

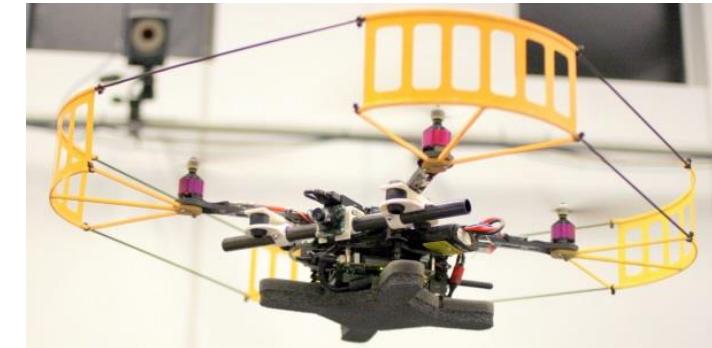
Introduction to Aerial Robotics

Lecture 1

Shaojie Shen

Associate Professor

Dept. of ECE, HKUST



2 February 2021

Logistics

About this Course...

- This course is about:
 - Autonomy for aerial robots
 - Modeling and control of multi-rotor aerial robots
 - Path and trajectory planning for multi-rotor aerial robots
 - Algorithms for vision-based state estimation
 - Algorithms for multi-sensor fusion
 - Real-time software implementations for autonomous aerial robots
 - Lots of fun with robots ☺
- This course is NOT about:
 - Aerodynamics ☹
 - Aircraft design ☹
 - Electromechanical systems of aerial robots ☹

Course structure

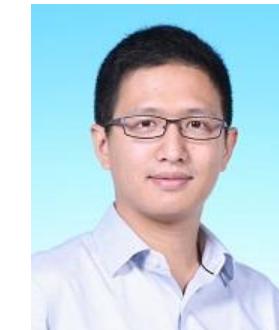
- Weekly lectures + lots of projects + an in-class midterm exam
- Due to COVID-19, all laboratory sessions for this course are cancelled. Projects are redesigned to utilize simulations and offline datasets. Project workload and the overall level of difficulty are similar to those offered in previous years.
- Grading:
 - Midterm: 20%
 - Project 1: 30%
 - Project 2: 25%
 - Project 3: 25%
- More details can be found on the Canvas homepage.

Teaching Team

- **Instructor:**

- Shaojie Shen (eeshaojie@ust.hk)

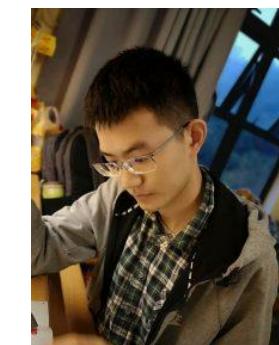
- Office Hour: by appointment



- **Teaching Assistants:**

- Xiuyuan LU (xluaj@ust.hk)

- Office Hour: by appointment



- Yichen ZHANG (yzhangec@ust.hk)

- Office Hour: by appointment

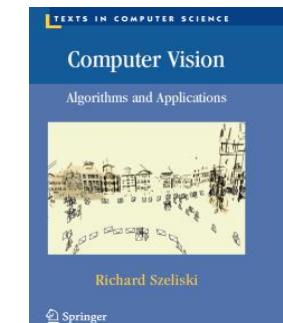
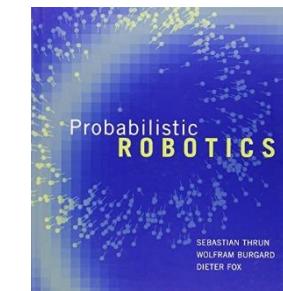
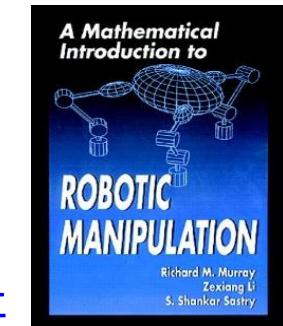


Administrative Stuff

- **Lecture:**
 - Tuesday 13:30 - 16:20, online lectures via Zoom due to COVID-19 until further notice.
- **Labs:**
 - All cancelled...
- **Course Email:**
 - elec5660@ust.hk
- **Course Website:**
 - <https://canvas.ust.hk/courses/36436>

(Non-Compulsory) Reference Books

- A Mathematical Introduction to Robotic Manipulation
 - Richard M. Murray, Zexiang Li, S. Shankar Sastry;
 - <http://www.cds.caltech.edu/~murray/books/MLS/pdf/mls94-complete.pdf>
- Probabilistic Robotics;
 - Sebastian Thrun, Wolfram Burgard, Dieter Fox;
- Computer Vision: Algorithms and Applications
 - Richard Szeliski
 - <http://szeliski.org/Book/>



Workload & Expectation

- **Expected Student Background:**
 - Linear algebra
 - Probability
 - MATLAB programming skills
 - C++ programming skills (**VERY IMPORTANT**)
 - Linux
 - Love robots ☺
- **Workload:**
 - Attend lectures
 - Lots of project work
 - Have fun with robots ☺

Programming!

- MATLAB
- C++
- Robot Operating System (ROS)
[<http://www.ros.org/>]
- Requires coding on both desktop PC and embedded platforms



Overview of Aerial Robotics

Aerial Robots = Military Drones?

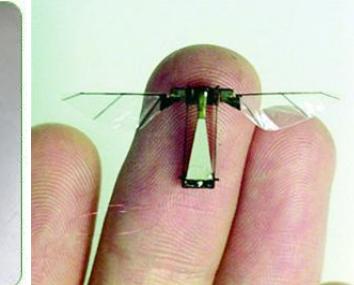
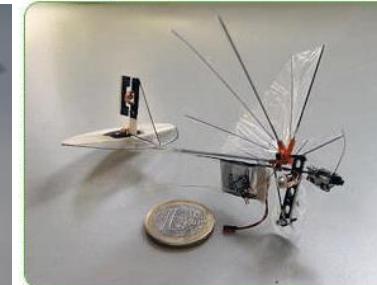
- Mostly Big
- 10+ Hours of Flight Time
- Remote Control
 - Waypoint planning
 - Some joystick
 - Flight crew 4-10



“Drones mischaracterize what these things are. They're not dumb. Nor are they unmanned, actually. They're remotely piloted aircraft.”

-- Gen. Norton Schwarz, August 10, 2012

Unmanned Aerial Vehicles

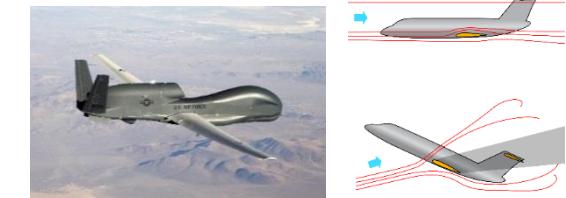


Unmanned Aerial Vehicles

- Types of UAVs

- Fixed wing

- Long flight time, large payload, self-stabilized system 😊
 - Requires runway, may stall, needs aerodynamic design 😞



- Helicopter

- Vertical takeoff and landing 😊
 - OK flight time and payload
 - Complex mechanical system, unstable systems 😞



- Multi-rotor

- VTOL, simple mechanical design 😊
 - Hard to scale up
 - Short flight time, small payload, unstable system 😞



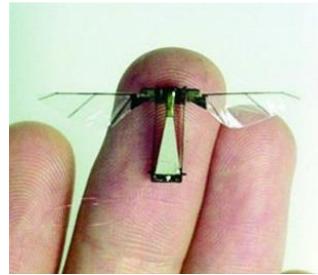
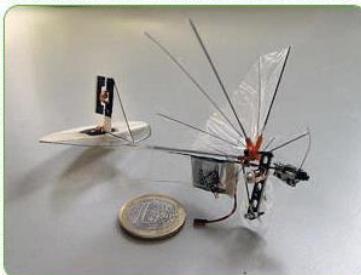
Unmanned Aerial Vehicles

- Anything even better?
 - Vertical Take-Off and Landing (VTOL) UAV
 - VTOL + long flight time + long range 😊
 - Technology not well developed 😞
 - Flapping Wing / Bio-Inspired UAVs
 - Suitable for small platforms 😊
 - Technology not well developed 😞



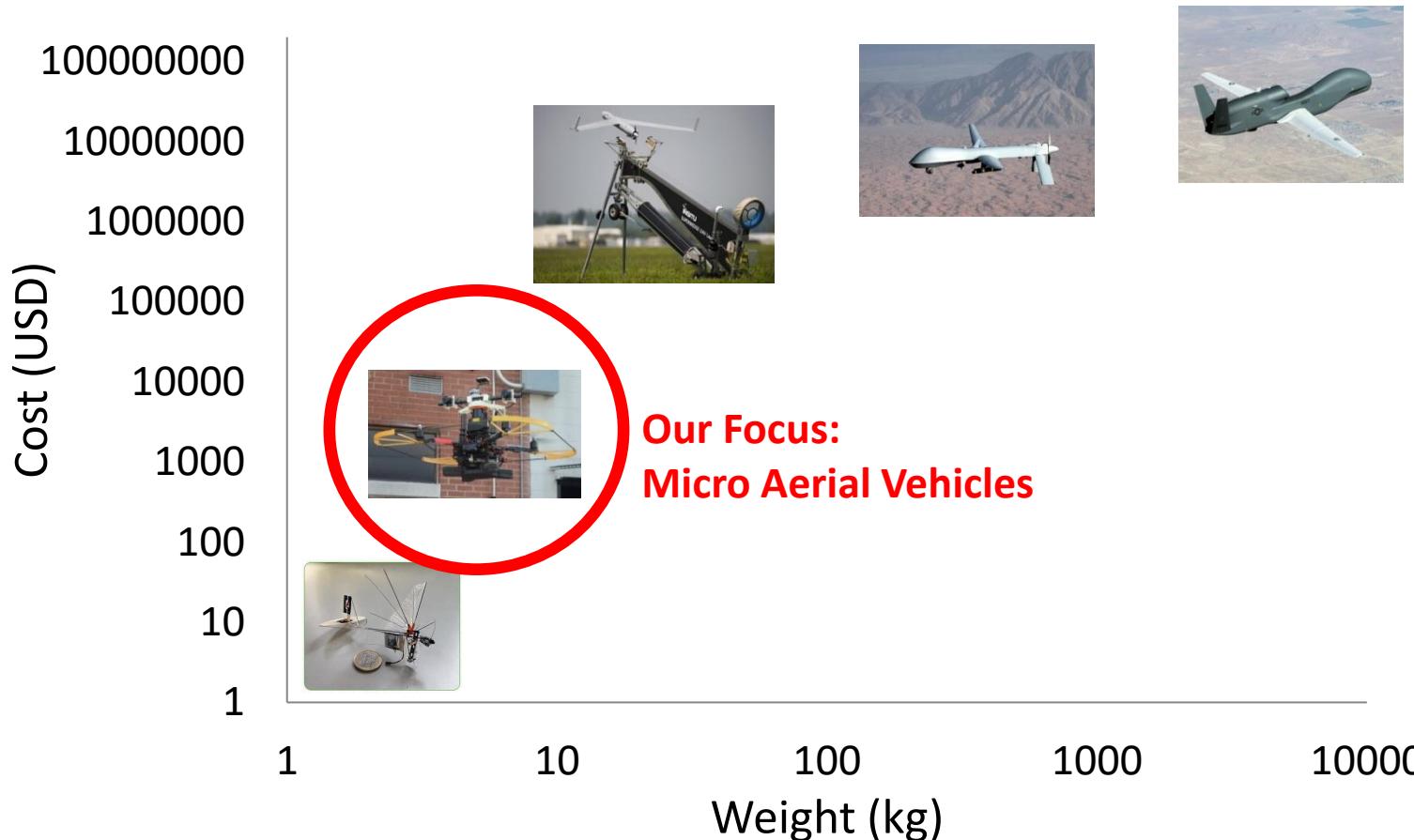
Contents [hide]

