Lecture 1: Introduction and Platform Model Overview

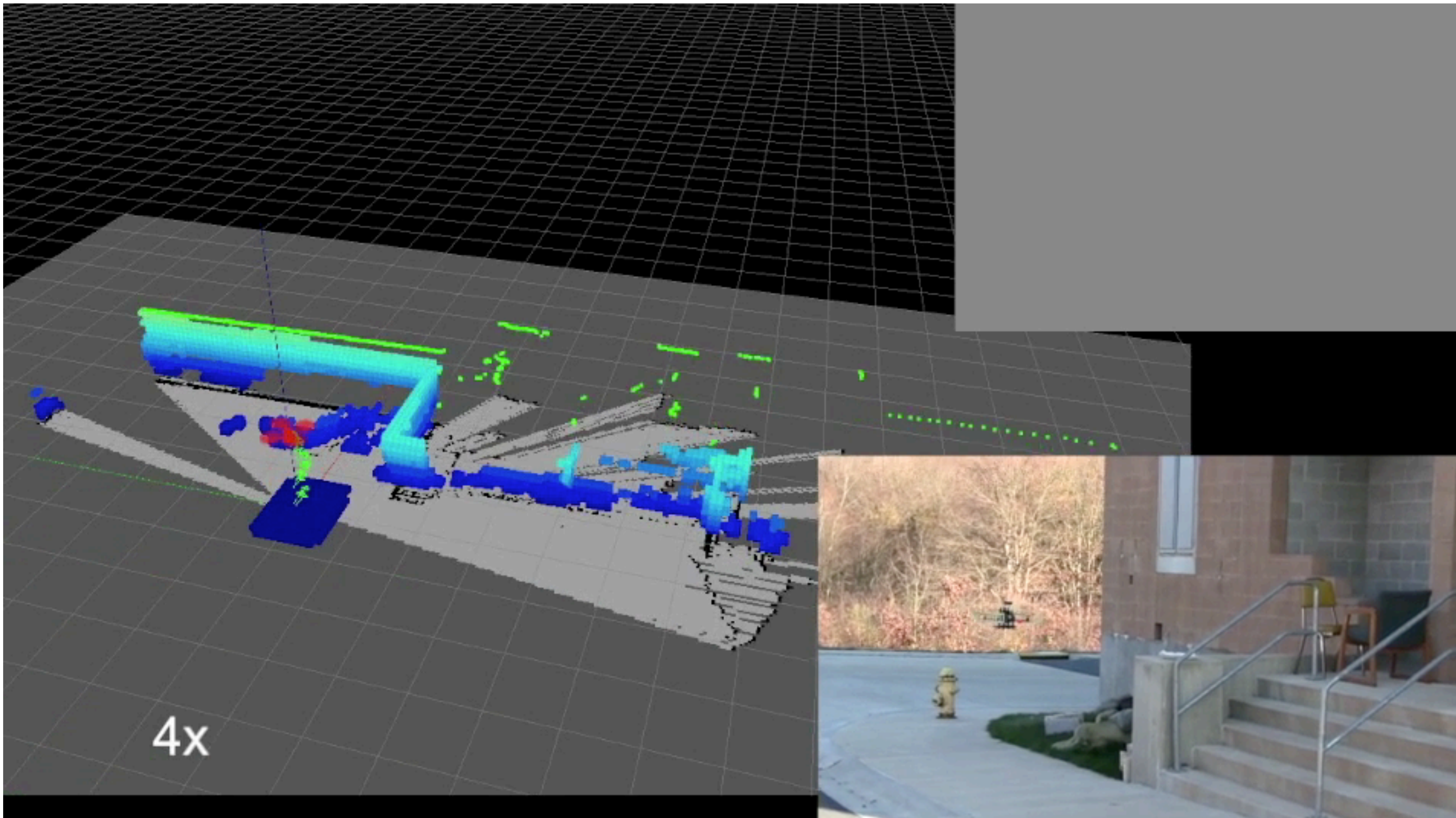
Nathan Michael

January 12, 2015

What is Robot Autonomy?

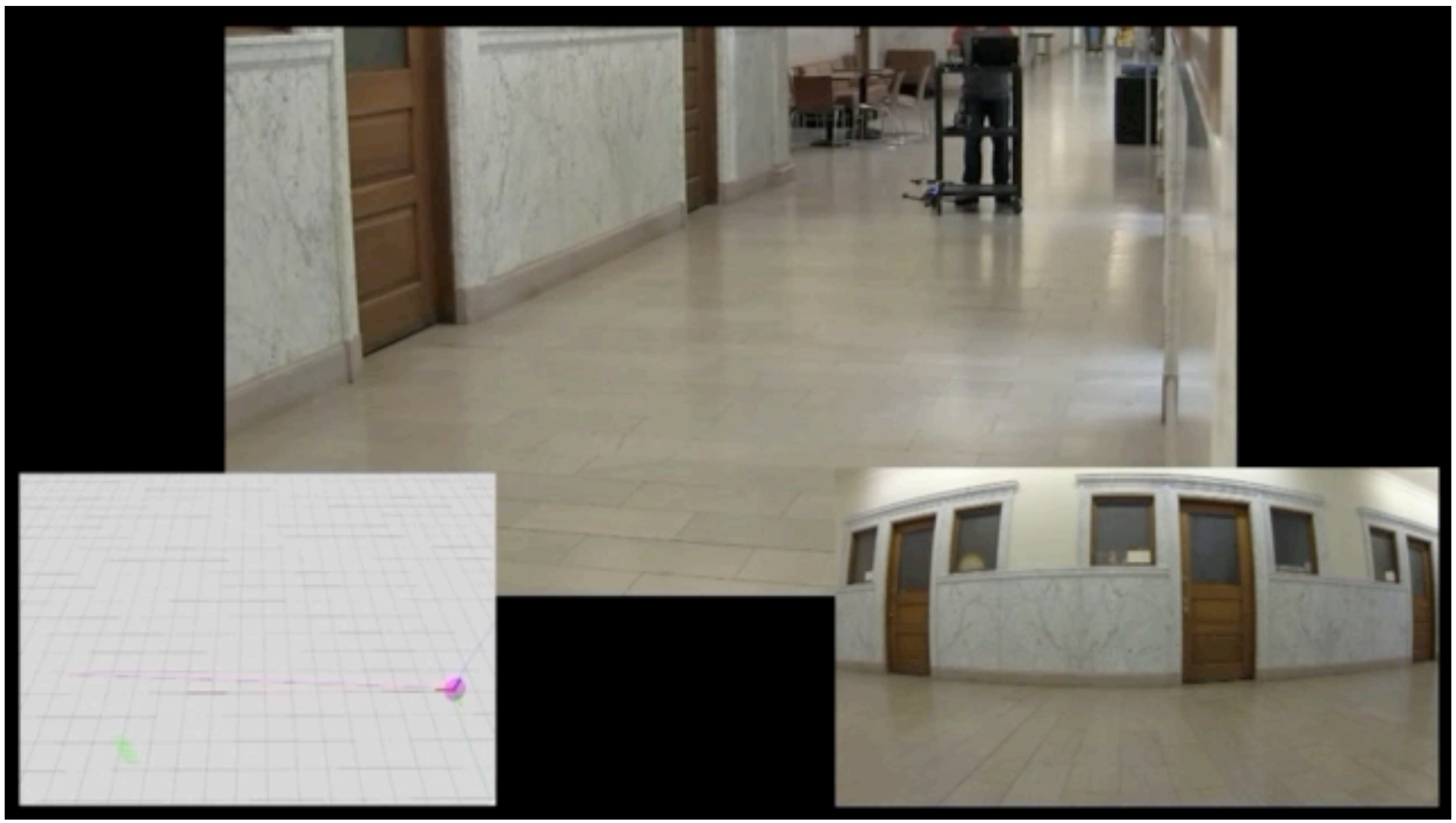
The theory, algorithms, and practice of building autonomous systems

