Outlines

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

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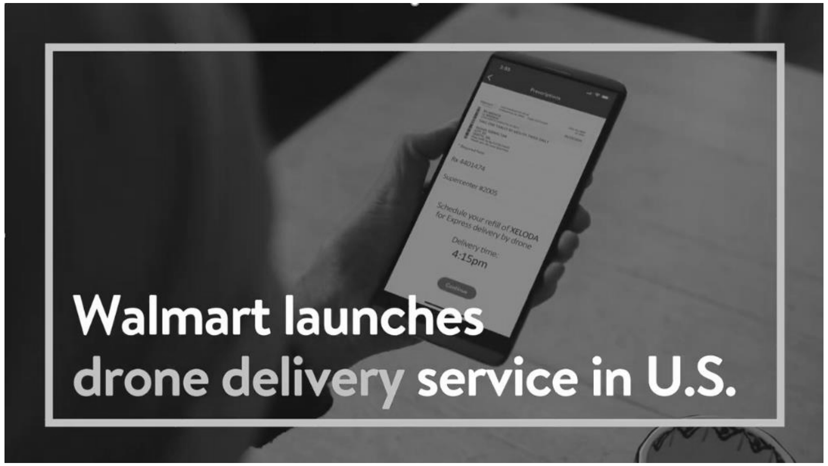
Motivation – from Walmart's drone delivery



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Motivation – from movies Angel Has Fallen

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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.

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Problem Formulation - Definition of Symbols

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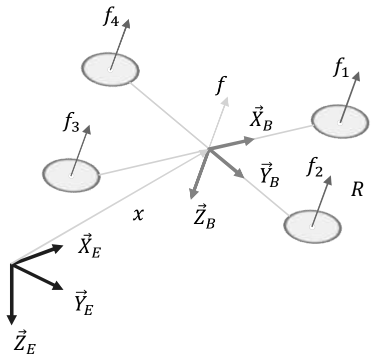
Symbol	Description
x	Position of the multirotor
v	Velocity of the multirotor
R	Rotation matrix from the body-fixed frame to the inertial frame
Ω	Angular velocity in the body-fixed frame
f	Net thrust control input
M	Moment control input
m	Mass of the multirotor
J	Moment of inertia of the multirotor



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
  $\Psi(R, R_d) \triangleq \frac{1}{2} tr[I - R_d^T R]$
- Attitude tracking error and the angular velocity tracking error
  $e_R \triangleq \frac{1}{2}(R_d^T R - R^T R_d)^\vee$
  $e_\Omega \triangleq \Omega - R^T R_d \Omega_d$
- 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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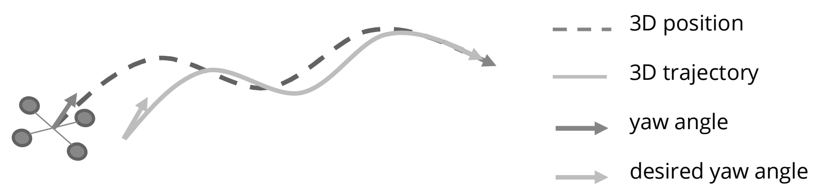
- Track a desired 3D trajectory
- Track a desired yaw angle
- Estimate the mass of the multirotor
- Estimate the moment of inertia of the multirotor

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



Controller Design – Control Architecture

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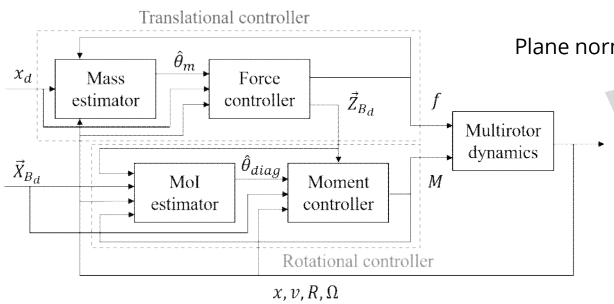

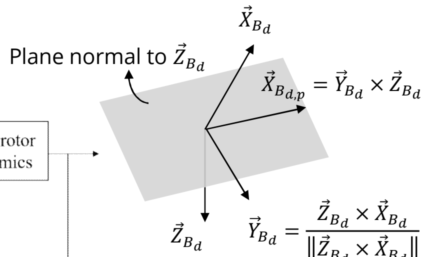

$$\vec{X}_{B_{d,p}} = \vec{Y}_{B_d} \times \vec{Z}_{B_d}$$

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

$$R_d = [\vec{X}_{B_{d,p}}; \quad \vec{Y}_{B_d}; \quad \vec{Z}_{B_d}] \in R^{3\times3}$$

Controller Design – Translational Controller

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- Translational controller

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

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

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

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

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

$$y_m^{cl}(t_j) \triangleq \begin{cases} 0_{n\times1} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} Y_m^{cl}(\tau) d\tau & t > \Delta t \end{cases}, \quad F(t_j) \triangleq \begin{cases} 0_{n\times1} & t \in [0, \Delta t] \\ \int_{t-\Delta t}^{t} fRe_3(\tau) d\tau & t > \Delta t \end{cases}$$

