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Parameter Estimation and Control of Multirotors Using Integral Concurrent Learning

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Outlines

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- Motivation
- Problem Formulation
- Controller Design
- Stability Analysis
- Simulation and Experiments
- Conclusion

Motivation – from Walmart's drone delivery

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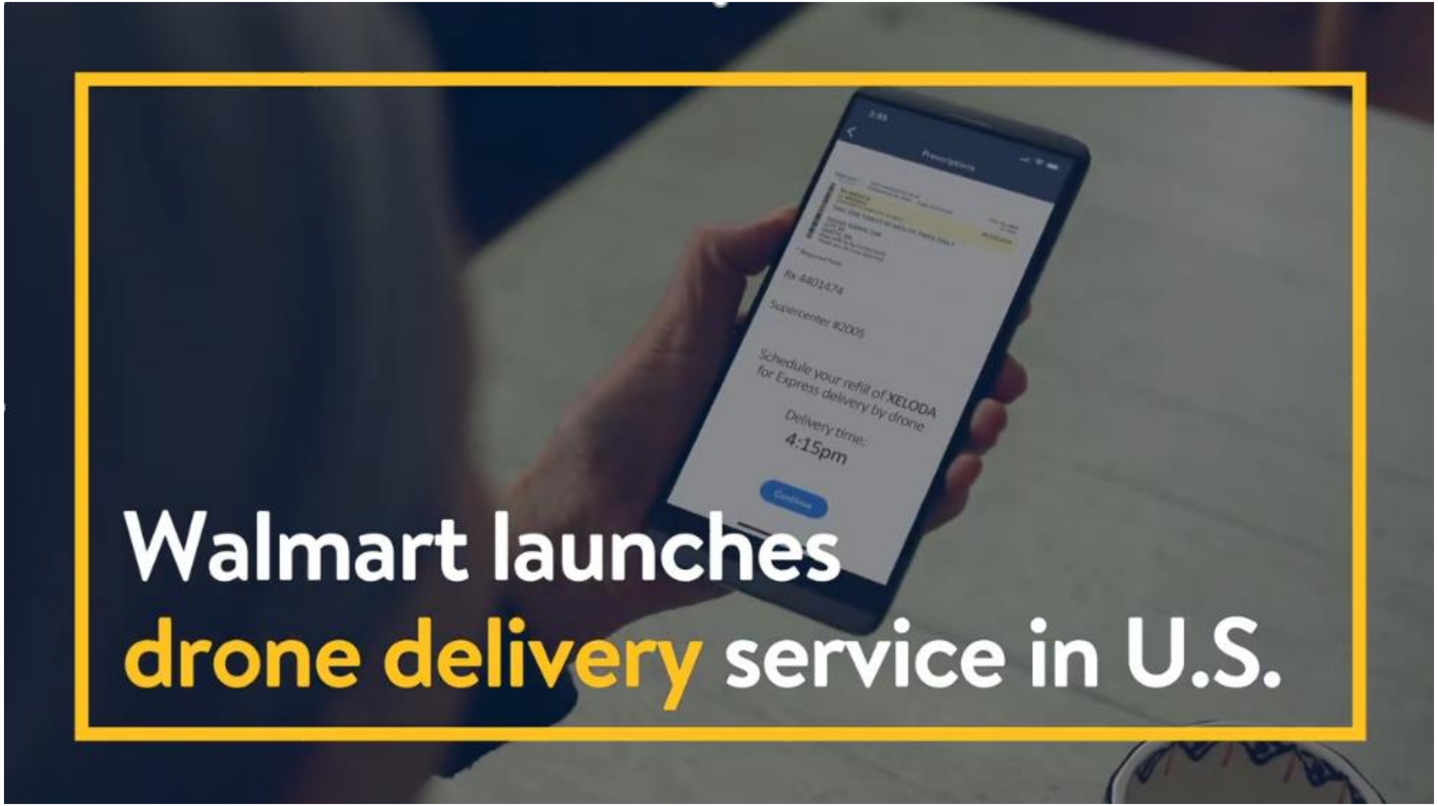


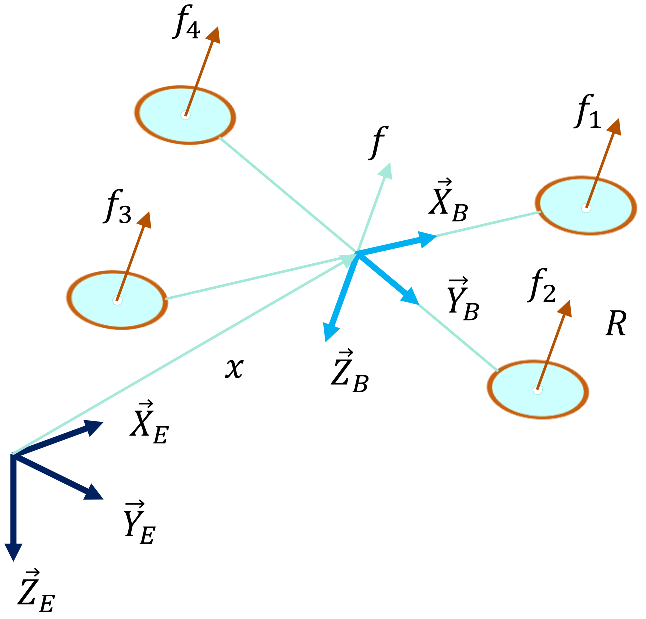
Motivation – from movies Angel Has Fallen

Motivation

- Knowledge of the geometric and inertia parameters is essential to achieving good control performance.
- The payload or sensors attaching to multirotors may change the geometric and inertia parameters.
- Some geometric and inertia parameters like moment of inertia can not be measured through instrument.
- Existing adaptive control method can only guarantee the stability of multirotors system, can not ensure the parameters converge.

