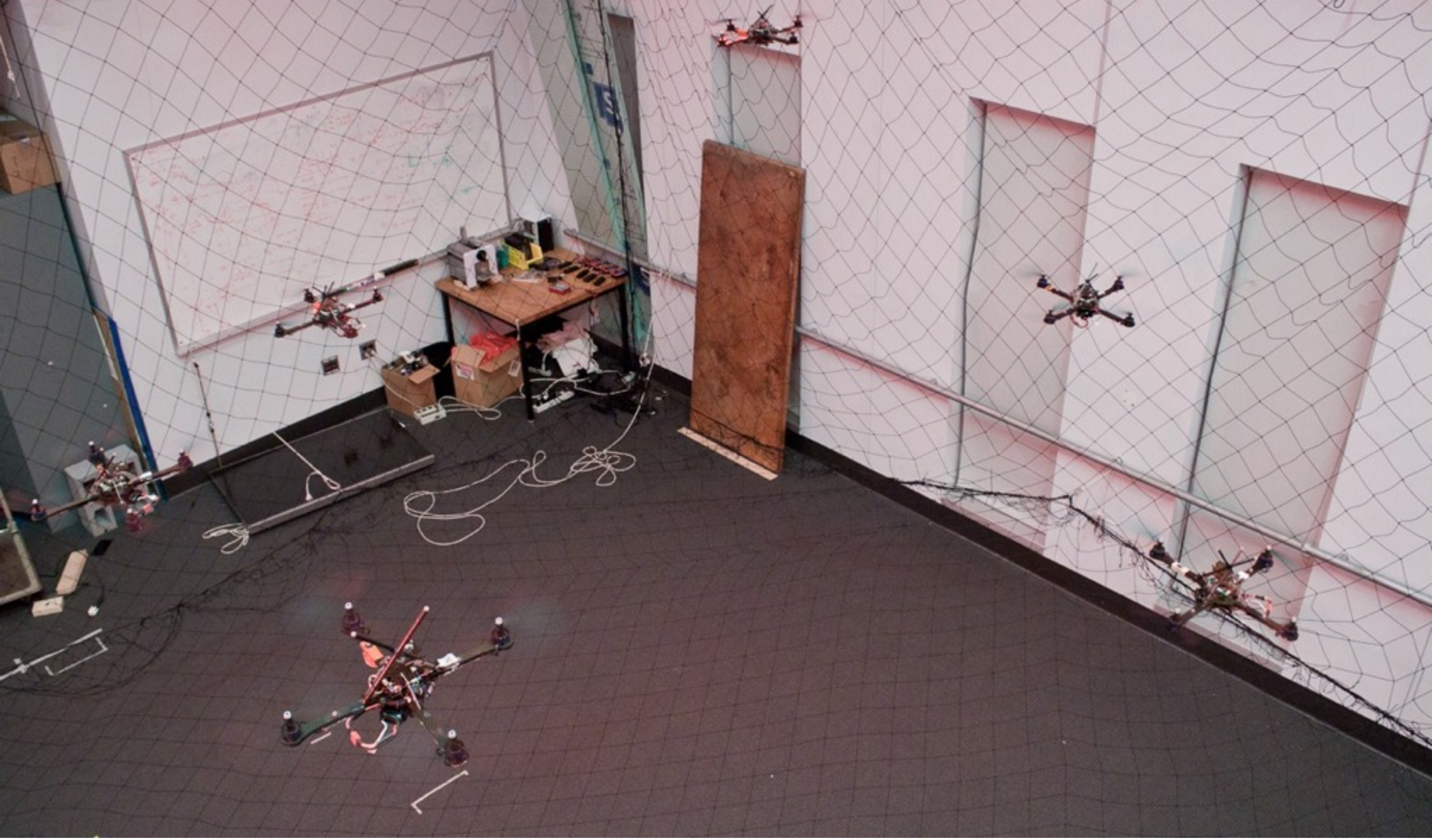
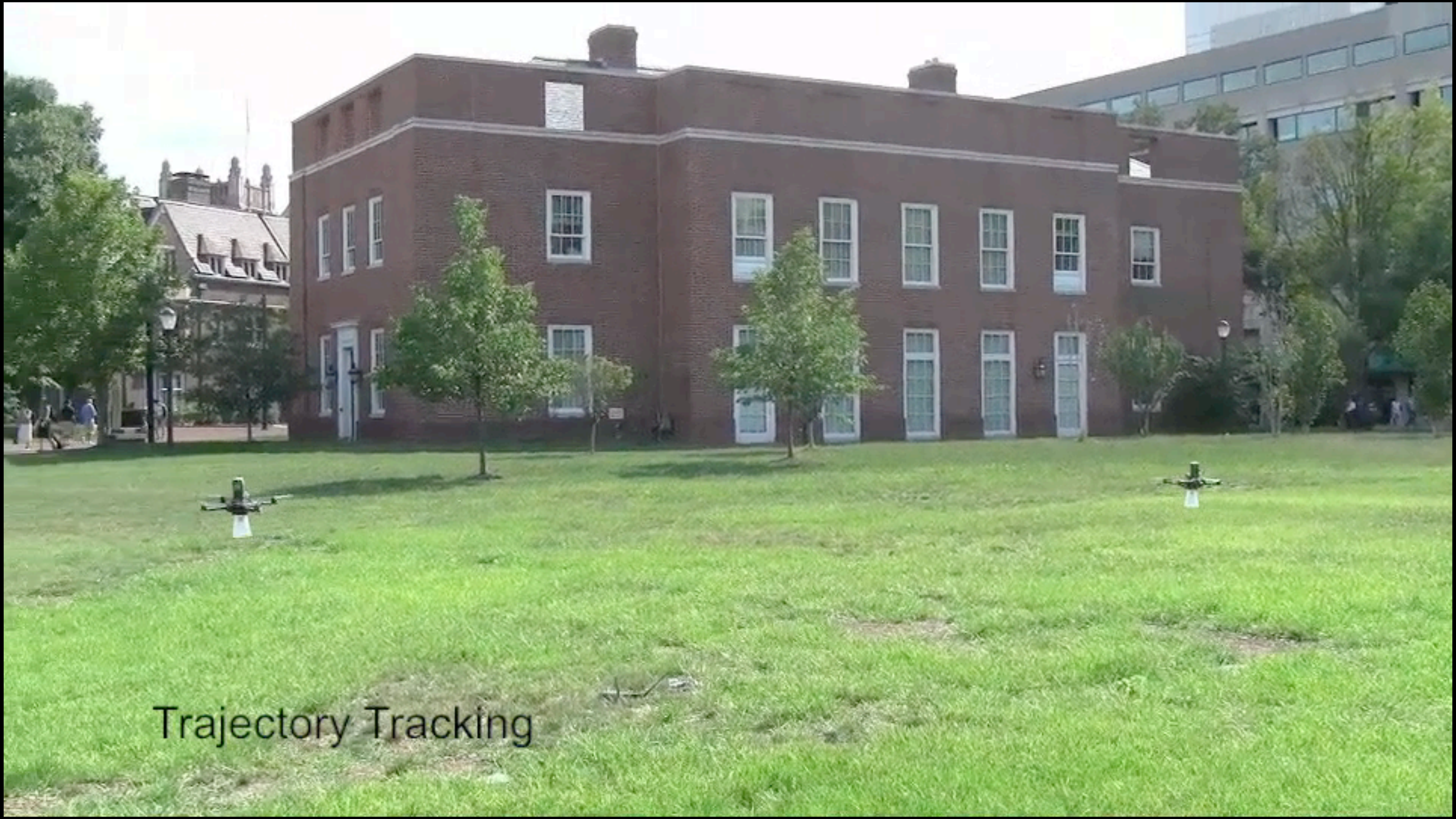


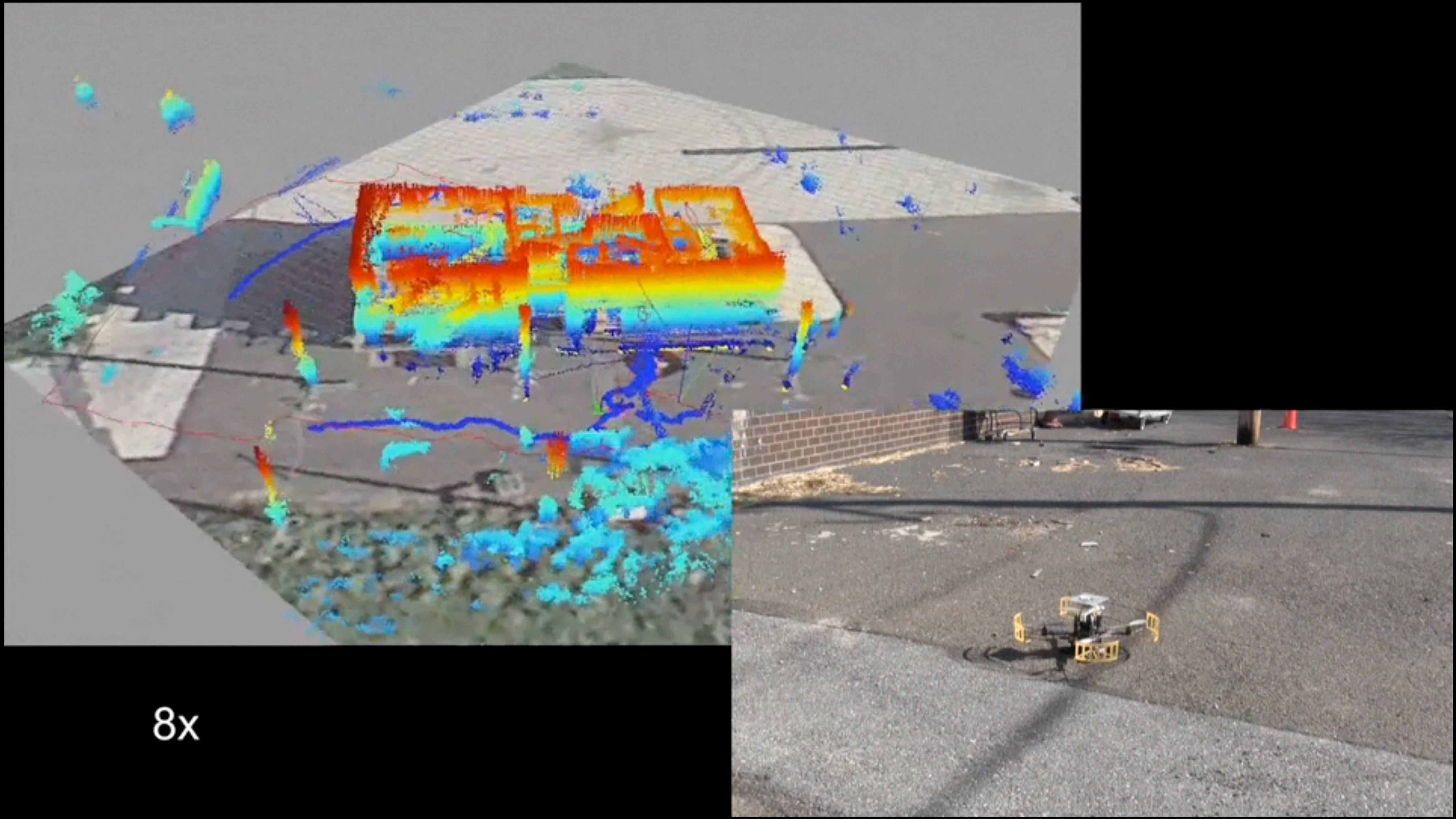
Estimation and Control Toward Autonomous Aerial Robot Systems

