

Automatic Tuning of Attitude Control System for Unmanned Aerial Vehicles

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Outline

- 1 **Motivation**
- 2 Presentation Outline
- 3 Quadrotor and Hexacopter Dynamics
- 4 Control System Configuration
- 5 Dynamics model of fixed-wing aircraft
- 6 Actuators and implementation of control signals
- 7 Relay Feedback Control Experiment
- 8 PID Controller Design
- 9 Experimental results:quadrotor
- 10 Experimental results:hexacopter
- 11 Experimental results:fixed wing micro-aircraft

Motivations

Applications

Unmanned Aerial Vehicles (UAVs) have become very popular in the last decade in both military and civilian applications:

- surveying dangerous or complex terrains, localization and mapping;
- localization and mapping.

Control

A robust attitude control system is required to enable safe and stable flight in most indoor/outdoor applications.

Popular control strategy

Proportional-Integral-Derivative (PID) controllers have become one of the most widely used controllers in autopilots due to

- 1 its simplicity and low computational intensity;
- 2 easiness to be understood by engineers;
- 3 reliability in implementation.

Challenges

Crash UAVs

When selecting the PID controller parameters by the trial and error process, it is easy to crash the UAV because it is a unstable system.

Time consuming

There are six PID controllers in cascade structures for a typical flight controller. This leads to high demanding of manpower and increased cost.

Automatic Tuning of PID Controllers

- Automatically find the mathematical model of the plant to be controlled;
 - identification experiment design to ensure the collection of input and output data contains useful information for controller design;
 - closed-loop system is required to be stable for safety of equipment during the experiments;
 - identification experiments need to be simple and easy to execute.
- Automatically determine the controller parameters with minimum human intervention.

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Presentation Outline

Dynamics of UAVs

- Quadrotor
- Hexacopter
- Fixed wing micro-aircraft

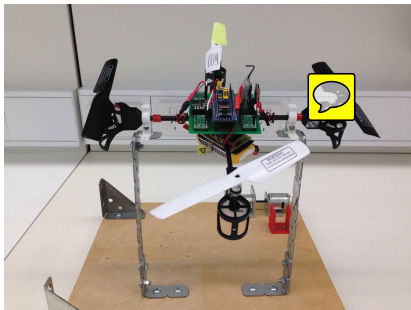
Automatic controller tuning

- Relay feedback control
- Estimation of plant frequency information
- PID controller design

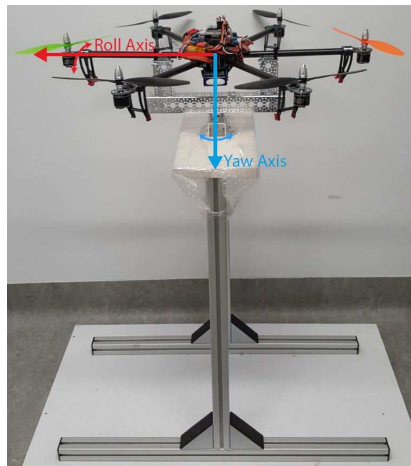
Experimental and flight testing results

- Quadcopter
- Hexacopter
- Fixed wing micro-aircraft

Multi-rotor UAVs



(a) Quadrotor



(b) Hexacopter

Figure: Unmanned aerial vehicles (multi-rotor)

Fixed-wing UAV

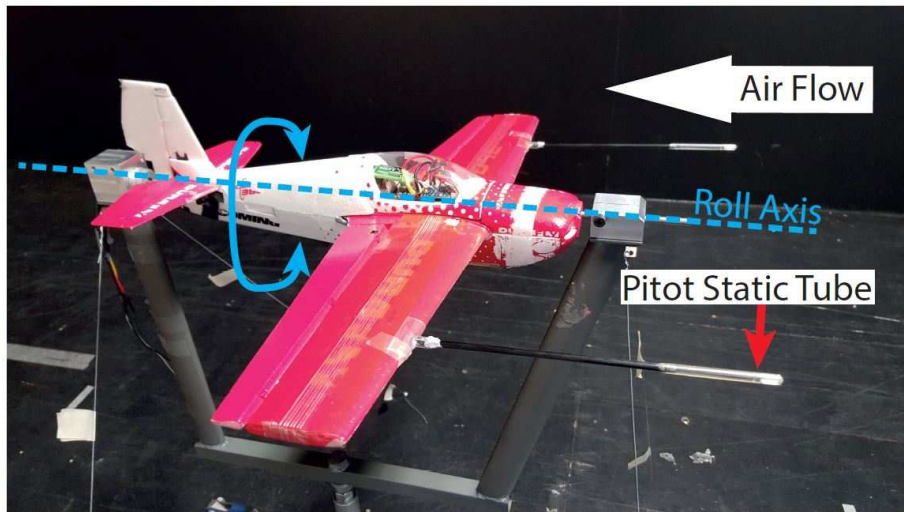
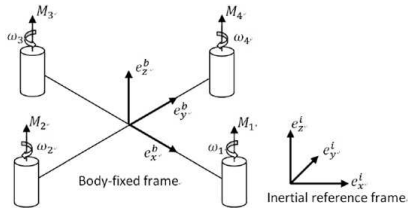