- 1 Crashes
 - 1.1 June 1991
 - 1.2 July 1992
 - 1.3 April 2000
 - 1.4 December 2000
 - 1.5 April 2010
 - 1.6 April 2012
 - 1.7 June 2012
- 2 Other accidents and notable incidents
 - 2.1 March 2006
 - 2.2 July 2006
 - 2.3 March 2007
 - 2.4 November 2007
 - 2.5 2009
 - 2.6 October 2014
 - 2.7 May 2015
- 3 References
- 4 External links



Unmanned Aerial Vehicles

- Projected civilian market of \$400 billion USD by 2020
- Regulations are coming in place



Multi-Rotor Micro Aerial Vehicles

- Small size (<1m)
- Adequate payload (1-5kg)
- Low cost (< 10k USD)
- Safe
- Superior mobility



Inspection



Search and Rescue



Transportation



Aerial Photography



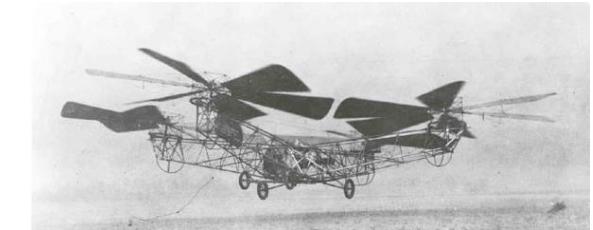
Law enforcement



Agriculture

Development of Multi-Rotors

- de Bothezat helicopter (1922)
 - Flight altitude 5m during demonstration
 - Fully manual controlled unstable system ☹
- Nothing happened in the next few decades
 - Almost impossible for manual control ☹
 - Multi-rotors cannot be scaled up ☹
 - No suitable sensors (tradition IMUs are big and expensive) ☹
- STARMAC @ Stanford University (2004)
 - Thanks to the development of smart mobile devices
 - MEMS sensors + embedded computers



Development of Multi-Rotors

- The Role of Academia

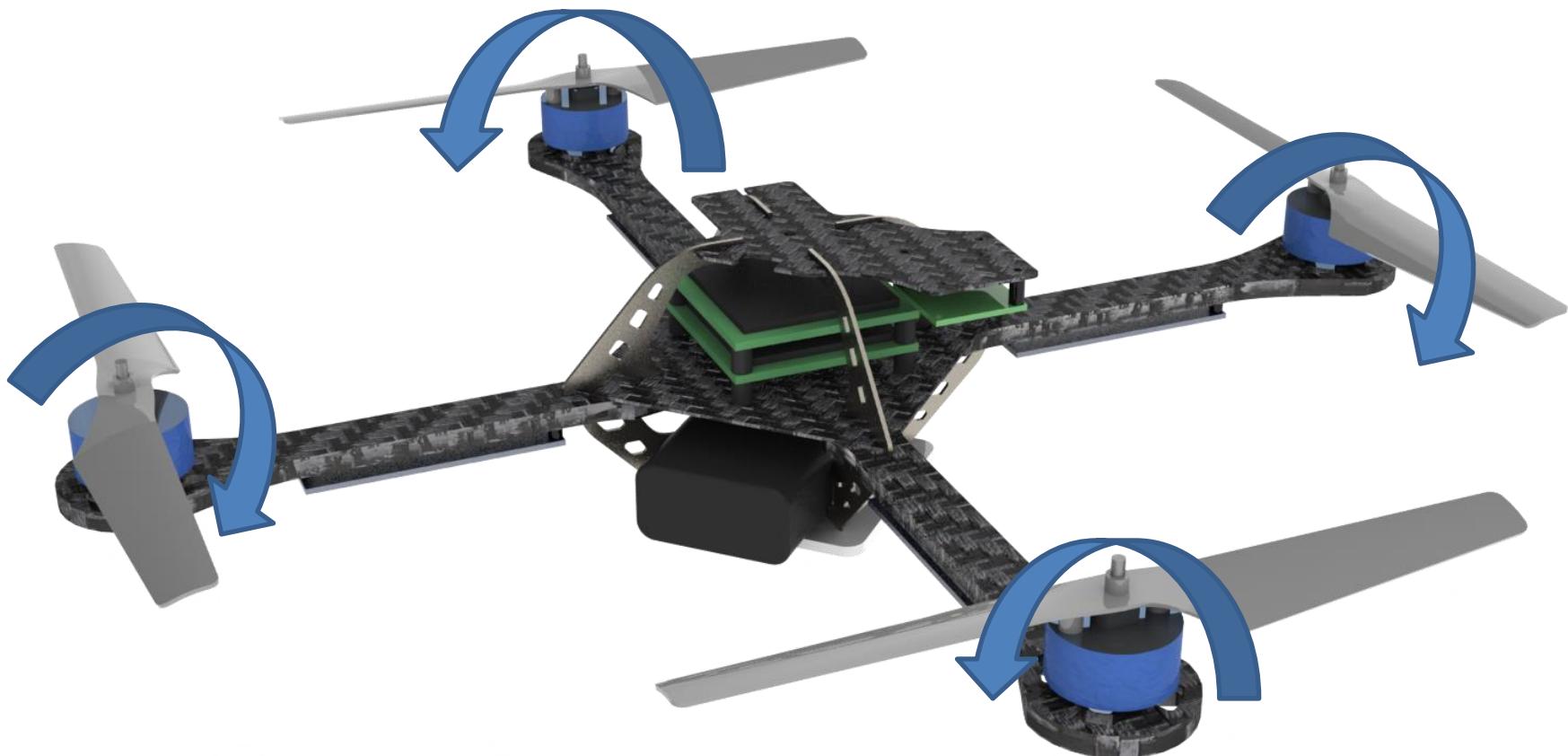
- University of Pennsylvania
 - Vijay Kumar (Planning, control, swarm)
- Massachusetts Institute of Technology
 - Jonathan How (modelling, control)
 - Nicolas Roy (perception)
- University of California, Berkeley
 - Claire Tomlin (control, policies)
- ETH Zurich
 - Roland Siegwart (perception, control)
 - Raffaello D'Andrea (control, swarm)
 - Marc Pollefeys (perception, Pixhawk)
- Hong Kong University of Science Technology
 - Zexiang Li (founded DJI with Frank Wang)
 - I actually want to put myself here, but...
- Also involves other areas such as communication, material science, mechanical engineering, electronics, aerospace engineering, system engineering...



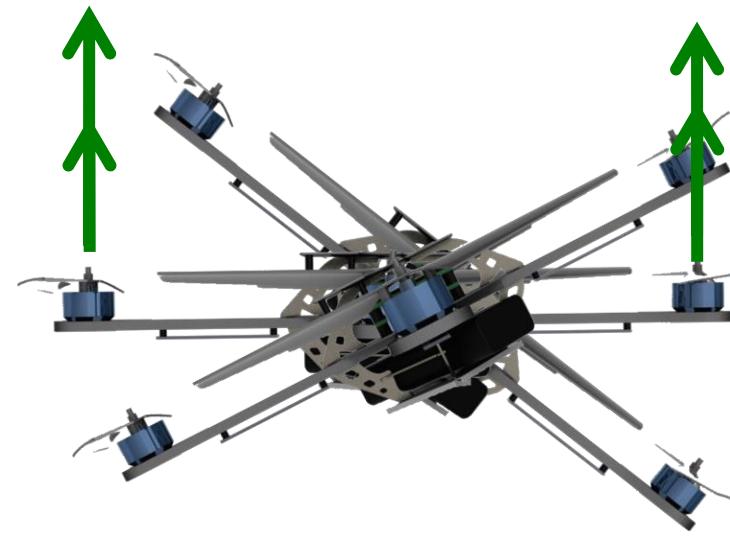
Commercialization of Aerial Robots



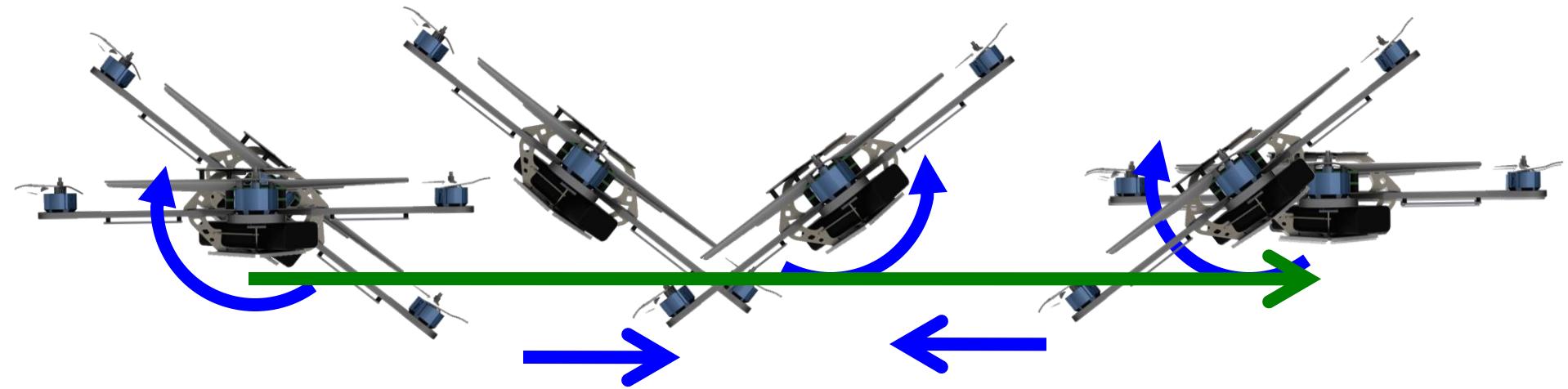
Quadrotors



Quadrotors - Rotation



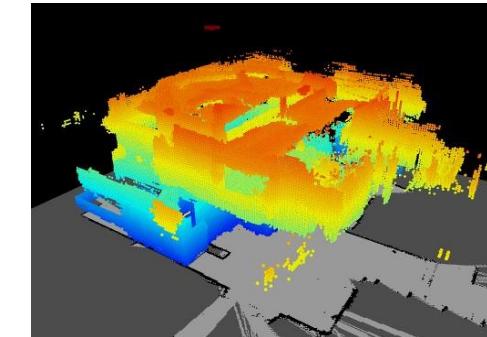
Quadrotors - Translation



Towards Autonomous Flight...