Nathan Michael, Assistant Research Professor
Carnegie Mellon University

→



N. Michael, E. Stump, and K. Mohta. Persistent surveillance with a team of MAVs. In *Proc. of the IEEE/RSJ Intl. Conf. on Intell. Robots and Syst.*, pages 2708–2714, San Francisco, CA, Sept. 2011.



8x

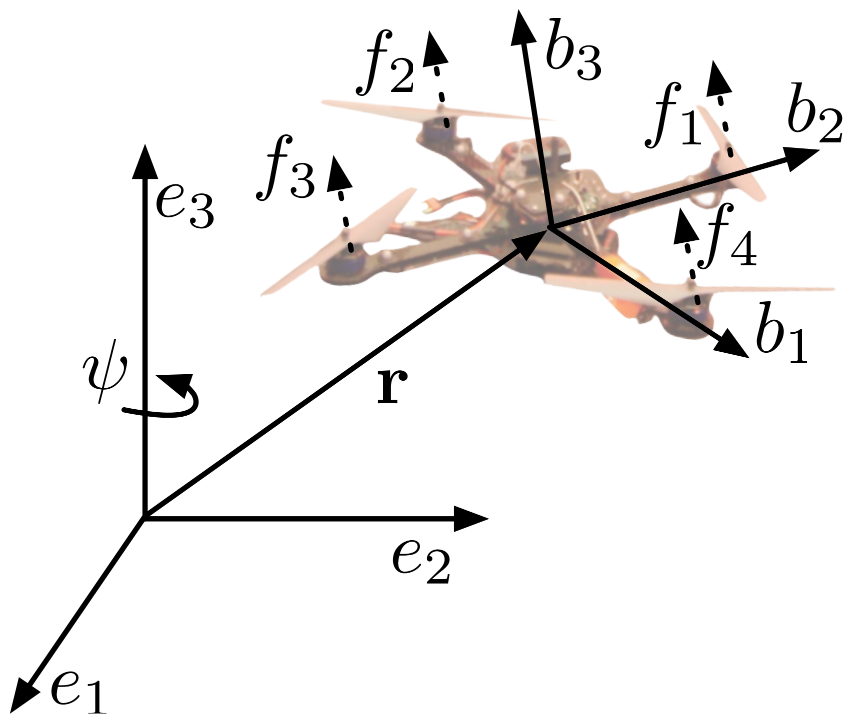
S. Shen and N. Michael. State estimation for indoor and outdoor operation with a micro-aerial vehicle. In *Proc. of the Intl. Sym. on Exp. Robot.*, Quebec City, Canada, June 2012.

Outline

- Quadrotor model and control
  - Aggressive maneuvers
  - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
  - Autonomous exploration
  - Application study: cooperative air-ground mapping
- Future research challenges

Model

Dynamic Model:



$$m\ddot{\mathbf{r}} = (fR - mg)e_3$$

$$J\dot{\Omega} + \Omega \times J\Omega = M$$

with $M = [M_1,\ M_2,\ M_3]^{\mathrm{T}}$

Relationship between body-frame force/moments and propeller forces:

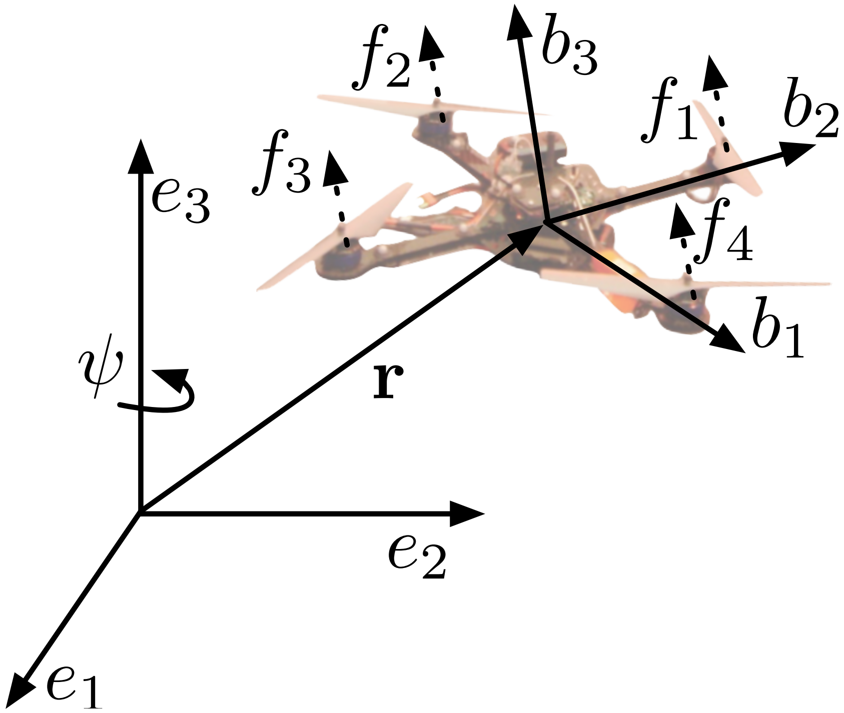
$$\begin{bmatrix} f \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ d & 0 & -d & 0 \\ 0 & d & 0 & -d \\ -c & c & -c & c \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}$$

Attitude Stabilization and Position Control

Define the desired trajectory:

$$\mathbf{x}_{\mathrm{d}}(t) : [t_0,\, t_f] \to \mathbb{R}^3 \times SO(2)$$

$$\mathbf{x}_{\mathrm{d}}(t) = \begin{bmatrix} \mathbf{r}_{\mathrm{d}}(t) \\ \psi_{\mathrm{d}}(t) \end{bmatrix} = \begin{bmatrix} x_{\mathrm{d}}(t) \\ y_{\mathrm{d}}(t) \\ z_{\mathrm{d}}(t) \\ \psi_{\mathrm{d}}(t) \end{bmatrix}$$



Attitude stabilization and position control follows approach proposed in:

N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar. The GRASP multiple micro UAV testbed. *IEEE Robot. Autom. Mag.*, 17(3):56–65, Sept. 2010.

T. Lee, M. Leok, and N. H. McClamroch. Geometric tracking control of a quadrotor UAV on SE(3). In *Proc. of the IEEE Conf. on Decision and Control*, Atlanta, GA, Dec. 2010.

Define desired force and moments:

$$
\begin{aligned}
f &= (-k_{\mathbf{r}} e_{\mathbf{r}} - k_{\dot{\mathbf{r}}} e_{\dot{\mathbf{r}}} + m g e_3 + m \ddot{\mathbf{r}}_{\mathrm{d}}) \cdot R e_3 \\
M &= -k_R e_R - k_\Omega e_\Omega + \Omega \times J\Omega + \cdots
\end{aligned}
$$

higher order terms

with error terms:

$$(\cdot)^\vee : so(3) \to \mathbb{R}^3$$

$$
\begin{aligned}
e_{\mathbf{r}} &= \mathbf{r} - \mathbf{r}_{\mathrm{d}} \\
e_{\dot{\mathbf{r}}} &= \dot{\mathbf{r}} - \dot{\mathbf{r}}_{\mathrm{d}} \\
&\boxed{e_R = \frac{1}{2}(R_{\mathrm{d}}^{\mathrm{T}} R - R^{\mathrm{T}} R_{\mathrm{d}})^\vee} \\
e_\Omega &= \Omega - R^{\mathrm{T}} R_{\mathrm{d}} \Omega_{\mathrm{d}}
\end{aligned}
$$

Basin of attraction includes full space of rotation matrices excluding full inversion

T. Lee. Geometric tracking control of the attitude dynamics of a rigid body on SO(3). In *Proc. of the Amer. Control Conf.*, San Francisco, CA, Apr. 2011.