Figure: Fixed-wing micro-aircraft

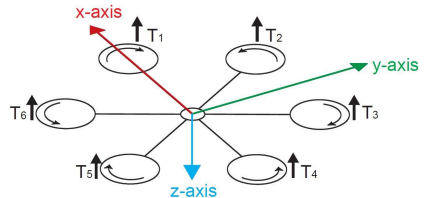
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Inertial Frame and Body Frame (i)



(a) Quadrotor



(b) Hexacopter

Figure: Inertial frame and body frame of multirotors

Inertial Frame and Body Frame (ii)

Origin of the body frame

- Figure 3 illustrates the frameworks used to find the dynamics models for the multi-rotors.
- The origin of the body frame is in the mass center of the multi-rotor and z -axis is upwards.
- M_1, M_2, M_3, M_4 are four rotors with DC motors or the six rotors with the hexacopter.
- The dynamics models are the same for the multi-rotors, however, the implementations of the control signals will be different depending on how many rotors are used.

Euler Angles

Euler angles

The multi-rotor's attitude is defined by three Euler angles, namely roll about x -axis, pitch about y -axis, and yaw about z -axis.

Notations

- Roll angle ϕ : about the x body axis;
- Pitch angle θ : about the y body axis;
- Yaw angle ψ : about the z body axis;
- The transformation sequence is $\psi \rightarrow \theta \rightarrow \phi$ in order to obtain the unique solution.

Dynamic Model

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} (I_{yy} - I_{zz})qr/I_{xx} \\ (I_{zz} - I_{xx})pr/I_{yy} \\ (I_{xx} - I_{yy})pq/I_{zz} \end{bmatrix} + \begin{bmatrix} 1/I_{xx} & 0 & 0 \\ 0 & 1/I_{yy} & 0 \\ 0 & 0 & 1/I_{zz} \end{bmatrix} \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad (1)$$

Notations and assumptions

- I_{xx} , I_{yy} and I_{zz} are the moments of inertia for the three axes in x , y , z directions;
- p , q and r the body frame angular velocities in x , y , z directions;
- τ_x , τ_y , τ_z are the corresponding torques in x , y , z directions, which are the manipulated variables in the multicopter control problem.
- The quadrotor is assumed to have symmetric structure with four arms aligned with the x -axis and y -axis, and as a result there is no interaction between the torques along the three axes.
- Similar assumptions are made for the hexacopter to ensure that there is no interactions between the torques along the three axes.

Relationships between ϕ , θ , ψ and p , q , r

The relationships between the Euler angular velocities and the body frame angular velocities are described in the following differential equation:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi) \tan(\theta) & \cos(\phi) \tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)/\cos(\theta) & \cos(\phi)/\cos(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}. \quad (2)$$

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Attitude Control (i)

System Outputs

- For attitude control of a multi-rotor, the objective is to feedback control the three Euler angles so that they follow three reference signals (ϕ^* , θ^* , ψ^*).
- Therefore, the outputs of the control systems are the three Euler angles: ϕ , θ , ψ .

Control variables or manipulated variables

The manipulated variables or the control signals are the three torques, τ_x , τ_y , τ_z , along the x, y and z directions.

Attitude Control (ii)

Intermittent variables

The body frame angular velocities p , q and r along the x , y and z directions are the intermittent variables.

Cascade control

- Because there are **two sets of nonlinear dynamic equations**, cascade control is a good choice for this nonlinear control problem.
- The body frame angular velocities p , q and r are the secondary variables because they are directly related to the manipulated variables τ_x , τ_y and τ_z .
- The three Euler angles, ϕ , θ , ψ are the primary variables to achieve the attitude control

Cascade Control of One Axis

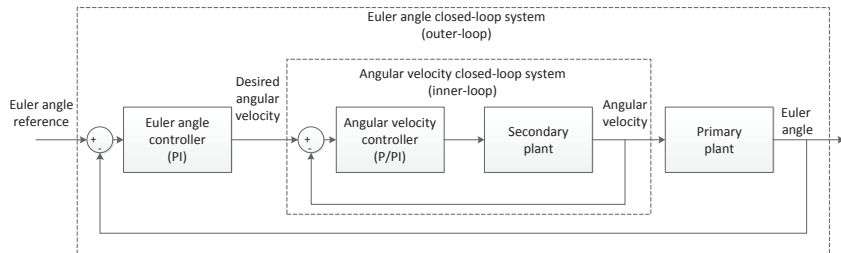


Figure: Cascade feedback control structure

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Dynamic model (i)

$$\begin{aligned}\dot{p} &= \Gamma_1 pq - \Gamma_2 qr + \frac{1}{2} \rho V_a^2 S b \left[C_{l_0} + C_{l_{\beta_C}} \beta_C + C_{l_p} \frac{bp}{2V_a} + C_{l_r} \frac{br}{2V_a} + C_{l_{\delta_a}} \delta_a \right] \\ \dot{q} &= \Gamma_5 pr - \Gamma_6 (p^2 - r^2) + \frac{\rho V_a^2 S c}{2I_y} \left[C_{m_0} + C_{m_\alpha} + C_{m_q} \frac{cq}{2V_a} + C_{m_{\delta_e}} \delta_e \right] \\ \dot{r} &= \Gamma_7 pq - \Gamma_1 qr + \frac{1}{2} \rho V_a^2 S b \left[C_{n_0} + C_{n_{\beta_C}} \beta_C + C_{n_p} \frac{bp}{2V_a} + C_{n_r} \frac{br}{2V_a} + C_{n_{\delta_a}} \delta_a \right]\end{aligned}\quad (3)$$

where p , q and r are angular rates in the body frame and the control surface inputs are δ_a , δ_e and δ_r .