Problem Formulation - Definition of Symbols

Symbol	Description
x	Position of the multirotor
v	Velocity of the multirotor
R	Rotation matrix from the body-fixed frame to the inertial frame
Ω	Angular velocity in the body-fixed frame
f	Net thrust control input
M	Moment control input
m	Mass of the multirotor
J	Moment of inertia of the multirotor



Body-fixed frame : $\{\vec{X}_B, \quad \vec{Y}_B, \quad \vec{Z}_B\}$

Inertial frame: $\{\vec{X}_E, \quad \vec{Y}_E, \quad \vec{Z}_E\}$

Problem Formulation - Dynamics of the Multirotor

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- The multirotor is described by both translational and rotational dynamics.
- The translational dynamics considers forces such as the effects of gravity, thrusts, and the external force.
- The rotational dynamics takes the moment of the control input, rotational speed, and moment of inertia into account.

$$\left.\begin{aligned} \dot{x} &= v \\ m\dot{v} &= mge_3 - fRe_3 \end{aligned}\right\} \text{Translational dynamics}$$

$$\left.\begin{aligned} \dot{R} &= R\hat{\Omega} \\ J\dot{\Omega} + \Omega \times J\Omega &= M \end{aligned}\right\} \text{Rotational dynamics}$$

$$J = \begin{bmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & 0 \\ 0 & 0 & J_{zz} \end{bmatrix}$$

Problem Formulation – Tracking Errors and Estimate Errors

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- Position and velocity tracking errors

  $e_x \triangleq x - x_d$

  $e_v \triangleq v - v_d$
- Attitude error function on SO(3) based on Geometric Tracking Control

  $\Psi(R, R_d) \triangleq \frac{1}{2} tr\left[I - R_d^T R\right]$
- Attitude tracking error and the angular velocity tracking error

  $e_R \triangleq \frac{1}{2}\left(R_d^T R - R^T R_d\right)^{\vee}$

  $e_\Omega \triangleq \Omega - R^T R_d \Omega_d$
- Estimate error of mass

  $\tilde{\theta}_m \triangleq \theta_m - \hat{\theta}_m$, $\theta_m = m$ (mass of the multirotor)
- Estimate error of moment of inertia

  $\tilde{\theta}_{diag} \triangleq \theta_{diag} - \hat{\theta}_{diag}$, $\theta_{diag} = [J_{xx} \quad J_{yy} \quad J_{zz}]^T$ (moment of inertia of the multirotor)

Problem Formulation – Control Objectives

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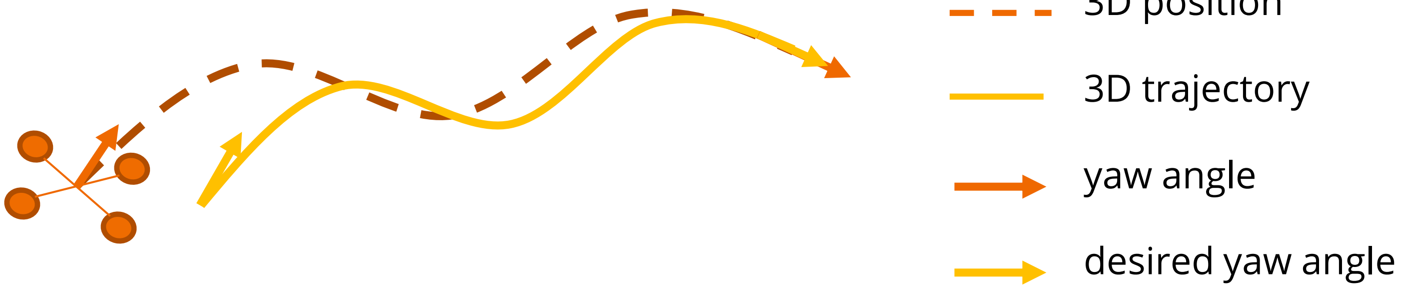
- Track a desired 3D trajectory
- Track a desired yaw angle
- Estimate the mass of the multirotor
- Estimate the moment of inertia of the multirotor

$$\begin{cases} e_x & \to 0 \\ e_v & \to 0 \\ e_R & \to 0 \\ e_\Omega & \to 0 \\ \tilde{\theta}_m & \to 0 \\ \tilde{\theta}_{diag} & \to 0 \end{cases} \quad as\ t \to \infty$$



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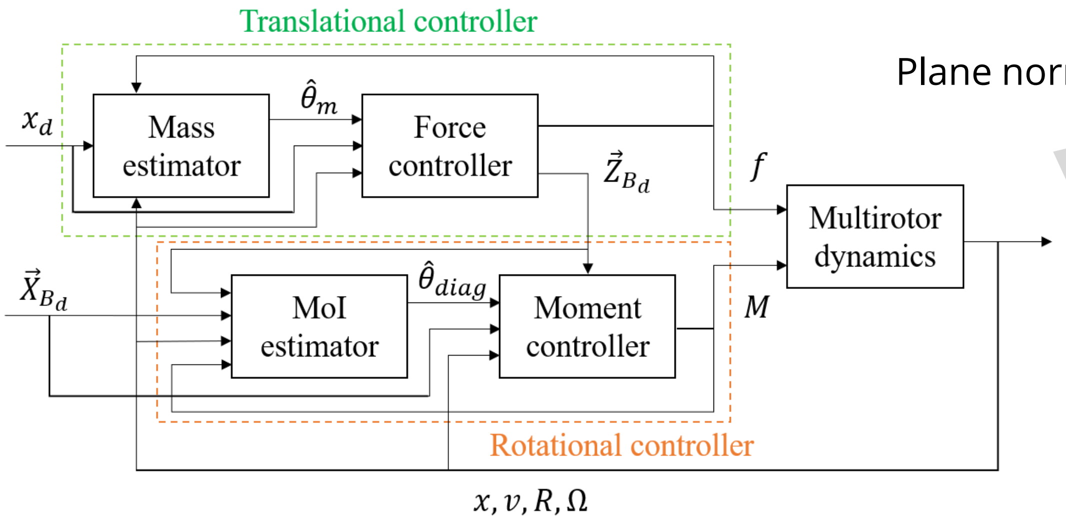
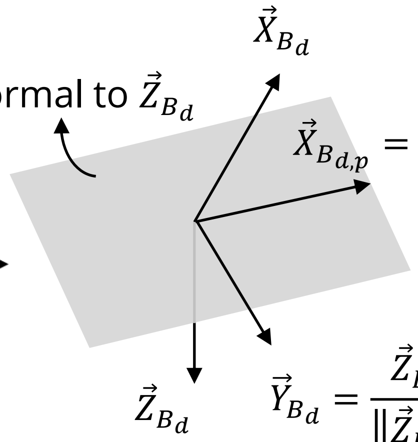
Controller Design – Control Architecture





$$\vec{X}_{B_{d,p}} = \vec{Y}_{B_d} \times \vec{Z}_{B_d}$$

$$\vec{Y}_{B_d} = \frac{\vec{Z}_{B_d} \times \vec{X}_{B_d}}{\left\|\vec{Z}_{B_d} \times \vec{X}_{B_d}\right\|}$$

$$R_d = \left[\vec{X}_{B_{d,p}};\quad \vec{Y}_{B_d};\quad \vec{Z}_{B_d}\right] \in R^{3\times 3}$$