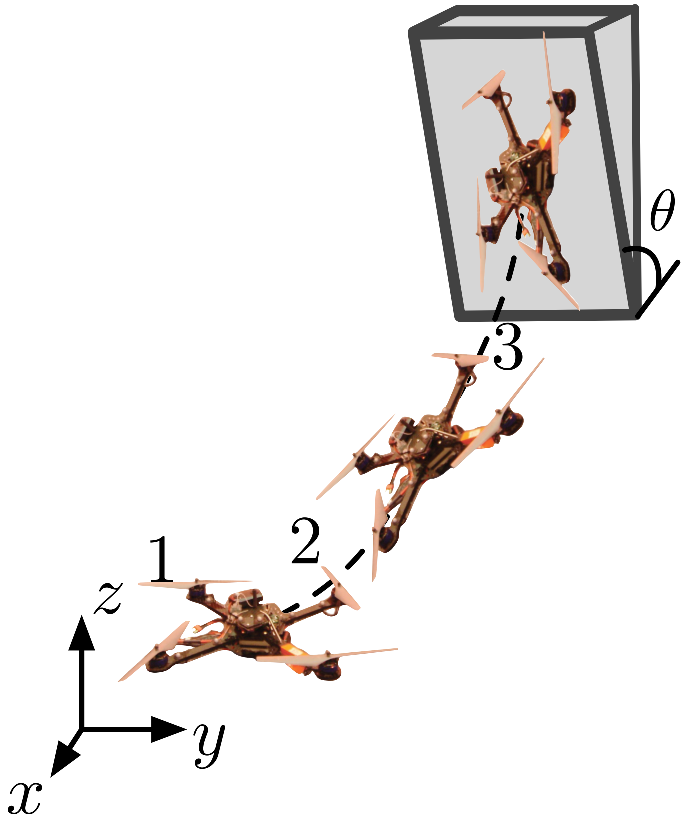
Outline

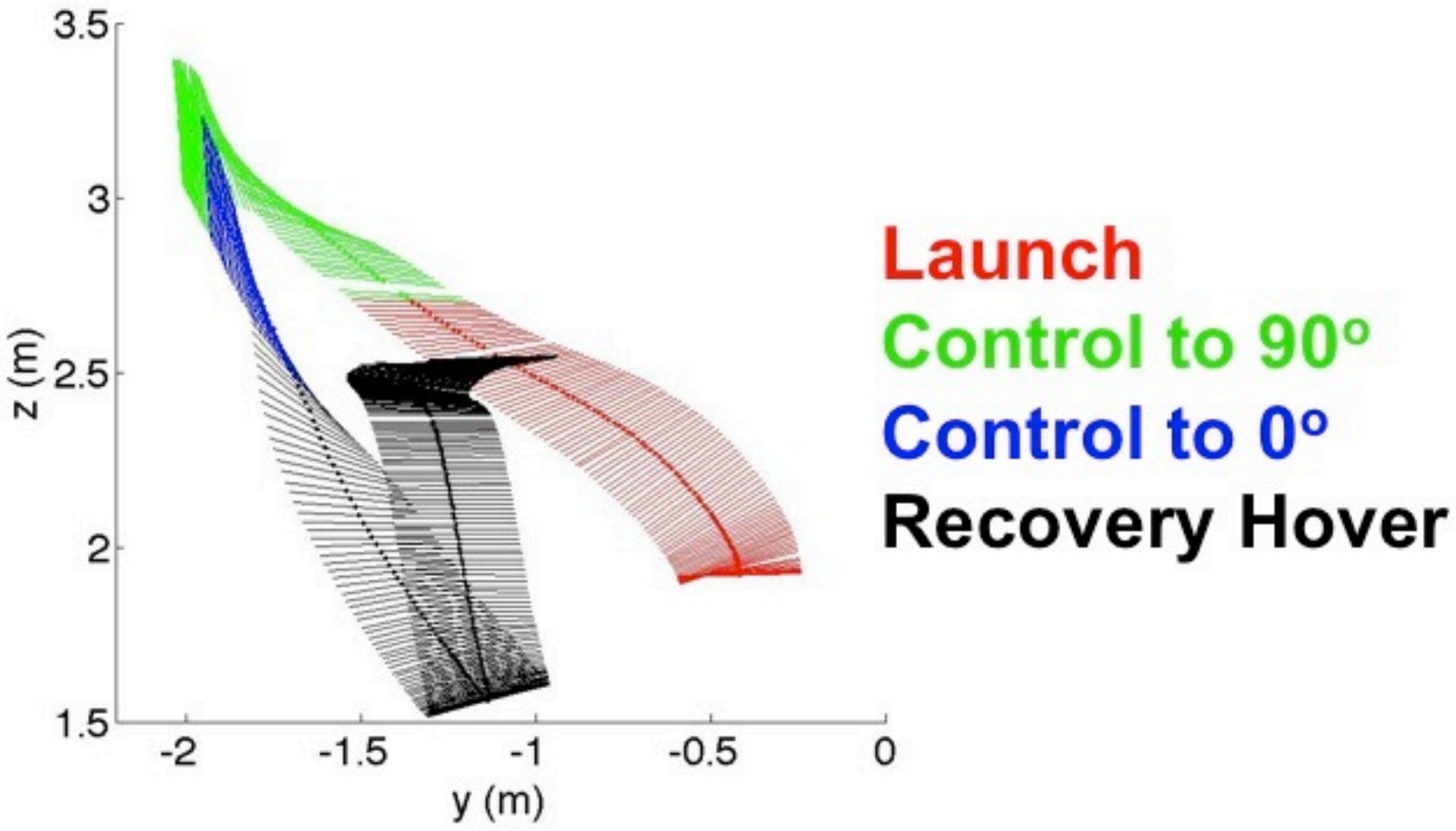
- Quadrotor model and control
  - Aggressive maneuvers
  - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
  - Autonomous exploration
  - Application study: cooperative air-ground mapping
- Future research challenges

N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar. The GRASP multiple micro UAV testbed. *IEEE Robot. Autom. Mag.*, 17(3):56–65, Sept. 2010.

D. Mellinger, N. Michael, and V. Kumar. Trajectory generation and control for precise aggressive maneuvers with quadrotors. *Intl. J. Robot. Research*, 31(5):664–674, Apr. 2012.

Perching Maneuver



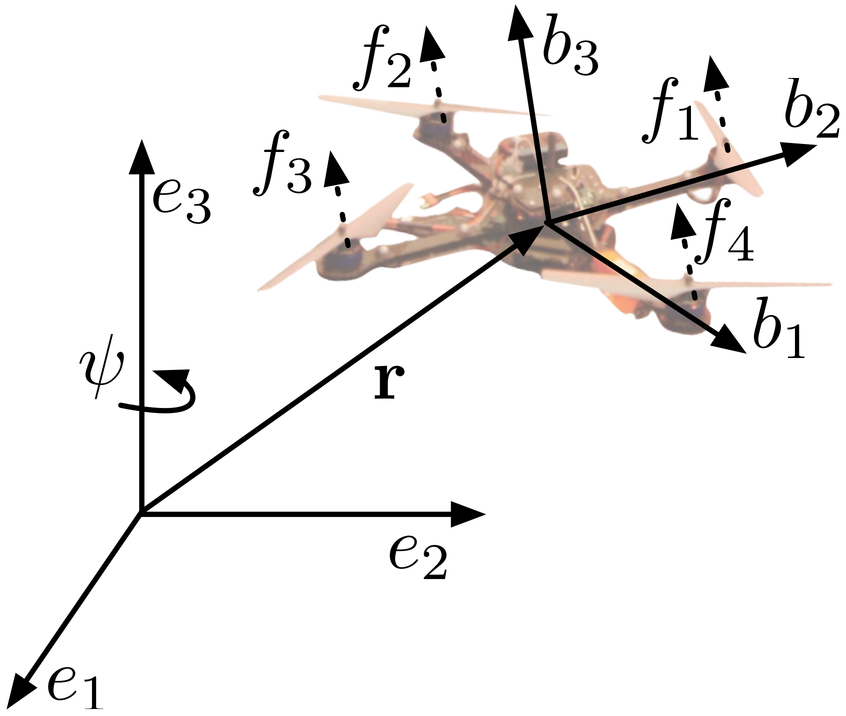


Approach problem as a composition of controllers

Controllers

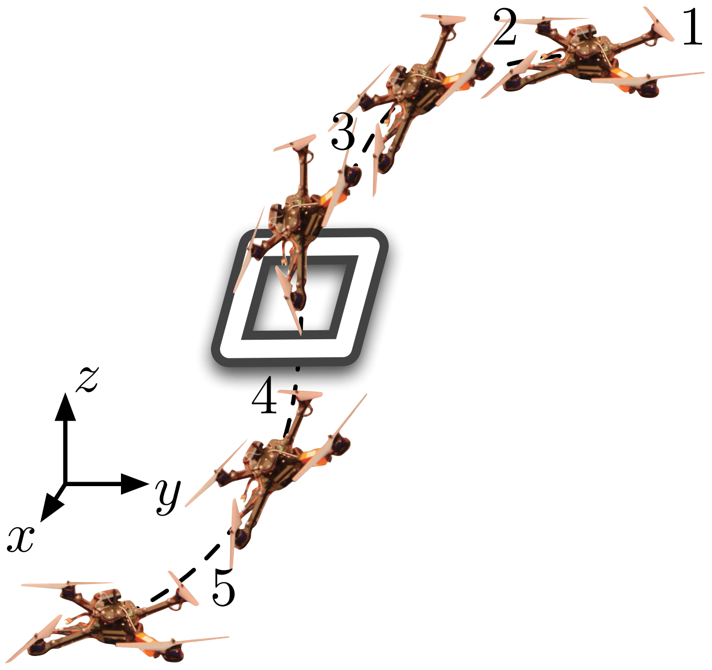
Three basic primitives:

1. Attitude Controller
2. Hover Controller
3. 3D Trajectory Controller

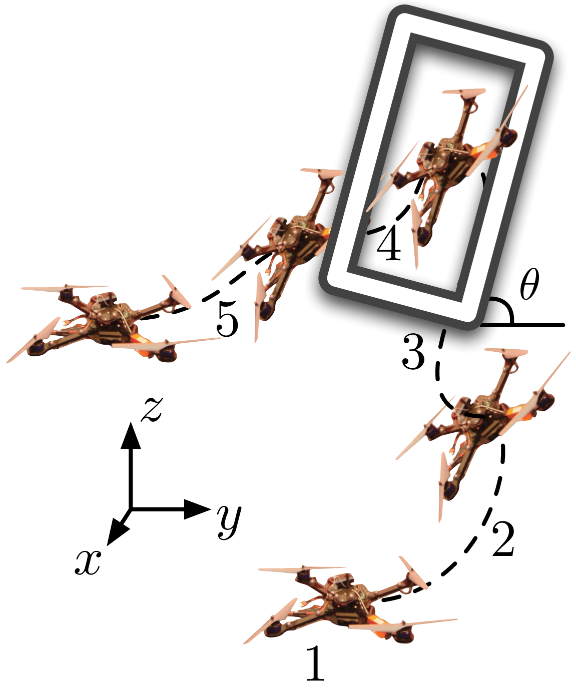


Based on PD or PID control and linearization about hover

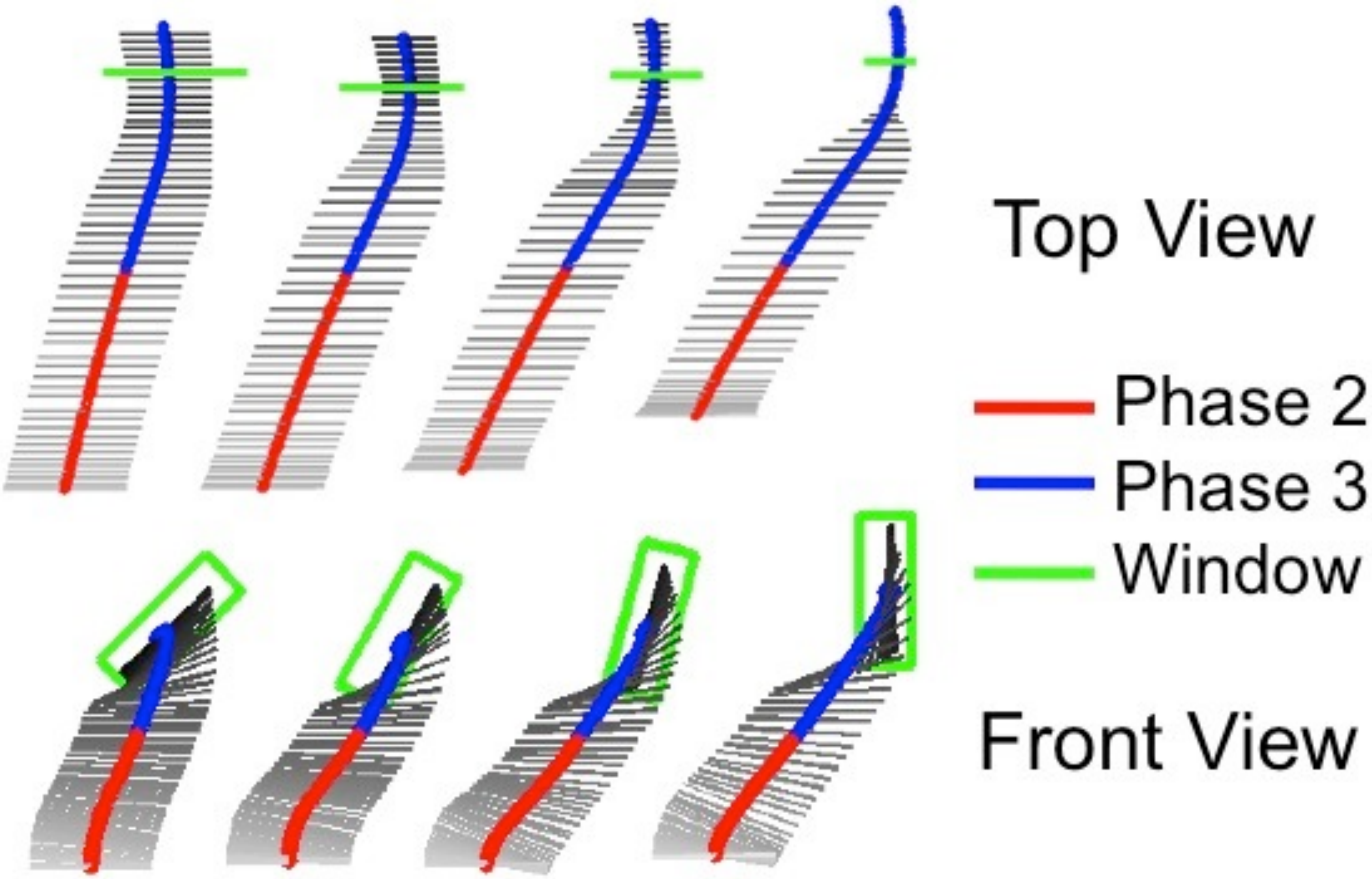
N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar. The GRASP multiple micro UAV testbed. *IEEE Robot. Autom. Mag.*, 17(3):56–65, Sept. 2010.



Horizontal window

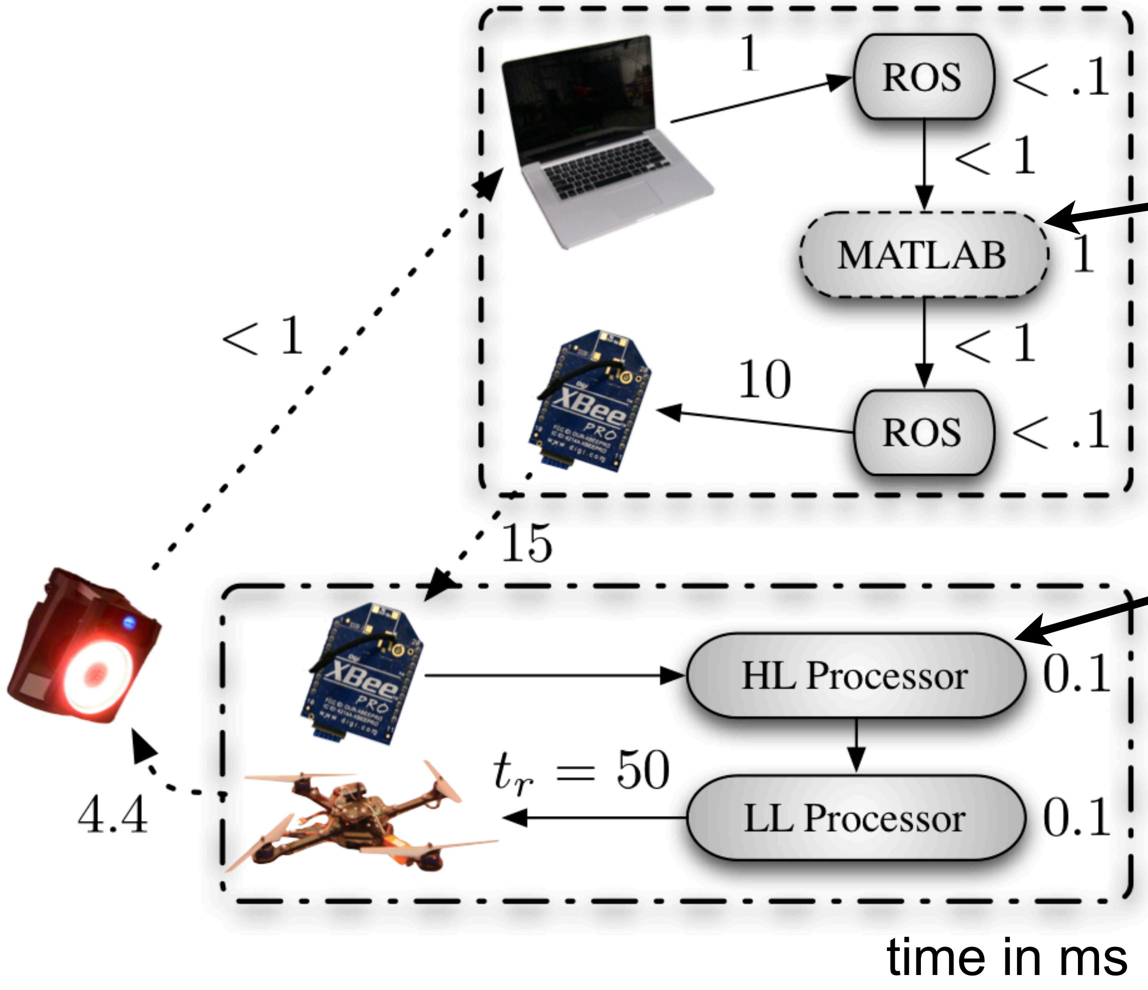


Vertical window



Implementation

Characterization of latencies:



Position and yaw control in Matlab (~100 Hz)