Dynamic model (ii)

The relationships between the body frame angular rates and the Euler angular rates are described in the following equation:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (4)$$

Attitude Control of Fixed-wing Aircraft

System Outputs

- For attitude control of a fixed-wing aircraft, the objective is to feedback control the three Euler angles so that they follow three reference signals $(\phi^*, \theta^*, \psi^*)$.
- Therefore, the outputs of the control systems are the three Euler angles: ϕ, θ, ψ .

Control variables or manipulated variables

The manipulated variables or the control signals are the three control surface inputs, δ_a (x-axis), δ_e (y-axis), δ_r (z-axis).

Cascade Control Structure

The control structure is identical to the multi-rotor UAV structure except that the manipulated variables are the three control surface inputs $(\delta_a, \delta_e, \delta_r)$.

Discussions of Cascade Control

- The dynamics of three axes are almost decoupled, thus PI controllers are designed for each axis separately.
- The inner-loop controller (also called secondary controller) is to control **inner-loop (secondary) plant**, where its reference signal is the desired angular velocity that is also the control signal generated from the outer-loop (primary) controller.
- For the cascade control system, the primary objective is to control the outer-loop (primary) plant to achieve desired closed-loop performance.

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Actuators

- The torques τ_x , τ_y and τ_z in the body frame are the control signals.
- The four DC motors are the actuators that will realize the control signals calculated using the controllers.
- The DC motors have dynamics and we need to consider them in the control system design.
- The challenge is how to realize the calculated torques from the cascade control system using the DC motors.

The Actuator Dynamics (i)

In quadrotor control, the torques τ_x , τ_y and τ_z in the body frame are generated by the differences in rotor thrusts.

Rotor thrusts

The upward thrust produced by each rotor is

$$T_i = b_t \omega_i^2, \quad i = 1, 2, 3, 4.$$

The total thrust is, hence,

$$T = \sum T_i$$

where b_t is the thrust constant determined by air density, the length of the blade and the blade radius, ω_i is the i th rotor's angular speed.

The Actuator Dynamics (ii)

Torques (τ_x, τ_y)

The torques about quadrotor's x -axis and y -axis are

$$\tau_x = d_{mm}(T_4 - T_2) = d_{mm}b_t(\omega_4^2 - \omega_2^2) \quad (5)$$

$$\tau_y = d_{mm}(T_3 - T_1) = d_{mm}b_t(\omega_3^2 - \omega_1^2), \quad (6)$$

Torque τ_z

The torque applied to each propeller by the motor is opposed by aerodynamic drag and the total reaction torque about the z -axis is

$$\tau_z = k_d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2), \quad (7)$$

where d_{mm} is the distance from the motor to the mass center, and k_d is a drag constant determined by the same factors as b_t .

The Actuator Dynamics in Matrix Form

The relationship between torques, thrust and rotors' angular speed is given in the following matrix form:

$$\begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} = \begin{bmatrix} 1/4b_t & 0 & -1/2d_{mm}b_t & -1/4k_d \\ 1/4b_t & -1/2d_{mm}b_t & 0 & 1/4k_d \\ 1/4b_t & 0 & 1/2d_{mm}b_t & -1/4k_d \\ 1/4b_t & 1/2d_{mm}b_t & 0 & 1/4k_d \end{bmatrix} \begin{bmatrix} T \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad (8)$$

Because the altitude of the UAV is not controlled in this case, the total thrust is manually set by the operator.

Implementation of Control Signal

- From (8), once the manipulated variables $T, \tau_x, \tau_y, \tau_z$ are decided by the cascade feedback controllers, the velocities of motors will be uniquely determined.
- The rotors acting as the actuators in this UAV control application will implement the control actions determined by $T, \tau_x, \tau_y, \tau_z$, through their reference signals $\omega_1, \omega_2, \omega_3$ and ω_4 .
- However, because the velocities of the DC motors are not measured and can not directly changed, they could not be chosen as the implementation of the control signals.
- Instead, the duty cycles of PWM signals regulating the DC voltages of the motors are used for the actual implementation of the control signals.

DC Motor Dynamics

- The DC motor dynamics are approximated by a first-order transfer function with time delay:

$$\frac{\Omega_i(s)}{V_i(s)} = \frac{r_{wv} e^{-d_m s}}{\epsilon_m s + 1}, \quad (9)$$

- $V_i(s)$ is the Laplace transform of the armature voltage to the i th motor, ϵ_m is the time constant, d_m is the time delay, and r_{wv} is the steady-state gain.