Autonomous MAV Navigation



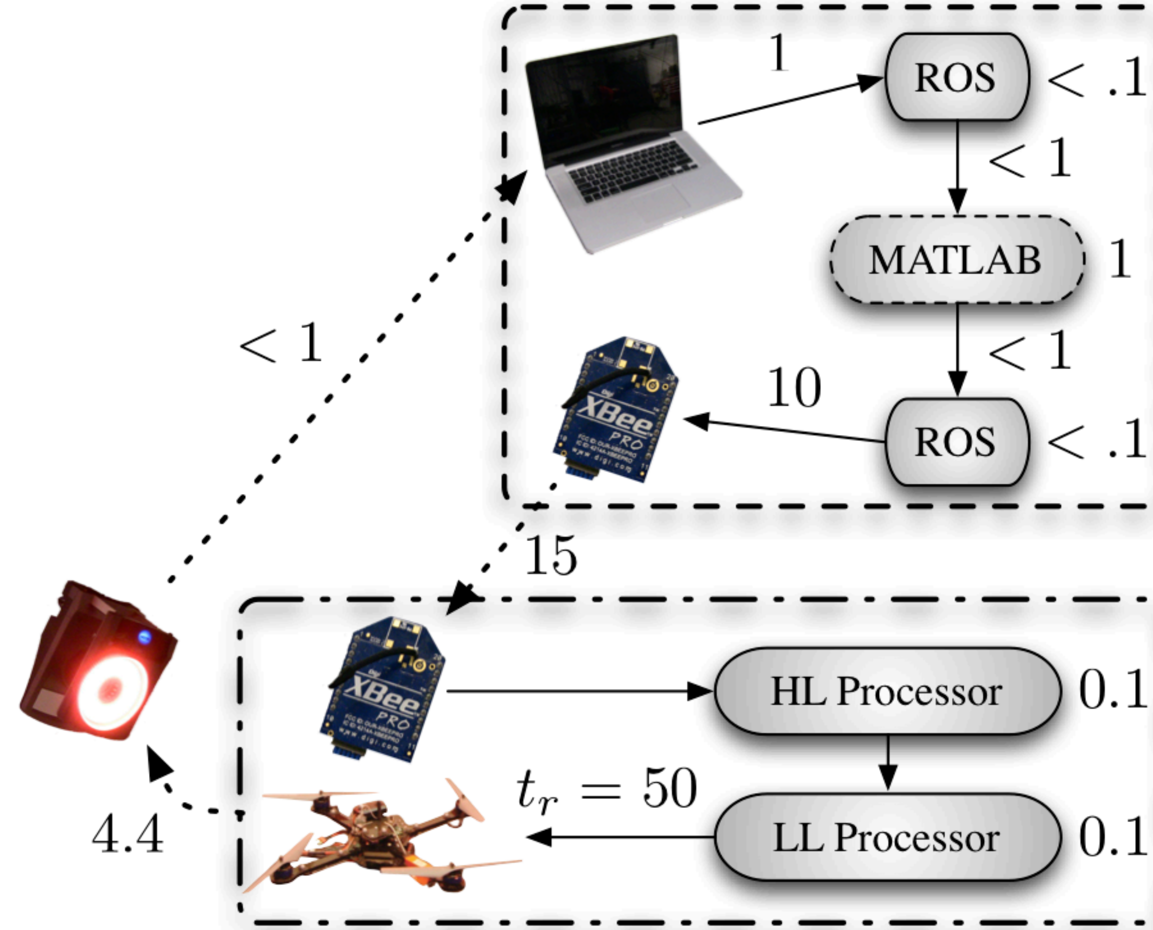
[Shen et al., RAM, 2013]