Controller Design – Translational Controller

- Translational controller

$$f = \underbrace{(k_x e_x + k_v e_v}_{} + \underbrace{Y_m \hat{\theta}_m}_{}) \cdot Re_3 \qquad , Y_m = \begin{bmatrix} -\ddot{x}_{d_1} \\ -\ddot{x}_{d_2} \\ g - \ddot{x}_{d_3} \end{bmatrix}$$ is a regression matrix

$$= \boldsymbol{feedback\ term} + \boldsymbol{adaptive\ term}$$

- Integral CL-based adaptive control update law $\dot{\hat{\theta}}_m$

$$\dot{\hat{\theta}}_m = \underbrace{\Gamma_m Y_m^T(e_v + C_1 e_x)}_{} + \underbrace{k_m^{cl}\Gamma_m \sum_{j=1}^{N_m} \left(y_m^{cl}(t_j)\right)^T \left(F(t_j) - y_m^{cl}(t_j)\,\hat{\theta}_m\right)}_{}$$

$$= \boldsymbol{adaptive\ term} + \boldsymbol{ICL - based\ term}$$

$$y_m^{cl}(t_j) \triangleq \begin{cases} 0_{n\times 1} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} Y_m^{cl}(\tau)d\tau & t > \Delta t \end{cases}, \quad F(t_j) \triangleq \begin{cases} 0_{n\times 1} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} fRe_3(\tau)d\tau & t > \Delta t \end{cases}$$

Controller Design – Translational Controller

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- Y_m^{cl} defined as follows contains acceleration terms which is not implementable

$$fRe_3 = mge_3 - m\dot{v} = Y_m^{cl}\theta_m, \quad Y_m^{cl} = \begin{bmatrix} -\ddot{x}_1 \\ -\ddot{x}_2 \\ g - \ddot{x}_3 \end{bmatrix}$$

- By integrating Y_m^{cl} to be y_m^{cl} as defined in last page, y_m^{cl} becomes implementable
- Integrating both sides of the translational dynamics $fRe_3 = Y_m^{cl}\theta_m$ yields

$$\int_{t-\Delta t}^{t} fRe_3(\tau)d\tau = \int_{t-\Delta t}^{t} Y_m^{cl}(\tau)\theta_m d\tau \Rightarrow \int \boldsymbol{fRe_3(\tau)}\Big|_{\tau=t} - \int \boldsymbol{fRe_3(\tau)}\Big|_{\tau=t-\Delta t} = y_m^{cl}\theta_m$$

$$\dot{\hat{\theta}}_m = \Gamma_m Y_m^T(e_v + C_1 e_x) + k_m^{cl}\Gamma_m \sum_{j=1}^{N_m} \left(y_m^{cl}(t_j)\right)^T \left(\boldsymbol{F(t_j)} - y_m^{cl}(t_j)\,\hat{\theta}_m\right)$$

$$= \Gamma_m Y_m^T(e_v + C_1 e_x) + k_m^{cl}\Gamma_m \sum_{j=1}^{N_m} \left(y_m^{cl}(t_j)\right)^T y_m^{cl}(t_j)\tilde{\theta}_m$$

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Controller Design – Rotational Controller

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- Rotational controller

$$M = \underbrace{-k_R e_R - k_\Omega e_\Omega}_{} \underbrace{- Y_{diag}\hat{\theta}_{diag}}_{} \quad , Y_{diag} = \begin{bmatrix} \bar{\Omega}_1 & \Omega_2 \cdot \Omega_3 & -\Omega_2 \cdot \Omega_3 \\ -\Omega_1 \cdot \Omega_3 & \bar{\Omega}_2 & \Omega_1 \cdot \Omega_3 \\ \Omega_1 \cdot \Omega_2 & -\Omega_1 \cdot \Omega_2 & \bar{\Omega}_3 \end{bmatrix}$$

$$= \boldsymbol{feedback\ term} + \boldsymbol{adaptive\ term}$$

- Integral CL-based adaptive control update law $\dot{\hat{\theta}}_{diag}$

$$\dot{\hat{\theta}}_{diag} = \underbrace{\Gamma_{diag} Y_{diag}^T (e_\Omega + C_2 e_R)}_{} + \underbrace{k_{diag}^{cl} \Gamma_{diag} \sum_{j=1}^{N} \left(y_{diag}^{cl}(t_j)\right)^T \left(\bar{M}(t_j) - y_{diag}^{cl}(t_j)\,\hat{\theta}_{diag}\right)}_{}$$

$$= \boldsymbol{adaptive\ term} + \boldsymbol{ICL - based\ term}$$

$$y_{diag}^{cl}(t_j) \triangleq \begin{cases} 0_{n\times m} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} Y_{diag}^{cl}(\tau)d\tau & t > \Delta t \end{cases} , \quad \bar{M}(t_j) \triangleq \begin{cases} 0_{n\times m} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} M(\tau)d\tau & t > \Delta t \end{cases}$$

Controller Design – Rotational Controller

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- Y_{diag}^{cl} defined as follows contains angular acceleration which is not implementable

$$M = J\dot{\Omega} + \Omega \times J\Omega = Y_{diag}^{cl}\theta_{diag}, \quad Y_{diag}^{cl} = \begin{bmatrix} \dot{\Omega}_1 & -\Omega_2 \cdot \Omega_3 & \Omega_2 \cdot \Omega_3 \\ \Omega_1 \cdot \Omega_3 & \dot{\Omega}_2 & -\Omega_1 \cdot \Omega_3 \\ -\Omega_1 \cdot \Omega_2 & \Omega_1 \cdot \Omega_2 & \dot{\Omega}_3 \end{bmatrix}$$