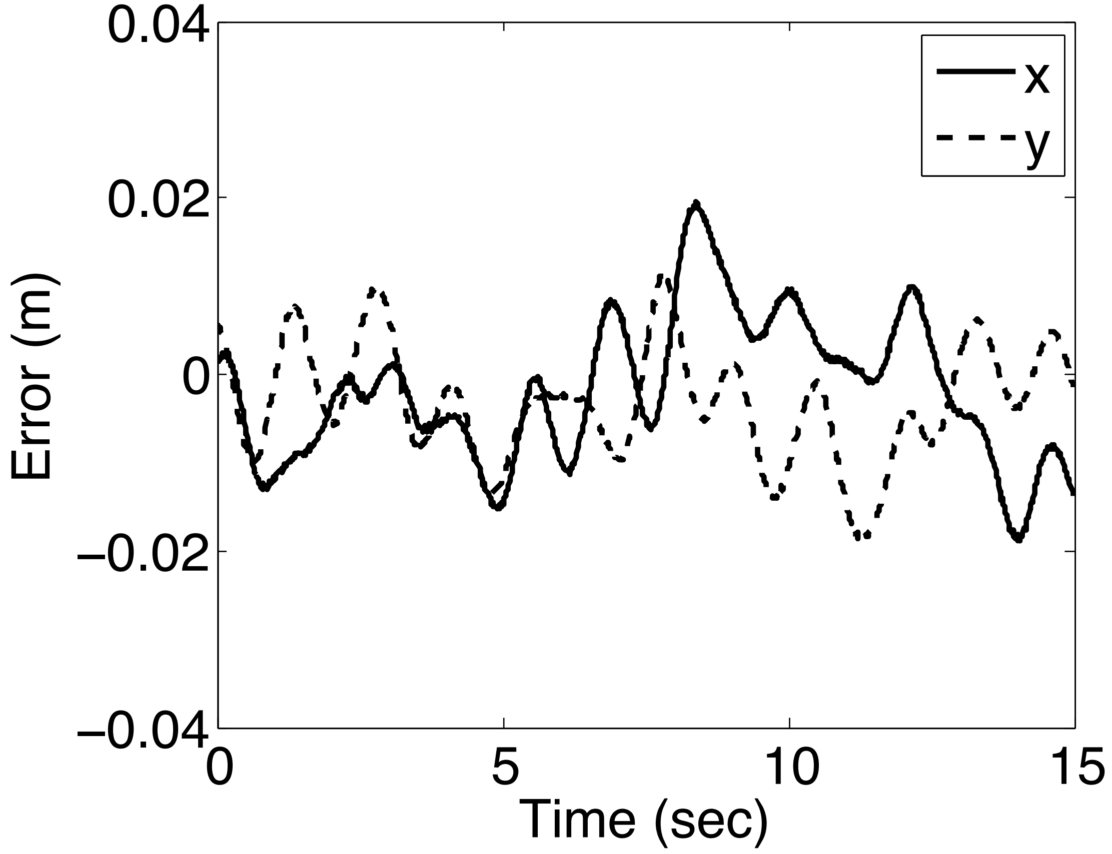
Attitude stabilization onboard (1 kHz)

Much of the source code is open-source:

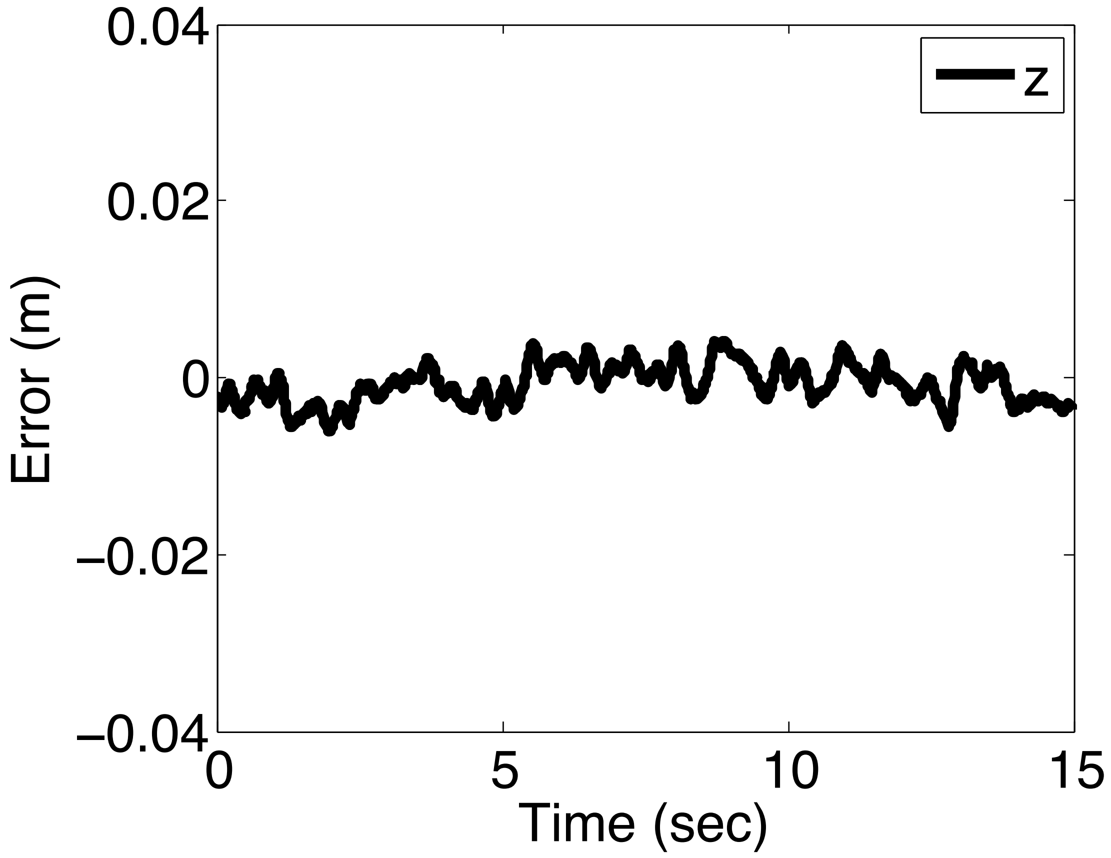
http://github.com/nmichael

Hover Accuracy

Error in X-Y



Error in Z

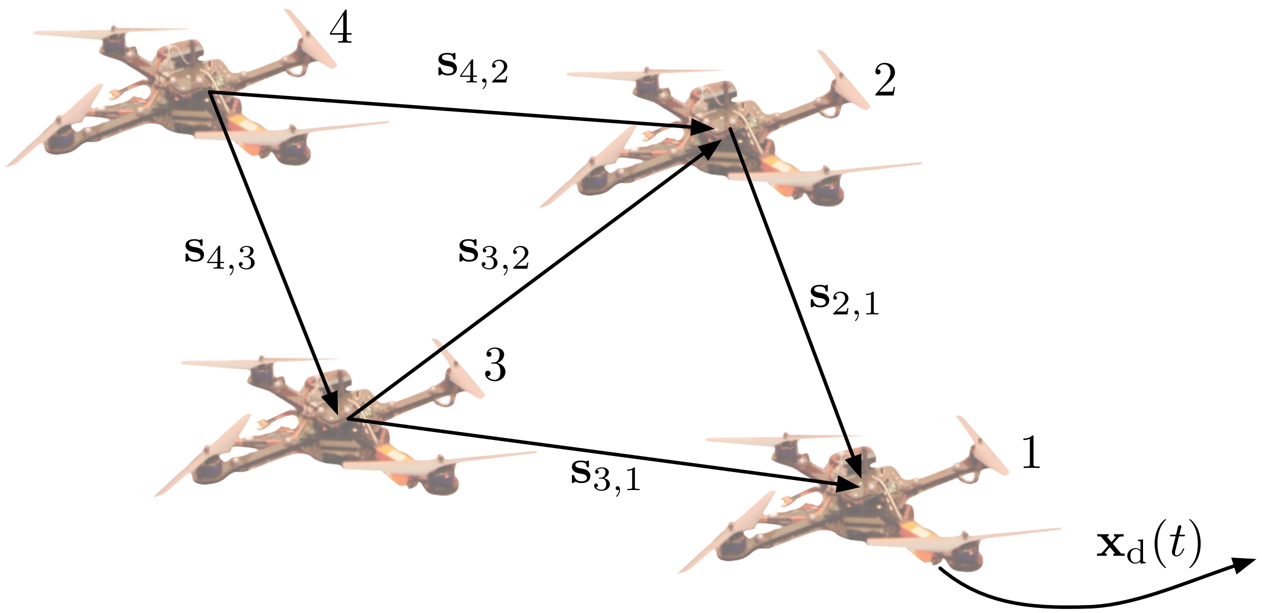


Outline

- Quadrotor model and control
    - Aggressive maneuvers
    - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
    - Autonomous exploration
    - Application study: cooperative air-ground mapping
- Future research challenges

M. Turpin, N. Michael, and V. Kumar. Trajectory design and control for aggressive formation flight with quadrotors. *Auton. Robots*, 33(1-2):143–156, Aug. 2012.