Vision-based MAV Flight

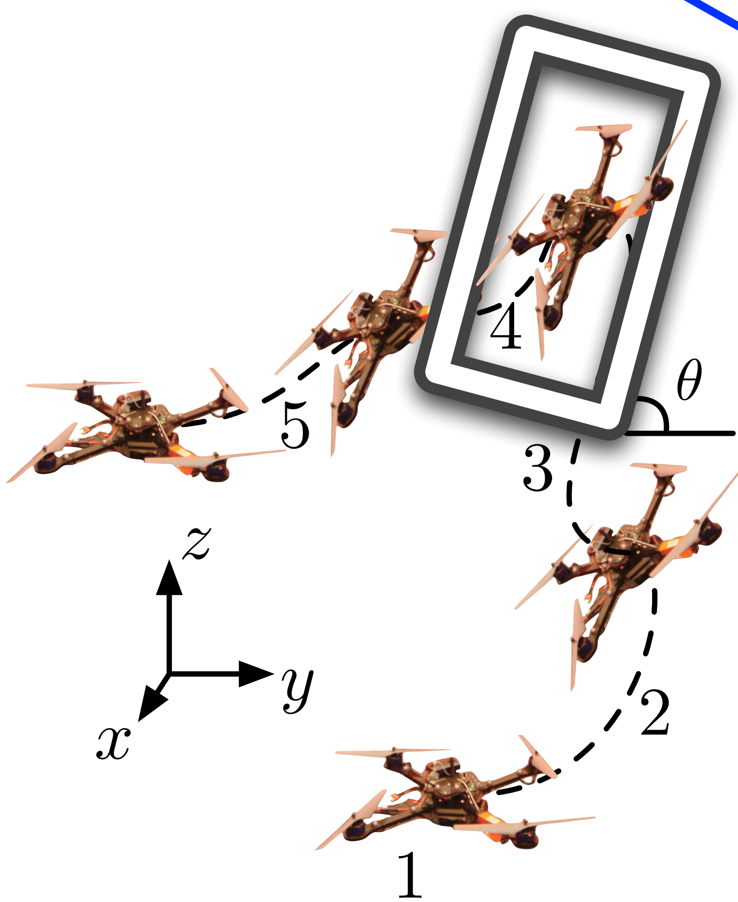


[Shen et al., RSS, 2013]

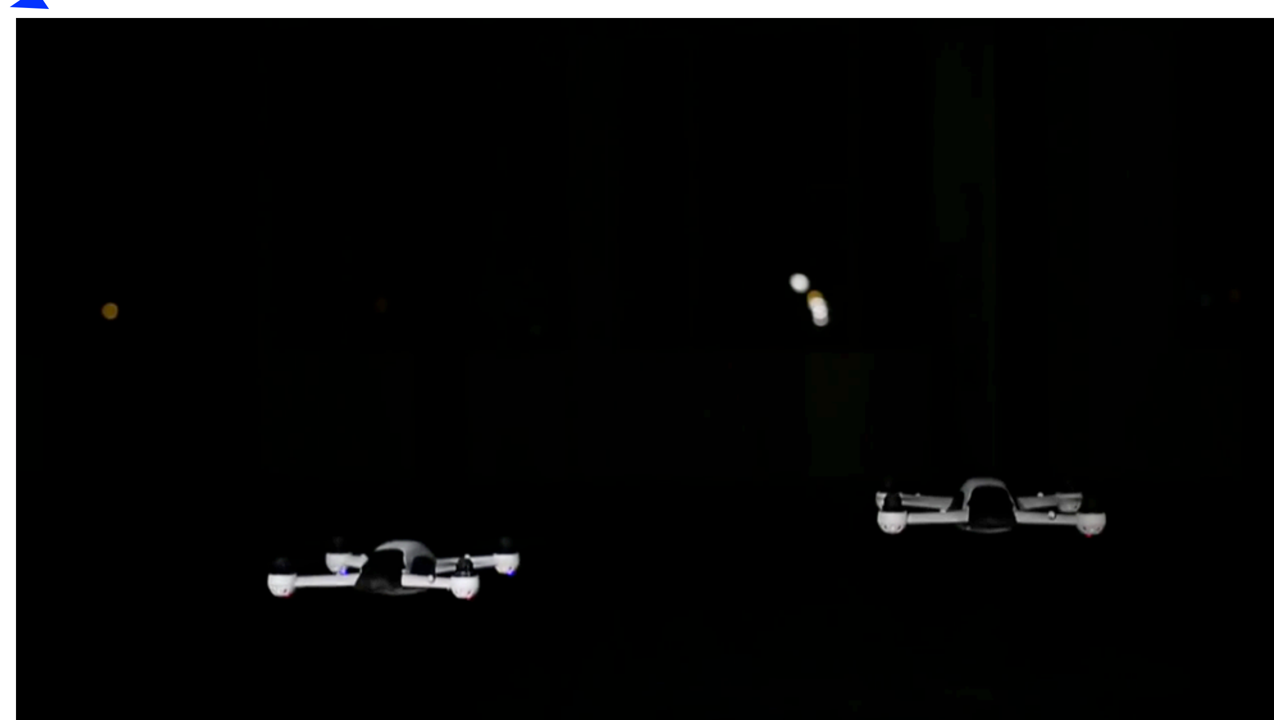
Mellinger et al., ISER, 2010
Mellinger et al., IJRR, 2012



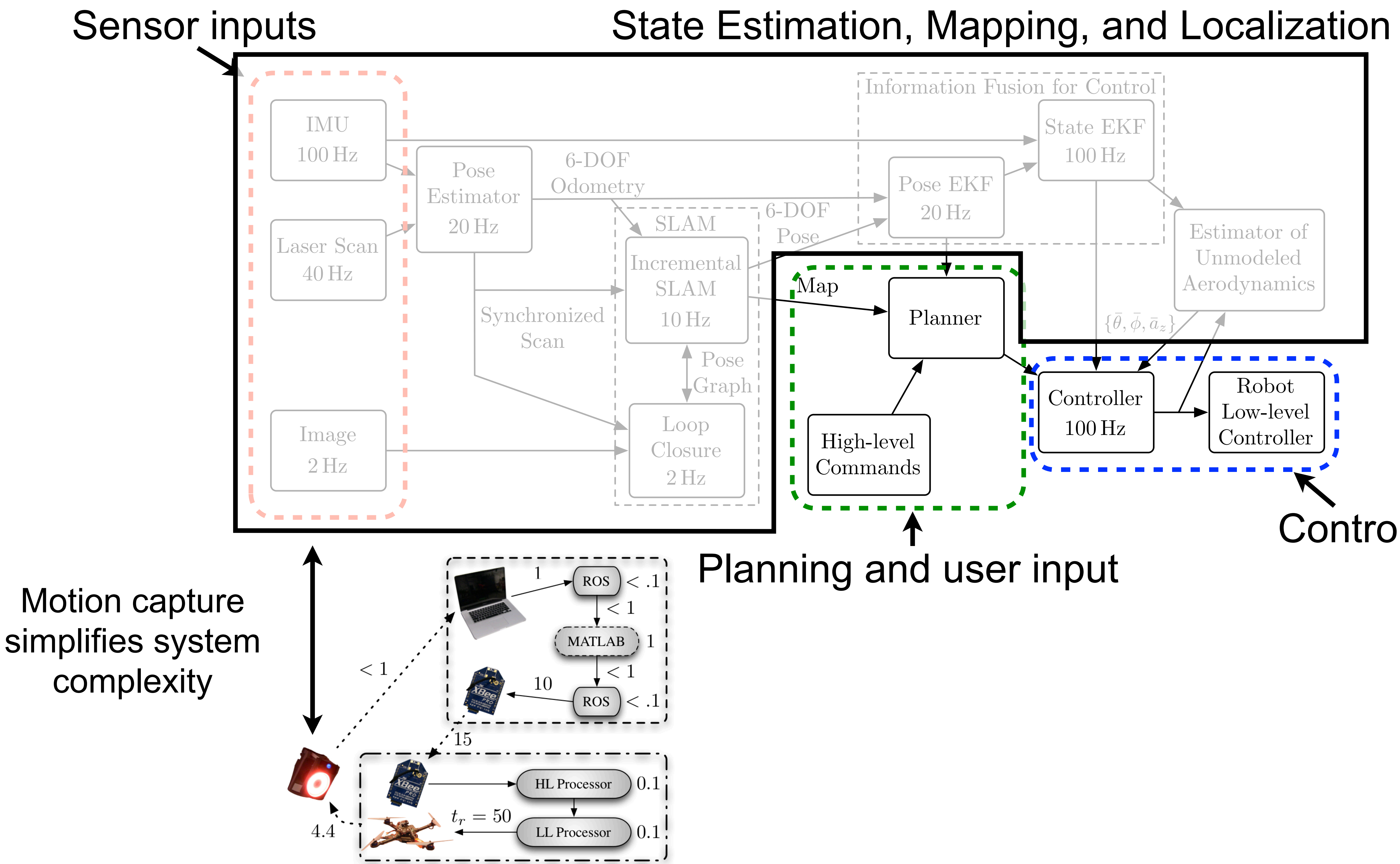
Closed-loop system with latencies (ms)