- By integrating Y_{diag}^{cl} to be y_{diag}^{cl} as defined in last page, y_m^{cl} becomes implementable
- Integrating both sides of the translational dynamics $M = Y_{diag}^{cl}\theta_{diag}$ yields

$$\int_{t-\Delt t}^{t} M(\tau)d\tau = \int_{t-\Delta t}^{t} Y_{diag}^{cl}(\tau)\theta_{diag}d\tau \Rightarrow \int \boldsymbol{M(\tau)}\Big|_{\tau=t} - \int \boldsymbol{M(\tau)}\Big|_{\tau=t-\Delta t} = y_{diag}^{cl}\theta_{diag}$$

$$\dot{\hat{\theta}}_{diag} = \Gamma_{diag}Y_{diag}^{T}(e_{\Omega} + C_2 e_R) + k_{diag}^{cl}\Gamma_{diag}\sum_{j=1}^{N}\left(y_{diag}^{cl}(t_j)\right)^T\left(\boldsymbol{\bar{M}(t_j)} - y_{diag}^{cl}(t_j)\,\hat{\theta}_{diag}\right)$$

$$= \Gamma_{diag}Y_{diag}^{T}(e_{\Omega} + C_2 e_R) + k_{diag}^{cl}\Gamma_{diag}\sum_{j=1}^{N}\left(y_{diag}^{cl}(t_j)\right)^T y_{diag}^{cl}(t_j)\tilde{\theta}_{diag}$$

Stability Analysis – Closed-Loop Error Systems

- Taking the time derivative of error dynamics e_x, e_v defined in Problem Formulation

$$
\begin{aligned}
\dot{e}_x &= \dot{e}_v \\
m\dot{e}_v &= mge_3 - fRe_3 - m\ddot{x}_d \\
&= Y_m\theta_m - \boldsymbol{f}Re_3 \\
&= -k_xe_x - k_ve_v + Y_m\tilde{\theta}_m - X \quad , X = \frac{f}{e_3^TR_d^TRe_3}\left((e_3^TR_d^TRe_3)Re_3 - R_de_3\right)
\end{aligned}
$$

- Taking the time derivative of error dynamics e_R, e_Ω defined in Problem Formulation

$$
\begin{aligned}
\dot{e}_R &= \frac{1}{2}\left(R_d^TR\hat{e}_\Omega + \hat{e}_\Omega R^TR_d\right)^\vee \\
&= \frac{1}{2}\left(tr[R^TR_d]I - R^TR_d\right) \equiv C(R_d^TR)e_\Omega \\
J\dot{e}_\Omega &= J\dot{\Omega} + J\left(\widehat{\Omega}R^TR_d\Omega_d - R^TR_d\dot{\Omega}_d\right) \\
&= J\dot{\Omega} + J\bar{\Omega} = \boldsymbol{M} + Y_{diag}\theta_{diag} = -k_Re_R - k_\Omega e_\Omega + Y_{diag}\tilde{\theta}_{diag}
\end{aligned}
$$

Stability Analysis – Translational Dynamics

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- Let Lyapunov function V_1 defined as

$$V_1 = \frac{1}{2} k_x e_x^T e_x + \frac{1}{2} m e_v^T e_v + C_1 m e_x \cdot e_v + \frac{1}{2} \tilde{\theta}_m^T \Gamma_m^{-1} \tilde{\theta}_m$$

- V_1 is P.D. and it can be lower and upper bounded by

$$z_1^T M_{11} z_1 + \frac{1}{2} \tilde{\theta}_m^T \Gamma_m^{-1} \tilde{\theta}_m \leq V_1 \leq z_1^T M_{12} z_1 + \frac{1}{2} \tilde{\theta}_m^T \Gamma_m^{-1} \tilde{\theta}_m$$

$$z_1 \triangleq [\|e_x\|, \quad \|e_v\|]^T$$

$$M_{11} = \frac{1}{2} \begin{bmatrix} k_x & -C_1 m \\ -C_1 m & m \end{bmatrix}$$

$$M_{12} = \frac{1}{2} \begin{bmatrix} k_x & C_1 m \\ C_1 m & m \end{bmatrix}$$

Stability Analysis – Translational Dynamics

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- Taking the time derivative of V_1 yields

$$\dot{V}_1 = k_x e_x \cdot \dot{\boldsymbol{e}}_{\boldsymbol{x}} + e_v \cdot \boldsymbol{m}\dot{\boldsymbol{e}}_{\boldsymbol{v}} + C_1 m \dot{\boldsymbol{e}}_{\boldsymbol{x}} \cdot e_v + C_1 e_x \cdot \boldsymbol{m}\dot{\boldsymbol{e}}_{\boldsymbol{v}} - \tilde{\theta}_m^T \Gamma_m^{-1} \dot{\hat{\boldsymbol{\theta}}}_{\boldsymbol{m}}$$

- Substitute $\dot{e}_x$ and $m\dot{e}_v$ defined in the previous page into $\dot{V}_1$

$$\dot{V}_1 \leq -z_1^T W_1 z_1 + z_1^T W_{12} z_2 - k_m^{cl} \tilde{\theta}_m^T \left(\sum_{j=1}^{N} \left(y_m^{cl}(t_j) \right)^T y_m^{cl}(t_j) \right) \tilde{\theta}_m$$

$$W_1 = \begin{bmatrix} k_x C_1 (1-\alpha) & -\frac{1}{2} C_1 k_v (1+\alpha) \\ -\frac{1}{2} C_1 k_v (1+\alpha) & k_v (1-\alpha) - C_1 m \end{bmatrix}, \quad W_{12} = \begin{bmatrix} k_x e_{v,max} + C_1 B & 0 \\ B & 0 \end{bmatrix}$$

- M_{11}, M_{12}, W_1 in V_1 and $\dot{V}_1$ are positive-definite matrices if C_1 satisfies

$$C_1 < min \left\{ \sqrt{\frac{k_x}{m}}, \frac{k_v(1-\alpha)}{m}, \frac{4 k_x k_v (1-\alpha)^2}{k_v^2 (1+\alpha)^2 + 4 m k_x (1-\alpha)} \right\}$$

Stability Analysis – Rotational Dynamics

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- Let Lyapunov function V_2 defined as

$$V_2 = \frac{1}{2} e_\Omega \cdot J e_\Omega + k_R \Psi(R, R_d) + J C_2 e_R \cdot e_\Omega + \frac{1}{2} \tilde{\theta}_{diag}^T \Gamma_{diag}^{-1} \tilde{\theta}_{diag}$$