- Sensing and perception

Part 2



- State estimation

Part 3

- Path planning

Part 1



- Trajectory generation

Projects!

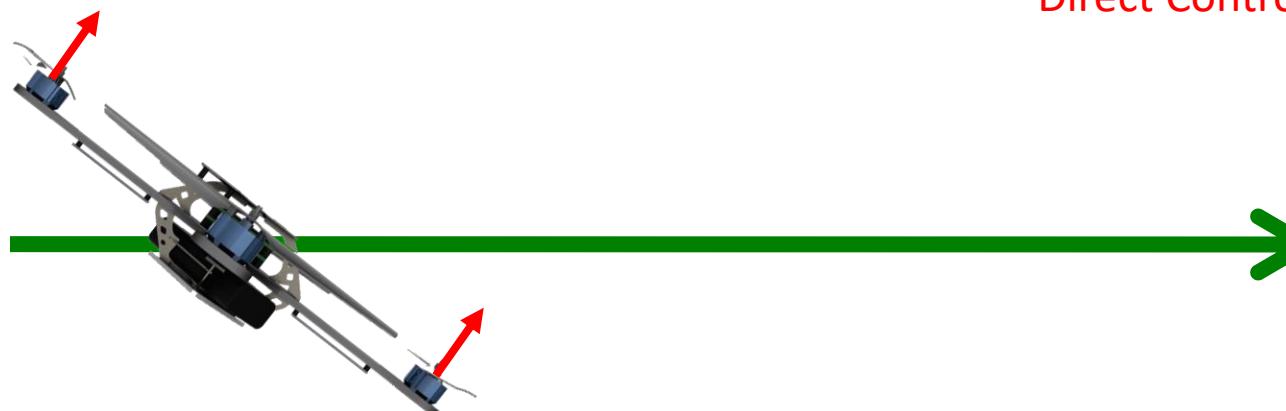
- Control



- System integration

How to fly? – Dynamics & Control

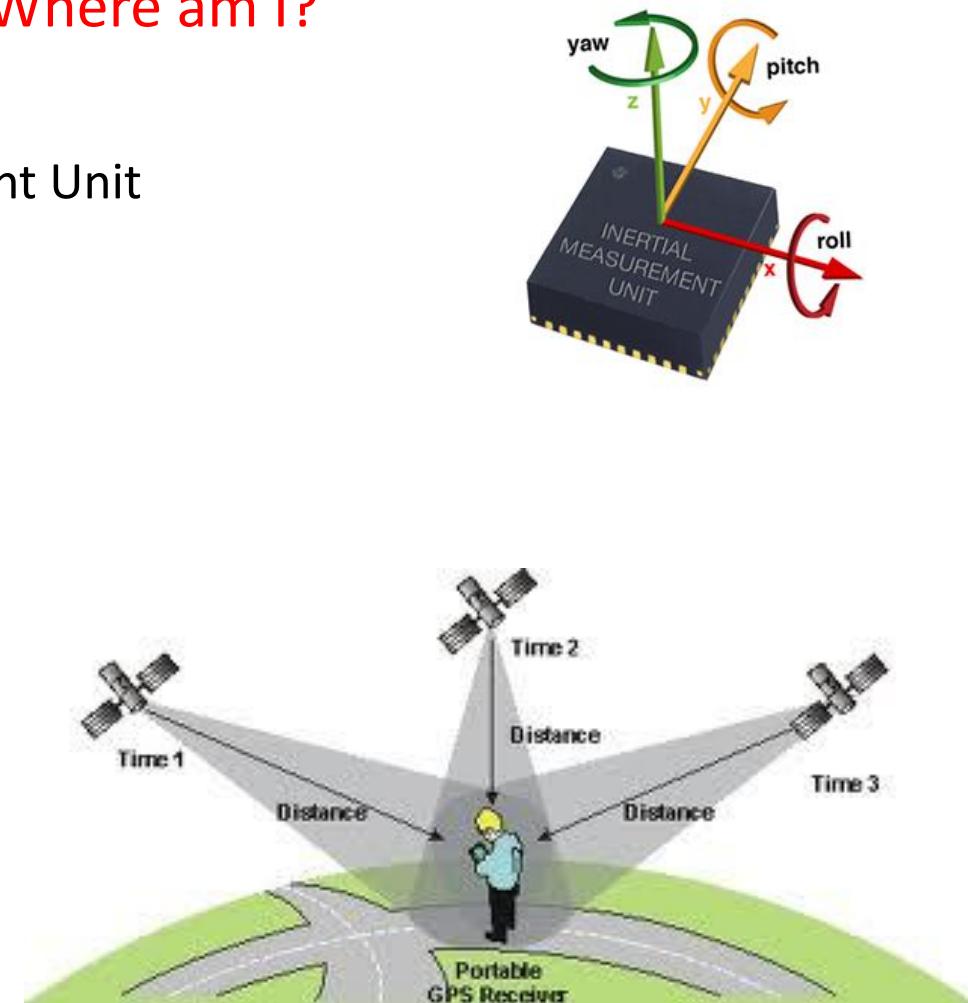
| Derivative | Translation | Rotation | Thrust |
|------------|---|----------------------|---|
| 0 | Position  Control Target | | |
| 1 | Velocity | | |
| 2 | Acceleration | Rotation | |
| 3 | Jerk | Angular Velocity | |
| 4 | Snap | Angular Acceleration | Differential Thrust |
| 5 | Crackle | Angular Jerk |  |



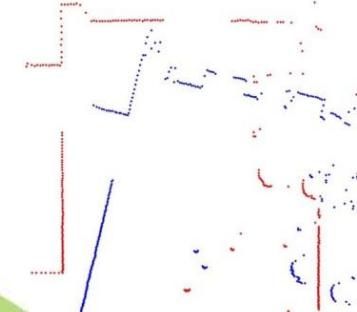
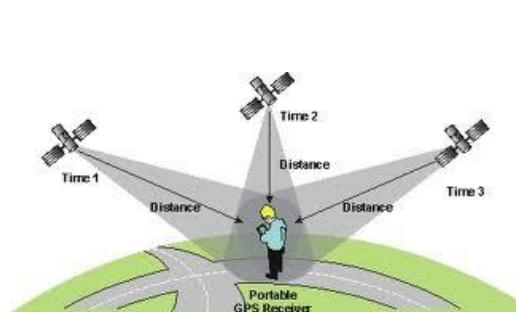
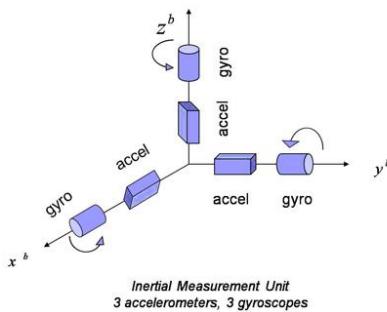
Direct Control Input

How to Fly? – Sensing & Estimation

- Answer the key question: **Where am I?**
- Proprioceptive sensors
 - Low cost Inertial Measurement Unit
- Exteroceptive sensors
 - GPS
 - Magnetometer
 - Barometer
 - Cameras
 - Laser range finders
 - etc.
- Processors
- Algorithms



How to Fly? – Sensing & Estimation



Inertial Measurement Unit

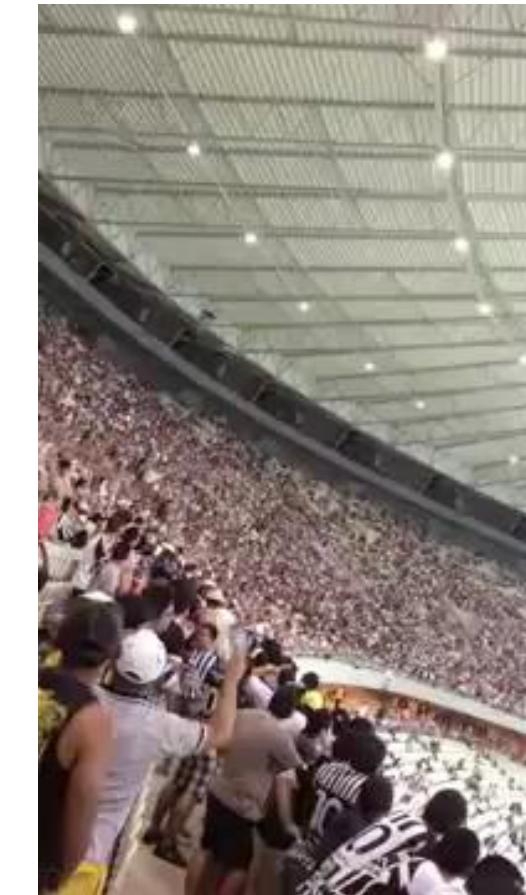
GPS

Laser Range Finder

Camera

How to Fly? – Navigation

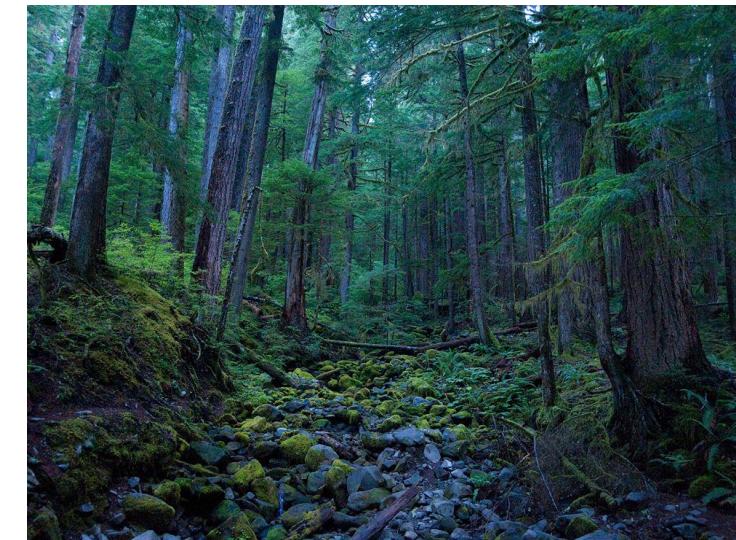
- Remote control
 - Requires line of sight
 - Requires communication link
 - Requires skilled pilots
- Inertial navigation
 - Requires aviation grade IMU
 - Heavy and expensive
- GPS-based navigation
 - Waypoint following
 - No obstacle avoidance
 - GPS can be unreliable