Sequenced control maneuvers



Representative Autonomous System



Why Robot Autonomy?

- Cover a broad range of topics:
  - Planning
  - Trajectory generation
  - Control
  - Perception (vision)
    - Vision-based ego motion
    - Visual inertial state estimation
- Contextualization and development with respect to a vibrant research and commercial application domain (CV/UAVs)
- Hands-on experience through applied projects with real-systems and data

Guest Lectures (tentative)

- Guest Lecture #1:
  - John Yao/Ke Sun: Robust Visual-Inertial State Estimation for Micro Air Vehicles
- Guest Lecture #2:
  - Vishnu Desaraju: Optimal Real-Time Finite-Horizon Trajectory Generation and Explicit Model Predictive Control
- Guest Lecture #3:
  - Erik Nelson: Rapid Information-Based Exploration with a UGV

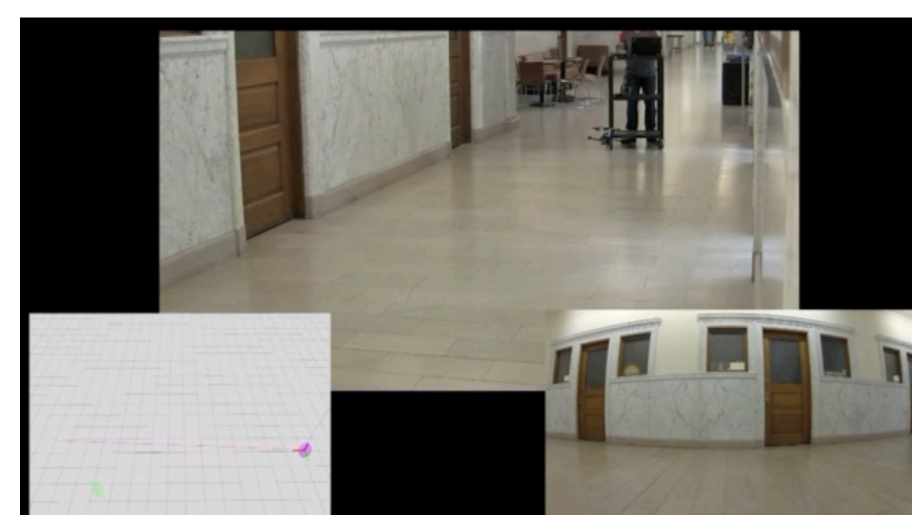
Schedule

Lecture	Date	Topic	Project	Lecturer	Description
1	1/12	Introduction/Modeling		Michael/Kitani	Course/autonomy overview, robot model, software environment
2	1/14	Modeling/Control		Michael	Quadrotor dynamic model and model linearization
3	1/21	Control	P1A	Michael	Control design (PID, LQR)
4	1/26	Control/Robot Hardware		Michael	Control design (feedback linearization) and tuning, Hardware discussion
5	1/28	Project 1 Lab			Hardware overview and distribution
6	2/2	Vision Model	P1B	Kitani	Feature detection (Harris, SIFT, SURF) and descriptors (SIFT, SURF)
7	2/4	Vision Model		Kitani	Feature matching/tracking (Lucas-Kanade or Approx. Nearest Neighbor)
8	2/9	Vision Model		Kitani	Camera calibration (SVD, QR decomposition, lens distortion) and pose estimation (PnP problem)
9	2/11	Vision Model		Kitani	Stereo (Rectification, Block Matching, Epipolar geometry)
10	2/16	State Estimation (VINS)	P2A	Kitani	Basics and terminology (pose, quaternions, velocity, acceleration) and Bayesian Networks
11	2/18	State Estimation (VINS)		Kitani	Kalman Filter
12	2/23	State Estimation (VINS)		Kitani	Extended Kalman Filter
13	2/25	State Estimation (VINS)		Kitani	Extended Kalman Filter Monocular Camera SLAM
14	3/2	Guest Lecture			Robust Visual-Inertial State Estimation for Micro Air Vehicles
15	3/4	Project 2 Lab			Work session in support of P2
16	3/16	Mapping	P2B	Michael	Occupancy grid representation
17	3/18	Mapping		Michael	Performance and Accuracy Consideration, 3D and NDT
18	3/23	Project 3 Lab			Work session in support of P3
19	3/25	Planning	P3	Michael	Motion Planning, Configuration Space, Configuration Space Obstacles
20	3/30	Planning		Michael	Probabilisitic Roadmaps and RRT
21	4/1	Planning		Michael	Discrete Search Algorithms
22	4/6	Trajectory Generation		Michael	Real-time optimal trajectory generation
23	4/8	Project 4 Lab			Work session in support of P4
24	4/13	Guest Lecture	P4A		Optimal Real-Time Finite-Horizon Trajectory Generation and Explicit Model Predictive Control
25	4/15	Exploration		Michael	Frontier-based exploration, information-based exploration
26	4/20	Guest Lecture			Rapid Information-Based Exploration with a UGV
27	4/22	Class Presentations	P4B		
28	4/27	Class Presentations	P4B		
29	4/29	Class Presentations	P4B		