Formation Definition



Leader-follower approach

- Leader (possibly virtual) designs trajectories using previous methods
- Followers design trajectories based on neighbor states and desired formation shape vectors:

$$\mathbf{s}_{i,j} = \mathbf{x}_j - \mathbf{x}_i = \begin{bmatrix} x_j - x_i \\ y_j - y_i \\ z_j - z_i \\ \psi_j - \psi_i \end{bmatrix}$$

Defines desired relative positions and bearings

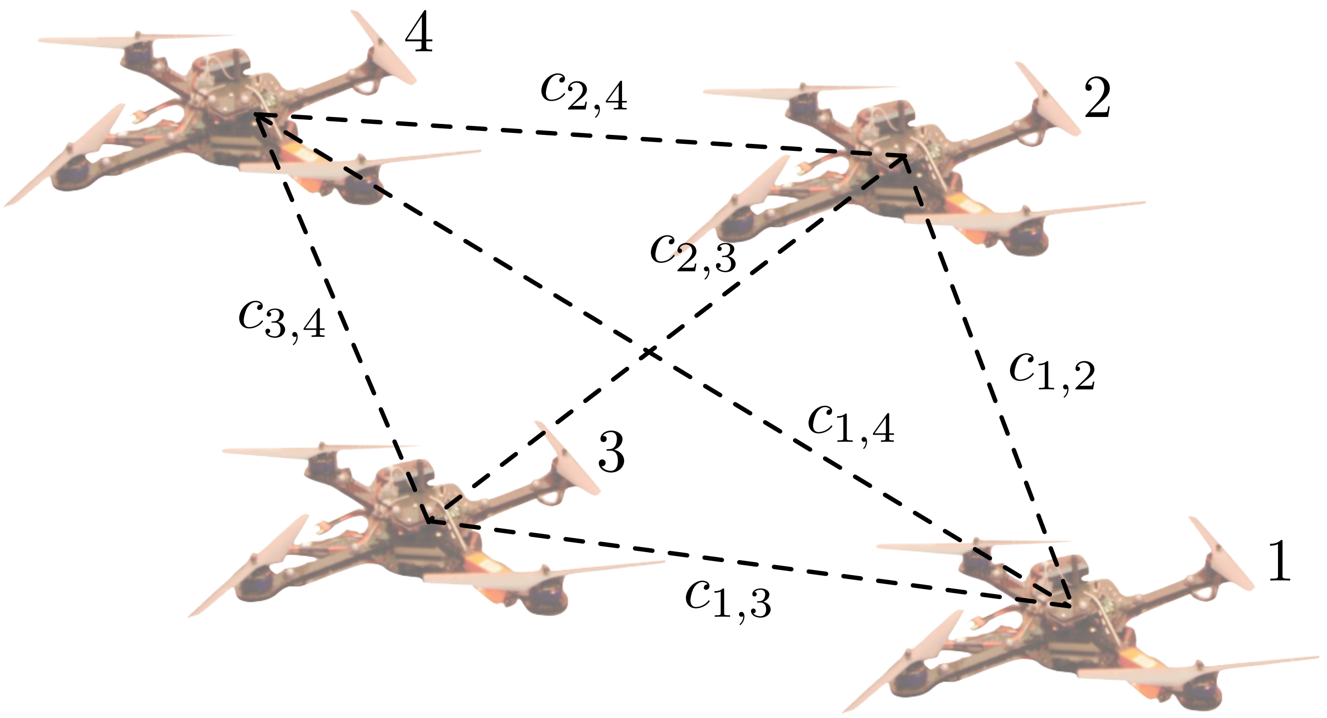
Capturing Communication and Perception

Define the confidence of robot i in the state estimate of robot j:

$$c_{i,j} \in \mathbb{R}$$

such that:

$$\sum_{j \in \mathcal{N}_i} c_{i,j} = 1 \quad \text{and} \quad c_{i,j} \geq 0$$



Define the desired state of each robot as:

$$\mathbf{x}_{i,\mathrm{d}} = \sum_{j \in \mathcal{N}_i} c_{i,j} \left(\mathbf{x}_j^i + \mathbf{s}_{i,j} \right)$$

Robot j state according to robot i

Formation Control

Define the error between the desired and current system state:

$$\mathbf{e}_i(t) = \sum_{j \in \mathcal{N}_i} c_{i,j}(\mathbf{x}_j(t) - \mathbf{x}_i(t) - \mathbf{s}_{i,j})$$

From the definition of piecewise-smooth polynomial trajectories:

$$\mathbf{e}_i(t) = \sum_{j=1}^{N} c_{i,j} \left(\sum_{k=1}^{n} \left(\alpha_j^k - \alpha_i^k \right) t^k - \mathbf{s}_{i,j} \right)$$

Wish to minimize this error across the time horizon:

$$\text{minimize} \quad \int_{t_c}^{t_h} \mathbf{e}_i(t)^{\mathrm{T}} \mathbf{e}_i(t) dt$$

Define the optimization program:

weighting factor

$$\text{minimize} \qquad \int_{t_c}^{t_h} \left[\mathbf{e}_i(t)^{\mathrm{T}} \mathbf{e}_i(t) + \sum_{j=1}^{k} \kappa_j \mathbf{e}_i^{(j)}(t)^{\mathrm{T}} \mathbf{e}_i^{(j)}(t) \right] dt$$

$$\text{subject to constraints on} \quad \mathbf{x}(t_c), \ldots, \mathbf{x}^{(k)}(t_c)$$

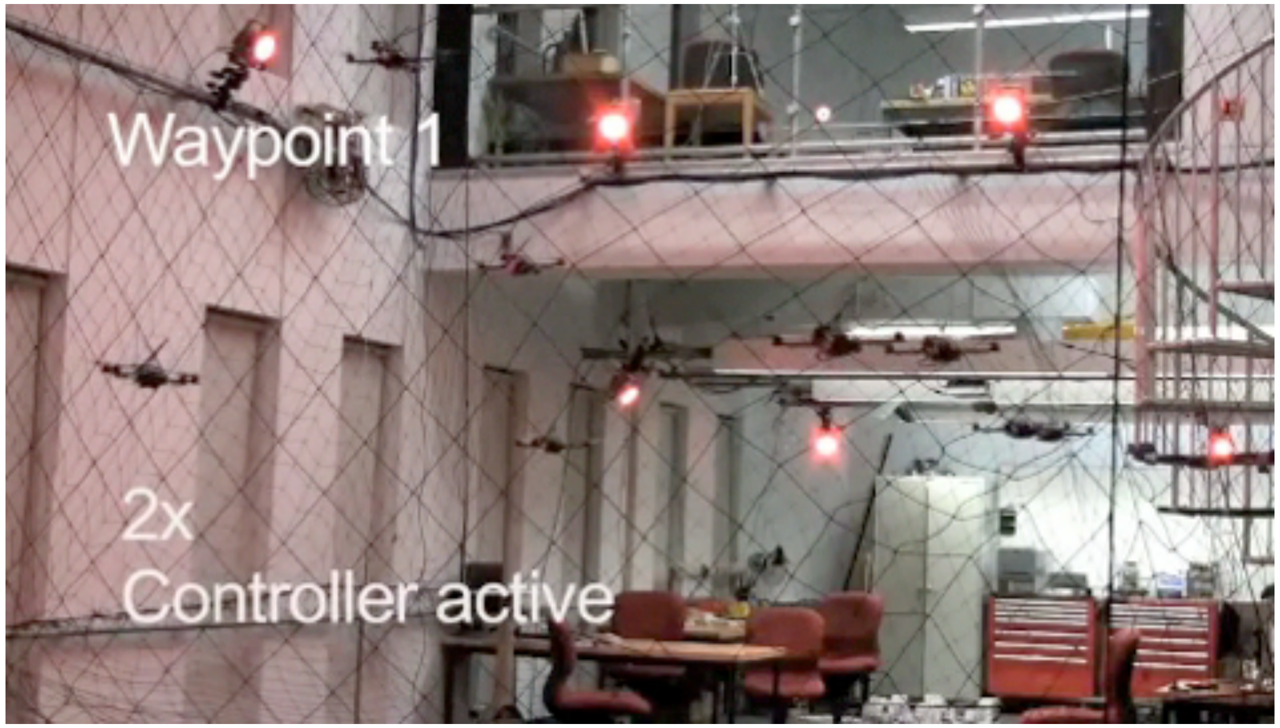
current time

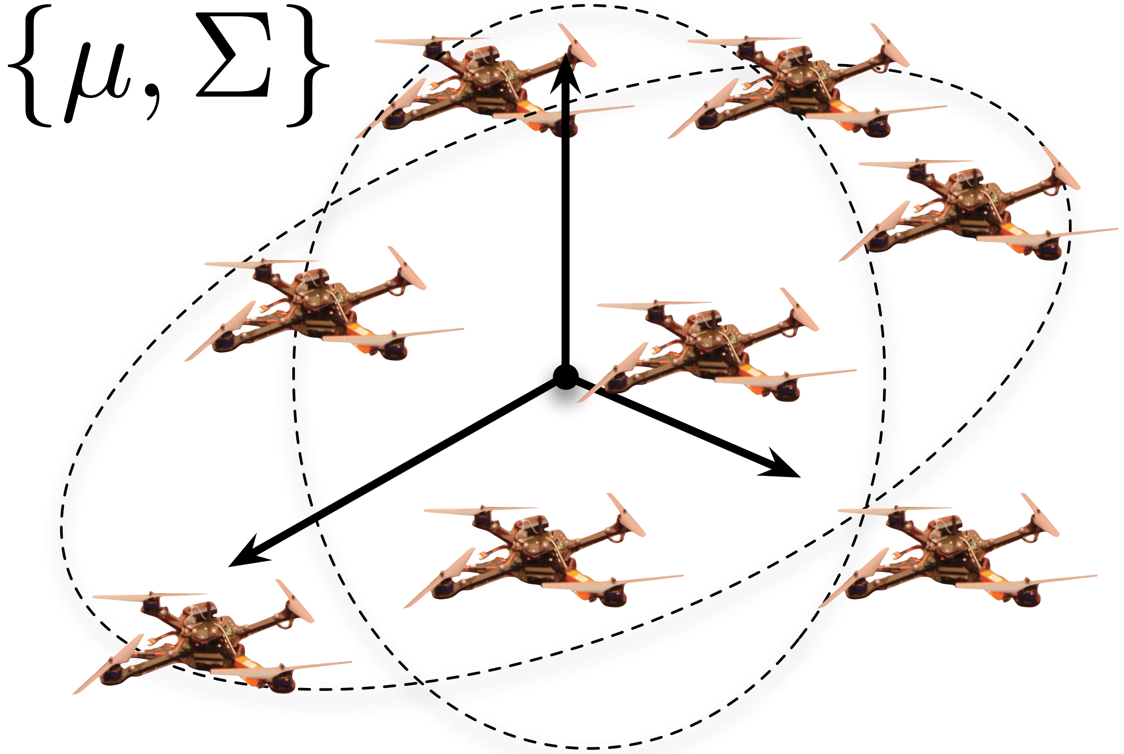
- Cast as QP and solve for local trajectory
- Solve in real-time based on neighboring robots’ trajectories and local knowledge
- Piecewise-smooth polynomial trajectory is analytic - access to derivatives

