香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY
電子及計算機工程學系
DEPARTMENT OF ELECTRONIC & COMPUTER ENGINEERING

Introduction to Aerial Robotics
Lecture 1

Shaojie Shen

Associate Professor

Dept. of ECE, HKUST

7 February 2023

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

- Grading Scheme:
  - Midterm exam: 20%
  - Project 1: 30%
  - Project 2: 20%
  - Project 3: 30%

- More details can be found on the Canvas homepage.

Teaching Team

- **Instructor:**
  - Shaojie Shen (eeshaojie@ust.hk)
    Office Hour: by appointment

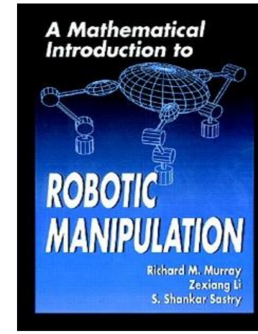
- **Teaching Assistants:**
  - Haokun Wang (hwangeh@connect.ust.hk)
    Office Hour: by appointment
  - Peize Liu (pliuan@connect.ust.hk)
    Office Hour: by appointment

Administrative Stuff

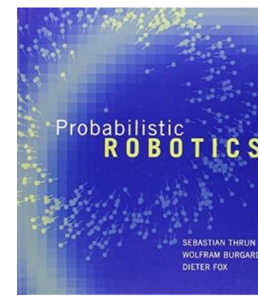
- **Lecture:**
  - Tuesday 1:30 pm - 4:20 pm
    - Rm 5560
    - Students who are not registered are welcome to sit in the lectures, but their assignments will not be graded
- **Labs:**
  - LA1: We 06:00PM - 08:50PM, LA2: Th 01:30PM - 04:20PM
    - Robotics Institute Flight Area
    - We will not have lab sessions every week, refer to Canvas site for details
- **Course Website:**
  - https://canvas.ust.hk/courses/48637

(Non-Compulsory) Reference Books

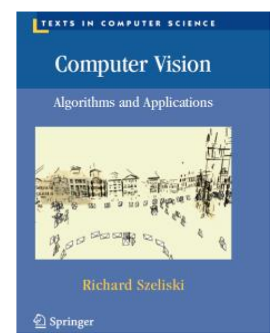
- A Mathematical Introduction to Robotic Manipulation
  - Richard M. Murray, Zexiang Li, S. Shankar Sastry;
  - http://www.cds.caltech.edu/~murray/books/MLS/pdf/mls94-complete.pdf



- 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

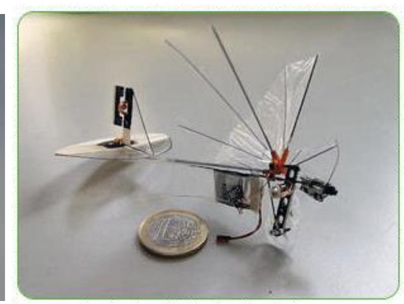
Aerial Robots = Military Drones?

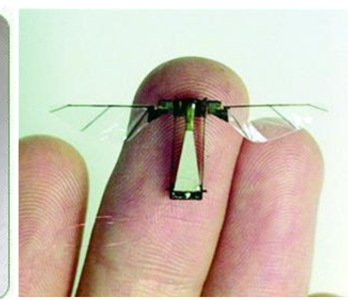
- Mostly Big
- 10+ Hours of Flight Time
- Remote Control
  - Waypoint planning
  - Some joystick
  - Flight crew 4-10

"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

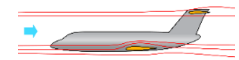
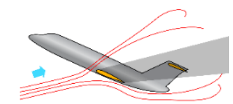
Unmanned Aerial Vehicles

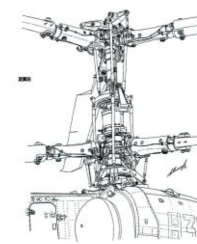




Unmanned Aerial Vehicles

- 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 ☹

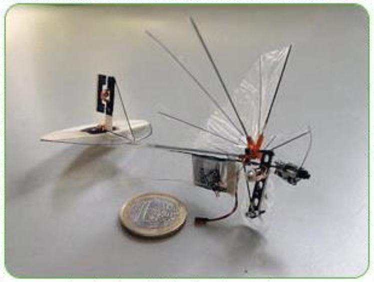




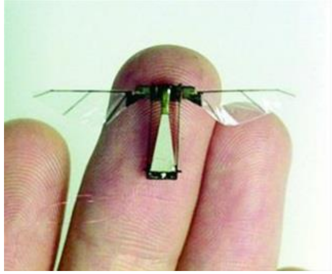


Unmanned Aerial Vehicles

- 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 ☹

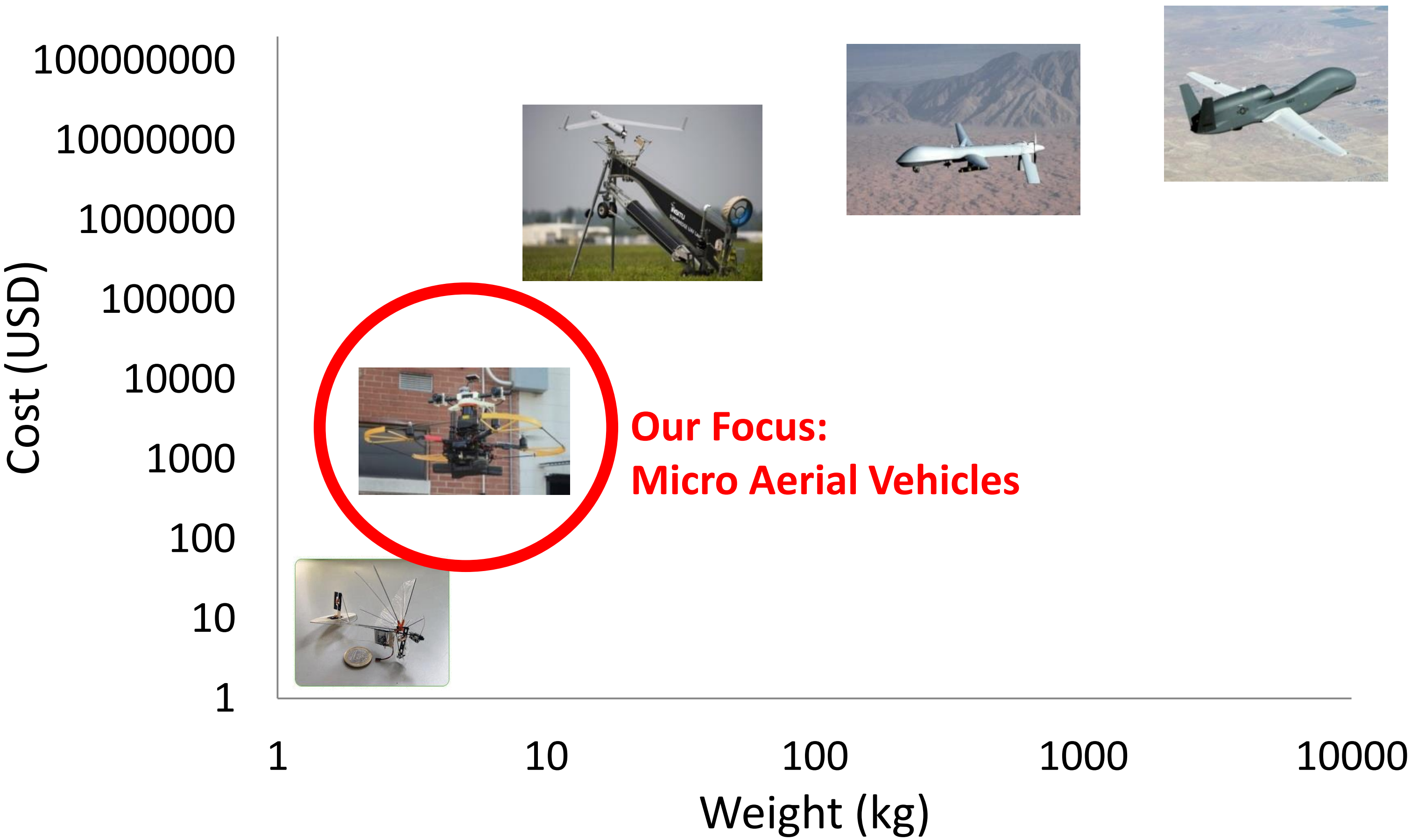
Contents [hide]





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

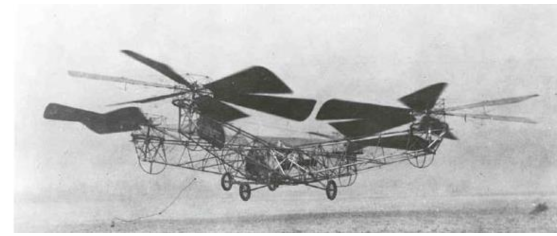

Aerial Photography

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) ☹

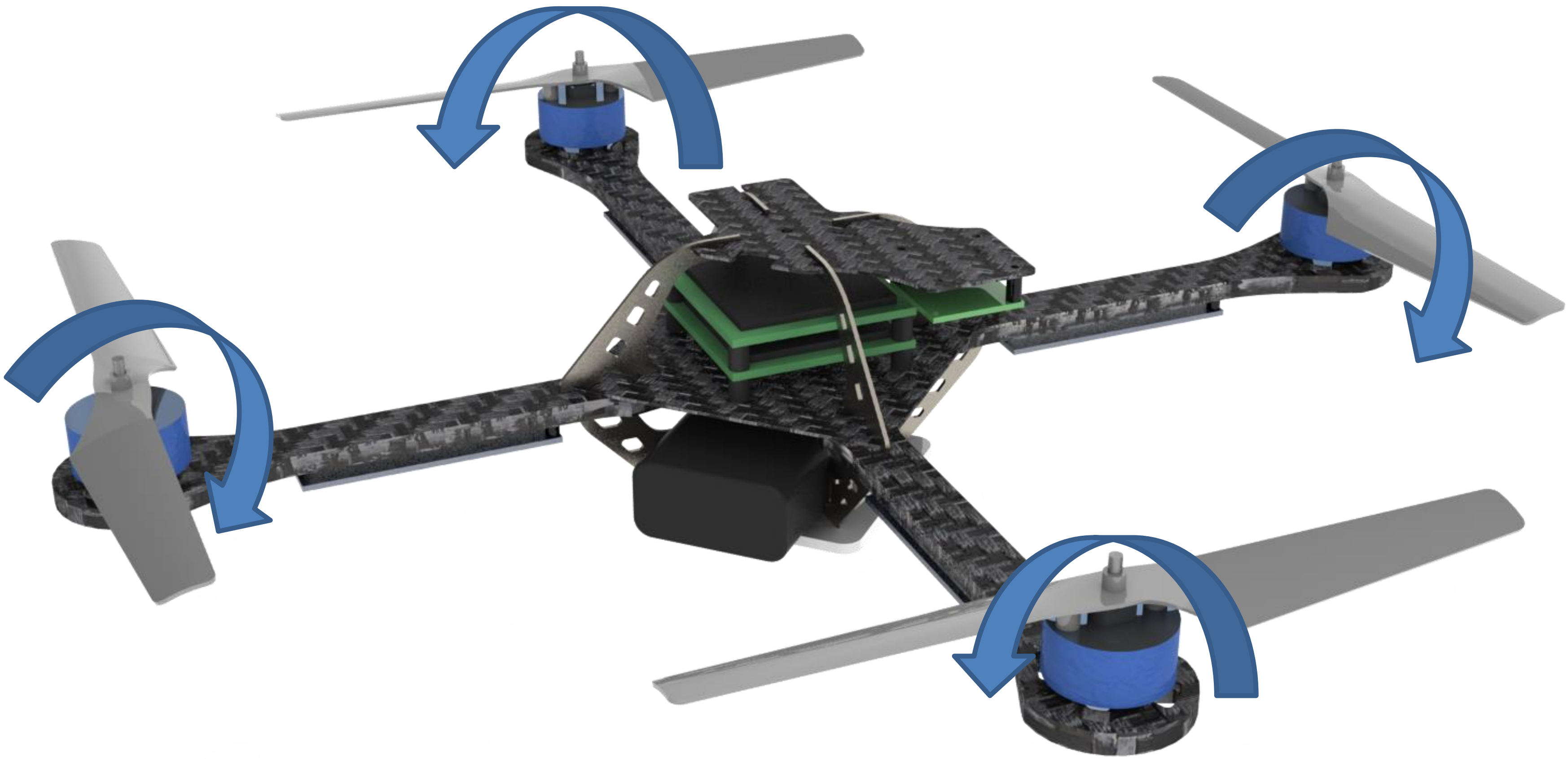
- STARMAC @ Stanford University (2004)
  - Thanks to the development of smart mobile devices
  - MEMS sensors + embedded computers