Important Dates

Date	Project	Description
1/21	P1A	Installation of simulation software framework and Matlab interfaces
2/2	P1B	Feedback control of a micro air vehicle
2/16	P2A	Vision-based MAV ego-motion estimation via post-processed data sets from flying platforms
3/16	P2B	Visual-inertial state estimation (data sets)
3/25	P3	Vision-based dense map construction
4/13	P4A	Path planning and optimal trajectory generation in cluttered environments
4/22 - 4/27	P4B	**Autonomous visual-inertial navigation** (presentations)

- Project 1A (template distributed next class):
  - Install Ubuntu/ROS
  - Install simulation software
  - Install Matlab/ROS interface
  - Limited flight controller evaluation



Projects and Grading

- Four projects that build toward developing a fully autonomous micro air vehicle using onboard sensing and processing
- Projects 1, 2, and 4 divided into two sub-projects
  - Sequential objectives with manageable milestones
- Projects assume Matlab experience and access to Ubuntu systems with ROS
- Group-based projects
  - Self-organized groups of 3 - 5 people
  - Members can change between projects (not sub-projects)

- Project deliverables
  - 2 - 4 page report depending on the project with a pre-defined template (pending)
  - Objective: Scholarly presentation of approach/methodology and results/analysis

- Grading
  - Project reports: 60% (P1A, P1B, P2A, P2B, P3, P4A)
  - Presentation and final report: 20% (P4B)
  - Capability marketplace: 20%

Capability Marketplace

- Sequential projects build toward developing a complete autonomous system
- What happens if a project capability doesn't work (or performs poorly)?
  - After the project is completed, you can purchase a capability upgrade:
    - Instructor/TA implementation
    - Peer implementation
      - Students can receive a 1-time extra credit per project
  - Percentage points will depend on capability complexity
    - Not to exceed 8% points (average module: 2-4%)

The goal is to enable forward progress
toward developing an autonomous system.

Be honest, don't copy code, attribute appropriately

Logistics and Administration

- Location: GHC 4215
- Time: M/W, 1500 - 1620
- Instructors: Nathan Michael, Kris Kitani
- Teaching assistant: John Yao
- Working sessions:
  - Structured sessions providing guided application/practice
  - Instructors and TA will be present
  - Attendance is mandatory

- Piazza course organization

Signup today via:

piazza.com/cmu/spring2015/16662

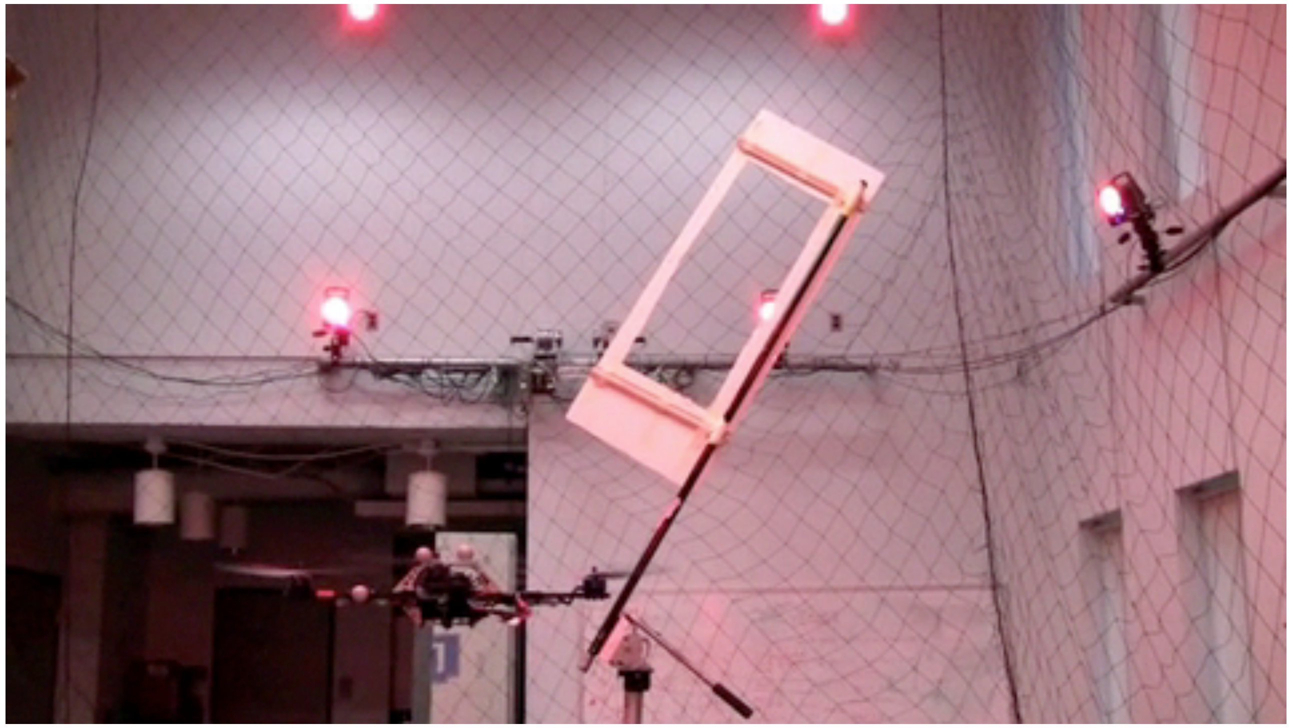
Questions?