Duty Cycle of the Motor

How do we change the armature voltage?

- The armature voltage v_i is changed by manipulating the duty cycle of the PWM signal of each motor drive.
- The relationship between the motor armature voltage and the PWM duty cycle is

$$v_i = d_i V_{bat}, \quad (10)$$

where d_i is the PWM signal duty cycle of the i th DC motor drive and V_{bat} is the battery voltage assumed to be constant.

Actuator Dynamics

$$\frac{\Omega_i(s)}{D_{cycle-i}(s)} = \frac{V_{bat}r_{wv}e^{-d_ms}}{\epsilon_ms + 1} \quad (11)$$

$D_{cycle-i}(s)$ is Laplace transform of the PWM signal duty cycle of the i th DC motor drive.

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Auto-tuner Mechanism

Relay Feedback Control

- A proportional controller with known gain K_T is used to stabilize the integrating system;
- a relay feedback control system is deployed for the output of the closed-loop system.

Block diagram

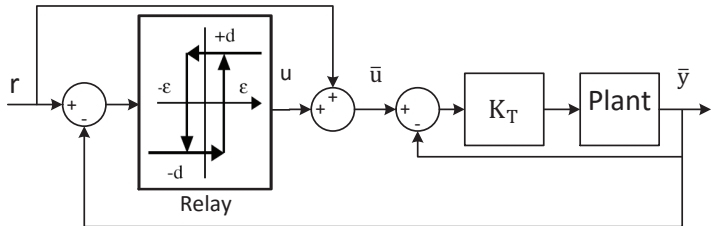


Figure: Block diagram of relay feedback control.

The Input and Output Signals

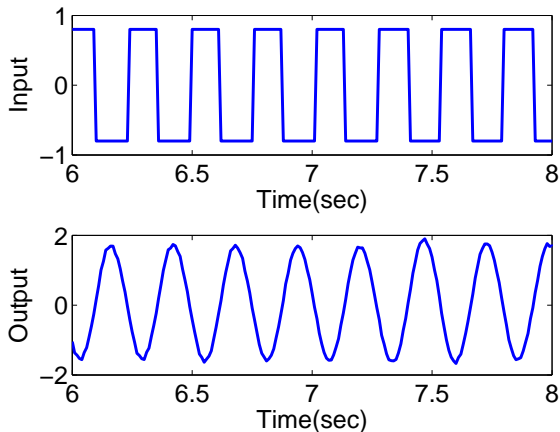
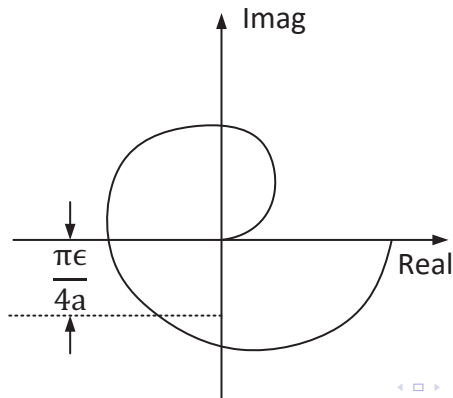


Figure: Relay feedback control signals from inner-loop system: top figure input signal; bottom figure output signal.

The Characteristics of Relay Control

- Assume that the period of the oscillation is T .
- The frequency of the periodic signal $\bar{u}(t)$, denoting by $\omega_1 = \frac{2\pi}{N\Delta t}$, approximately corresponds to the frequency illustrated on the Nyquist curve shown in Figure 7.



Characteristics of Periodic Signals

- For a period T , the Fourier series expansion of the periodic input signal $u(t)$, is expressed as

$$u(t) = \frac{4a}{\pi} \left(\sin \frac{2\pi}{T}t + \frac{1}{3} \sin \frac{6\pi}{T}t + \frac{1}{5} \sin \frac{10\pi}{T}t + \dots \right) \quad (12)$$

- By choosing sampling interval Δt and the number of samples within one period $N = \frac{T}{\Delta t}$, the discretized input signal $u(t)$ at sampling instant $t_k = k\Delta t$ becomes

$$u(k) = \frac{4a}{\pi} \left(\sin \frac{2\pi k}{N} + \frac{1}{3} \sin \frac{6\pi k}{N} + \frac{1}{5} \sin \frac{10\pi k}{N} + \dots \right) \quad (13)$$

Estimation of $T(j\omega_1)$ using Fast Fourier Transform

- The simplest way to estimate the frequency response of the system under relay feedback is to use Fast Fourier Transform.
- Assuming that the data length is L , the Fourier transform of the input signal $u(k)$, $k = 1, 2, \dots, L$, is

$$U(n) = \frac{1}{L} \sum_{k=1}^L u(k) e^{-j \frac{2\pi(k-1)(n-1)}{L}} \quad (14)$$