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

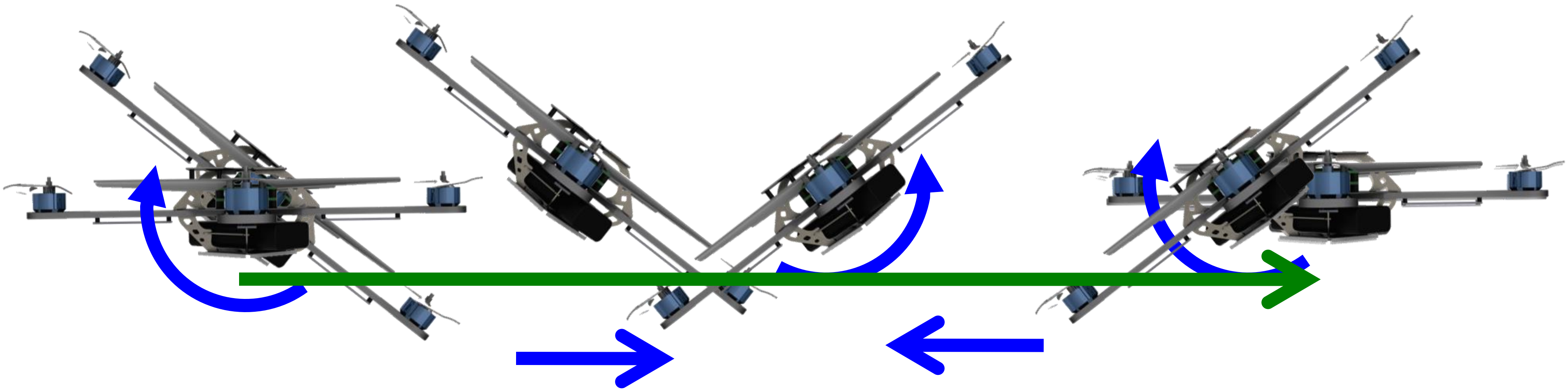


CAD Models from V. Kumar

Quadrotors - Rotation

CAD Models from V. Kumar

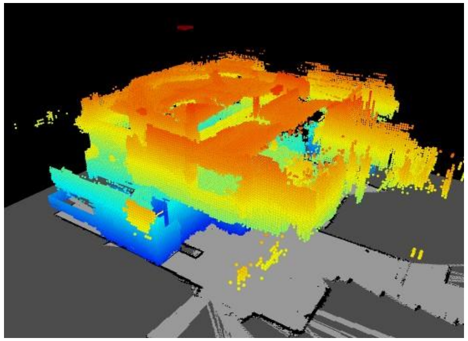
Quadrotors - Translation

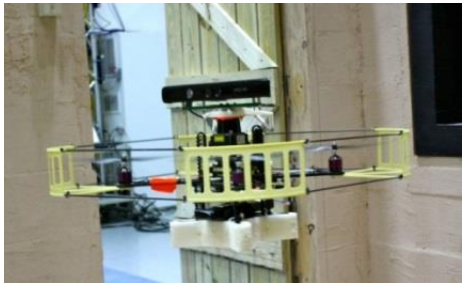


CAD Models from V. Kumar

Towards Autonomous Flight...

- Sensing and perception — Part 2
- State estimation — Part 3
- Path planning
- Trajectory generation — Part 1
- Control
- System integration — Projects!



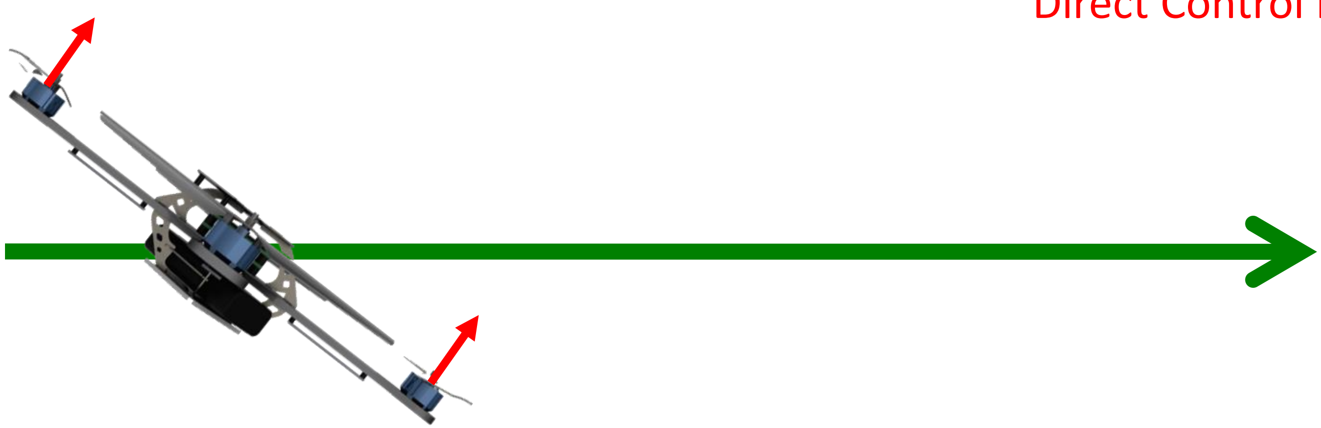


How to fly? – Dynamics & Control

Derivative	Translation	Rotation	Thrust
0	Position		
1	Velocity		
2	Acceleration	Rotation	
3	Jerk	Angular Velocity	
4	Snap	Angular Acceleration	Differential Thrust
5	Crackle	Angular Jerk	Change in Thrust