Lecture Outline

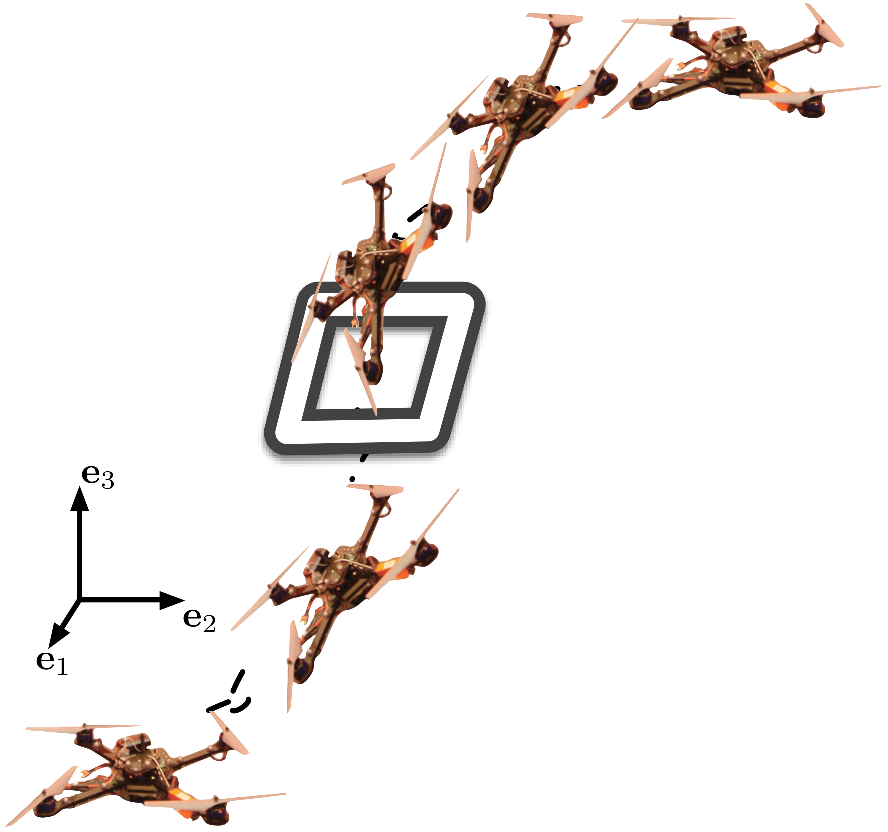
- Modeling:
  - Dynamic model from first principles
  - Propeller model and force and moments generation
- Control
  - Attitude control (inner loop)
  - Position control (outer loop)

Lecture Objective

Develop preliminary concepts required to enable autonomous flight:



[Mellinger et al., IJRR, 2012]



1. <u>Vehicle model</u>
2. <u>Attitude and position control</u>
3. Trajectory generation

Quadrotor Model

Concept Review

Newton-Euler equations:

total force

mass

linear acceleration

linear velocity

$$\begin{bmatrix} \mathbf{F} \\ \tau \end{bmatrix} = \begin{bmatrix} m\mathbb{1}_3 & \mathbb{0}_3 \\ \mathbb{0}_3 & \mathbf{I}_3 \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \alpha \end{bmatrix} + \begin{bmatrix} \omega \times m\mathbf{v} \\ \omega \times \mathbf{I}_3 \omega \end{bmatrix}$$

total torque

moment of inertia

angular velocity

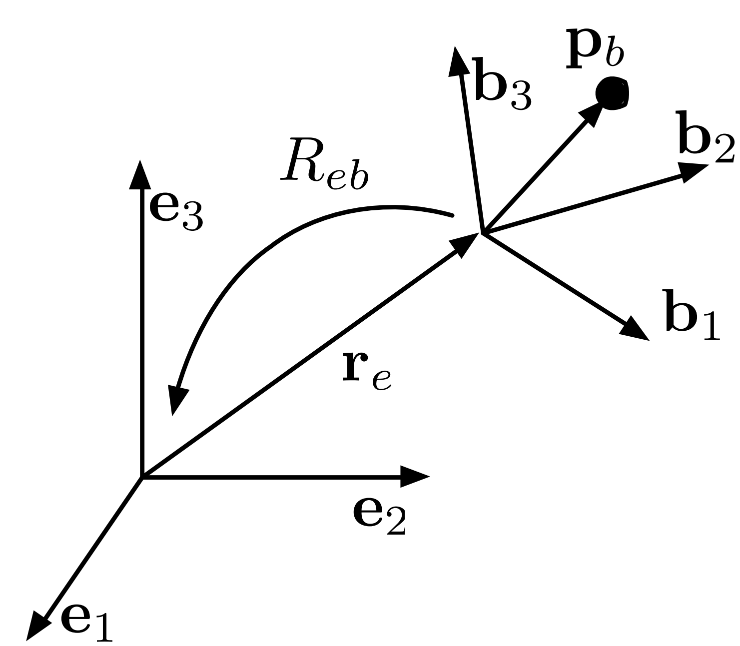
angular acceleration

Quadrotor Model

Concept Review

Rigid transformation:

$$\mathbf{p}_e = \underbrace{R_{eb}}_{\text{rotation}}\mathbf{p}_b + \underbrace{\mathbf{r}_e}_{\text{translation}}$$



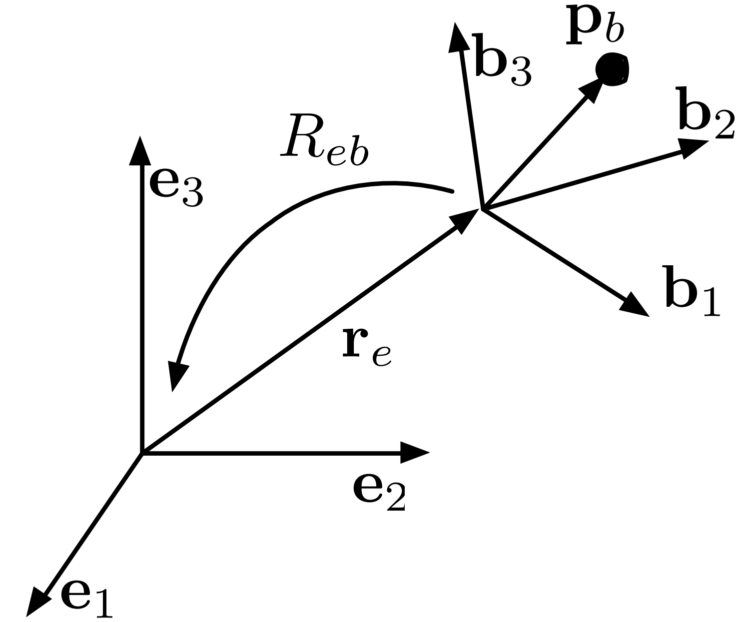
Euler angle parameterization of rotation:

$$R_{eb} = R_z(\psi)R_y(\theta)R_x(\phi) \qquad \text{ZYX (321) form}$$

Quadrotor Model

Concept Review

Euler angle parameterization of rotation:



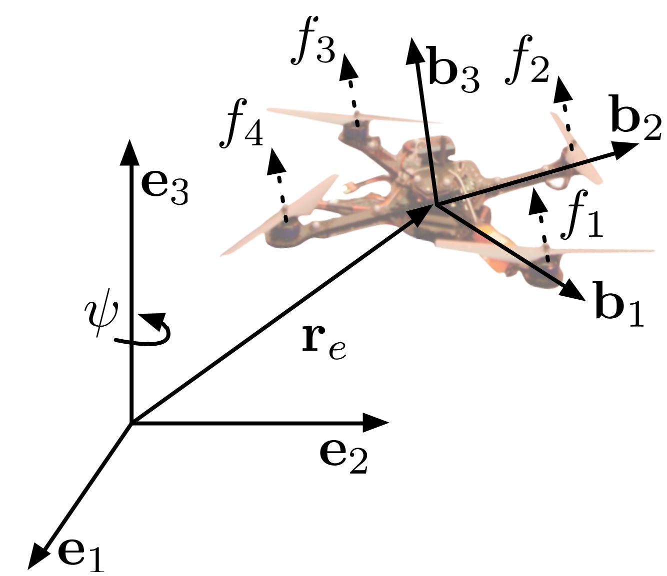
$$R_{eb} = \underbrace{R_z(\psi)}_{\text{yaw}}\underbrace{R_y(\theta)}_{\text{pitch}}\underbrace{R_x(\phi)}_{\text{roll}}$$

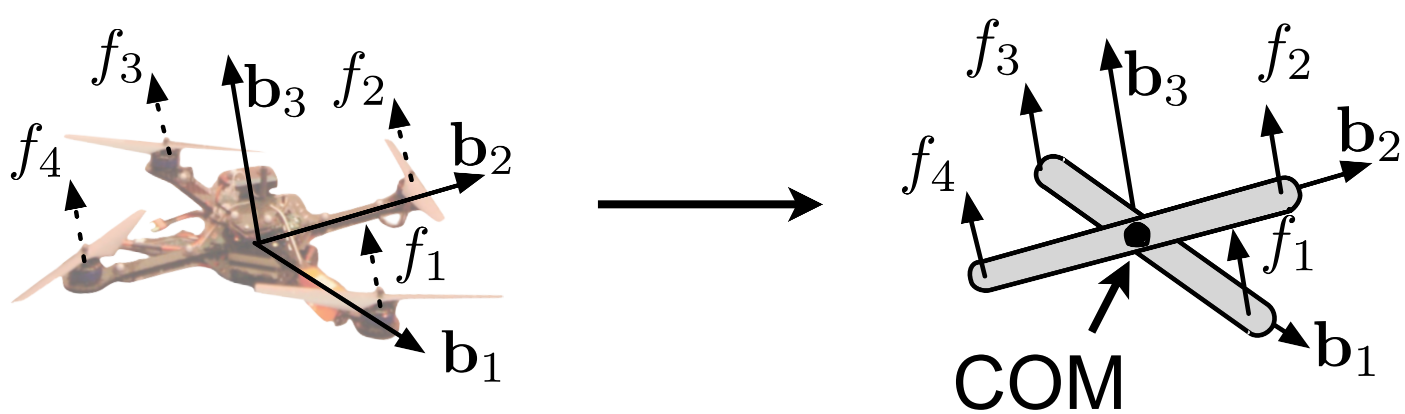
$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & -s\phi \\ 0 & s\phi & c\phi \end{bmatrix} \quad R_y(\theta) = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \quad R_z(\psi) = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Quadrotor Model

Newton-Euler equations:

$$\begin{bmatrix} \mathbf{F} \\ \tau \end{bmatrix} = \begin{bmatrix} m\mathbb{1}_3 & \mathbb{0}_3 \\ \mathbb{0}_3 & \mathbf{I}_3 \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \alpha \end{bmatrix} + \begin{bmatrix} \omega \times m\mathbf{v} \\ \omega \times \mathbf{I}_3\omega \end{bmatrix}$$





Total force:

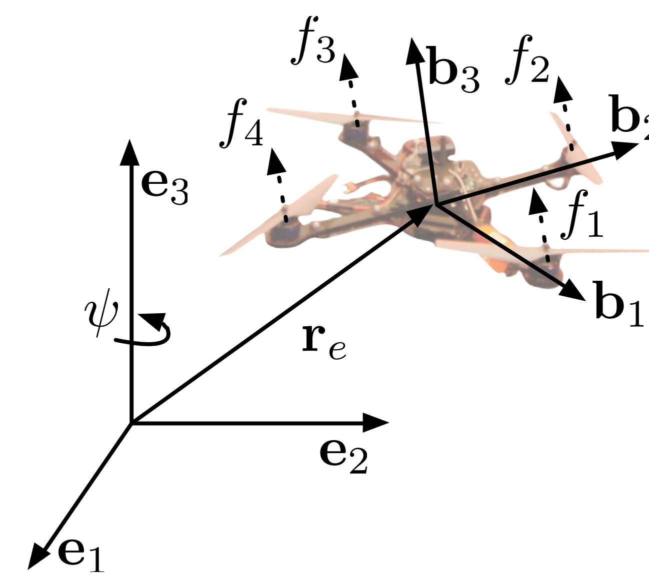
Body: $$f = \sum_{i=1}^{4} f_i \xrightarrow[\text{along } \mathbf{b}_3]{} \mathbf{F}_b = \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$$