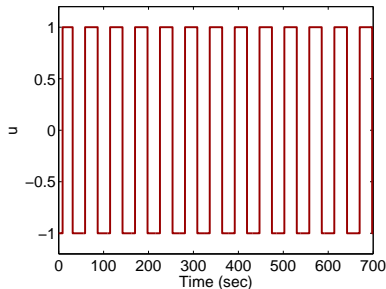
and the corresponding Fourier transform of the output is

$$Y(n) = \frac{1}{L} \sum_{k=1}^L y(k) e^{-j \frac{2\pi(k-1)(n-1)}{L}} \quad (15)$$

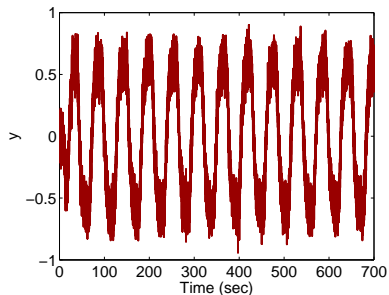
where $n = 1, 2, 3, \dots, L$.

- From both (14) and (15), with the definition of Fourier transform, the corresponding discrete frequency ω_d is defined from 0 to $\frac{2\pi(L-1)}{L}$ with an incremental of $\frac{2\pi}{L}$.

Example: Input and Output Data

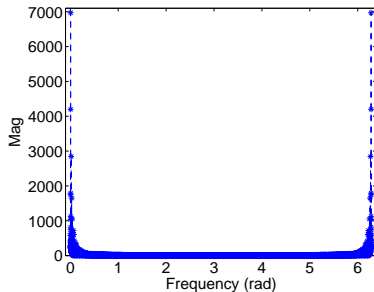


(a) Input data

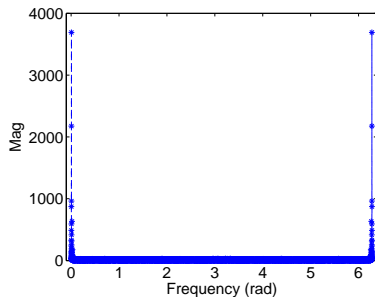


(b) Output data

Fourier Transform (1)

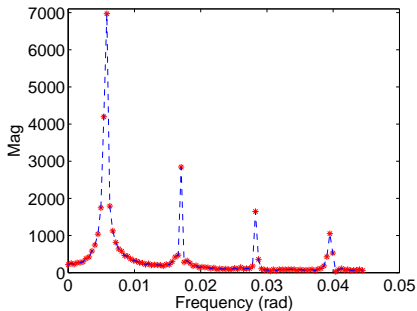


(c) Fourier transform $U(e^{j\omega_d})$

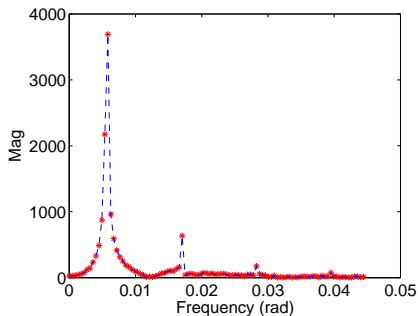


(d) Fourier transform $Y(e^{j\omega_d})$

Fourier Transform (2)



(e) Fourier transform $U(e^{j\omega_d})$, $0 \leq \omega_d \leq 0.045$



(f) Fourier transform $Y(e^{j\omega_d})$, $0 \leq \omega_d \leq 0.045$

Example (iii)

- Locating the fundamental frequency of the relay signal as the maximum value of $U(e^{j\omega_d})$, Identify the peaks of $U(e^{j\omega_d})$ as the 14th sample, which is the frequency at $\omega_d = \frac{2*\pi(14-1)}{L}$, $L = 14001$.
- The estimation of the frequency response of the system is then given by

$$T(14) = Y(14)/U(14) = -0.0040 - 0.5293i$$

- The second peak is identified at the 39th sample, which is the frequency at $\omega_d = \frac{2*\pi(39-1)}{L}$, $T = -0.1081 + 0.1950i$. The third peak is identified at 64th sample, which is the frequency at $\omega_d = \frac{2*\pi(64-1)}{L}$, $T = 0.1054 - 0.0151i$.

Comparative Results

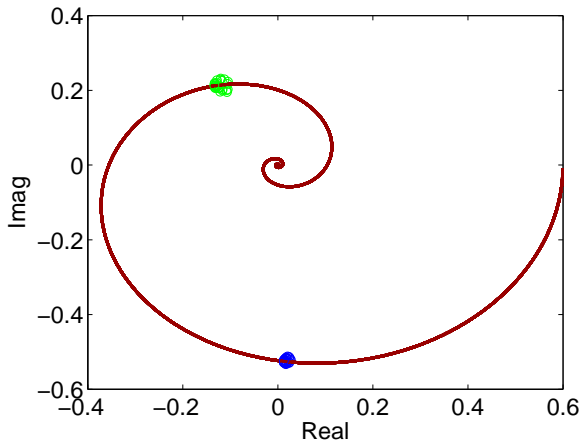


Figure: Comparison between the estimated frequency points with the actual frequency response.