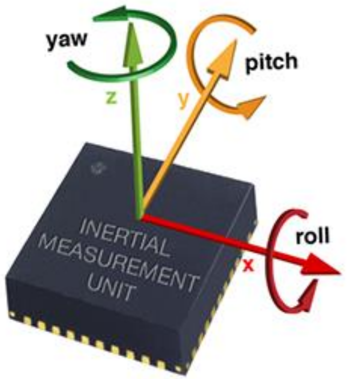
Control Target

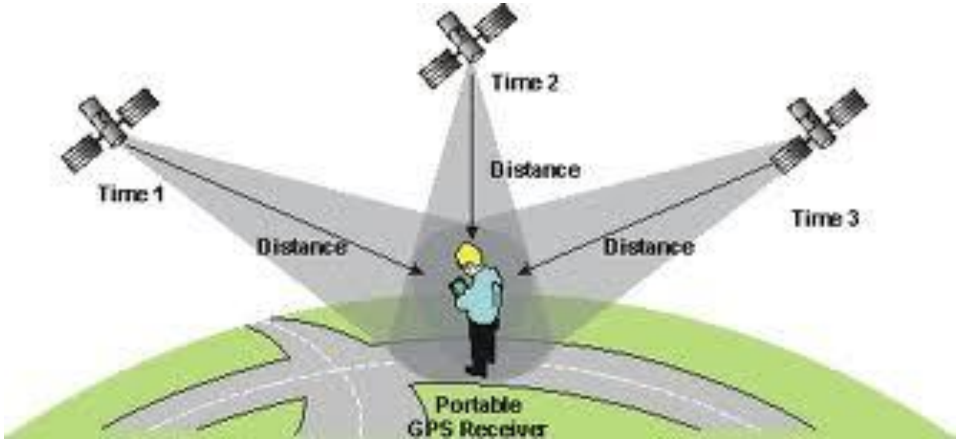
Direct Control Input



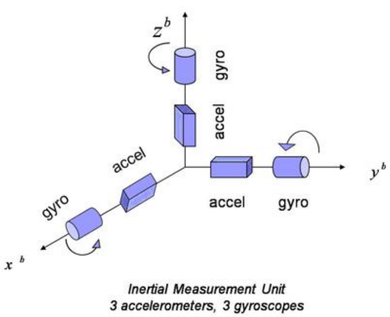
How to Fly? – Sensing & Estimation

- 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

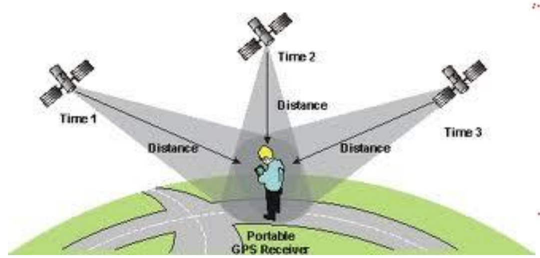




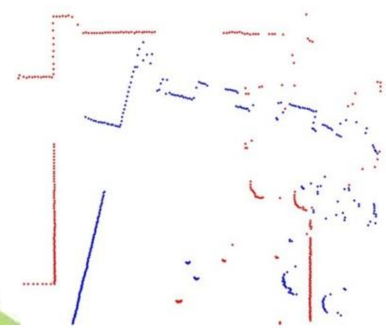
How to Fly? – Sensing & Estimation



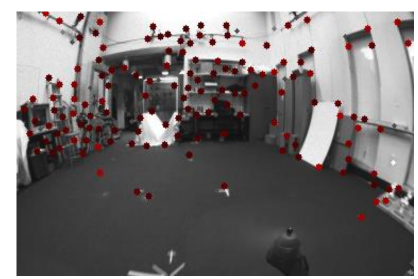
Inertial Measurement Unit



GPS



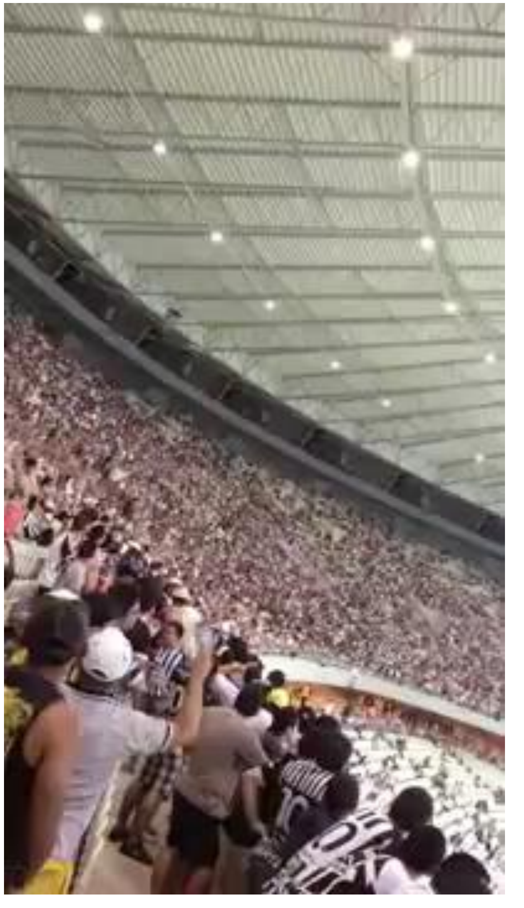
Laser Range Finder



Camera

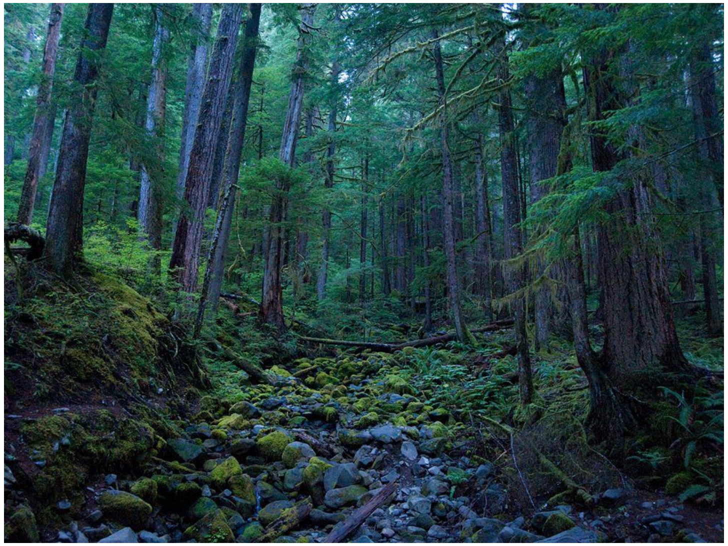
How to Fly? – Navigation

- 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

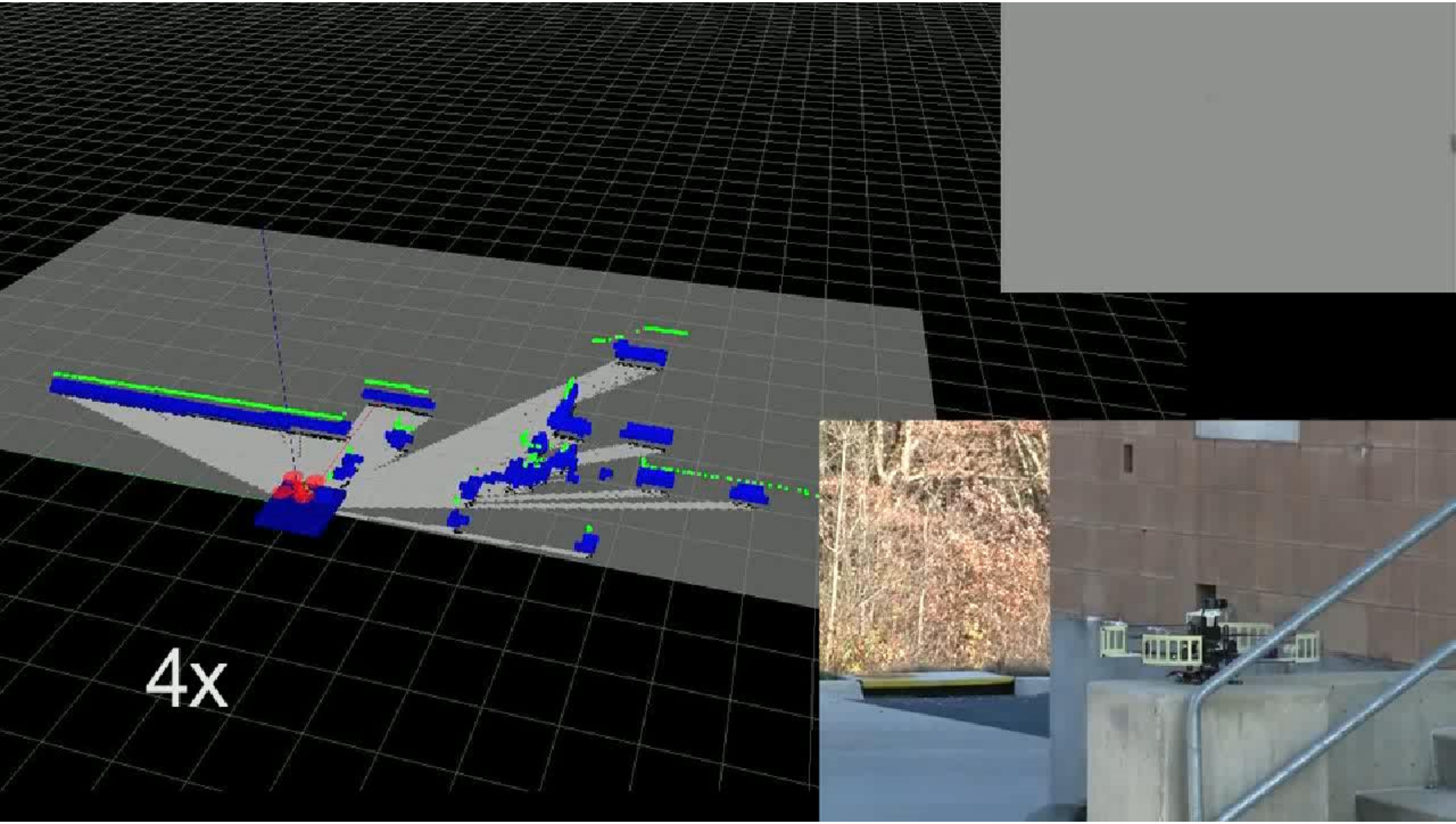


How to Fly? – GPS-based Navigation

How to Fly? – GPS-denied Navigation



How to Fly? – Laser-based Navigation



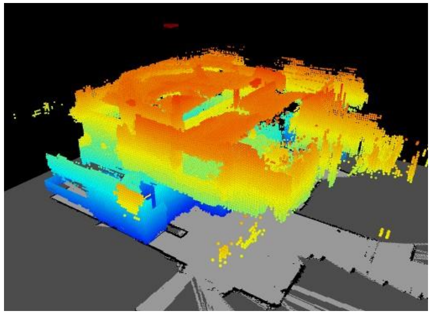
How to Fly? – Laser-based Navigation

Gao F, Shen S. SSRR, 2016

How to Fly? – Vision-based Navigation

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



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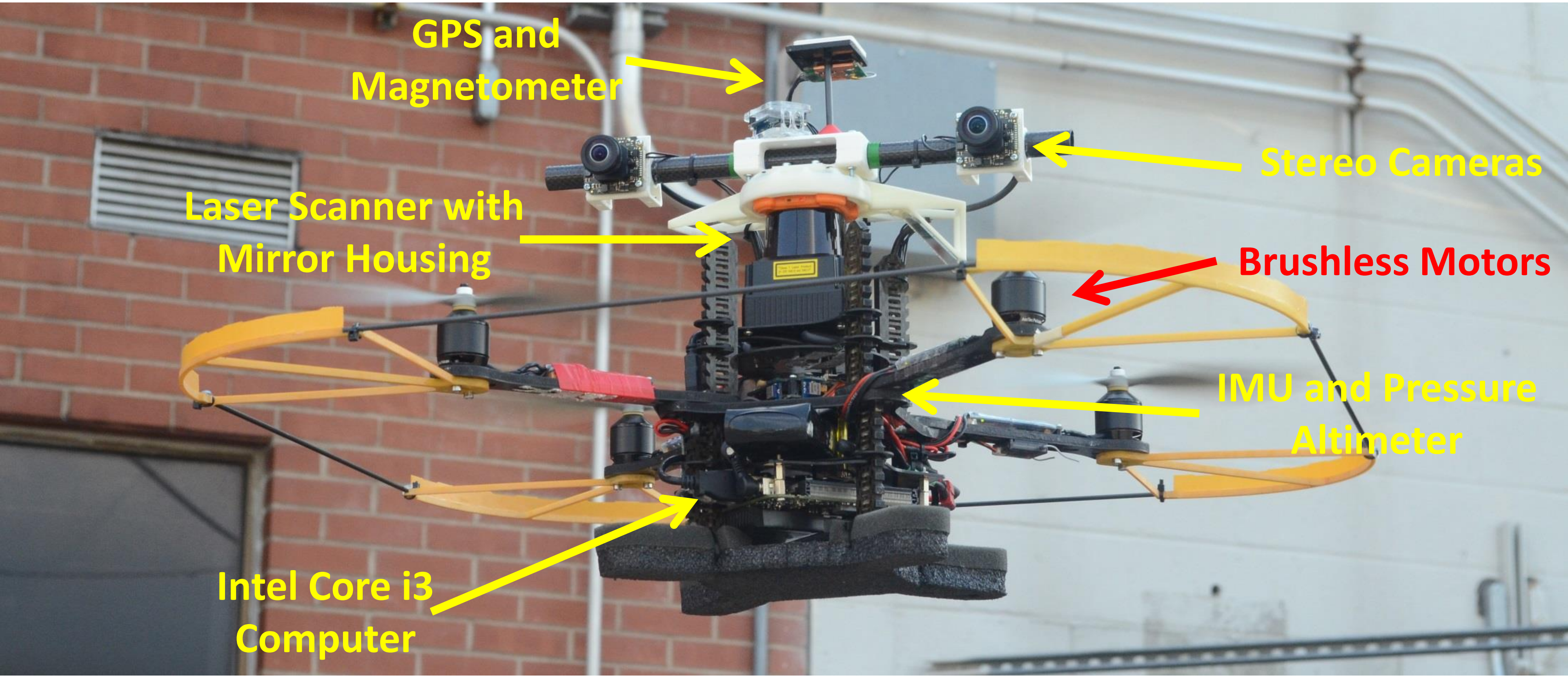
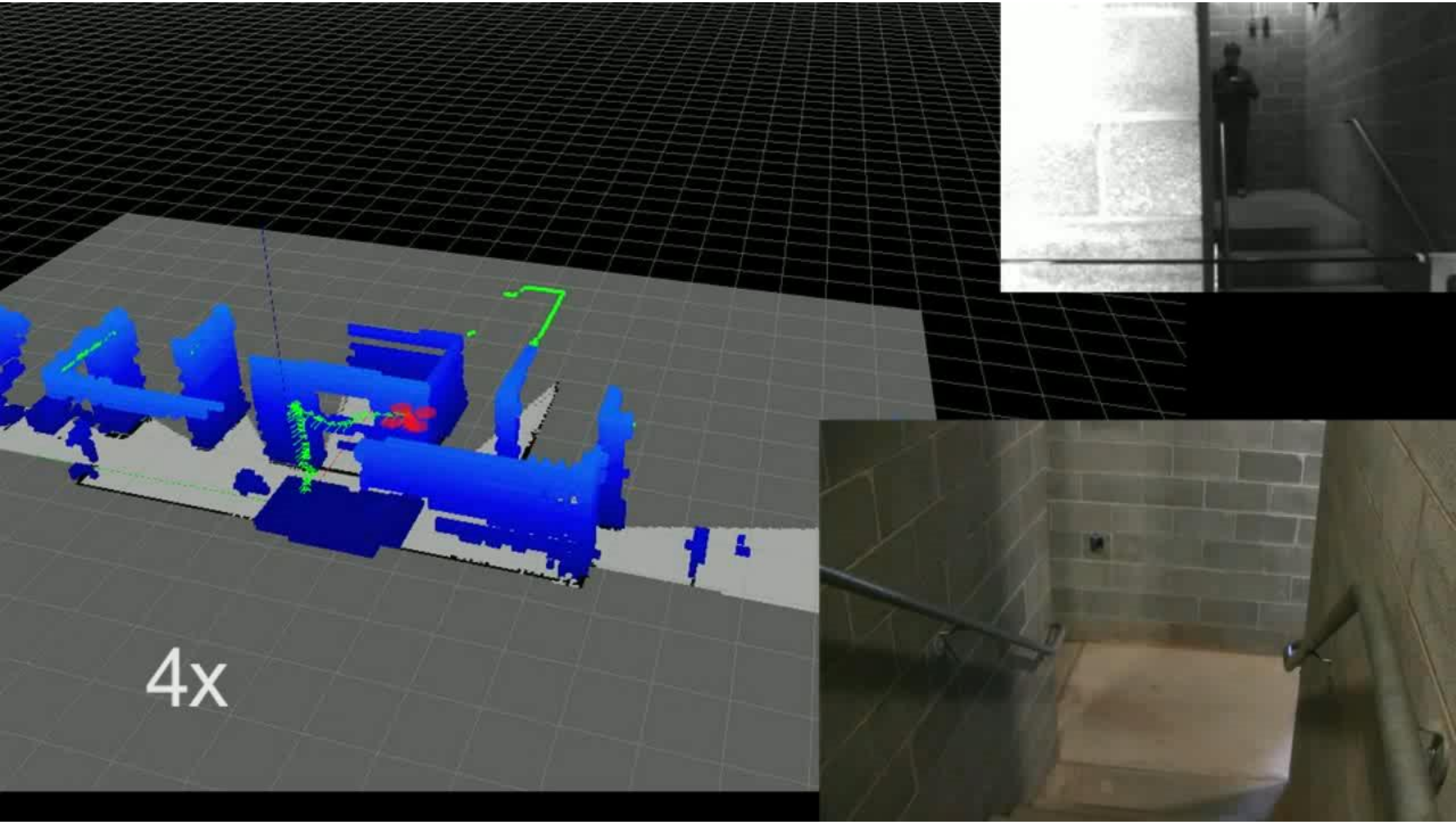
A Flying Robot