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

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

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

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

Controller Design – Rotational Controller

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- Rotational controller

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

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

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

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

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

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

Controller Design – Rotational Controller

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

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

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

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

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

$$= \Gamma_{diag}Y^T_{diag}(e_\Omega + C_2 e_R) + k^{cl}_{diag}\Gamma_{diag}\sum_{j=1}^{N}\left(y^{cl}_{diag}(t_j)\right)^T y^{cl}_{diag}(t_j)\tilde{\theta}_{diag}$$

Stability Analysis – Closed-Loop Error Systems

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

$$\dot{e}_x = \dot{e}_v$$

$$m\dot{e}_v = mge_3 - fRe_3 - m\ddot{x}_d$$

$$= Y_m\theta_m - fRe_3$$

$$= -k_x e_x - k_v e_v + Y_m\tilde{\theta}_m - X \quad , X = \frac{f}{e_3^T R_d^T R e_3}\left(\left(e_3^T R_d^T R e_3\right)Re_3 - R_d e_3\right)$$

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

$$\dot{e}_R = \frac{1}{2}\left(R_d^T R\hat{e}_\Omega + \hat{e}_\Omega R^T R_d\right)^\vee$$

$$= \frac{1}{2}\left(tr[R^T R_d]I - R^T R_d\right) \equiv C\left(R_d^T R\right)e_\Omega$$

$$J\dot{e}_\Omega = J\dot{\Omega} + J\left(\hat{\Omega}R^T R_d\Omega_d - R^T R_d\dot{\Omega}_d\right)$$

$$= J\dot{\Omega} + J\bar{\Omega} = \boldsymbol{M} + Y_{diag}\theta_{diag} = -k_R e_R - k_\Omega e_\Omega + Y_{diag}\tilde{\theta}_{diag}$$

Stability Analysis – Translational Dynamics

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- Let Lyapunov function V_1 defined as

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

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

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

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

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

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

Stability Analysis – Translational Dynamics

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- Taking the time derivative of V_1 yields

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

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

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

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

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

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

Stability Analysis – Rotational Dynamics

- 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

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

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

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

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

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Stability Analysis – Rotational Dynamics

- Taking the time derivative of V_2 yields

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

- 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

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

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Stability Analysis – Overall System

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

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

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

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

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

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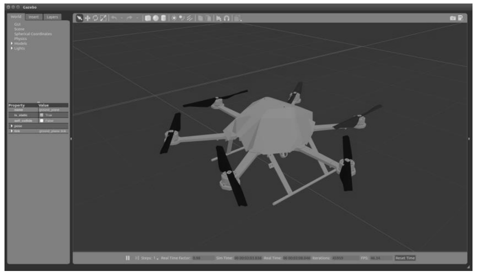
Simulation – Setup and Ground Truth

- 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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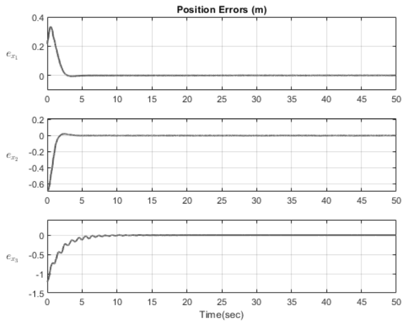
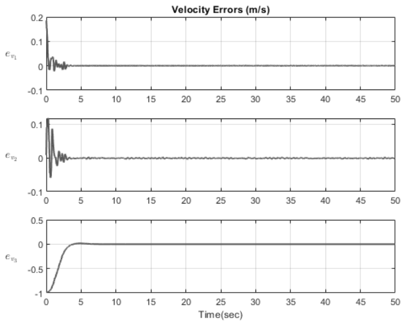
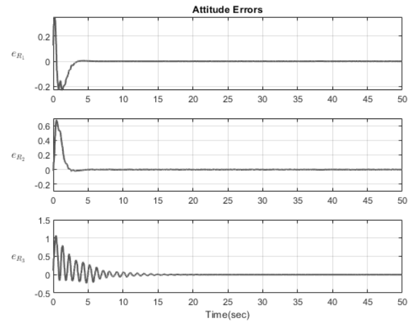
Simulation – Translational Error Tracking

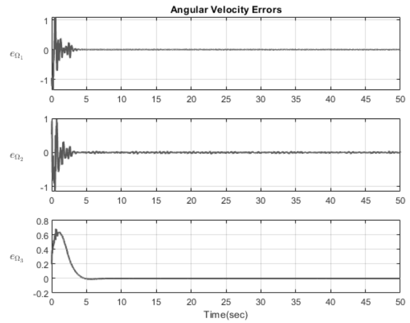




- The tracking errors of the position and velocity converged asymptotically to zero
- The multirotor can track a desired 3D trajectory without the information of mass and moment of inertia