- V_2 is P.D. and it can be lower and upper bounded by

$$z_2^T M_{21} z_2 + \frac{1}{2} \tilde{\theta}_{diag}^T \Gamma_{diag}^{-1} \tilde{\theta}_{diag} \le V_2 \le z_2^T M_{22} z_2 + \frac{1}{2} \tilde{\theta}_{diag}^T \Gamma_{diag}^{-1} \tilde{\theta}_{diag}$$

$$z_2 \triangleq [\|e_R\|, \quad \|e_\Omega\|]^T$$

$$M_{21} = \frac{1}{2} \begin{bmatrix} k_R & -C_2 \lambda_{max}(J) \\ -C_2 \lambda_{max}(J) & \lambda_{min}(J) \end{bmatrix}$$

$$M_{22} = \frac{1}{2} \begin{bmatrix} \dfrac{2k_R}{2 - \psi_2} & -C_2 \lambda_{max}(J) \\ -C_2 \lambda_{max}(J) & \lambda_{min}(J) \end{bmatrix}$$

Stability Analysis – Rotational Dynamics

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- Taking the time derivative of V_2 yields

$$\dot{V}_2 = (e_\Omega + C_2 e_R) \cdot (J\dot{\boldsymbol{e}}_{\boldsymbol{\Omega}}) + k_R e_\Omega \cdot e_R + J C_2 \dot{\boldsymbol{e}}_{\boldsymbol{R}} \cdot e_\Omega - \tilde{\theta}_{diag}^T \Gamma_{diag}^{-1} \dot{\hat{\boldsymbol{\theta}}}_{\boldsymbol{diag}}$$

- Substitute $\dot{e}_R$ and $J\dot{e}_\Omega$ defined in the previous page into $\dot{V}_2$

$$\dot{V}_2 \le -z_2^T W_2 z_2 - k_{diag}^{cl} \tilde{\theta}_{diag}^T \left(\sum_{j=1}^{N} \left(y_{diag}^{cl}(t_j) \right)^T y_{diag}^{cl}(t_j) \right) \tilde{\theta}_{diag}$$

$$W_2 = \begin{bmatrix} C_2 k_R & -\dfrac{C_2 k_\Omega}{2} \\ -\dfrac{C_2 k_\Omega}{2} & k_\Omega - C_2 \lambda_{max}(J) \end{bmatrix}$$

- M_{21}, M_{22}, W_2 in V_2 and $\dot{V}_2$ are positive-definite matrices if C_2 satisfies

$$C_2 < min\left\{ \frac{k_\Omega}{\lambda_{max}(J)}, \frac{4k_\Omega k_R}{k_\Omega^2 + 4k_R \lambda_{max}(J)}, \sqrt{\frac{k_R \lambda_{min}(J)}{\lambda_{max}(J)^2}} \right\}$$

Stability Analysis – Overall System

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- Let $V = V_1 + V_2$ be a Lyapunov function for the system containing rotational and translational dynamics

$$V = V_1 + V_2$$
$$= \frac{1}{2}k_x e_x^T e_x + \frac{1}{2}m e_v^T e_v + C_1 m e_x \cdot e_v + \frac{1}{2}\tilde{\theta}_m^T \Gamma_m^{-1} \tilde{\theta}_m$$
$$+ \frac{1}{2}e_\Omega \cdot J e_\Omega + k_R \Psi(R, R_d) + J C_2 e_R \cdot e_\Omega + \frac{1}{2}\tilde{\theta}_{diag}^T \Gamma_{diag}^{-1} \tilde{\theta}_{diag} \quad \text{... P.D.}$$

- Taking the time derivative of V and substituting $\dot{V}_1$ and $\dot{V}_2$ yields

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \le -z_1^T W_1 z_1 + z_1^T W_{12} z_2 - k_m^{cl} \tilde{\theta}_m^T \left(\sum_{j=1}^{N} \left(y_m^{cl}(t_j) \right)^T y_m^{cl}(t_j) \right) \tilde{\theta}_m$$
$$-z_2^T W_2 z_2 - k_{diag}^{cl} \tilde{\theta}_{diag}^T \left(\sum_{j=1}^{N} \left(y_{diag}^{cl}(t_j) \right)^T y_{diag}^{cl}(t_j) \right) \tilde{\theta}_{diag} \quad \text{... N.D.}$$

, where $\lambda_{min}(W_2) > {}^{4\|W_{12}\|^2}/_{\lambda_{min}(W_1)}$

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- **Stability Analysis**
- Simulation and Experiments
- Conclusion

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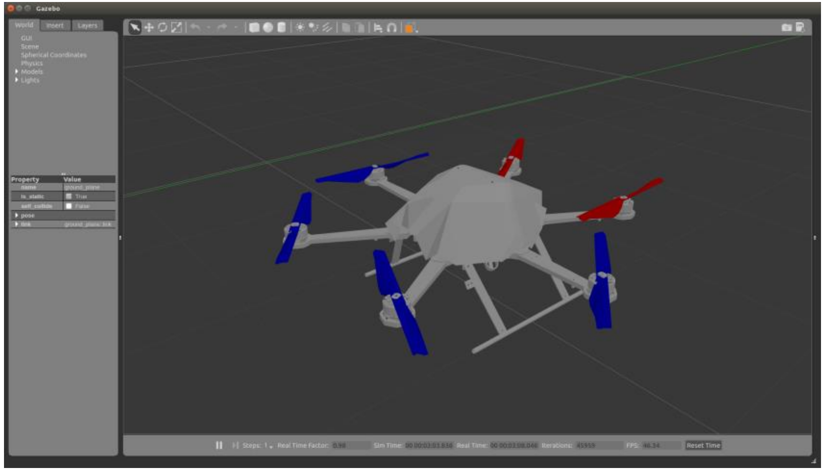
Simulation – Setup and Ground Truth

- A six-rotor multirotor was used as our model in ROS Gazebo
- The ground truth of moment of inertia J and m were unknown parameters to be estimated in the simulations, and were used for evaluating the estimate error but not for implementing the controller



Parameter	Value
m	1.568(kg)
J	$\begin{bmatrix} 0.035 & 0 & 0 \\ 0 & 0.046 & 0 \\ 0 & 0 & 0.0977 \end{bmatrix} (kg \cdot m^2)$
d	0.215(m)