Goal

"Prometheus"

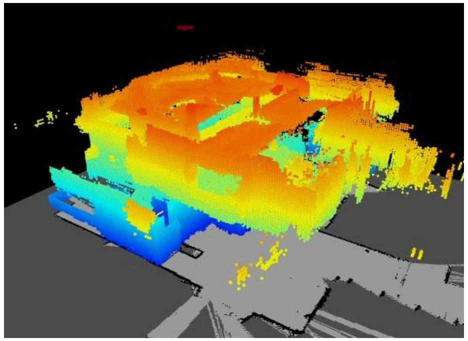
Fly over Multiple Floors

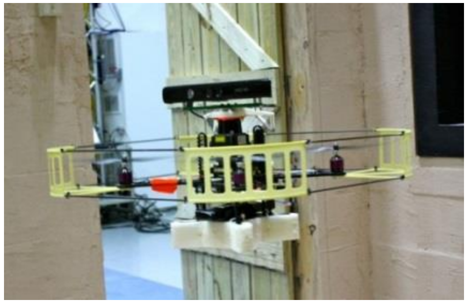


Shen, et al, 2013

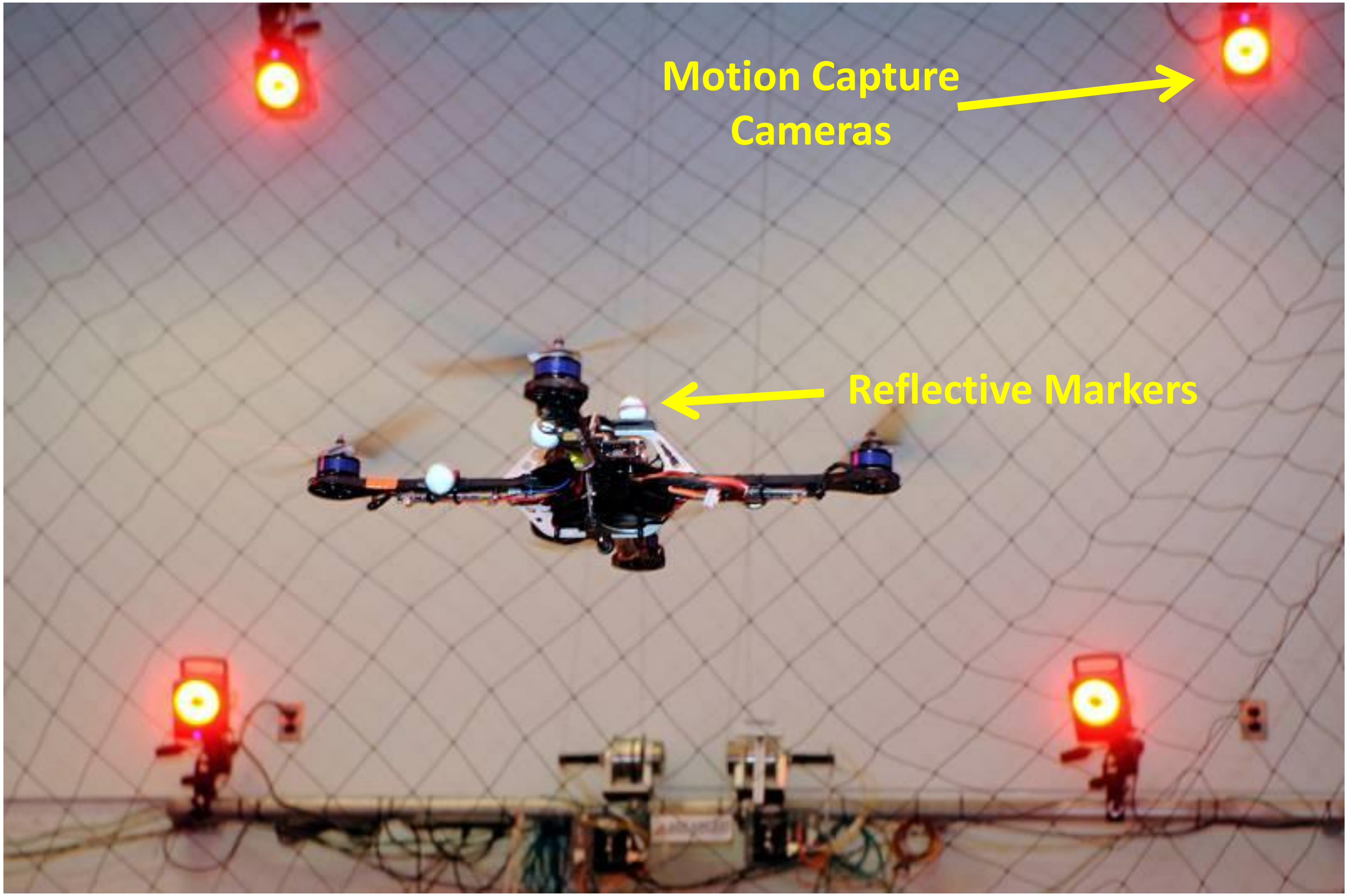
Towards Autonomous Flight…

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





Bypass the Sensing Problem



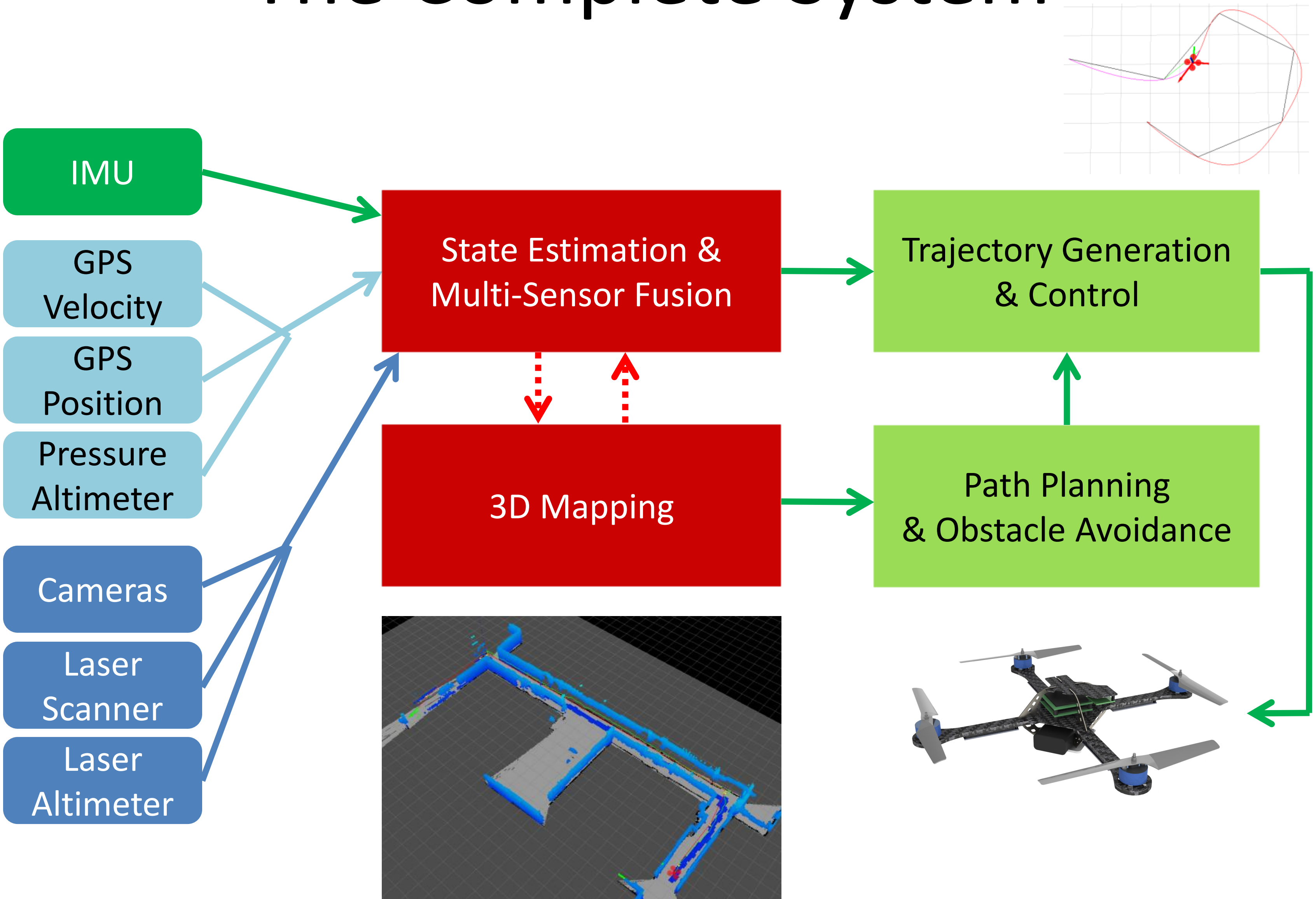
Robust Control

Mellinger, 2011

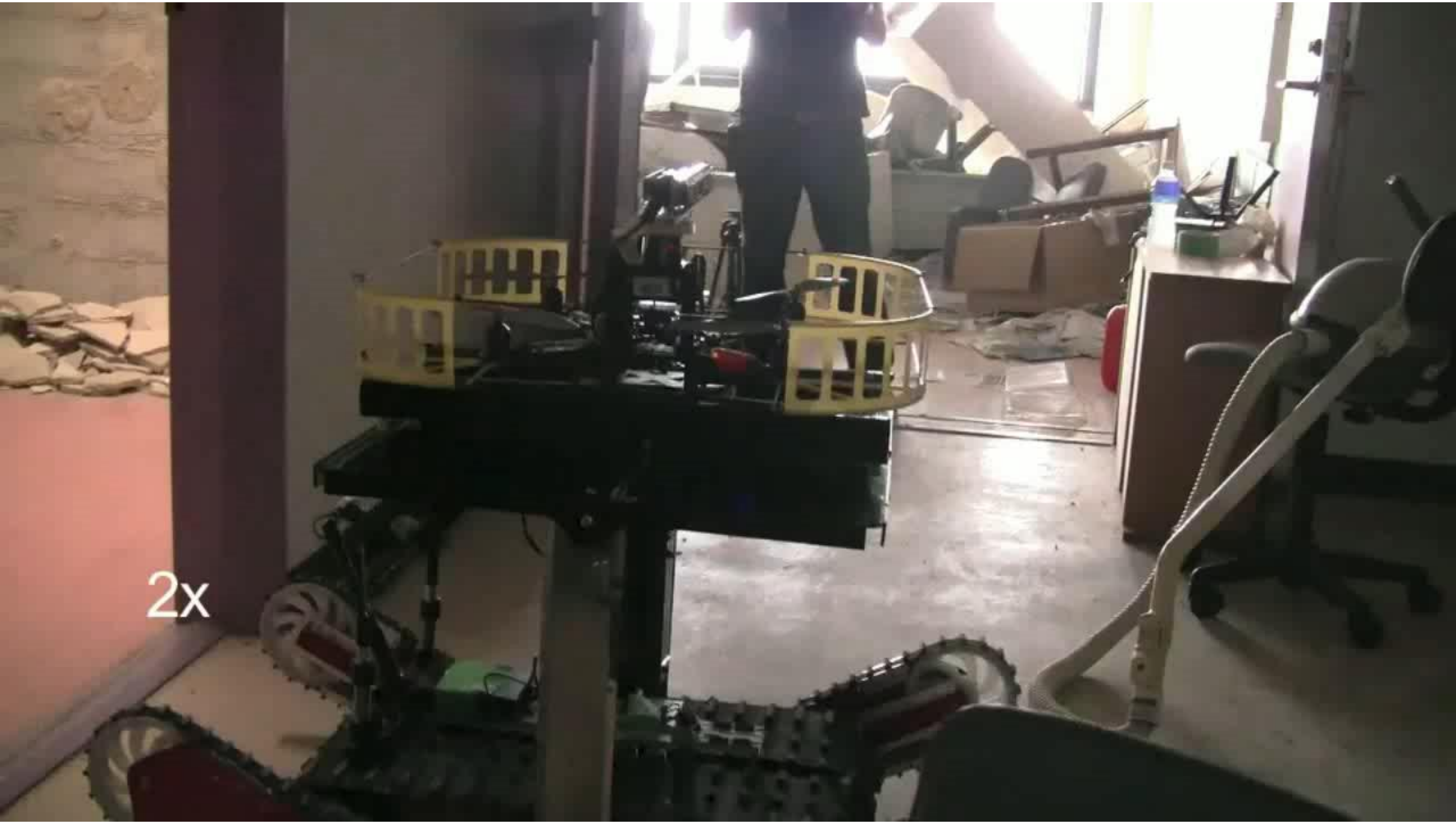
Flying Inverted Pendulum

Cooperative Ball Throwing

The Complete System



Search and Rescue

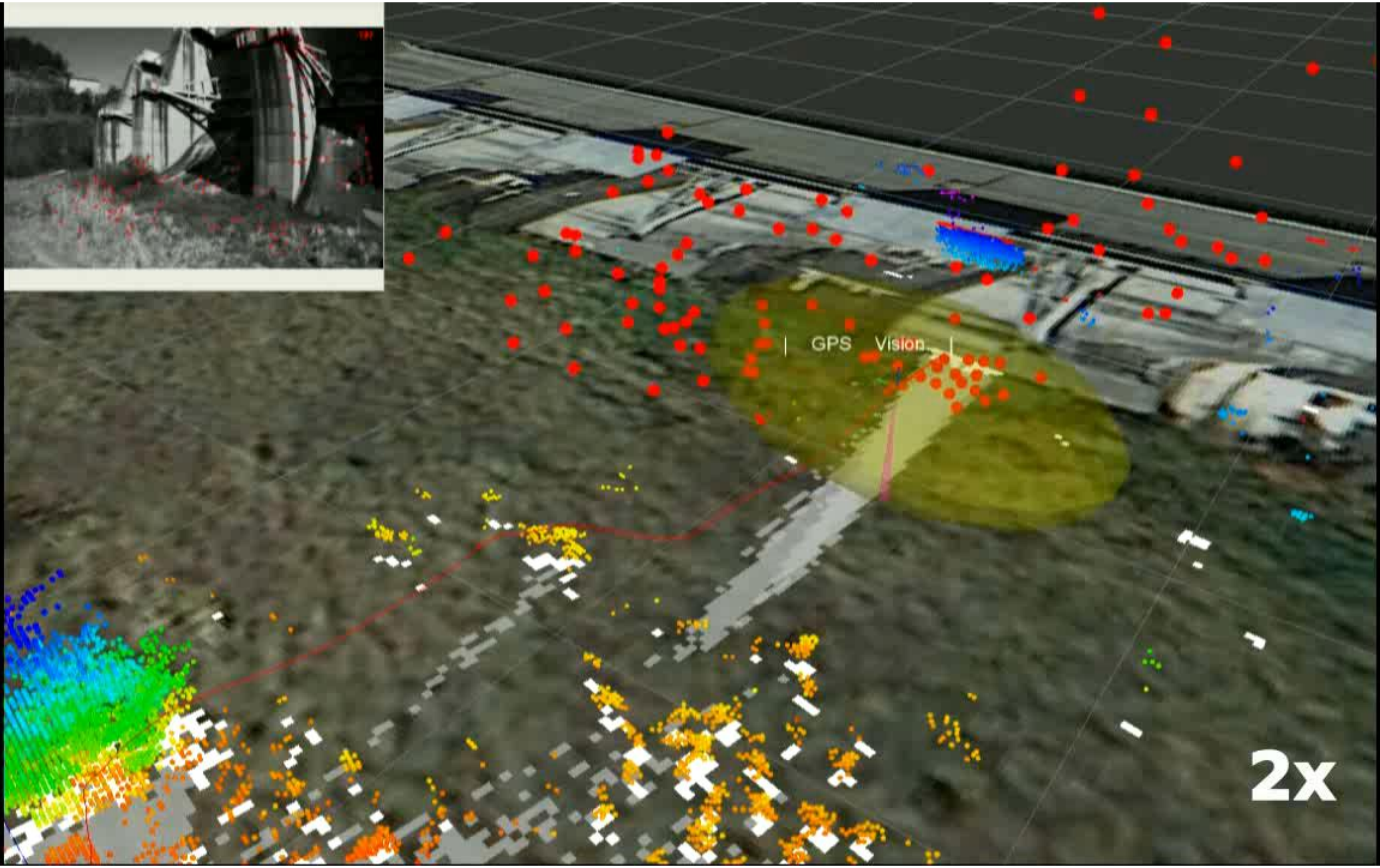


Michael, et al, 2012

Dam Inspection

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

Dam Inspection



Shen, et al, 2014

Dam Inspection

Penstock at the Carter's Dam, GA, USA

Dam Inspection

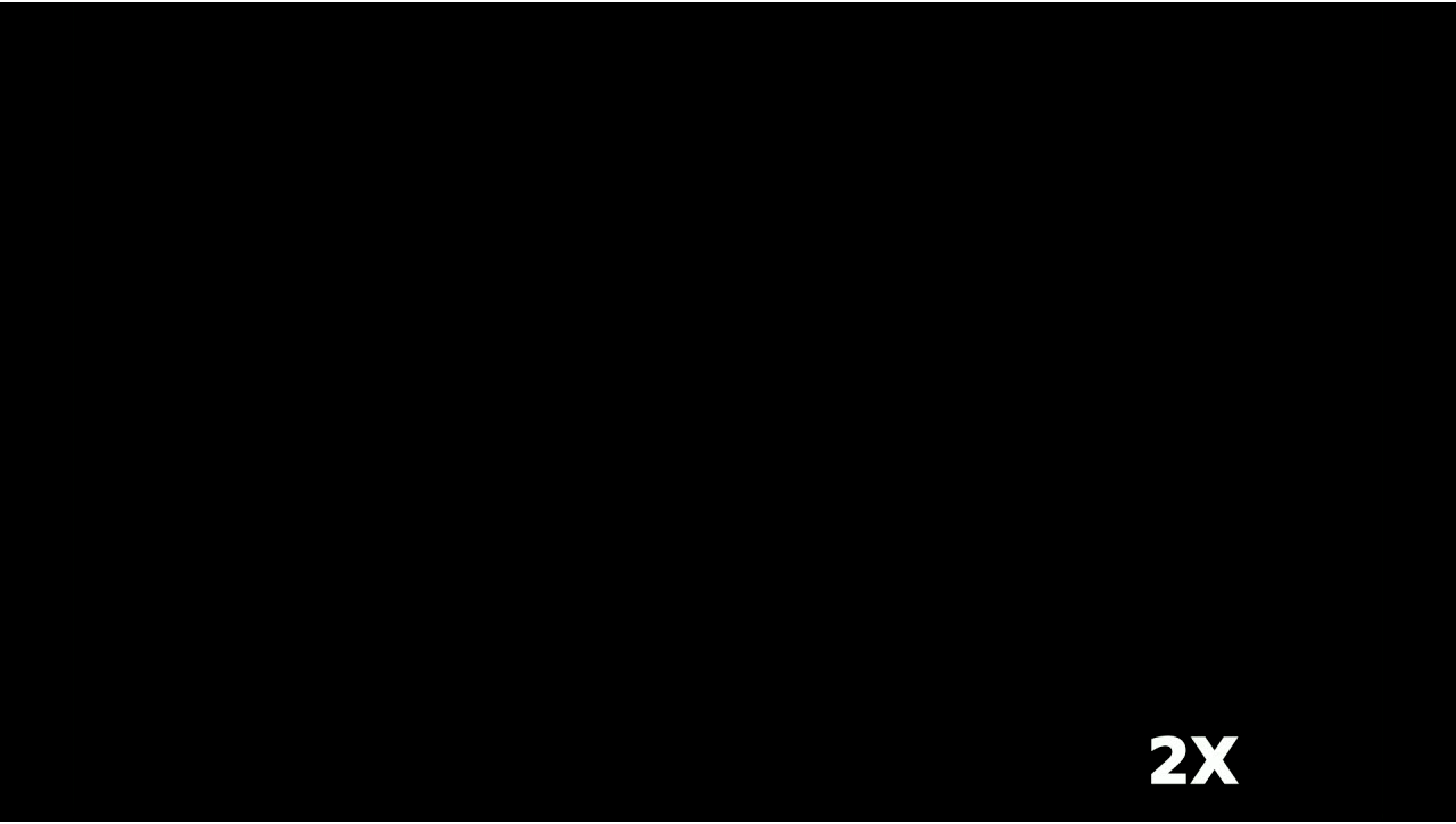
Ozaslan, et al, 2014

Cellular Tower Inspection

Precision Farming

E.&J. Gallo Winery, CA, USA

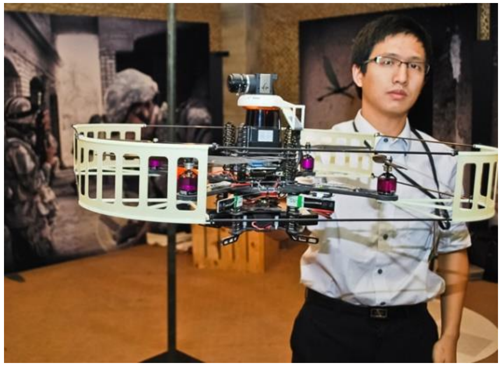
Precision Farming



Shen, et al, 2014

Delivery

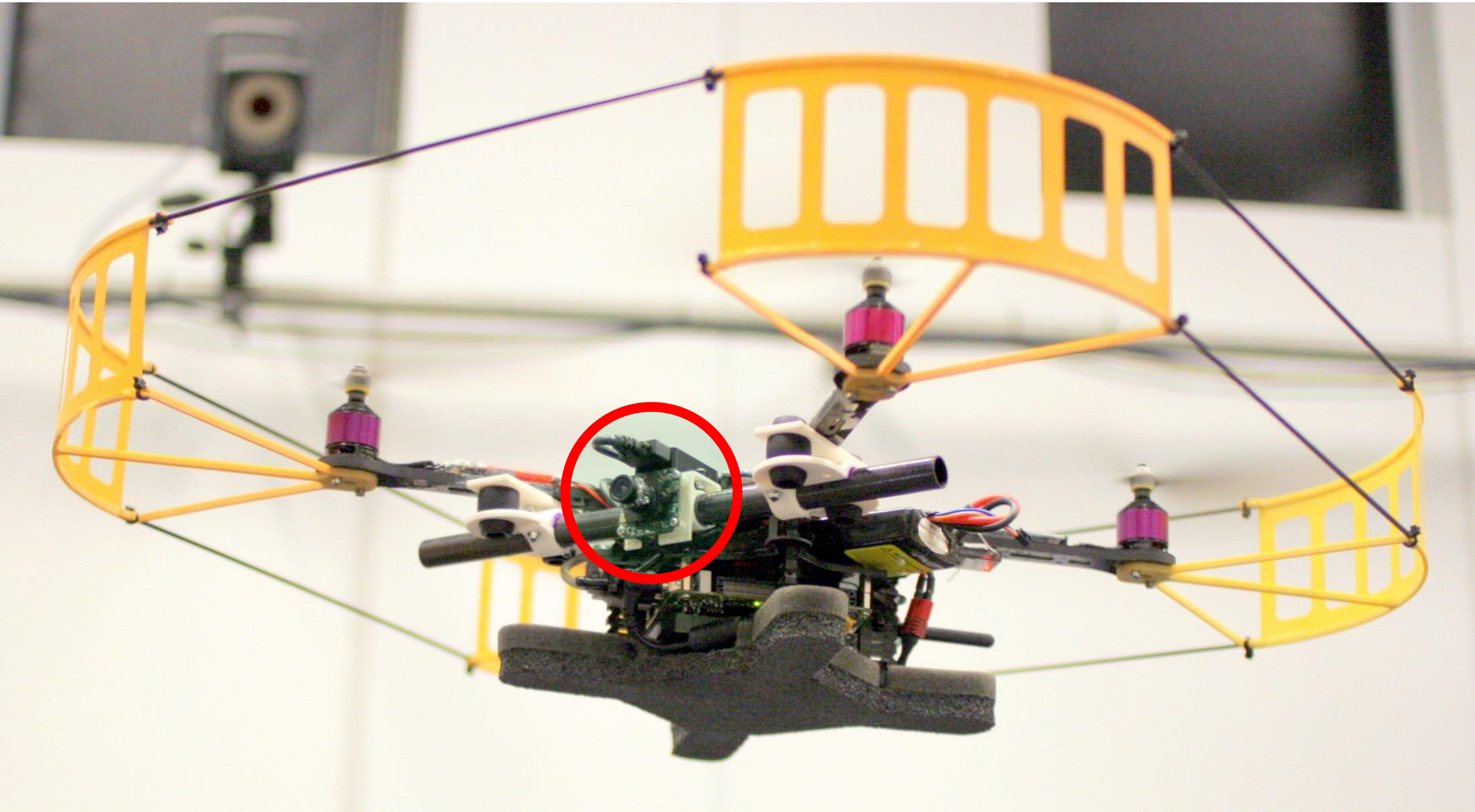
Small and Autonomous