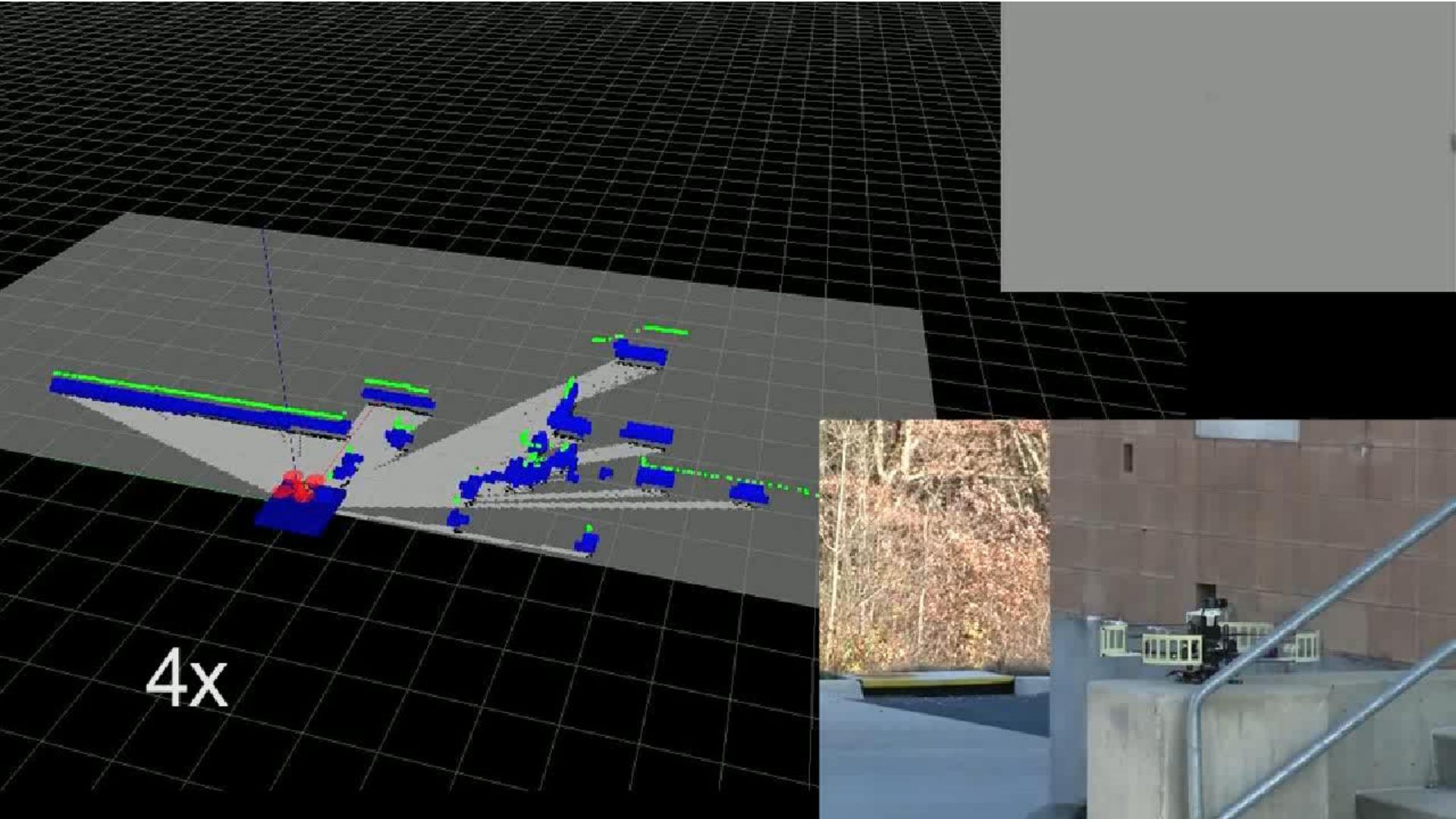
How to Fly? – GPS-based Navigation



How to Fly? – GPS-denied Navigation



How to Fly? – Laser-based Navigation



How to Fly? – Laser-based Navigation

Online Quadrotor Trajectory Generation and Autonomous Navigation on Point Clouds

Fei Gao and Shaojie Shen



香港科技大學
THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

High resolution video available at
<http://www.ece.ust.hk/~eeshaojie/ssrr2016fei.mp4>

How to Fly? – Vision-based Navigation

Aggresive Quadrotor Flight Using Dense Visual-Inertial Fusion

Yonggen Ling, Tianbo Liu, and Shaojie Shen

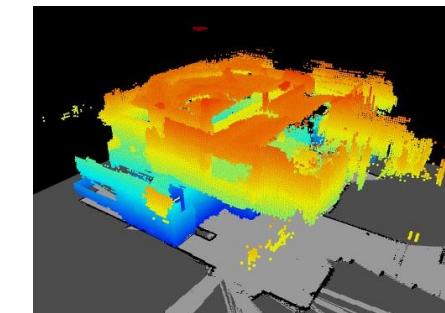


香港科技大學
THE HONG KONG UNIVERSITY OF
SCIENCE AND TECHNOLOGY

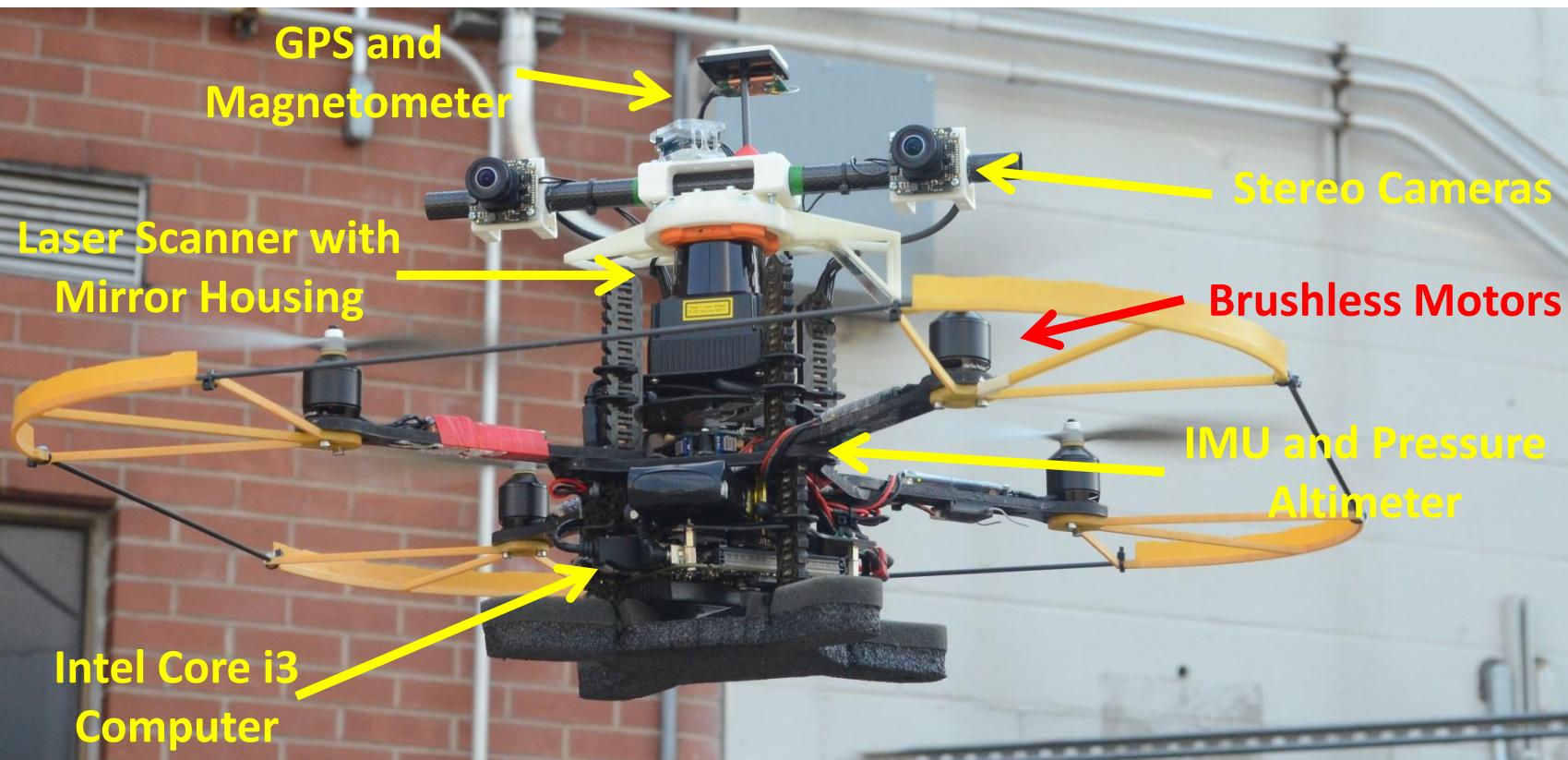
High resolution video and our open-source code are
available at: https://github.com/ygling2008/dense_new