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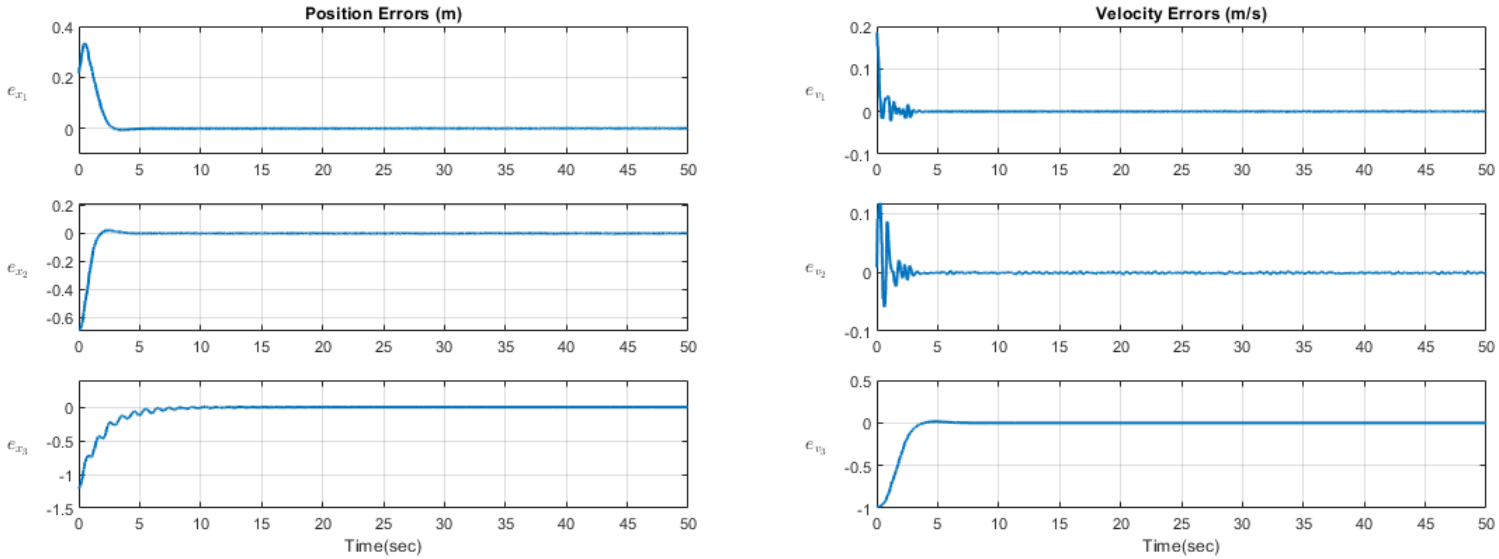
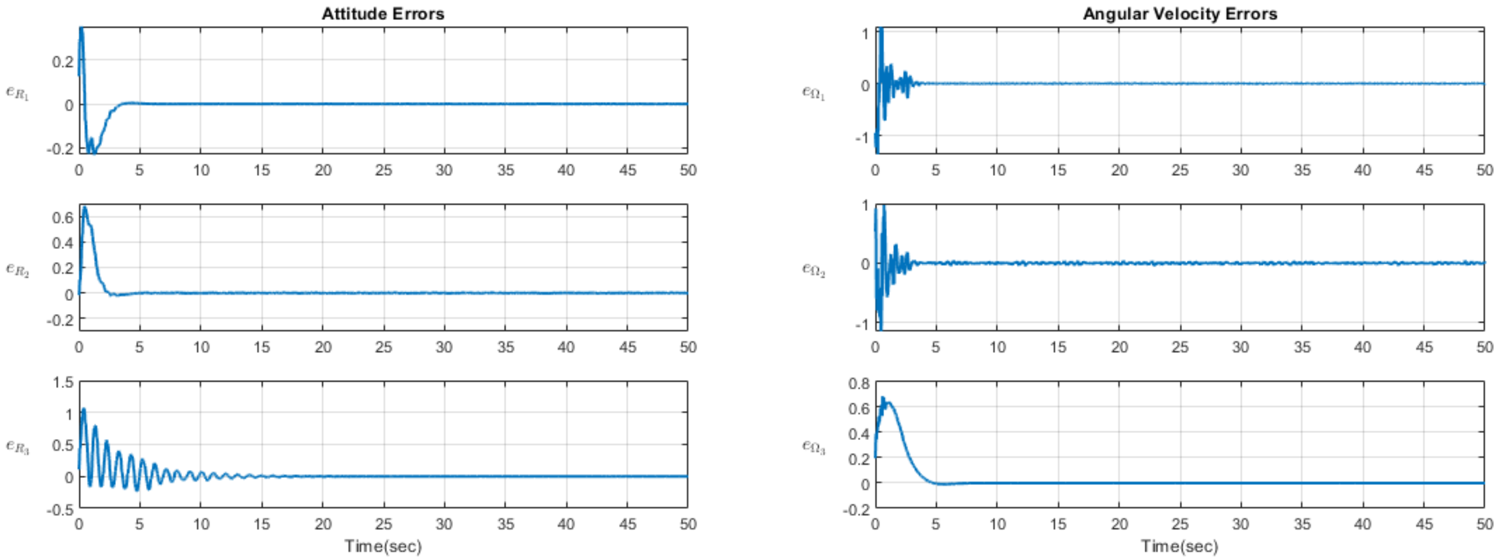
Simulation – Translational Error Tracking



- The tracking errors of the position and velocity converged asymptotically to zero
- The multirotor can track a desired 3D trajectory without the information of mass and moment of inertia

Simulation – Rotational Error Tracking



- The tracking errors of the attitude and angular velocity converged asymptotically to zero