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

Sensing: **YES!**

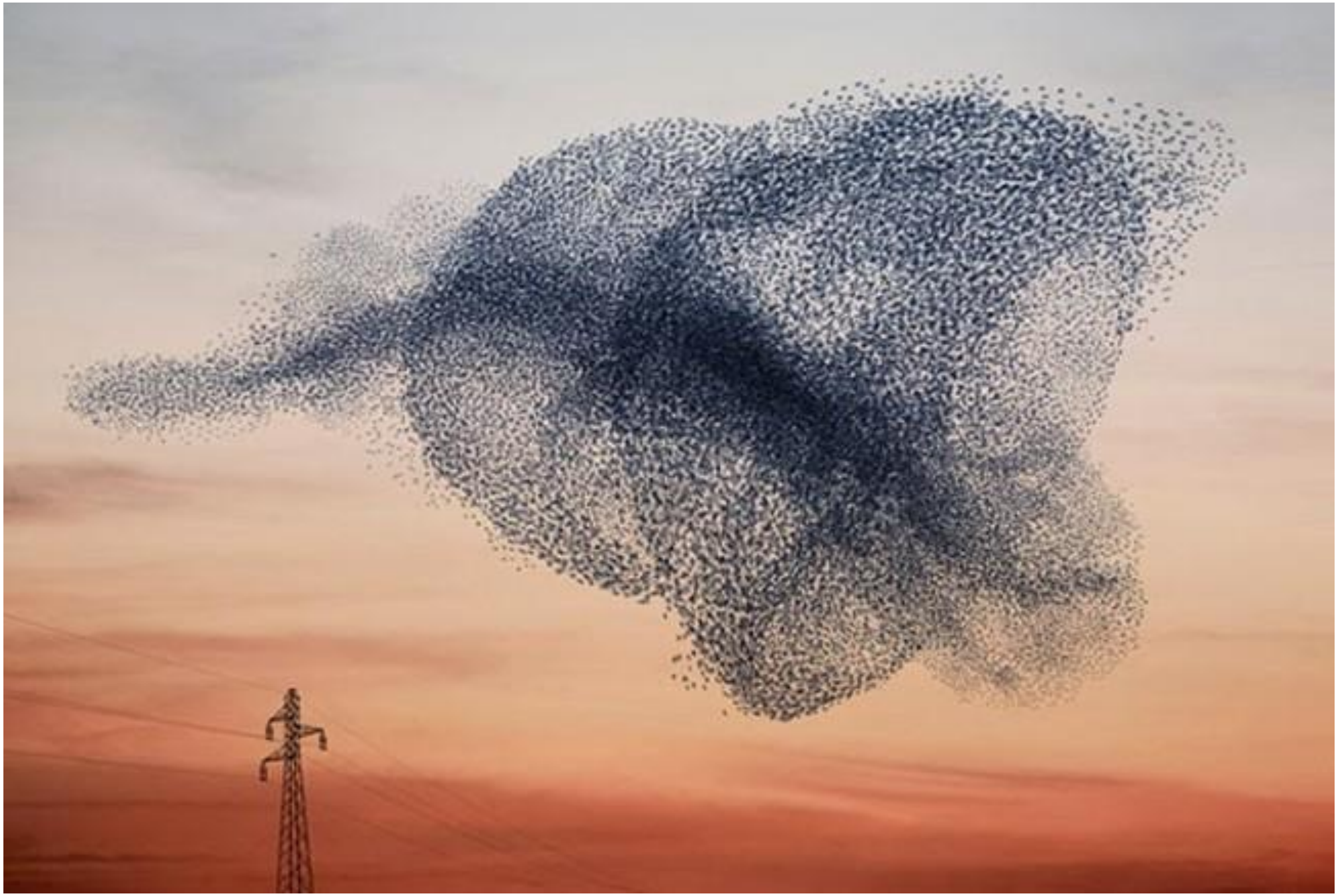
Minimum Sensing: 1 Camera + 1 IMU



Minimum Sensing: 1 Camera + 1 IMU

Lin, et al, 2017

Swarm



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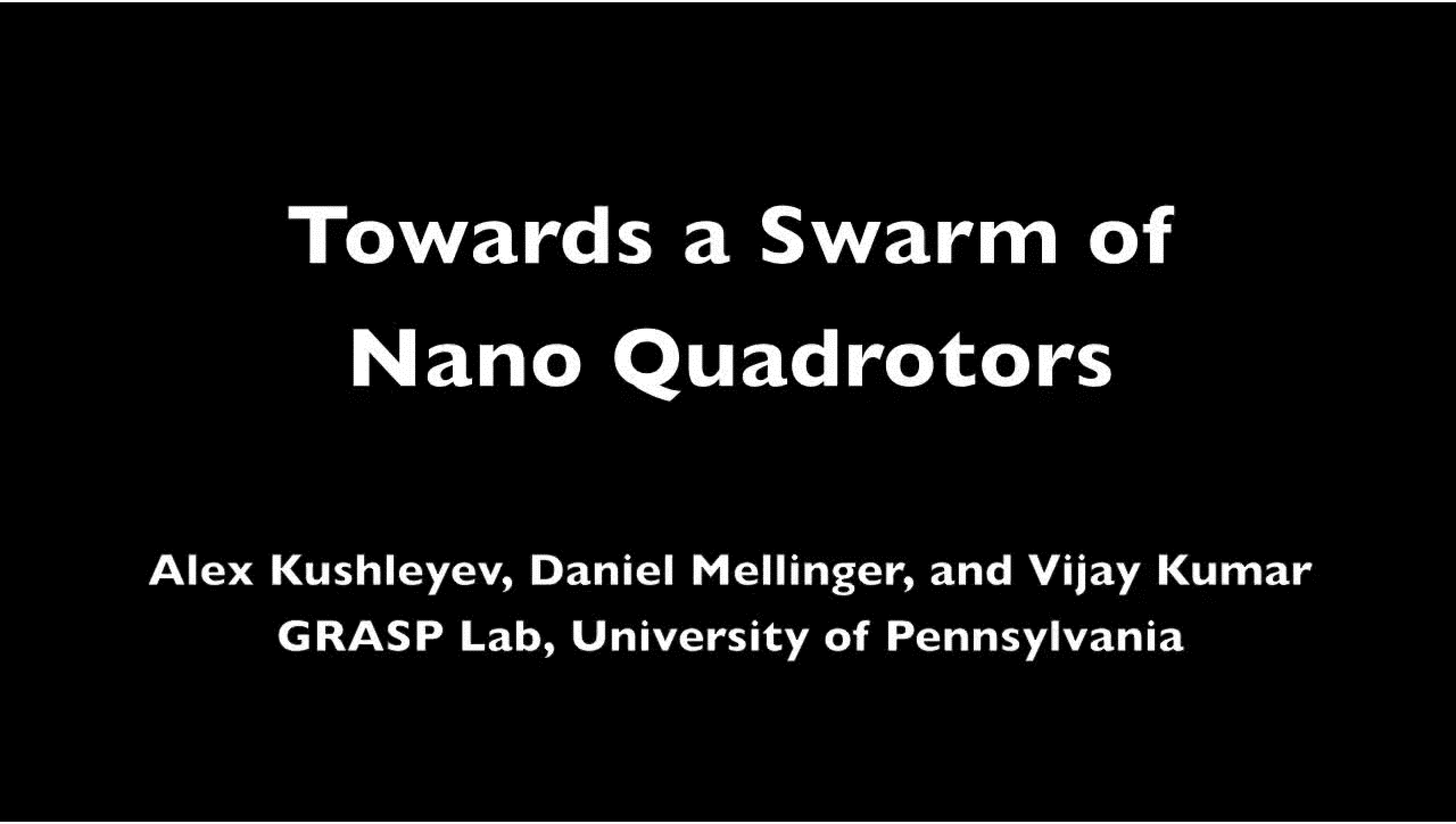
Swarm



Mellinger, et al, 2013

Amazing In Motion

Kmel Robotics, 2014

Course Outline

Course Outline

- Dynamics, Planning & Control
- Vision
- Estimation

Week	Lecture Date Tus 13:30-16:20	Topic	Assignment (due 11:59 PM on Friday of the corresponding week)	Lab Wed 18:00-20:50 Thu 13:30-16:20
1	2/7	Introduction		No Lab
2	2/14	Rigid Body Transformation Quadrotor Modeling		No Lab
3	2/21	Control Basics Quadrotor Control Trajectory Generation	Project 1 Phase 1 Out	No Lab
4	2/28	Trajectory Generation Path Planning	Project 1 Phase 1 Due Project 1 Phase 2 Out	No Lab
5	3/7	Camera Modeling & Calibration Feature Detection & Matching	Project 1 Phase 2 Due Project 1 Phase 3 Out	Lab Tutorial 1: Robot Assembly