Simulation – Rotational Error Tracking



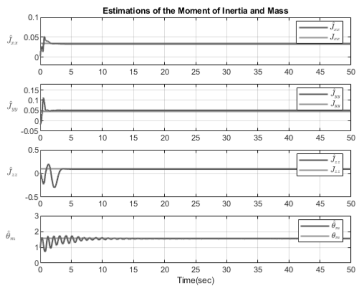


- The tracking errors of the attitude and angular velocity converged asymptotically to zero

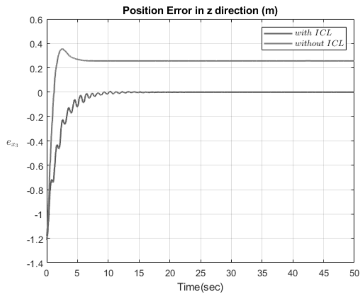
Simulation – Estimate Mass and Moment of Inertia

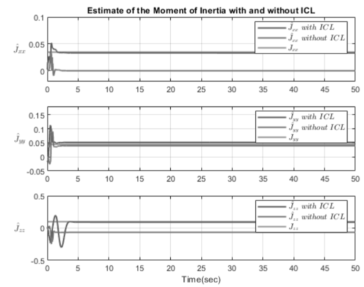
	Estimation value	Ground truth
Mass	1.534	1.568
Moment of inertia	$\begin{bmatrix}0.033 & 0 & 0\\ 0 & 0.051 & 0\\ 0 & 0 & 0.091\end{bmatrix}$	$\begin{bmatrix}0.035 & 0 & 0\\ 0 & 0.046 & 0\\ 0 & 0 & 0.0977\end{bmatrix}$

- 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

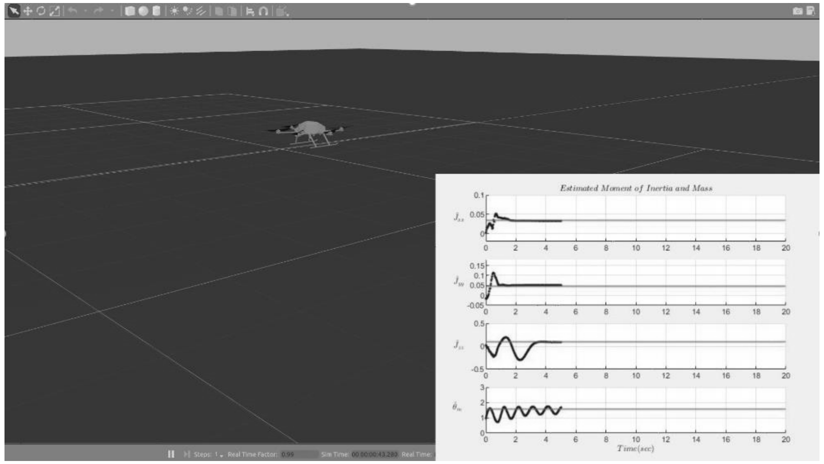




- The figure above compares the controller performance without and with the ICL controller
- This demonstrates the importance and robustness of our developed controller

- 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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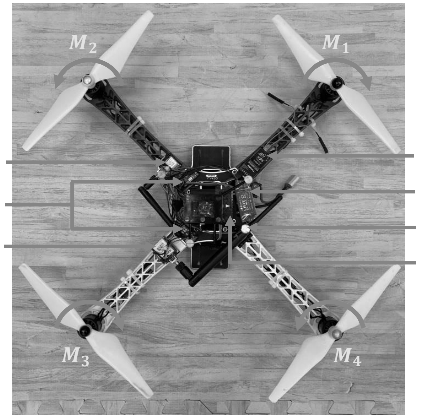

Motivation
Problem Formulation
Controller Design
Stability Analysis
Simulation and Experiments
Conclusion

Experiments - Video

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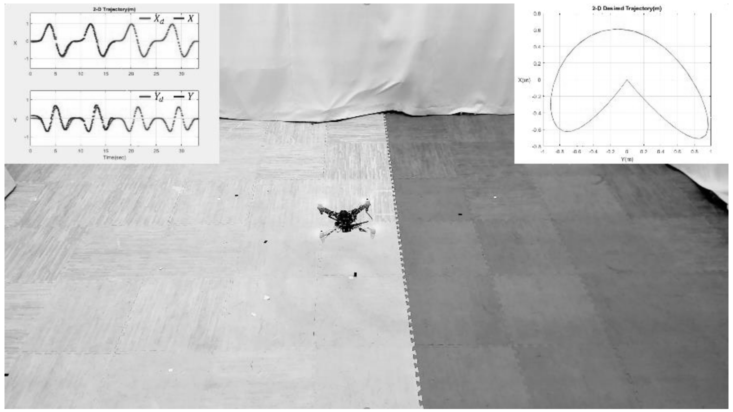
- The experiments is based on ncrl-flight-control mainly contributed by Shengwen



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- 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.

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