Challenges

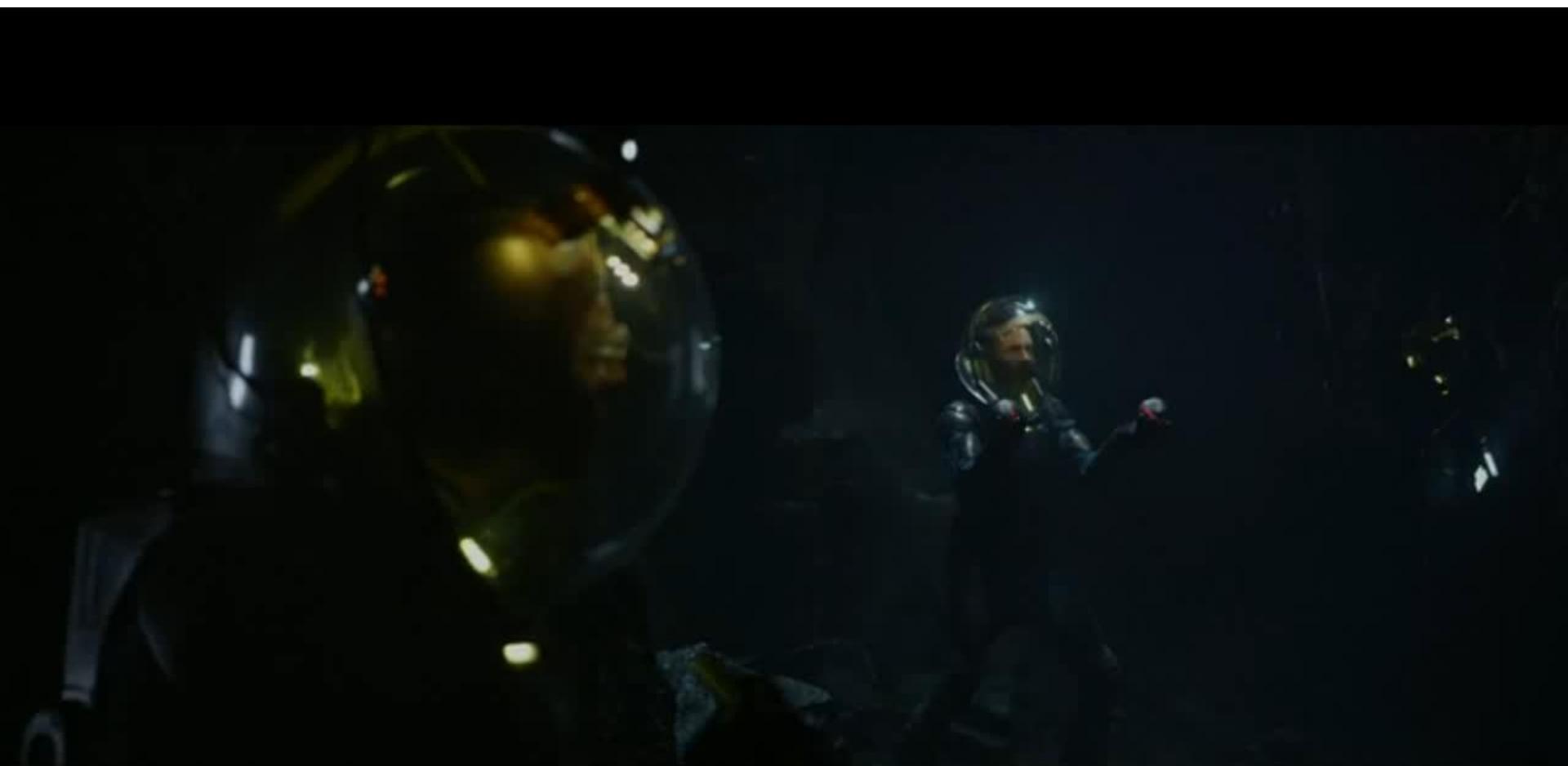
- Sensing & Perception
 - 3D sensing & mapping
- State Estimation & Localization
 - Low latency & high accuracy
- Obstacle avoidance
 - Complex & unknown environments
- Trajectory Control
 - Aggressive maneuvers
 - Smooth trajectory tracking
- System integration
 - Limited sensing & computation
 - Autonomous operations



A Flying Robot

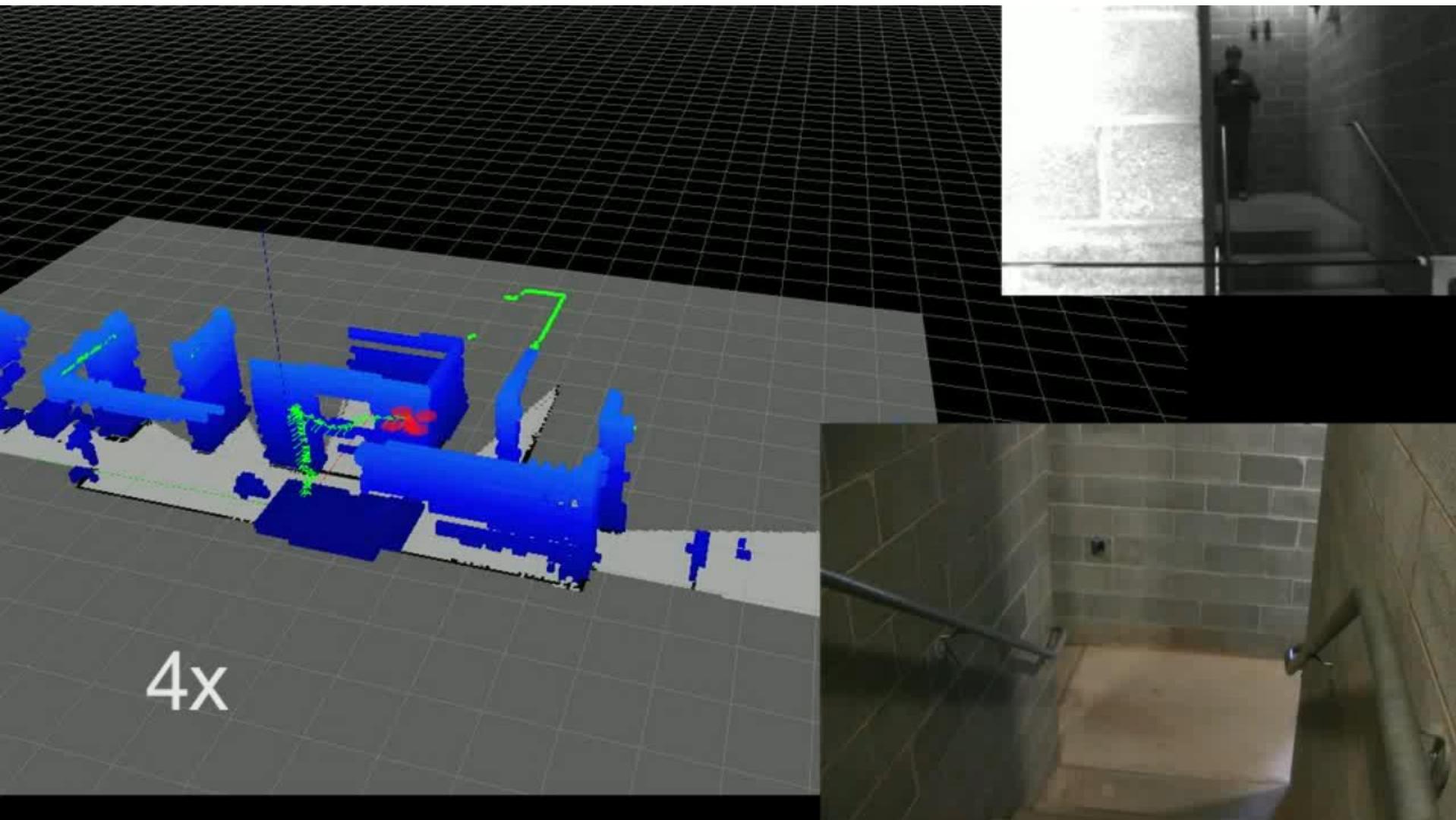


Goal



“Prometheus”

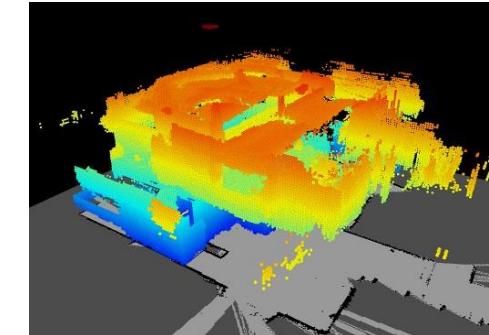
Fly over Multiple Floors



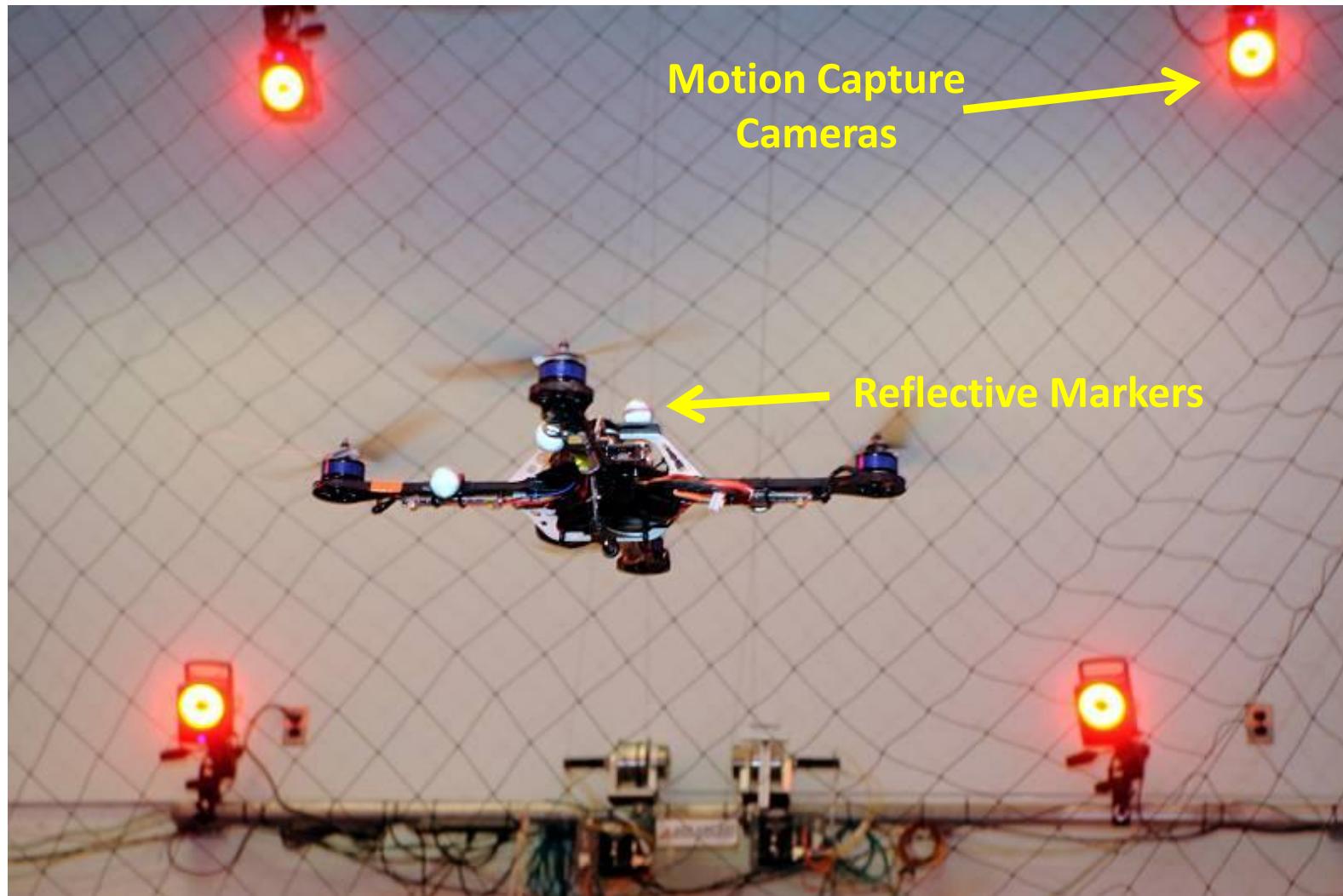
Shen, et al, 2013

Towards Autonomous Flight...