6	3/14	Midterm Exam	Project 1 Phase 3 Due Project 1 Phase 4 Out	Lab Tutorial 2: Prepare P1P4
7	3/21	Multi-View Geometry Pose Estimation	Project 2 Phase 1 Out	Free Lab Time
8	3/28	Optical Flow Dense Stereo	Project 1 Phase 4 Due Project 2 Phase 1 Due Project 2 Phase 2 Out	Free Lab Time
9	4/4	Probability Basics Bayesian Inferencing Kalman Filter	Project 2 Phase 2 Due Project 3 Phase 1 Out	No Lab
10	4/11	Midterm Break		No Lab
11	4/18	Extended Kalman Filter Augmented State EKF Particle Filter	Project 3 Phase 1 Due Project 3 Phase 2 Out	No Lab
12	4/25	SLAM	Project 3 Phase 2 Due Project 3 Phase 3 Out	Lab Tutorial 3: Prepare P3P3
13	5/2	x		Free Lab Time
14	5/9	x	Project 3 Phase 3 Due	Free Lab Time

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

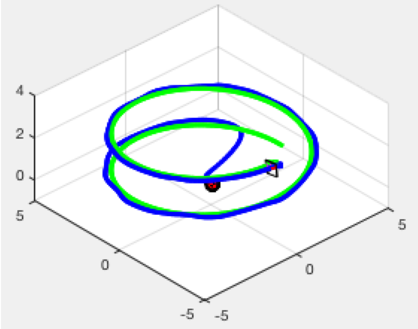
Project 1

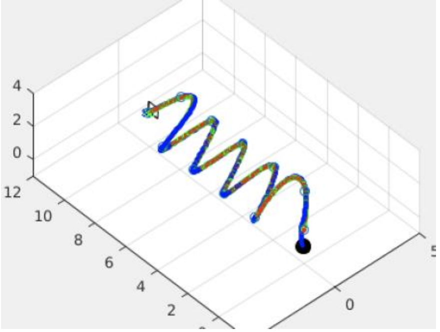
- Phase 1: Hovering and trajectory tracking of a simulated quadrotor
  - MATLAB, offline

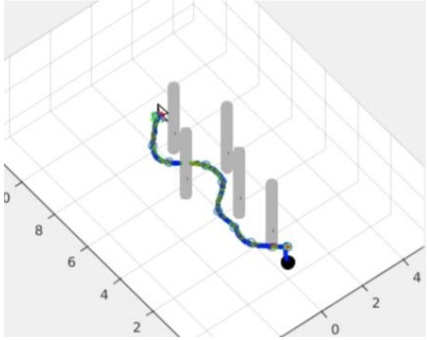
- Phase 2: Trajectory generation and tracking of a simulated quadrotor
  - MATLAB, offline