Controller is fully decentralized

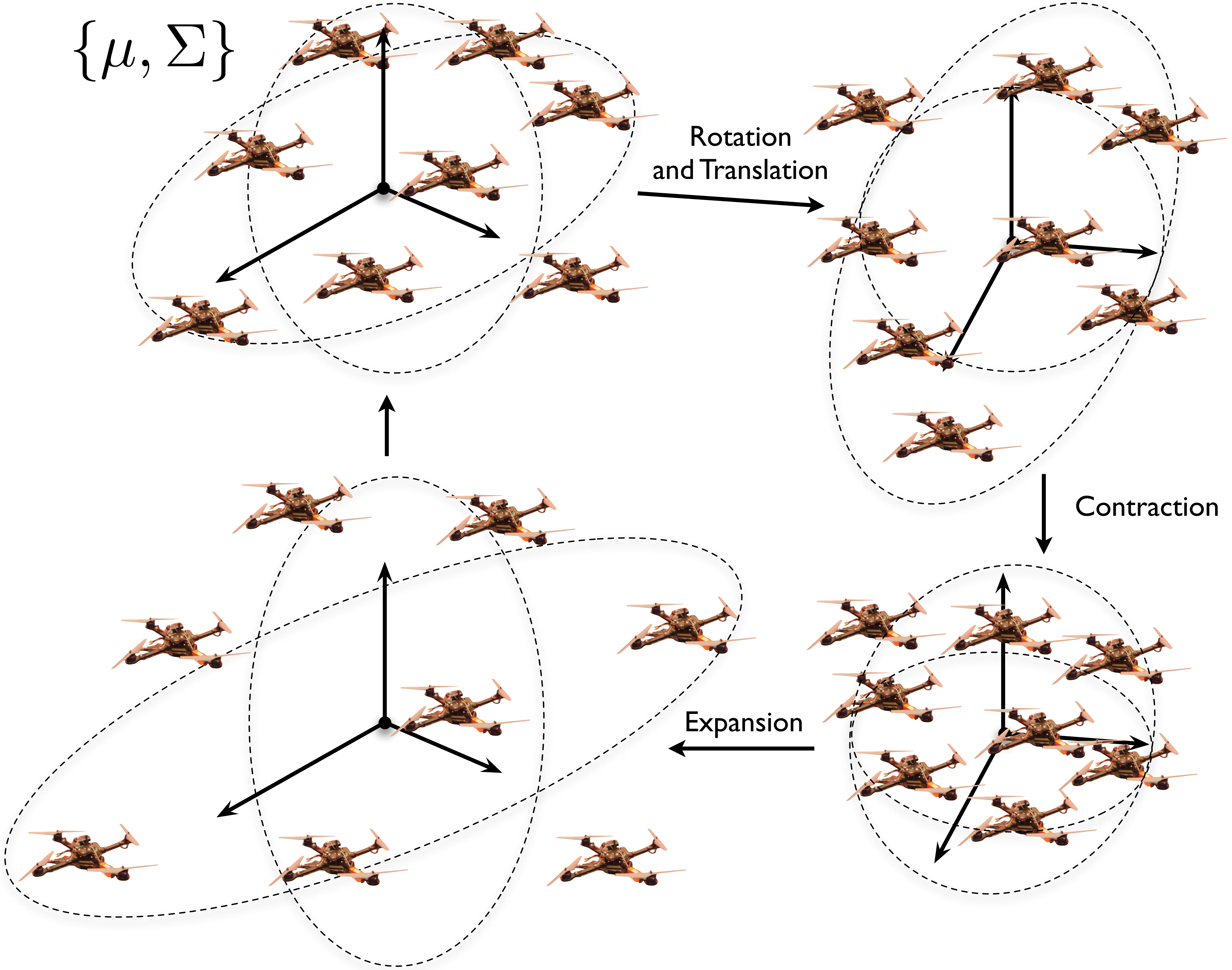
Additional Formation Definitions

Statistical models





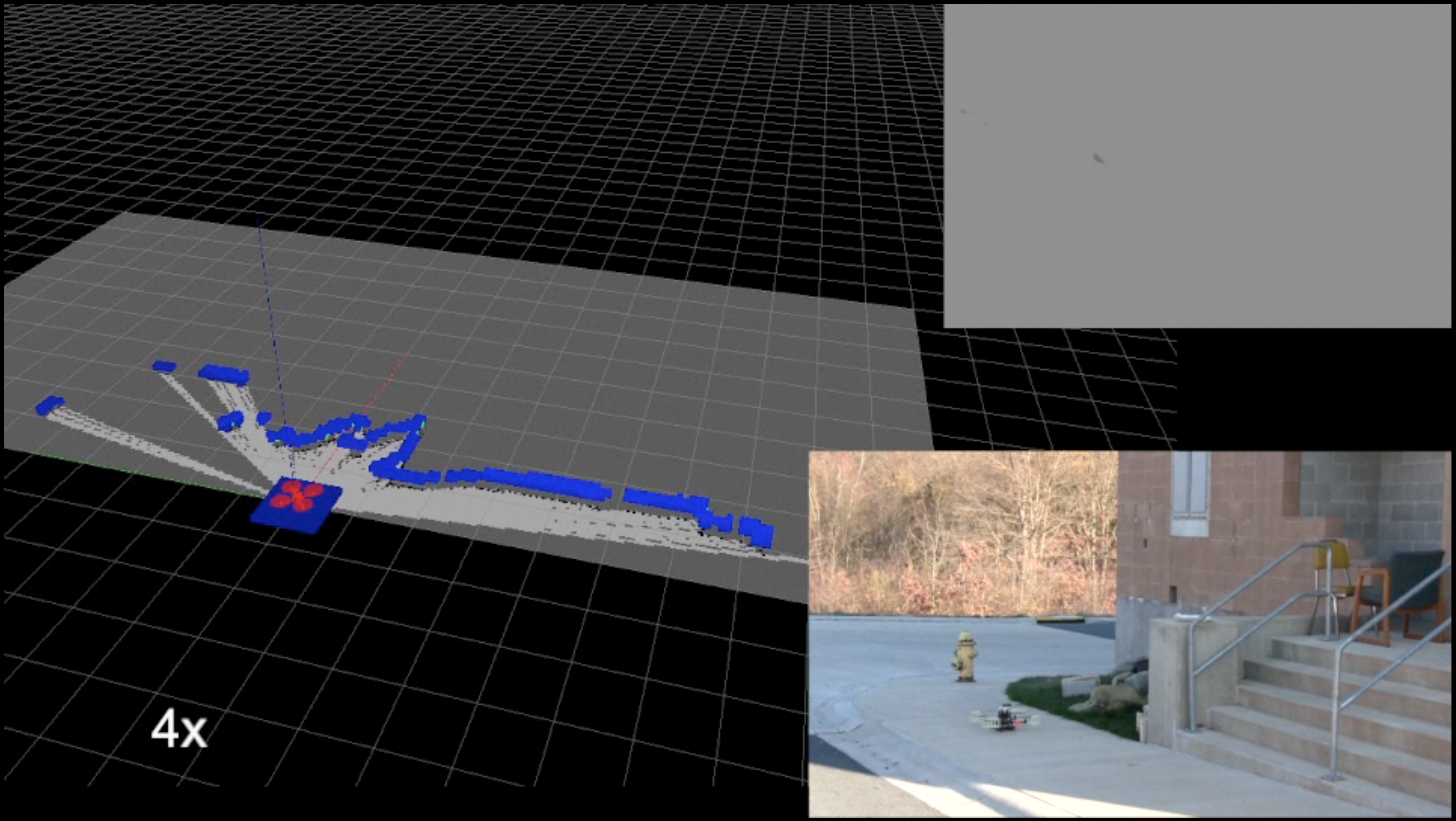
N. Michael and V. Kumar. Control of ensembles of aerial robots. *Proc. of the IEEE*, 99(9):1587–1602, Sept. 2011.


$\{\mu, \Sigma\}$
Rotation and Translation
Contraction
Expansion

L. C. A. Pimenta, G. A. S. Pereira, M. M. Goncalves, N. Michael, M. Turpin, and V. Kumar. Decentralized controllers for perimeter surveillance with aerial robots. *Adv. Robot.*, Sept. 2012. Submitted.