Simulation – Estimate Mass and Moment of Inertia

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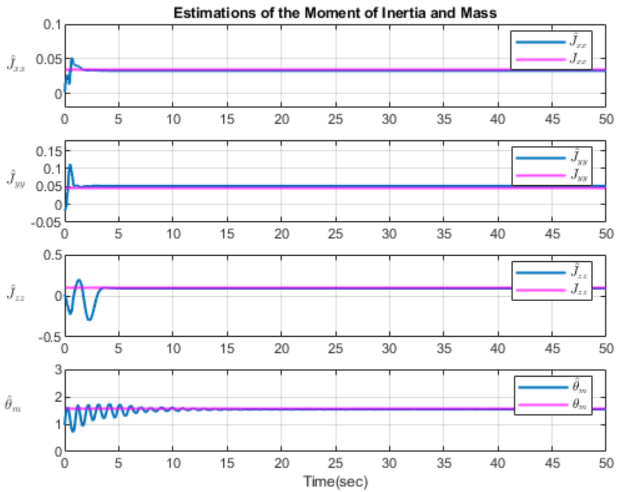
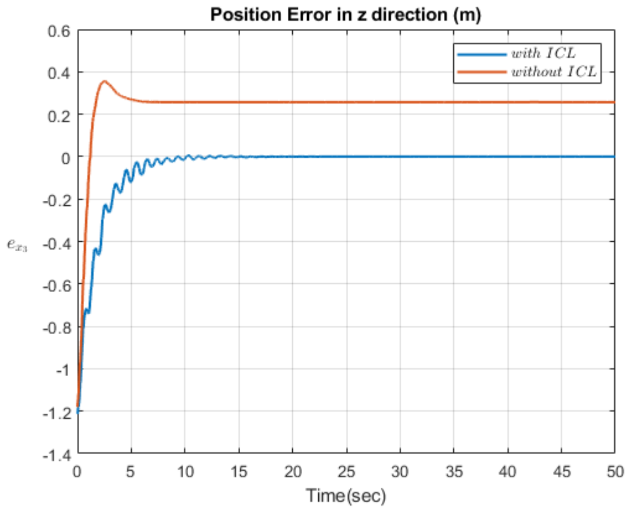
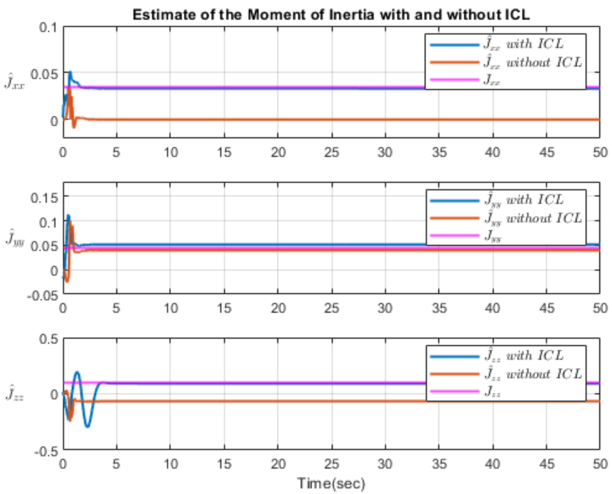
	Estimation value	Ground truth
Mass	1.534	1.568
Moment of inertia	$\begin{bmatrix} 0.033 & 0 & 0 \\ 0 & 0.051 & 0 \\ 0 & 0 & 0.091 \end{bmatrix}$	$\begin{bmatrix} 0.035 & 0 & 0 \\ 0 & 0.046 & 0 \\ 0 & 0 & 0.0977 \end{bmatrix}$

- The estimates of the moment of inertia and mass during flight
- The normalized estimate errors of the moment of inertia and mass were 7.9% and 1.5%, respectively



Simulation – Adaptive Control v.s. Adaptive ICL Control

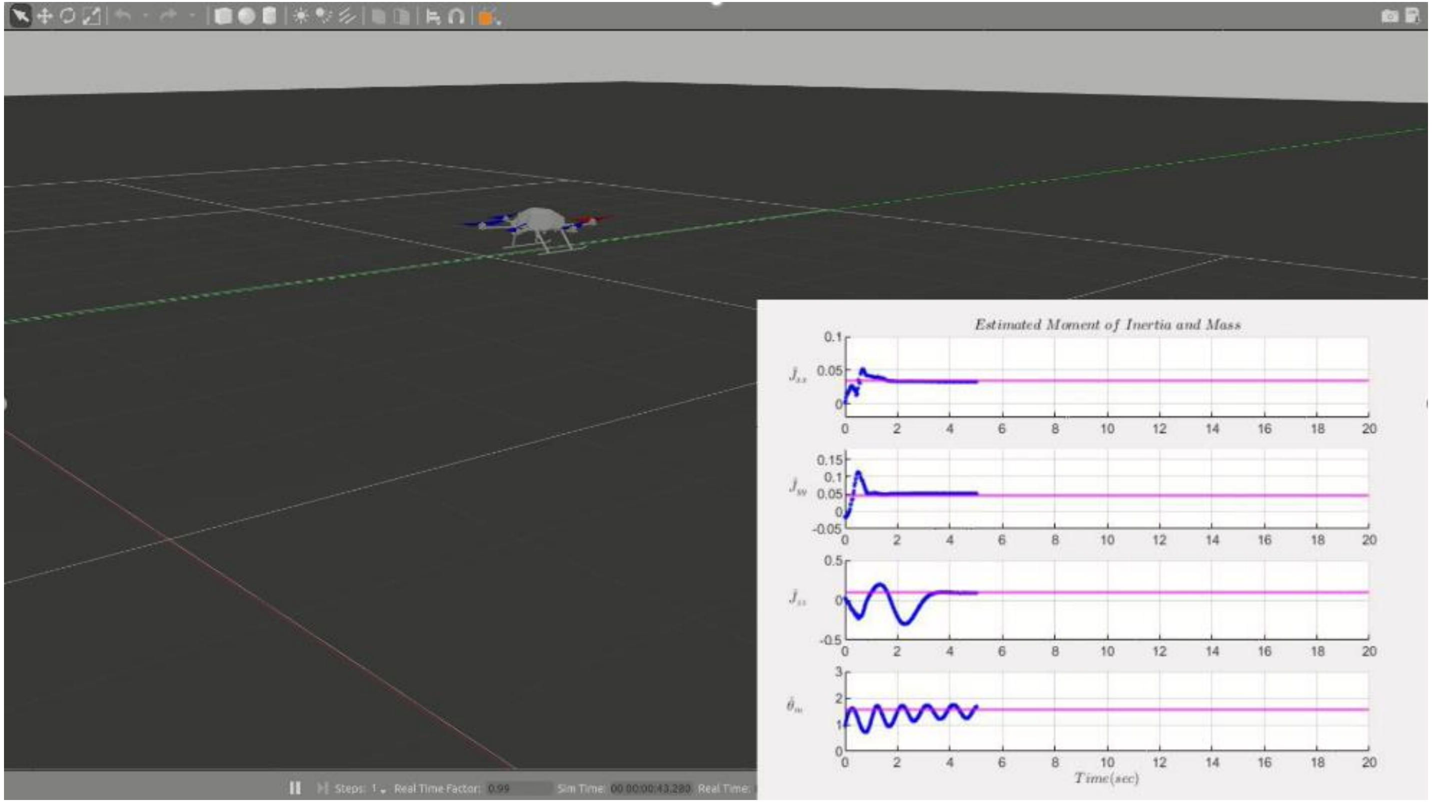




- The figure above compares the controller performance without and with the ICL controller
- This demonstrates the importance and robustness of our developed controller

