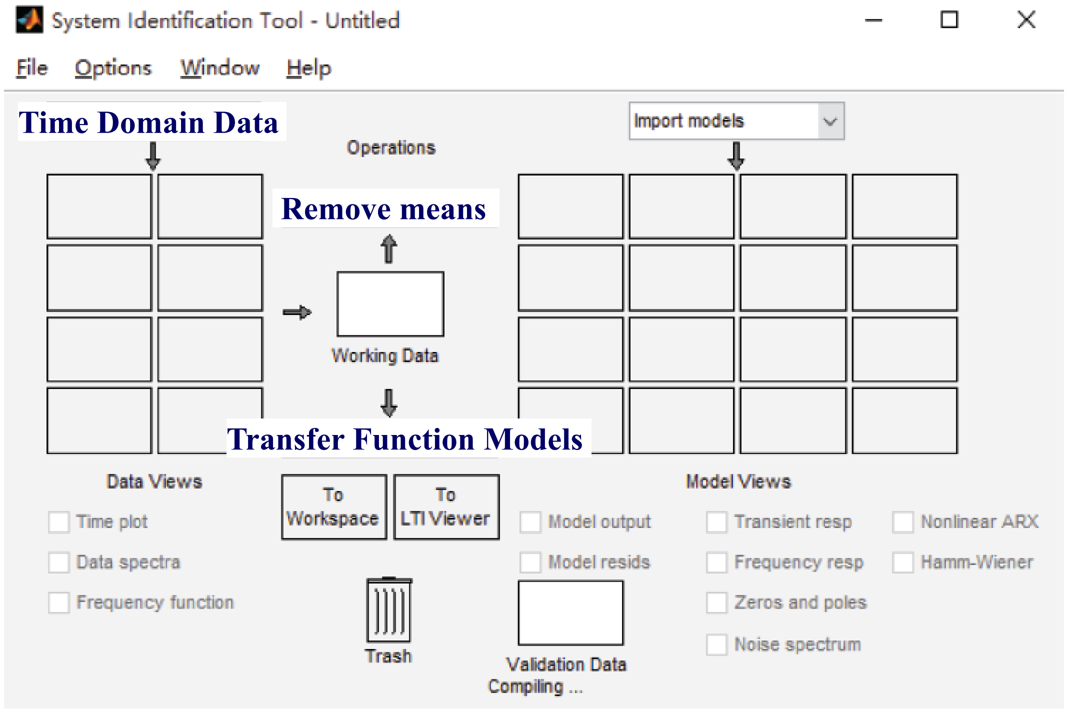
(2) The identification results are supposed to be minimum-phase systems, because nonminimum phase systems are hard to tackle for most controller designs.

(3) While the previous two principles are guaranteed, the order of the transfer function needs to be chosen as small as possible.

4. Simulation

□ System Identification

5.Model calculation



The math works. System identification toolbox. http://www.mathworks.com/help/ident/index.html. Accessed 20 Jan 2016

4. Simulation

□ System Identification

5. Model calculation

$$
\hat{G}\begin{cases}
G_{v_x u_{v_x}}(s)=\dfrac{15.48s+29.9}{s^3+4.642s^2+16.09s+10.91}\\
G_{v_y u_{v_y}}(s)=\dfrac{7.086s+17.02}{s^3+4.742s^2+15.49s+7.063}\\
G_{p_z u_{p_z}}(s)=-\dfrac{6.25}{s^2+7.077s+6.249}\\
G_{\psi u_\psi}(s)=\dfrac{1.277s+3.506}{s^2+4.045s+3.522}
\end{cases}
$$

The fitness of the four channels are: 98.56%, 98.08%, 95.84%, 90.40%

4. Simulation

□ AOD-Based DIC

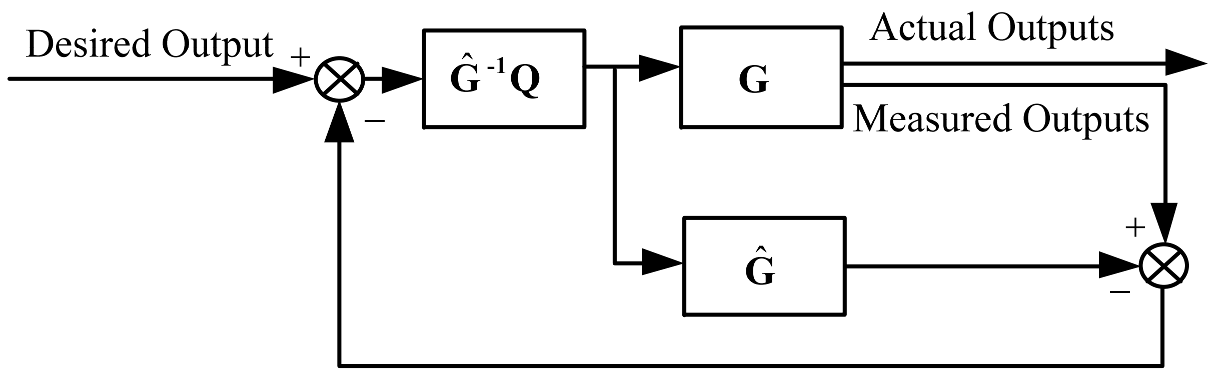


Figure 12.10 The simulation structure for the AOD-based DIC controller

$$\mathbf{Q}_{\mathbf{v}_{h_b}}\mathbf{u}_{\mathbf{v}_h}(s)=\mathrm{diag}\left(\frac{1}{(\eta_x s+1)^2},\frac{1}{(\eta_y s+1)^2}\right)$$