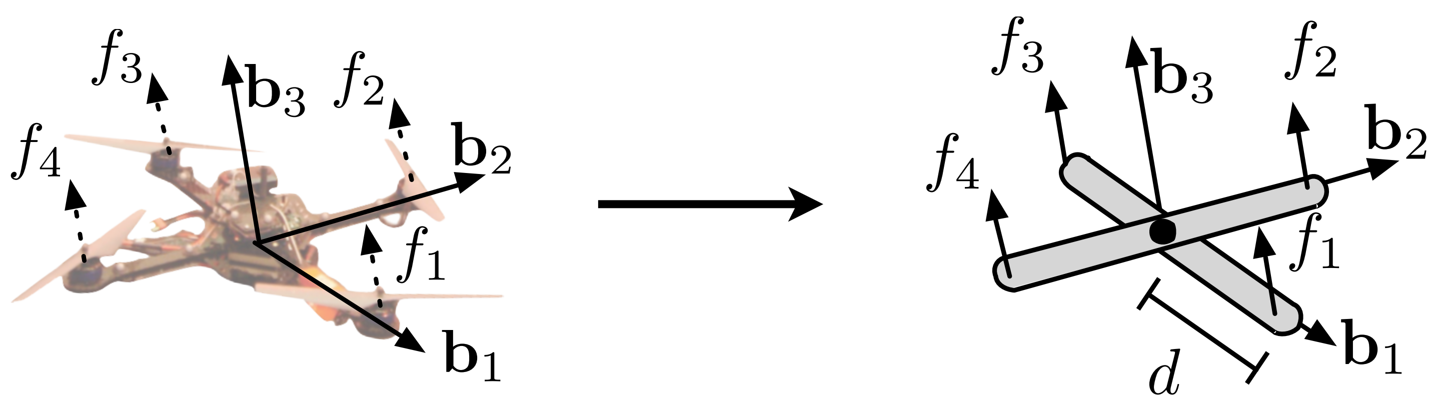
Inertial: $$\mathbf{F}_e = R_{eb}\mathbf{F}_b - m\mathbf{g} \longleftarrow \text{gravity}$$

Quadrotor Model

Newton-Euler equations:

$$\begin{bmatrix} \mathbf{F} \\ \tau \end{bmatrix} = \begin{bmatrix} m\mathbb{1}_3 & \mathbb{0}_3 \\ \mathbb{0}_3 & \mathbf{I}_3 \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \alpha \end{bmatrix} + \begin{bmatrix} \omega \times m\mathbf{v} \\ \omega \times \mathbf{I}_3\omega \end{bmatrix}$$



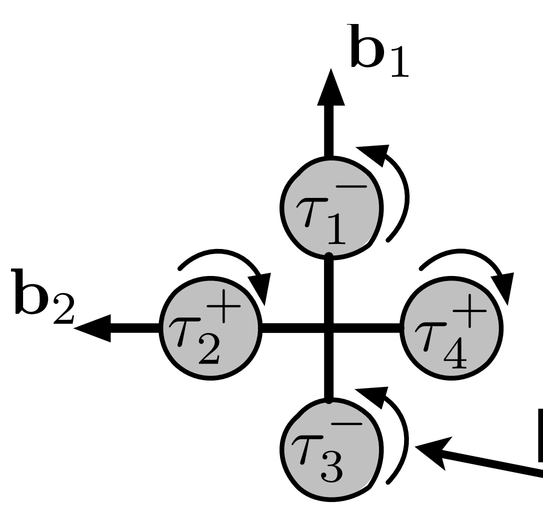


Total torque:

Recall: $\tau = \mathbf{r} \times \mathbf{F}$

$$\tau_{\mathbf{b}_1} = d\,(f_2 - f_4)$$

$$\tau_{\mathbf{b}_2} = d\,(f_3 - f_1)$$



induced moments

$$\tau_{\mathbf{b}_3} = -\tau_1 + \tau_2 - \tau_3 + \tau_4$$

propeller direction of rotation

Quadrotor Model

Equations of motion:

$$\begin{bmatrix} m\mathbb{1}_3 & \mathbb{0}_3 \\ \mathbb{0}_3 & \mathbf{I}_3 \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \alpha \end{bmatrix} + \begin{bmatrix} \cancel{\omega \times m\mathbf{v}} \\ \omega \times \mathbf{I}_3 \omega \end{bmatrix} = \begin{bmatrix} \mathbf{F}_e \\ \tau \end{bmatrix} = \begin{bmatrix} R_{eb}\mathbf{F}_b - m\mathbf{g} \\ \left[\tau_{\mathbf{b}_1}, \tau_{\mathbf{b}_2}, \tau_{\mathbf{b}_3}\right]^{\mathrm{T}} \end{bmatrix}$$

$$\mathbf{F}_e = R_{eb}\mathbf{F}_b - m\mathbf{g}$$

$$\mathbf{F}_b = \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$$

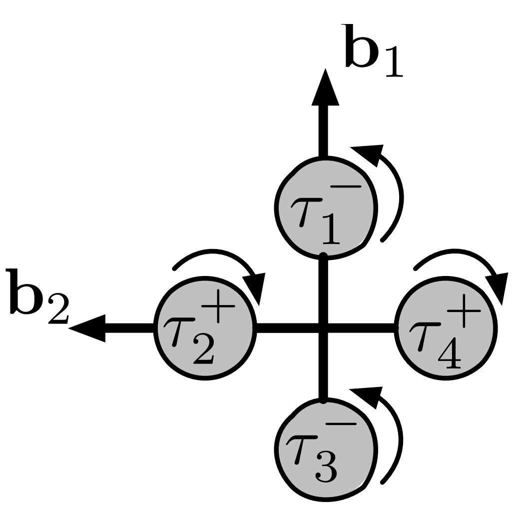
$$\begin{aligned} \tau_{\mathbf{b}_1} &= d\left(f_2 - f_4\right) \\ \tau_{\mathbf{b}_2} &= d\left(f_3 - f_1\right) \\ \tau_{\mathbf{b}_3} &= -\tau_1 + \tau_2 - \tau_3 + \tau_4 \end{aligned}$$

Motor model:

$$f_i = c_{\mathrm{T}}\bar{\omega}_i^2$$

$$\tau_i = \pm c_{\mathrm{Q}}\bar{\omega}_i^2$$

<u>Approximate</u> relationship between propeller speeds and generated thrusts and moments



$$\begin{bmatrix} f \\ \tau_{\mathbf{b}_1} \\ \tau_{\mathbf{b}_2} \\ \tau_{\mathbf{b}_3} \end{bmatrix} = \begin{bmatrix} c_{\mathrm{T}} & c_{\mathrm{T}} & c_{\mathrm{T}} & c_{\mathrm{T}} \\ 0 & dc_{\mathrm{T}} & 0 & -dc_{\mathrm{T}} \\ -dc_{\mathrm{T}} & 0 & dc_{\mathrm{T}} & 0 \\ -c_{\mathrm{Q}} & c_{\mathrm{Q}} & -c_{\mathrm{Q}} & c_{\mathrm{Q}} \end{bmatrix} \begin{bmatrix} \bar{w}_1^2 \\ \bar{w}_2^2 \\ \bar{w}_3^2 \\ \bar{w}_4^2 \end{bmatrix}$$