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Integrator Plus Time Delay Model

- For an integrating plus time delay system, a single frequency is sufficient to determine its gain K_p and time delay d .
- The approximate model of an integrating system is assumed to be of the following form:

$$G_p(s) = \frac{K_p e^{-ds}}{s} \quad (16)$$

Finding the Parameters (i)

- Letting the frequency response of the integrator plus delay model (16) be equal to the estimated $G_p(j\omega_1)$ leads to

$$\frac{K_p e^{-jd\omega_1}}{j\omega_1} = G_p(j\omega_1) \quad (17)$$

- Equating the magnitudes on both side of (17) gives

$$K_p = \omega_1 |G_p(j\omega_1)| \quad (18)$$

where $|e^{-jd\omega_1}| = 1$.

Finding the Parameters (ii)

- Additionally, from (17), the following relationship holds:

$$e^{-jd\omega_1} = \frac{j\omega_1 G_p(j\omega_1)}{K_p}$$

- This gives the estimate of time delay as

$$d = -\frac{1}{\omega_1} \tan^{-1} \frac{\text{Imag}(jG_p(j\omega_1))}{\text{Real}(jG_p(j\omega_1))} \quad (19)$$

PID Controller Design

The parameter β is the scaling factor for the desired closed-loop time constant, which is defined as

$$\tau_{cl} = \beta d$$

$$K_c = \frac{\hat{K}_c}{dK_p}$$

$$\tau_I = d\hat{\tau}_I$$

$$\tau_D = d\hat{\tau}_D$$

Normalized PID Parameters (i)

Table: Normalized PID controller parameters ($\xi = 0.707$)

	$0.7 \leq \beta \leq 1$	$1 < \beta \leq 11$
\hat{K}_C	$\frac{1}{0.3280\beta^2 + 0.0786\beta + 0.6442}$	$\frac{1}{0.7184\beta + 0.3661}$
$\hat{\tau}_I$	$-3.7845\beta^2 + 10.2044\beta - 4.0298$	$1.3970\beta + 1.2271$
$\hat{\tau}_D$	$\frac{1}{-1.9064\beta^2 + 6.1545\beta - 1.5875}$	$\frac{1}{1.4275\beta + 1.6450}$

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Components

Function	Model
DC motor drive	DRV8833 Dual Motor Driver Carrier
Sensor board	MPU6050
Micro processor	STM32F103C8T6
RC receiver	WFLY065
DC motor	820 Coreless Motor
RC transmitter	WFT06X-A
Data logger	SparkFun OpenLog

Table: quadrotor hardware list

Experimental Data

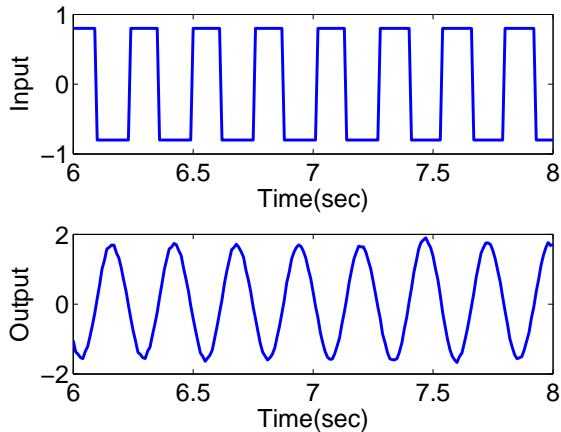


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Closed-loop Control Results

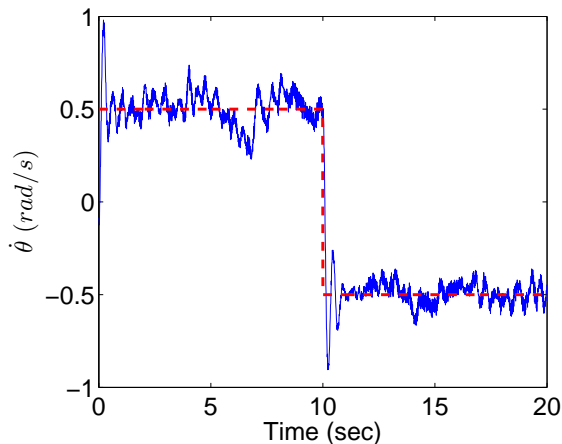


Figure: Inner-loop step response in closed-loop control. Dashed line: reference signal; solid line: output.