- Sensing and perception
- State estimation
- Path planning
- Trajectory generation
- Control
- System integration



Bypass the Sensing Problem



Robust Control

Precise Aggressive Maneuvers for Autonomous Quadrotors

Daniel Mellinger, Nathan Michael, Vijay Kumar
GRASP Lab, University of Pennsylvania

Flying Inverted Pendulum

A Flying Inverted Pendulum



Cooperative Ball Throwing

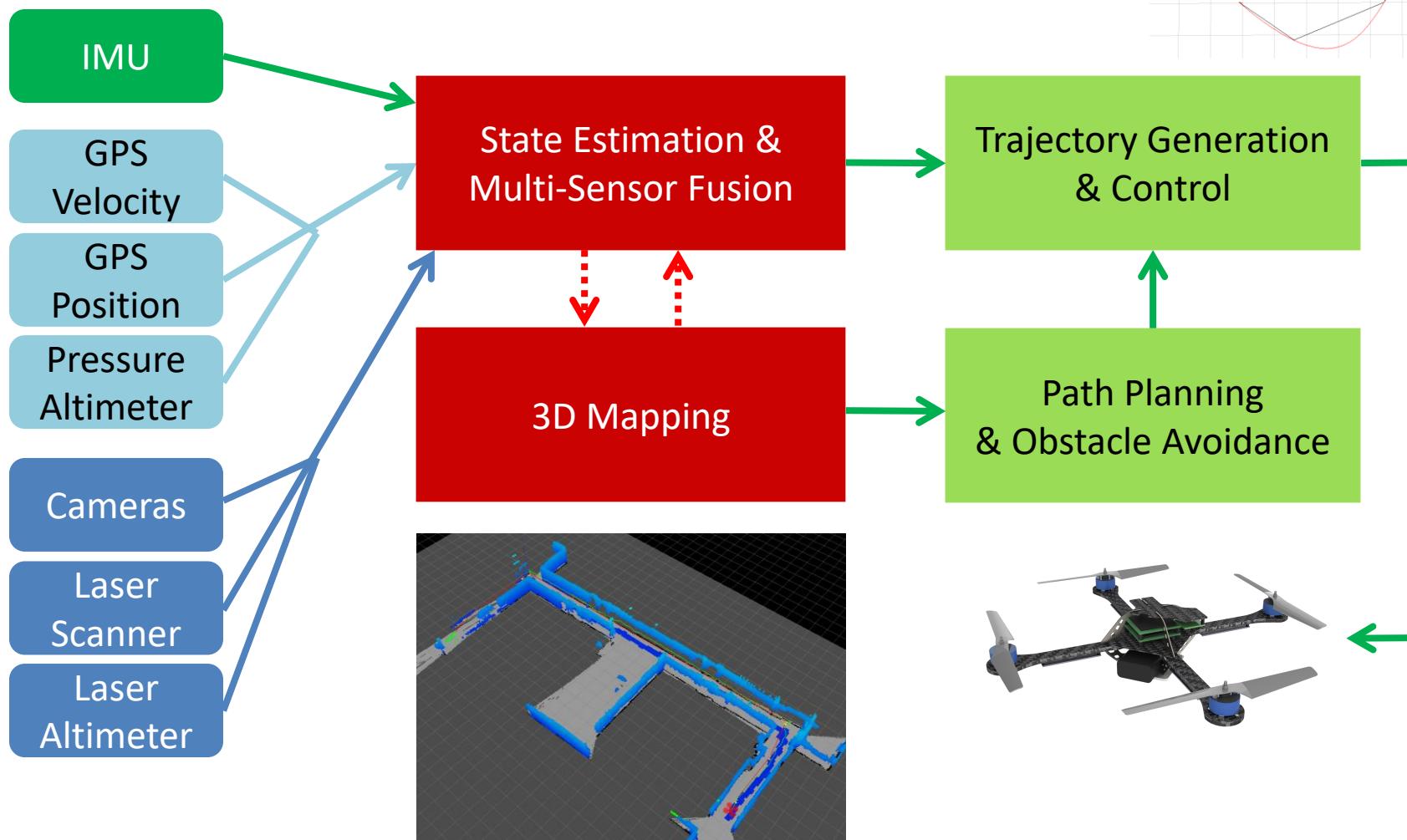
The Flying Machine Arena

Cooperative Quadrocopter Ball Throwing and Catching



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The Complete System



Search and Rescue



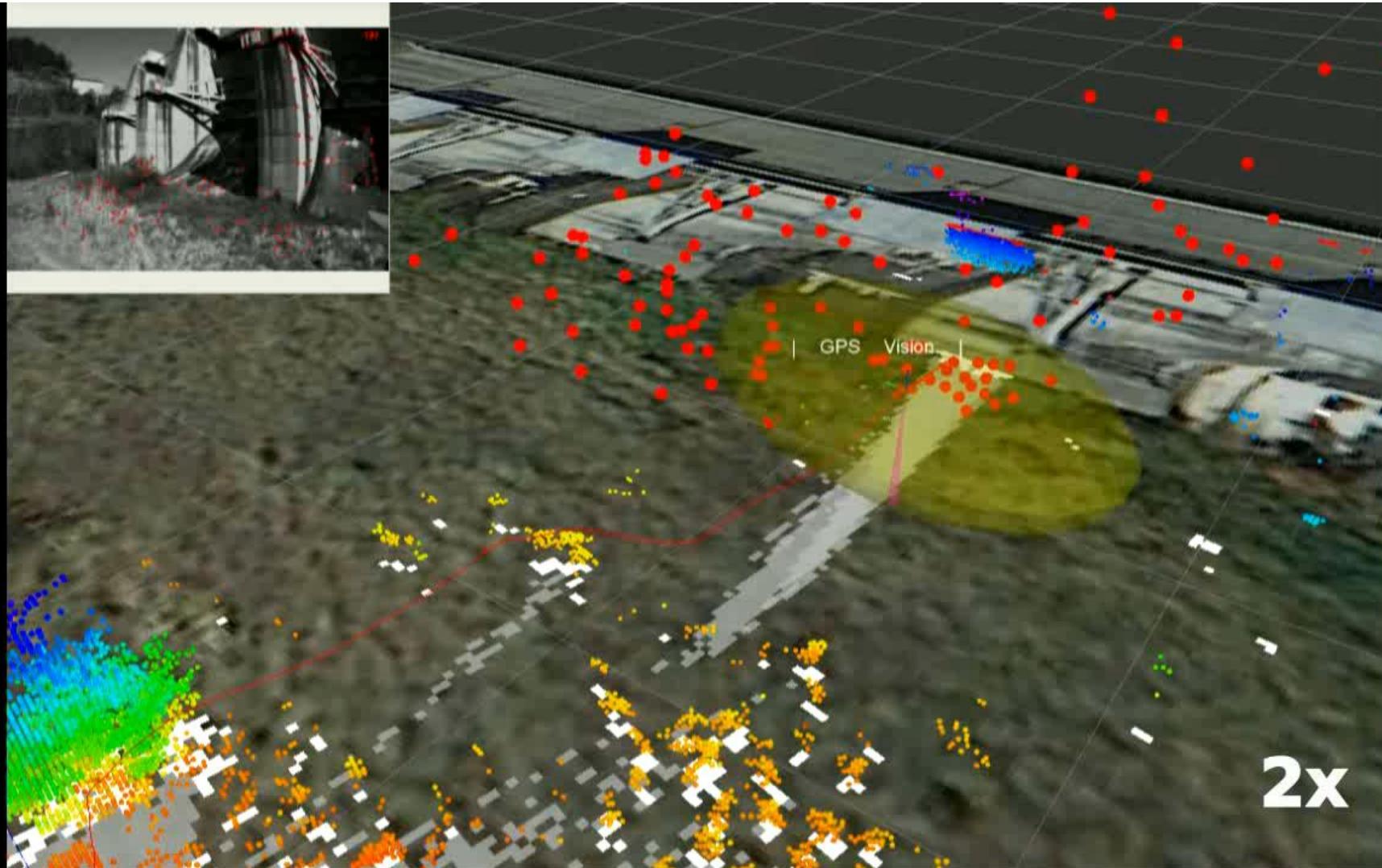
Michael, et al, 2012

Dam Inspection

Emergency flooding gates at the Carter's Dam, GA, USA



Dam Inspection



Dam Inspection

Penstock at the Carter's Dam, GA, USA



Dam Inspection

Carters Dam, Atlanta, GA
Semi-autonomous flight along the
inclined region of the penstock without
external illumination