$$Q_{p_z u_{p_z}}(s)=\frac{1}{(\eta_z s+1)^2}$$

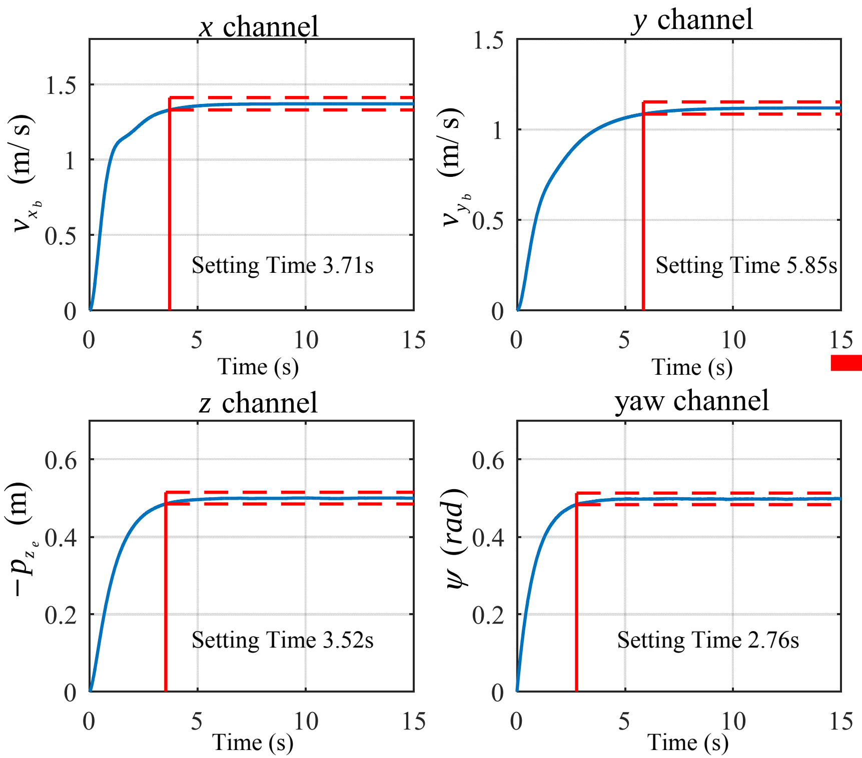
$$Q_{\psi u_\psi}=\frac{1}{(\eta_\psi s+1)^2}$$