- Phase 3: Obstacle avoidance using A* path planning and smooth trajectory generation
  - MATLAB, offline

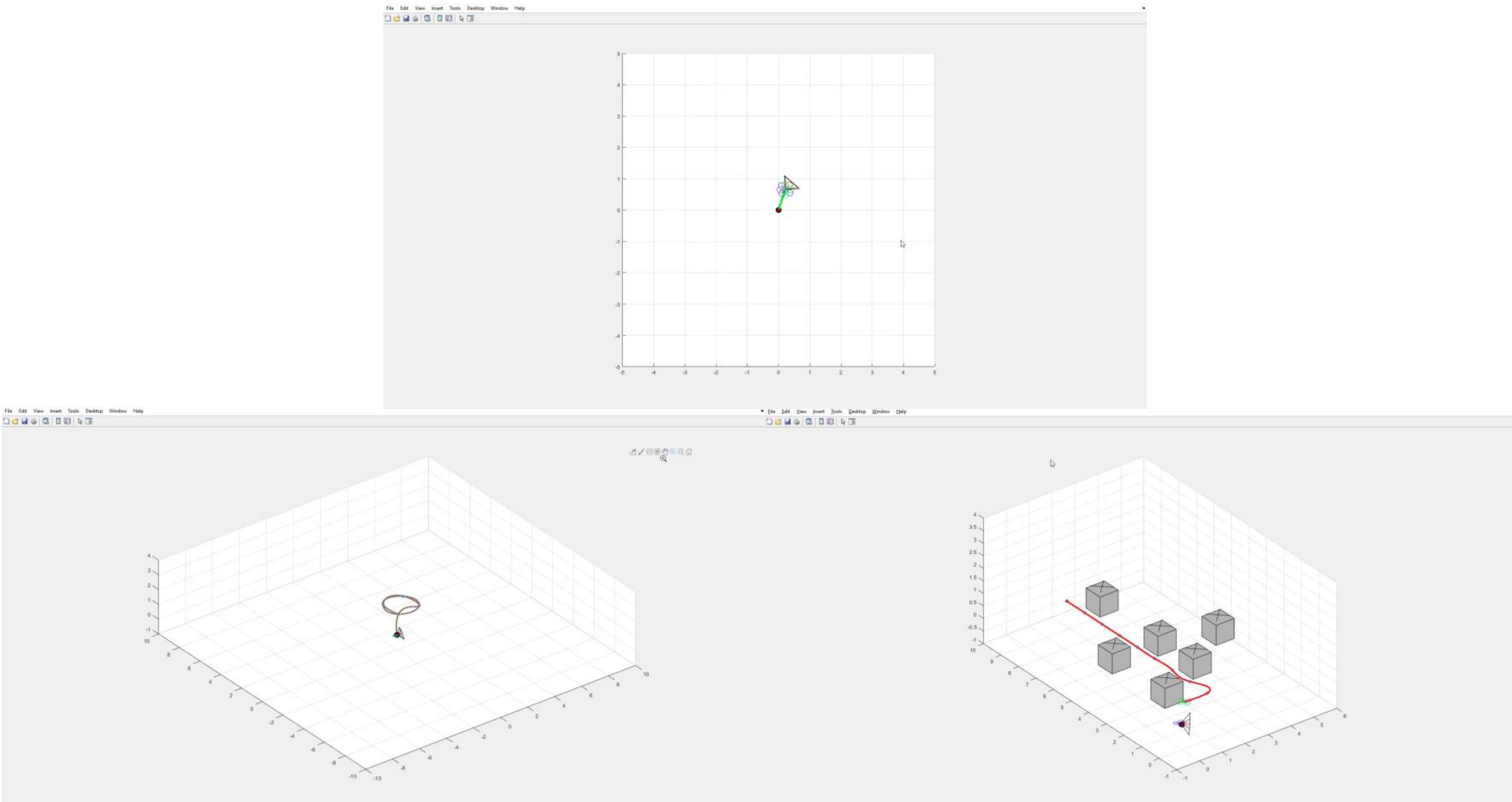
- Phase 4: Fly the robot!





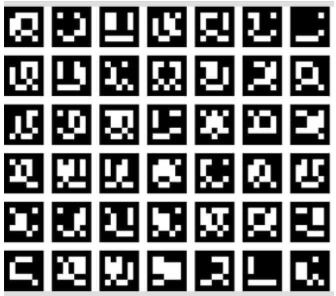


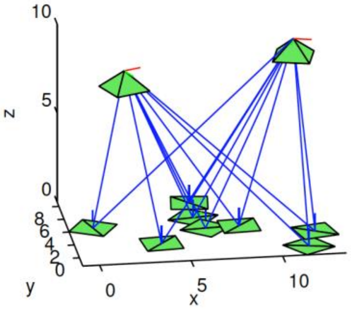
Project 1 in Past Years



Project 2

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

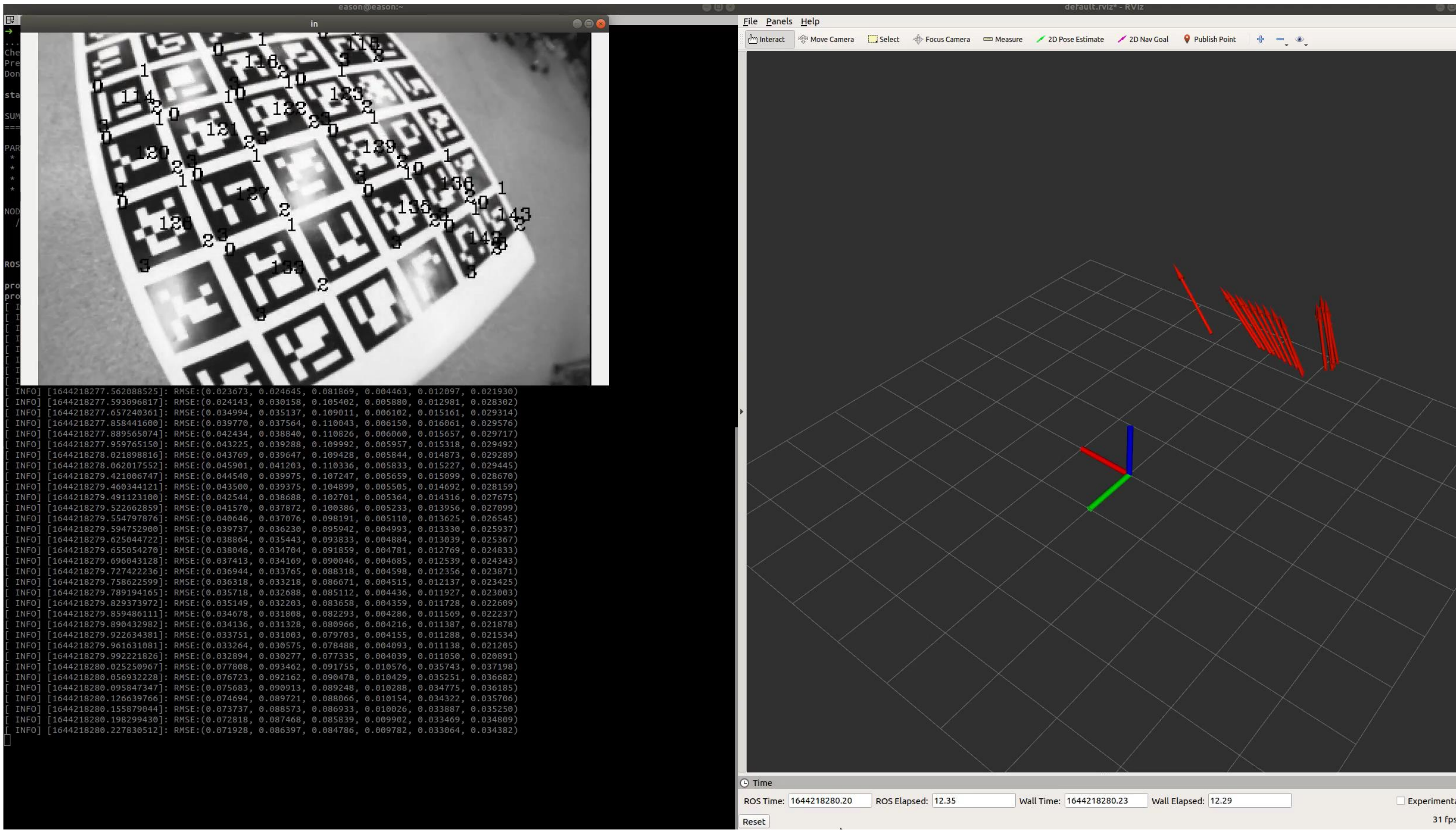




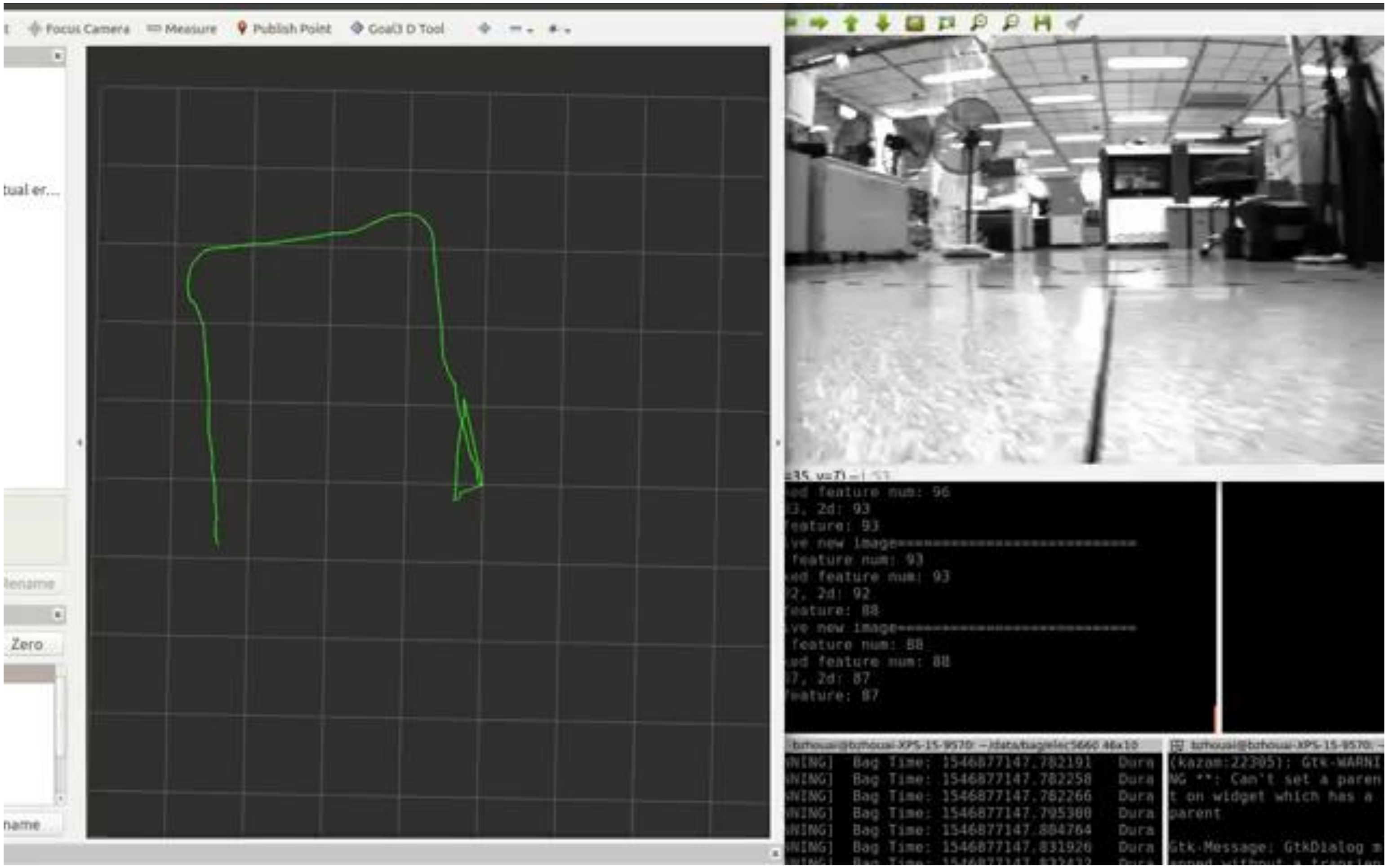
- Phase 2: Visual odometry in markerless environment
  - ROS & C++, Desktop PC, offline