2x

Cellular Tower Inspection



Precision Farming

E.&J. Gallo Winery, CA, USA



Precision Farming

2X

Delivery



30 SESSION

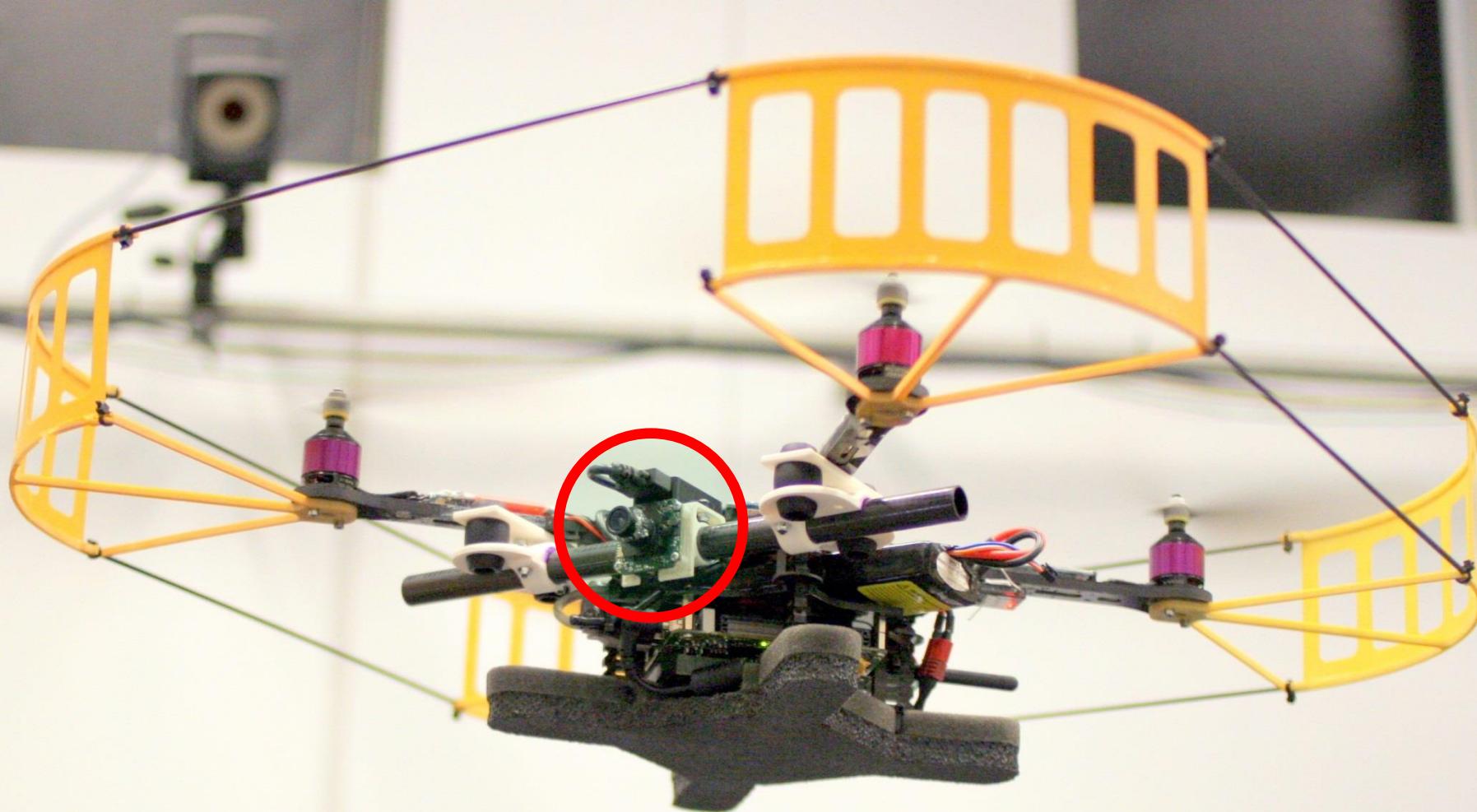
Small and Autonomous



Processing: Not quite there yet, but remember the **Moore's Law!**
Sensing: **YES!**



Minimum Sensing: 1 Camera + 1 IMU



Minimum Sensing: 1 Camera + 1 IMU

Autonomous Aerial Navigation Using Monocular Visual-Inertial Fusion

Yi Lin, Fei Gao, Tong Qin, Wenliang Gao,
Tianbo Liu, William Wu, Zhenfei Yang and Shaojie Shen



High resolution video available at:
<http://ece.ust.hk/~eeshaojie/jfr2017yi.mp4>

Swarm



Swarm

Towards a Swarm of Nano Quadrotors

Alex Kushleyev, Daniel Mellinger, and Vijay Kumar
GRASP Lab, University of Pennsylvania

Amazing In Motion



AMAZING IN MOTION

Course Outline

Course Outline

- Dynamics, Planning & Control

- Vision

- Estimation

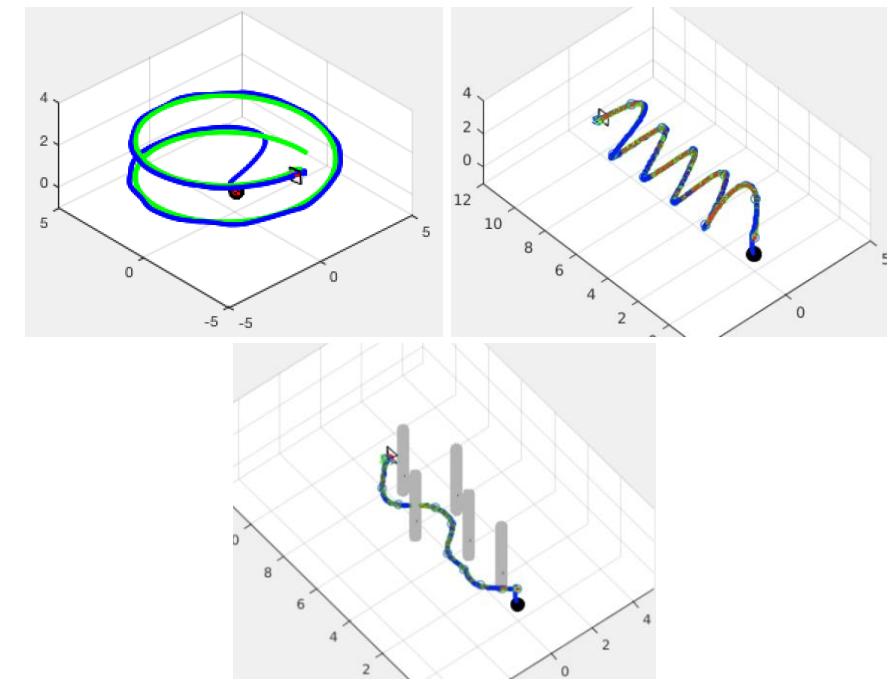
| Week | Lecture Date | Topic | Assignment (due by 11:59 PM on the corresponding lecture date) |
|------|--------------|--|---|
| 1 | 2/2 | Introduction Rigid Body Transformation | |
| 2 | 2/9 | Rigid Body Transformation Quadrotor Modeling | |
| 3 | 2/16 | Control Basics Quadrotor Control Trajectory Generation | Project 1 Phase 1 Out |
| 4 | 2/23 | Trajectory Generation Path Planning | Project 1 Phase 1 Due Project 1 Phase 2 Out |
| 5 | 3/2 | Camera Modeling & Calibration Feature Detection & Matching | Project 1 Phase 2 Due Project 1 Phase 3 Out |
| 6 | 3/9 | Midterm Exam | Project 1 Phase 3 Due |
| 7 | 3/16 | Multi-View Geometry 2D-2D, 3D-2D, 3D-3D | Project 2 Phase 1 Out |
| 8 | 3/23 | Optical Flow Dense Stereo | Project 2 Phase 1 Due Project 2 Phase 2 Out |
| 9 | 3/30 | Probability Basics Bayesian Inferencing | |
| 10 | 4/6 | Midterm Break | |
| 11 | 4/13 | Kalman Filter Sensor Fusion | Project 2 Phase 2 Due Project 3 Phase 1 Out |
| 12 | 4/20 | Augmented State KF SLAM | Project 3 Phase 1 Due Project 3 Phase 2 Out |
| 13 | 4/27 | x | |
| 14 | 5/4 | x | Project 3 Phase 2 Due |

Course Outline

- Dynamics, Control, and Planning
 - Understand 3D rigid body transformation
 - Derive the model of quadrotor aerial robots
 - Able to hover the quadrotor given perfect localization
 - Able to generate and track smooth trajectories given user-defined waypoints
 - Able to generate smooth and safe paths and trajectories given obstacle locations
 - Project 1
- Vision
 - Understand how cameras capture the world
 - Understand feature-based and optical flow-based image processing pipeline
 - Able to use only images to compute camera position, orientation, and velocity
 - Project 2
- Estimation
 - Understand how to incorporate probability principles into robotics
 - Able to integrate heterogeneous noisy measurements to get robust estimates of the platform motion
 - A light touch of simultaneous localization and mapping (SLAM)
 - Project 3

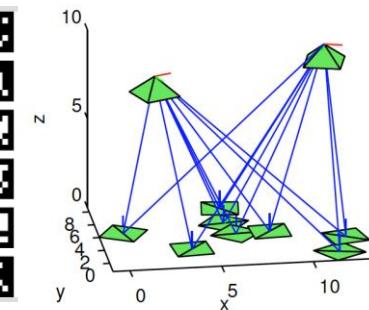
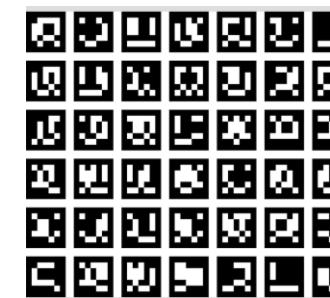
Project 1

- Phase 1: Hovering and trajectory tracking of a simulated quadrotor
 - MATLAB, offline
- Phase 2: Trajectory generation and tracking of a simulated quadrotor
 - MATLAB, offline
- Phase 3: Obstacle avoidance using A* path planning and smooth trajectory generation
 - MATLAB, offline



Project 2

- Phase 1: PnP-based localization on marker map
 - ROS & C++, Desktop PC, offline



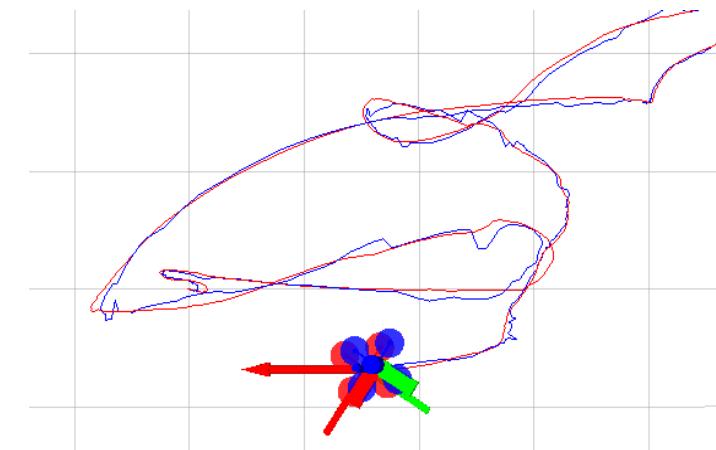
- Phase 2: Visual odometry in markerless environment
 - ROS & C++, Desktop PC, offline