$$\eta_x=0.2,\eta_y=0.2,\eta_z=0.3,\eta_\psi=0.3$$

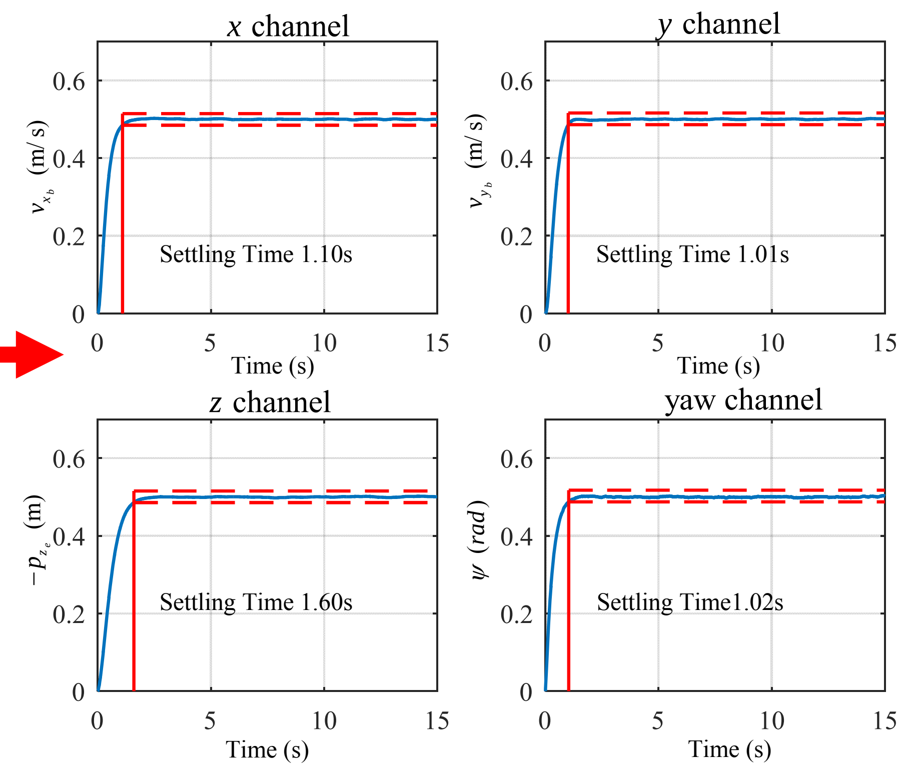
4. Simulation

AOD-Based DIC

Tracking performance is improved



Simple P/PD Stabilizing Controller



AOD-Based DIC

4. Simulation

AOD-Based DIC

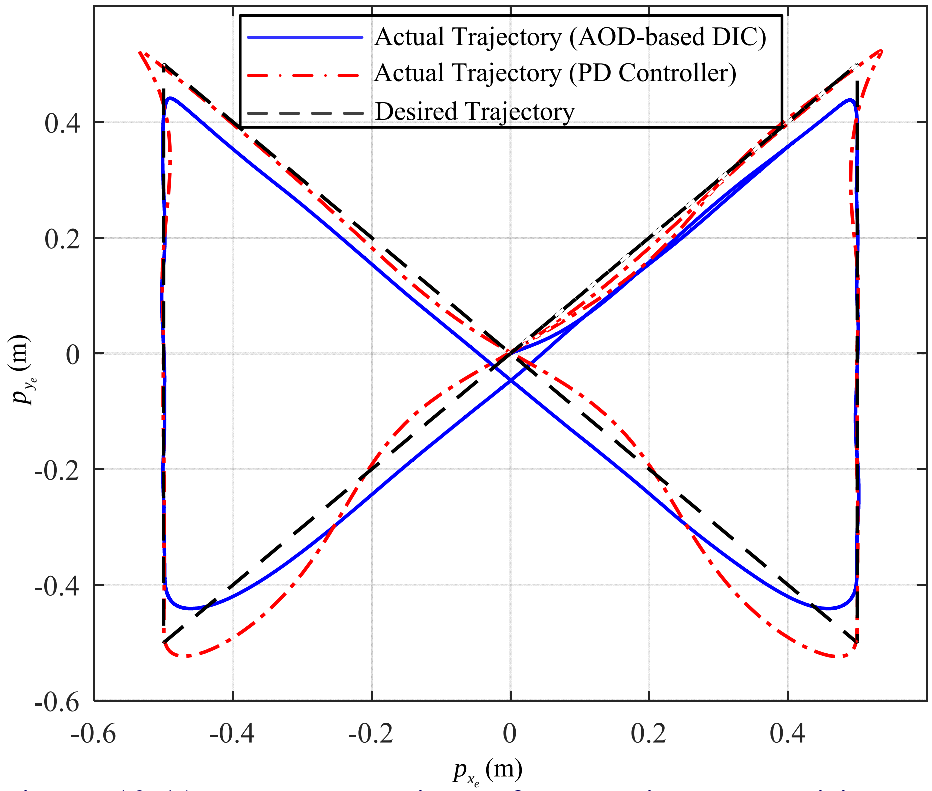


Figure 12.11. The comparison of the horizontal position tracking performance

DIC controller has an excellent tracking performance. However, the tracking trajectories of the DIC controller lag behind those of the PD controller a little. The reason is the gain Kph is not large enough. If Kph increases, the time delay of the tracking will decrease, but the transient process will get worse, vice versa. Thus, users need to adjust Kph of the DIC controller according to actual requirements.

5. Summery

1. More and more multicopter companies open the SDKs of their autopilots. Based on these autopilots, tasks can be accomplished by secondary developments.

2. Practice method is proposed for secondary developments.

3. In the future, one possibility of the development on multicopters is that some companies provide a stable and reliable multicopter platform or operating systems, based on which new applications can be developed easily.

Acknowledgement

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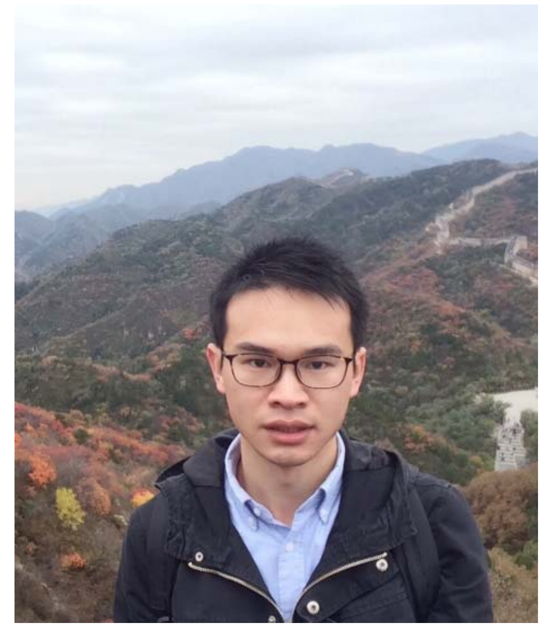

Xunhua Dai

for material preparation.

Thank you!

All course PPTs and resources can be downloaded at
http://rfly.buaa.edu.cn/course

For more detailed content, please refer to the textbook:

Quan, Quan. Introduction to Multicopter Design and Control. Springer, 2017. ISBN: 978-981-10-3382-7.

It is available now, please visit http://www.springer.com/us/book/9789811033810