- The figure above compares the estimated parameters when using the adaptive controller and the developed ICL controller
- Asymptotic convergence of the estimate errors converged asymptotically when using the ICL controller

Simulation - Video



Experiments – Hardware Architecture

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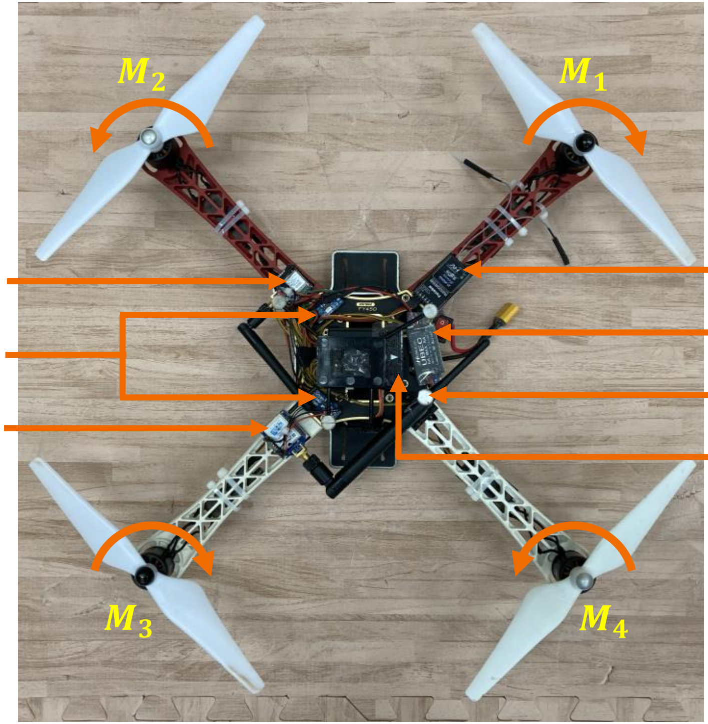

2.4 GHz Xbee Module

5V to 3V3 switching regulator

900 MHz Xbee Module

RC receiver

UBEC

OptiTrack marker

Flight control board

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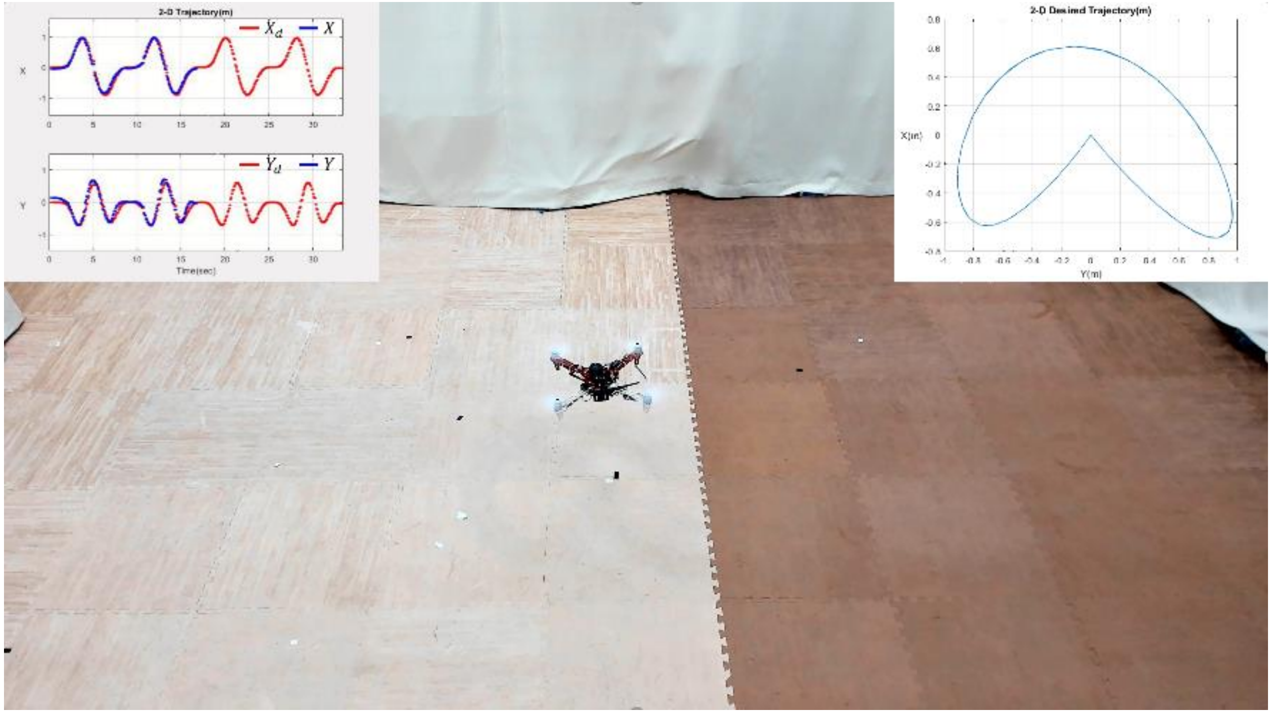
Experiments - Video

- The experiments is based on ncrl-flight-control mainly contributed by Shengwen



Motivation
Problem Formulation
Controller Design
Stability Analysis
Simulation and Experiments
Conclusion

Conclusion

- An ICL controller has been developed for controlling a multirotor with an unknown mass and moment of inertia
- The control architecture can be applied to many types of multirotors of unknown mass, including hexacopters and octocopters
- The ICL controller ensures the steady-state errors resulted from the wrong parameters be eliminated
- The ICL controller can guarantee asymptotic convergence of the system parameters, while the adaptive controller cannot
- Future work can be estimate other parameters of the multirotor, such as off-diagonal elements in the inertia matrix and the center of mass.

Thanks for listening!