(b)

Project 2 Phase 1 in Past Years

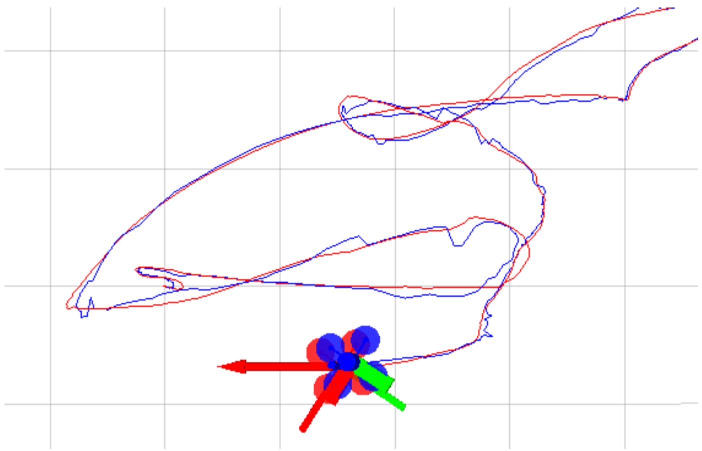


Project 2 Phase 2 in Past Years

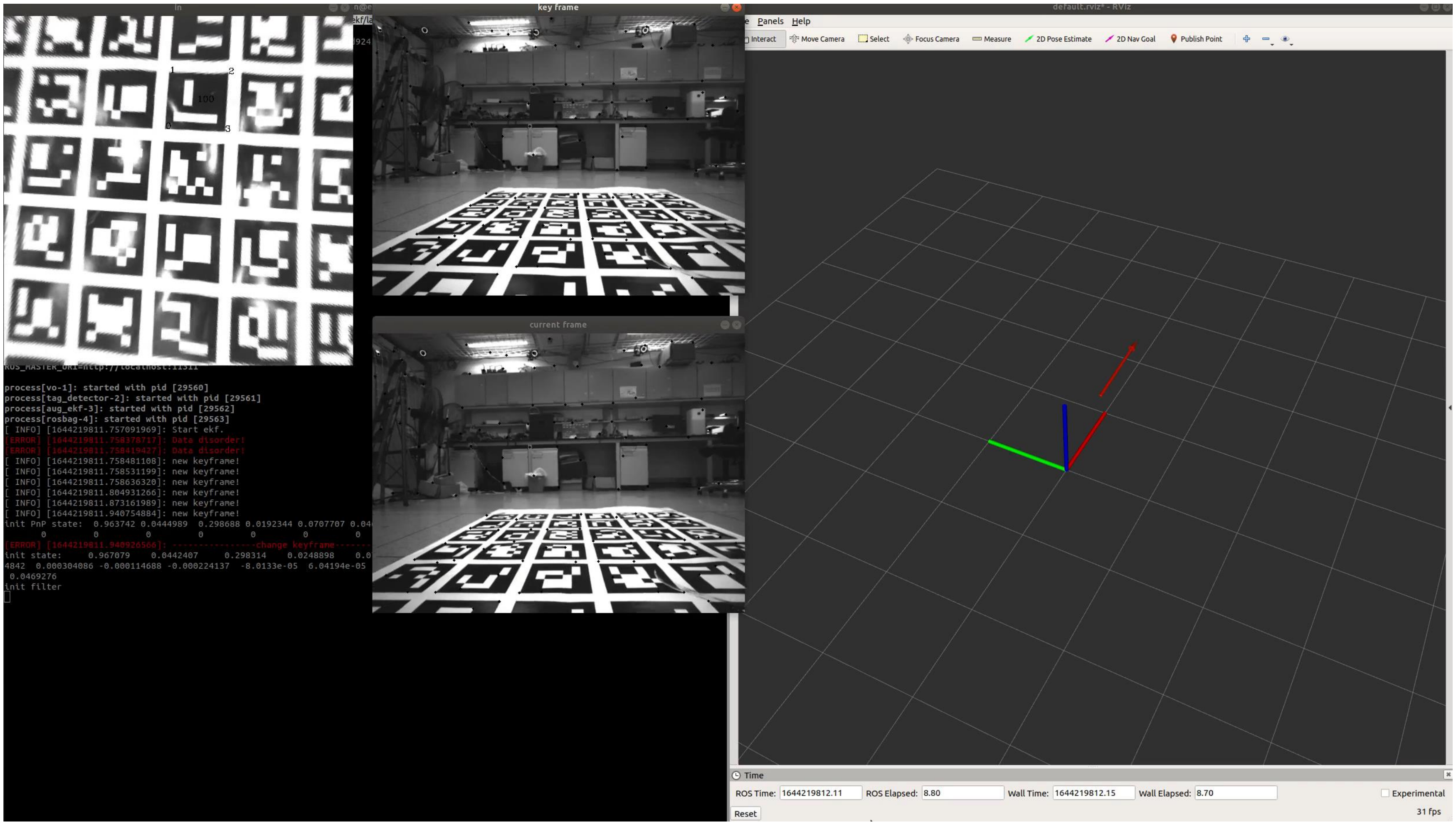


Project 3

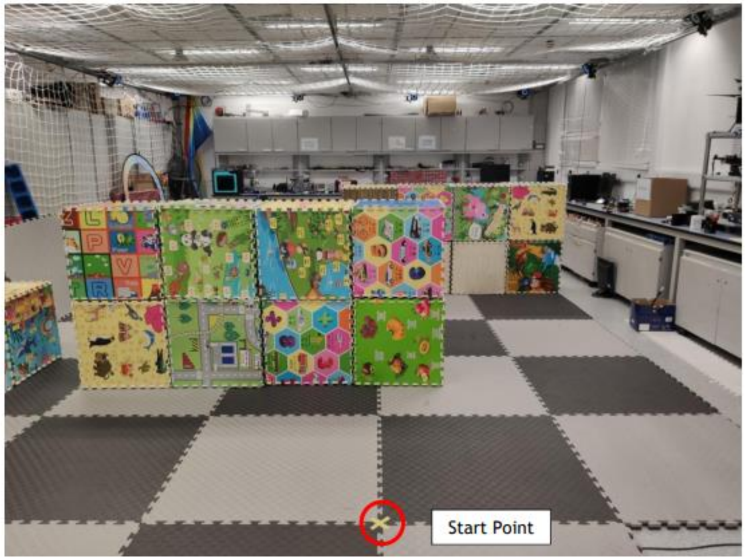
- Phase 1: EKF-based sensor fusion of IMU and tag-based position estimation
  - ROS & C++, Desktop PC, offline
- Phase 2: Augmented state EKF for fusion of IMU and keyframe-based visual odometry together with the PnP localization on markers
  - ROS & C++, Desktop PC, offline
- Phase 3: Fly the robot!

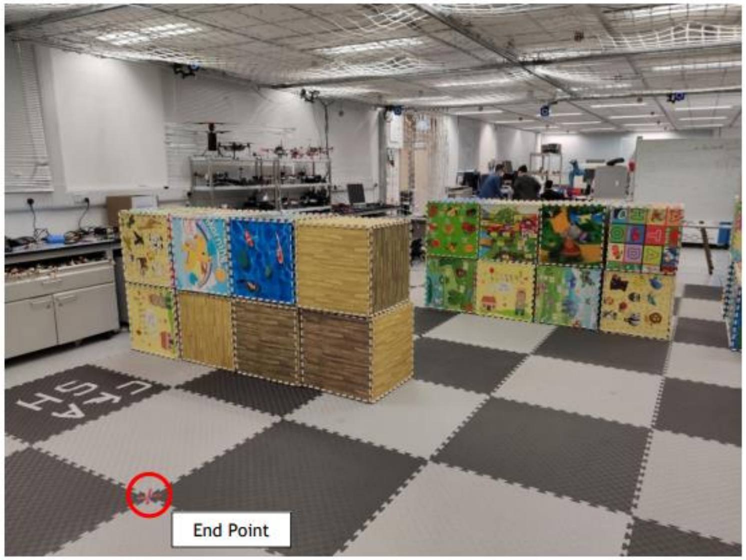


Project 3 in Past Years

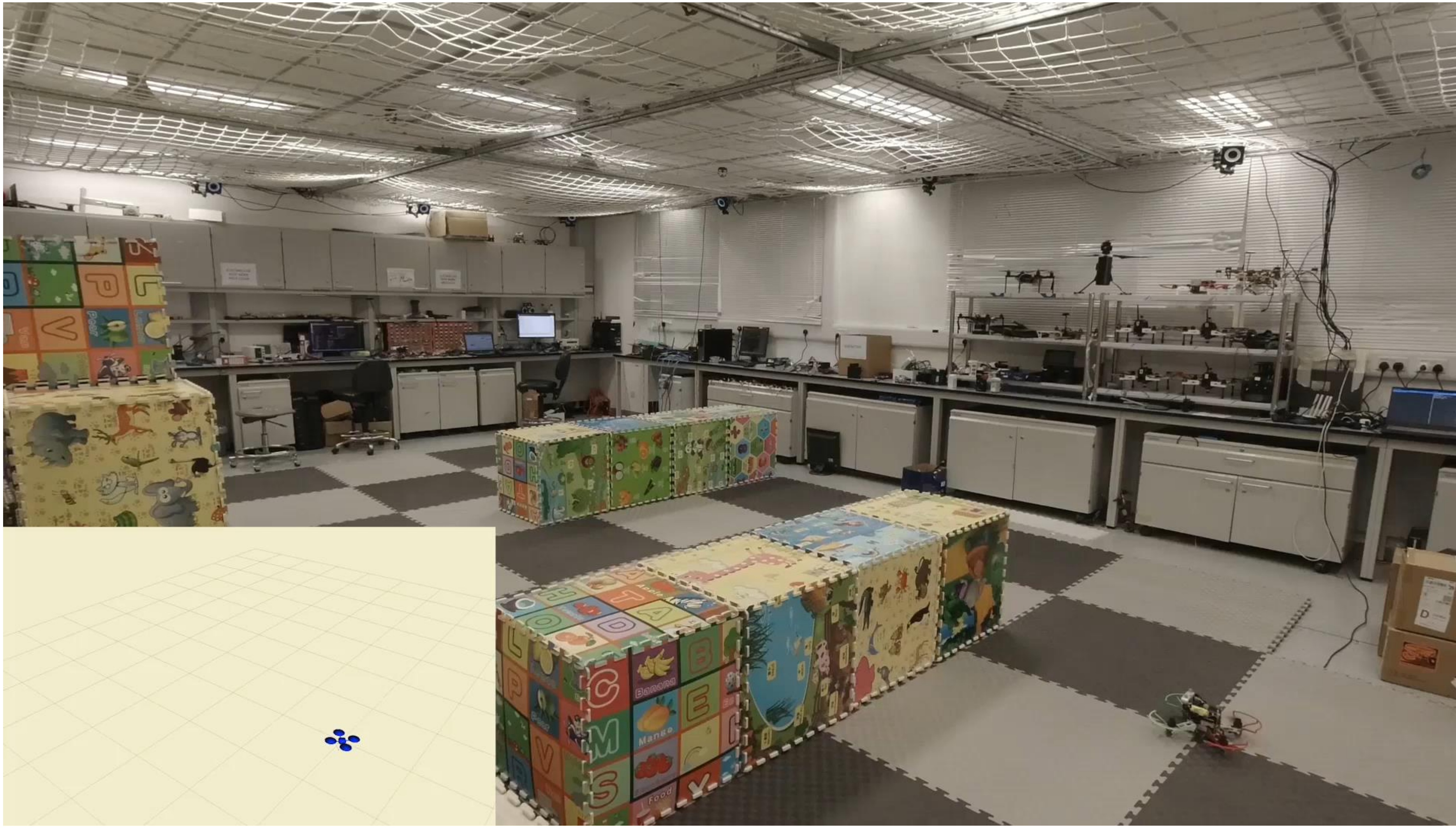


Project 3 in Past Years





Project 3 in Past Years



Next Lecture…

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