Auto-tuning of Primary PI Controller

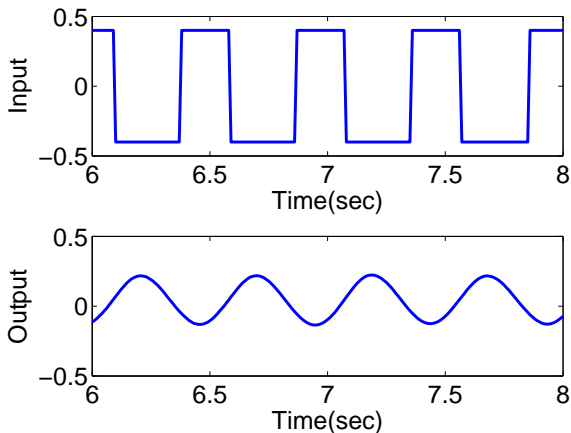
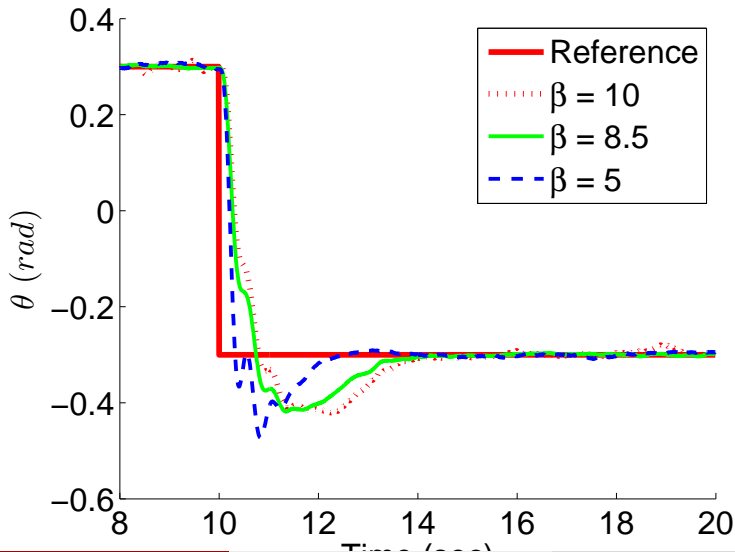


Figure: Relay feedback control signals from outer-loop system: top figure input signal; bottom figure output signal.

Closed-loop Control Results



Outline

- 1 Motivation
- 2 Presentation Outline
- 3 Quadrotor and Hexacopter Dynamics
- 4 Control System Configuration
- 5 Dynamics model of fixed-wing aircraft
- 6 Actuators and implementation of control signals
- 7 Relay Feedback Control Experiment
- 8 PID Controller Design
- 9 Experimental results:quadrotor
- 10 Experimental results:hexacopter**
- 11 Experimental results:fixed wing micro-aircraft

Components

Table: Flight controller and avionic components

Components	Descriptions
Airframe	Turnigy Talon Hexacopter
Microprocessor	ATMega2560
Inertial measurement unit	MPU6050
Electronic speed controllers	Turnigy 25A Speed Controller
Brushless DC motors	NTM Prop Drive 28-26 235W
Propellers	10x4.5 SF Props
RC Receiver	OrangeRX R815X 2.4Ghz receiver
RC Transmitter	Turnigy 9XR PRO transmitter
Datalogger	CleanFlight Blackbox Datalogger

Relay experimental data

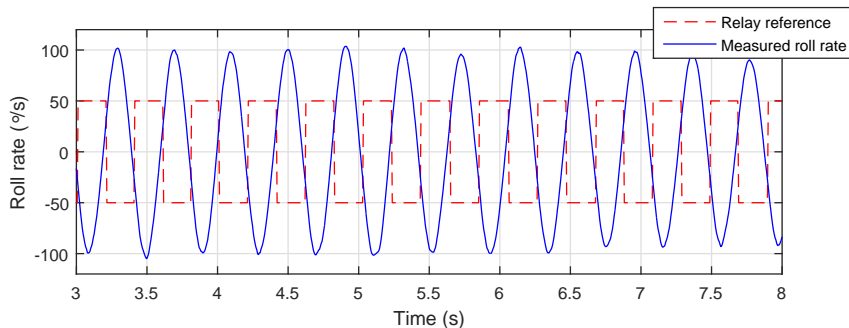


Figure: Inner loop relay test result. $K_T = 0.3$, $R_a = 50^\circ/\text{s}$, $\epsilon = 30^\circ/\text{s}$

Controller parameters

Controller parameters found for inner-loop

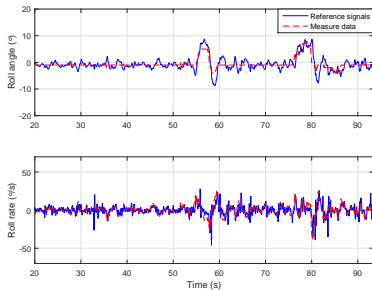
$K_c = 0.33, \tau_I = 0.26$ and $\tau_D = 0.03$

Controller parameters found for outer-loop

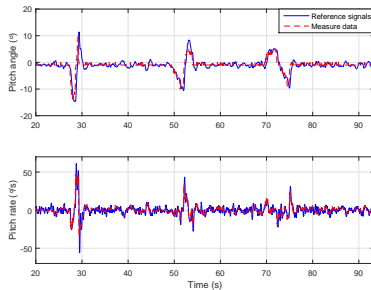
$K_c = 3.3, \tau_I = 0.63$ and $\tau_D = 0.013$.