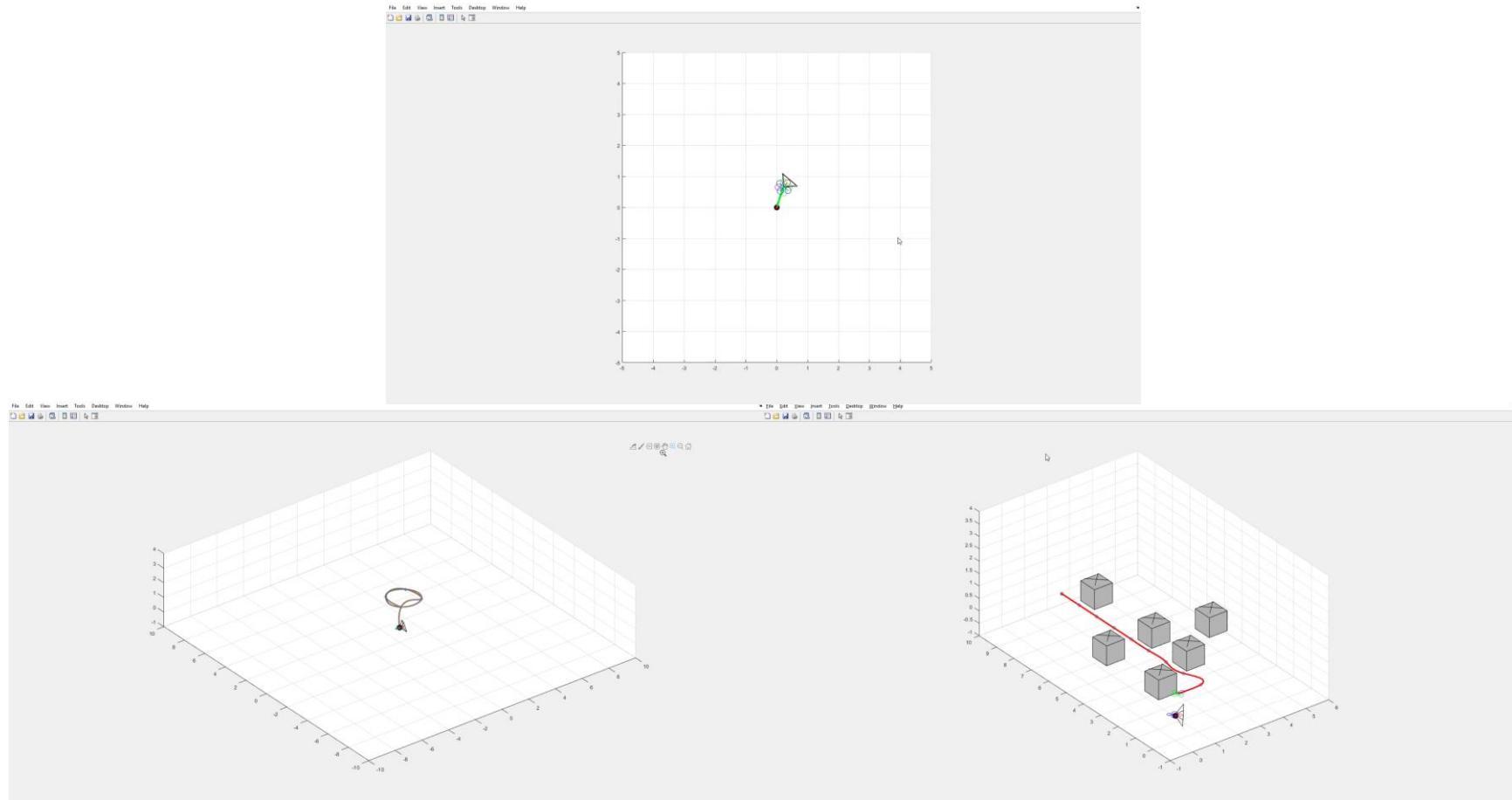
(b)

Project 3

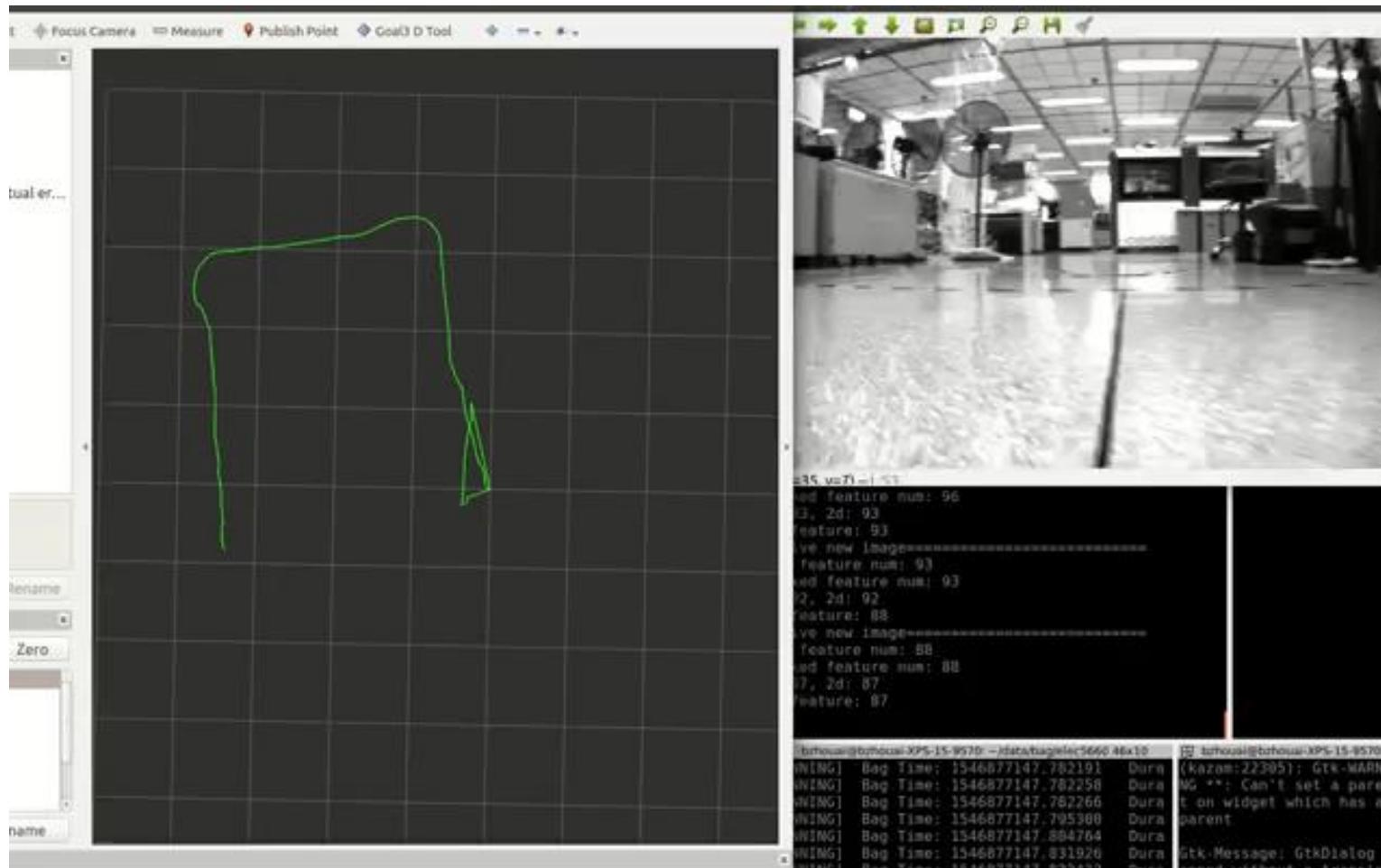
- Phase 1: EKF-based sensor fusion of IMU, tag-based position estimation, and optical flow-based velocity estimation
 - ROS & C++, Desktop PC, offline
- Phase 2: Augmented state EKF for fusion of IMU and keyframe-based visual odometry together with the PnP localization on markers
 - ROS & C++, Desktop PC, offline



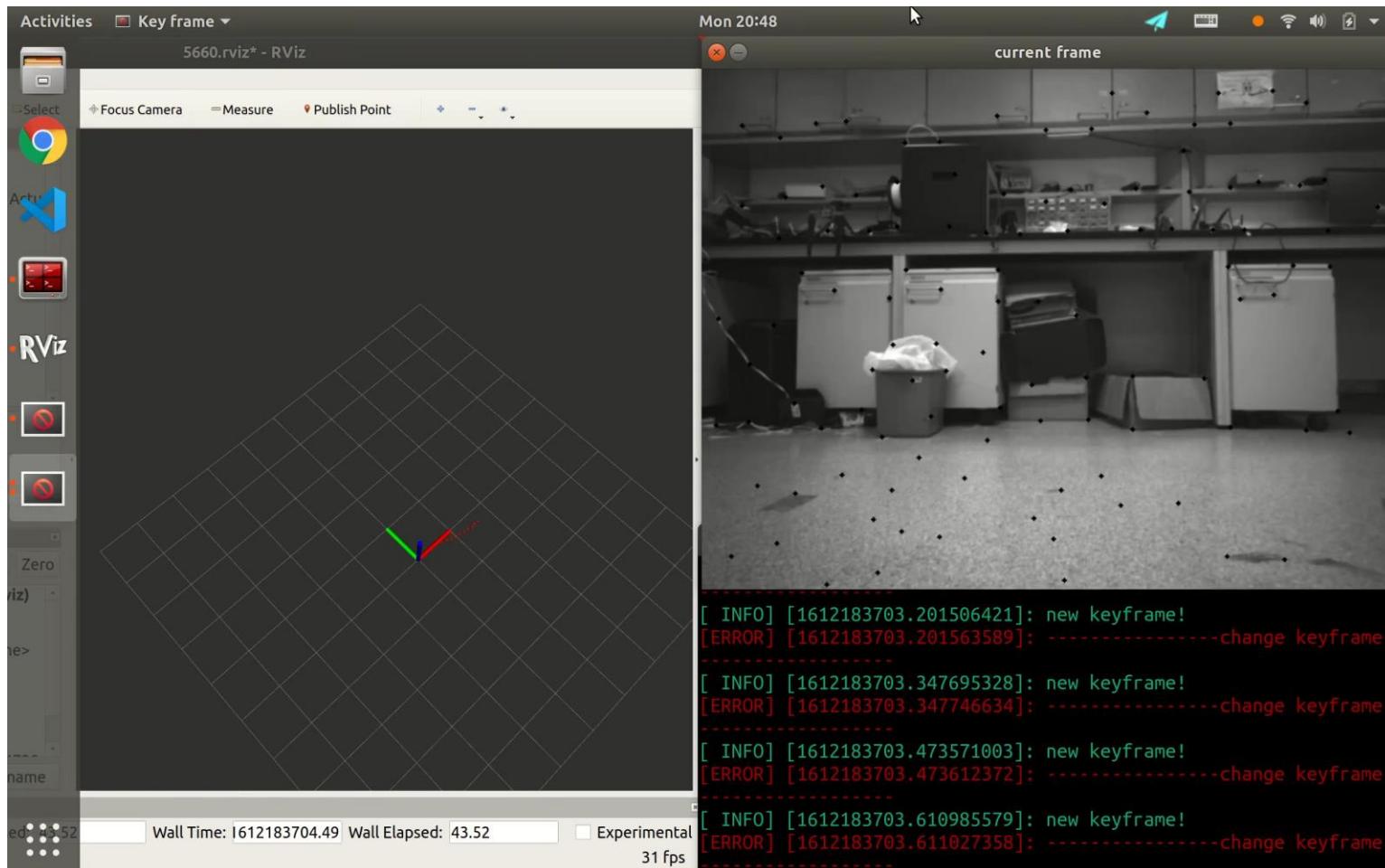
Last Year's Project 1



Last Year's Project 2



Last Year's Project 3



Next Lecture...

- Rigid Body Transformations
- Rotational Motions
- Rotation Representations
- Rigid Body Motions
- Rigid Body Velocities
- Quadrotor Dynamics