Outdoor flight testing

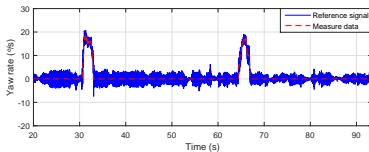




(a) Roll control:top-angle,bottom- rate



(b) Pitch control:top-angle,bottom- rate



(c) Yaw control results

Figure: Experimental testing results. Key- red dashed lines: the reference signals; blue solid lines: the measured data

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Table: Fixed-wing UAV Specifications

Description	Details
Airframe	Slick 360
Airfoil	NACA0012
Wing span	0.490m
Fuselage length	0.421m
Wing area	0.44m ²
Average chord	0.0885m
Weight	130g
Cruise speed	10m/s

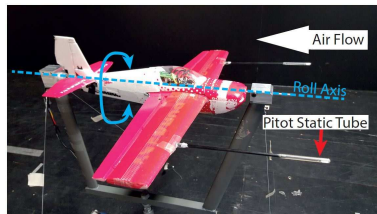


Figure: The fixed-wing UAV on the roll test rig

Relay experimental data

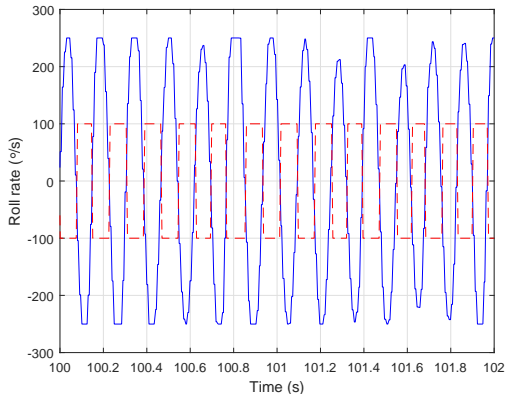
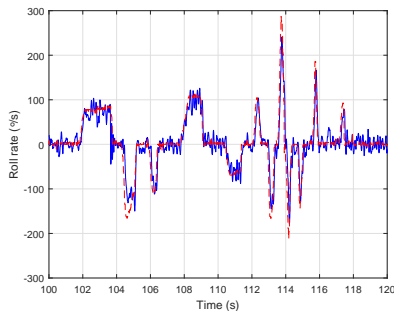
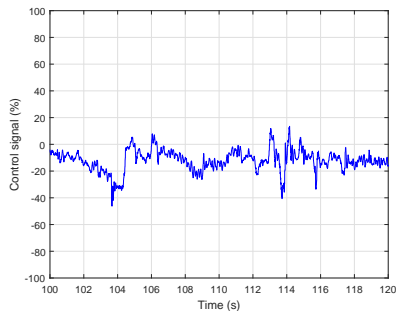


Figure: Inner loop relay experiment: red (dashed) = reference signal, blue (solid) = measured data

Inner-loop control testing results



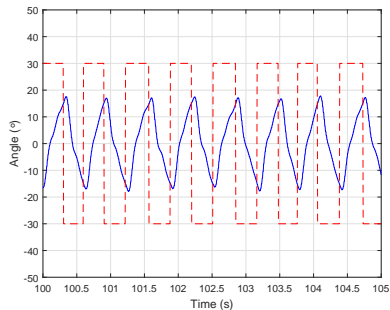
(a) Angular rate tracking



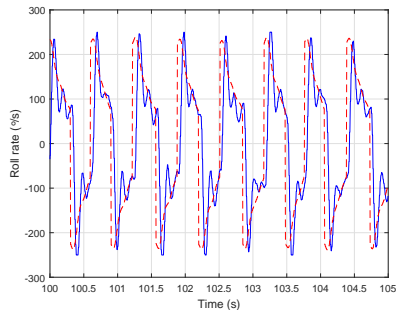
(b) Control signal δ_a

Figure: Inner loop experimental validation: red (dashed) = reference signal; blue (solid) = measured data

Outer-loop relay control

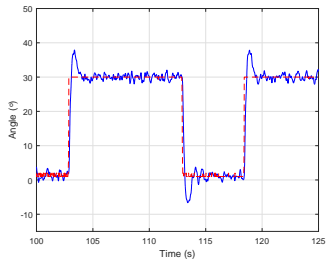


(a) Angular loop

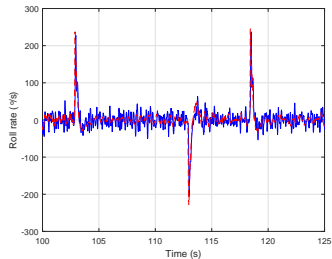


(b) Angular rate loop

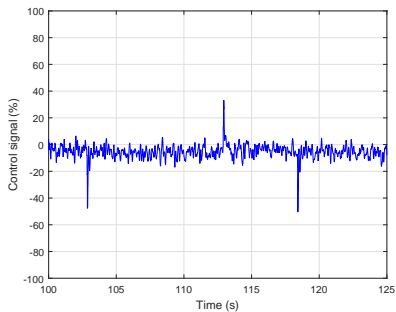
Figure: Outer loop relay experiment: red (dashed)- reference signal; blue (solid)- measured data



(a) Angular tracking



(b) Angular rate tracking



(c) Control signal δ_a

Summary

- Conduct a relay control experiment to obtain the set of input and output data;
- Estimation of the plant frequency information;
- Find the integrating plus delay model;
- Find the PID controller parameters based on the delay and gain.