Outline

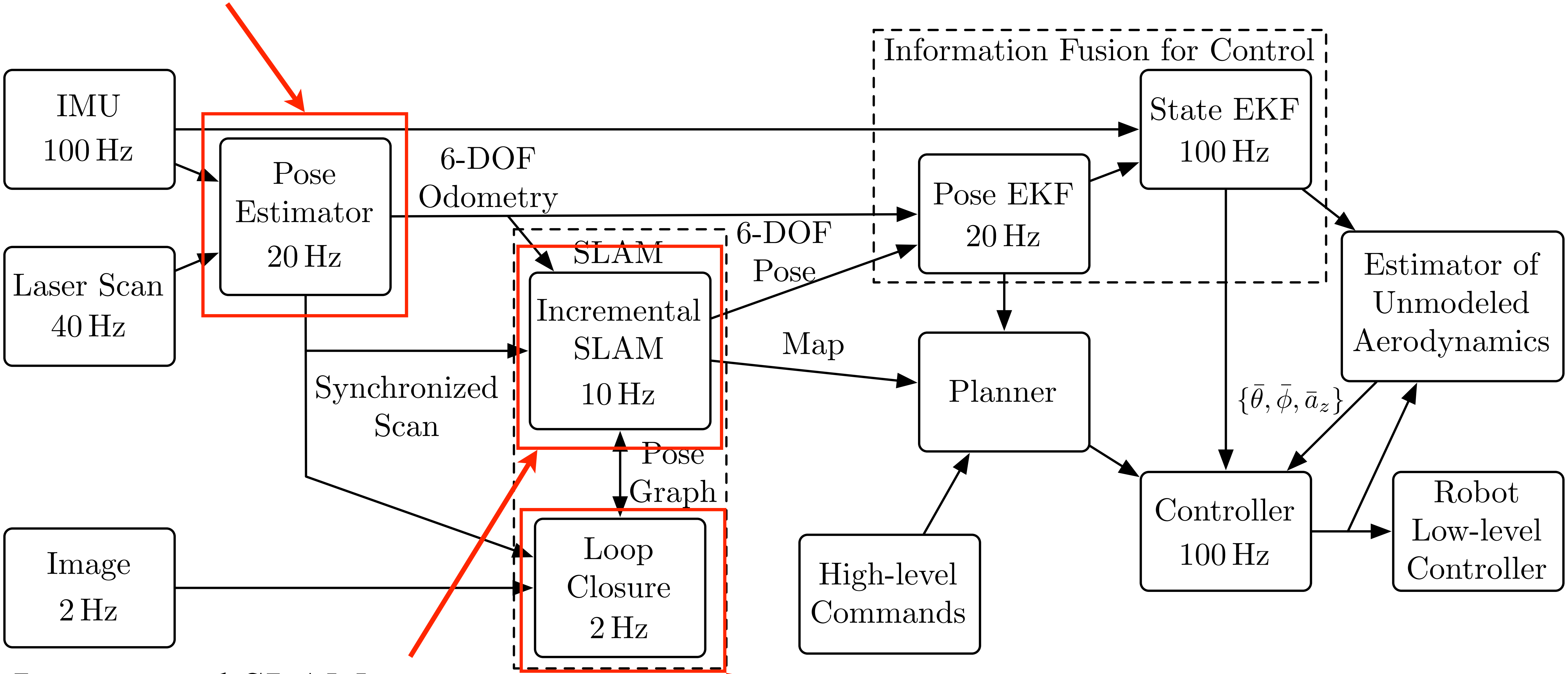
- Quadrotor model and control
    - Aggressive maneuvers
    - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
    - Autonomous exploration
    - Application study: cooperative air-ground mapping
- Future research challenges



S. Shen and N. Michael. Autonomous navigation in confined indoor environments with a micro-aerial vehicle. *IEEE Robot. Autom. Mag.*, Jan. 2012. Submitted.

Pose Estimate:

- Iterative closest point (laser) for 2D position, yaw
- IMU for roll, pitch
- IMU+laser for z altitude



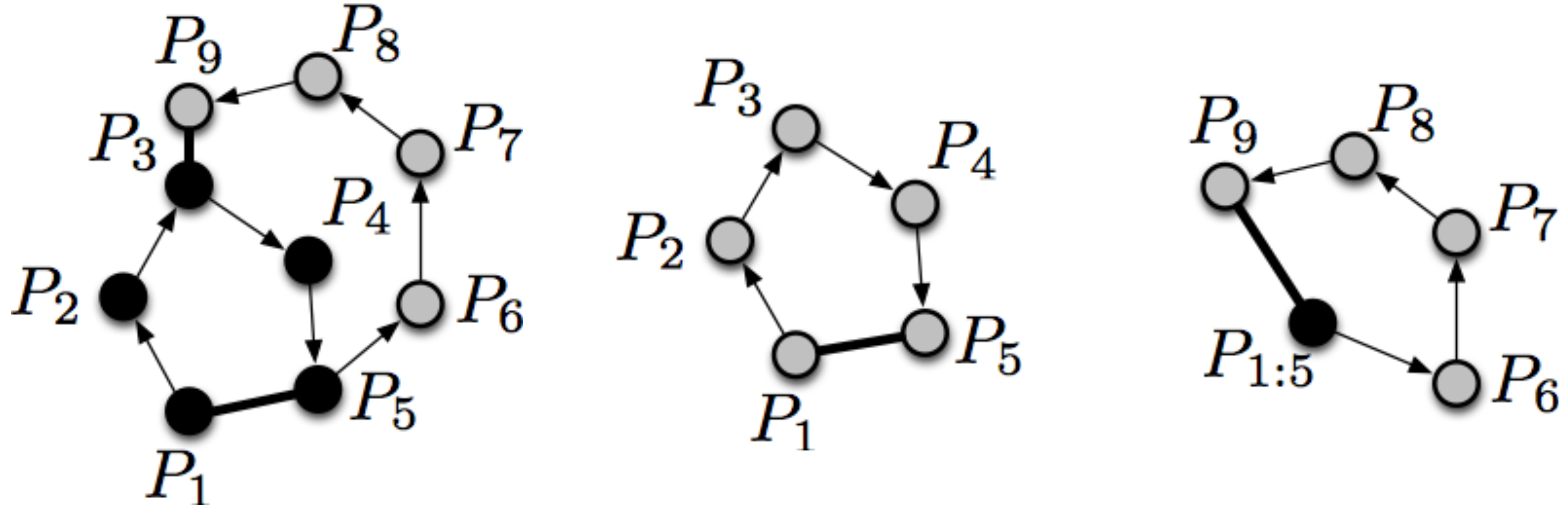
Incremental SLAM:

- Align incoming laser scans against the existing map
- Assumes 2.5D environment
- Detect stable floor transitions

Loop-Closure:

- Vision-based (SURF) features
- Bag-of-words methods
- Optimize pose graph using IEKF

Simplify graph by contracting closed loops to avoid repeated optimizations



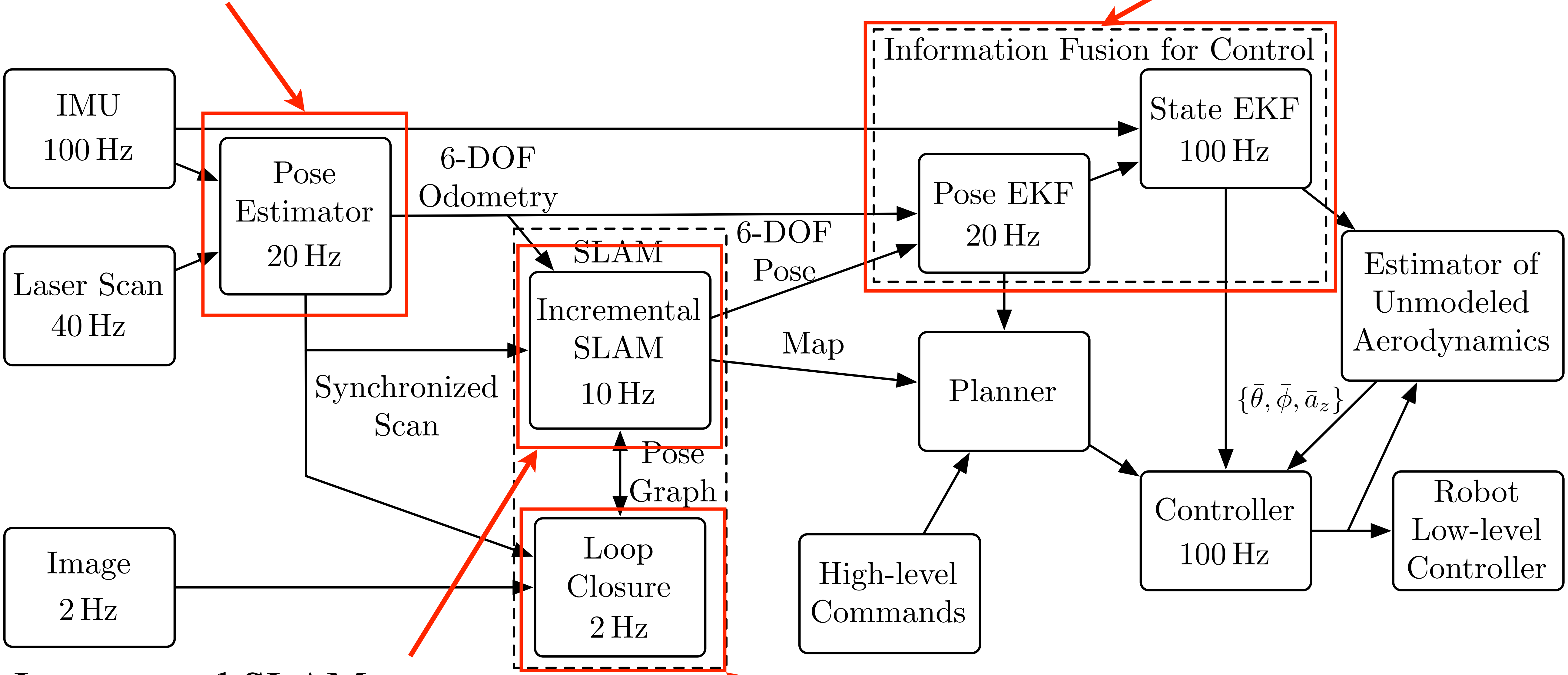
Does not improve accuracy of maps in previously traversed regions if already closed

Pose Estimate:

- Iterative closest point (laser) for 2D position, yaw
- IMU for roll, pitch
- IMU+laser for z altitude

Fusion for Control:

- Smooth delayed output from SLAM with more recent IMU/pose information
- Increase rate for feedback control

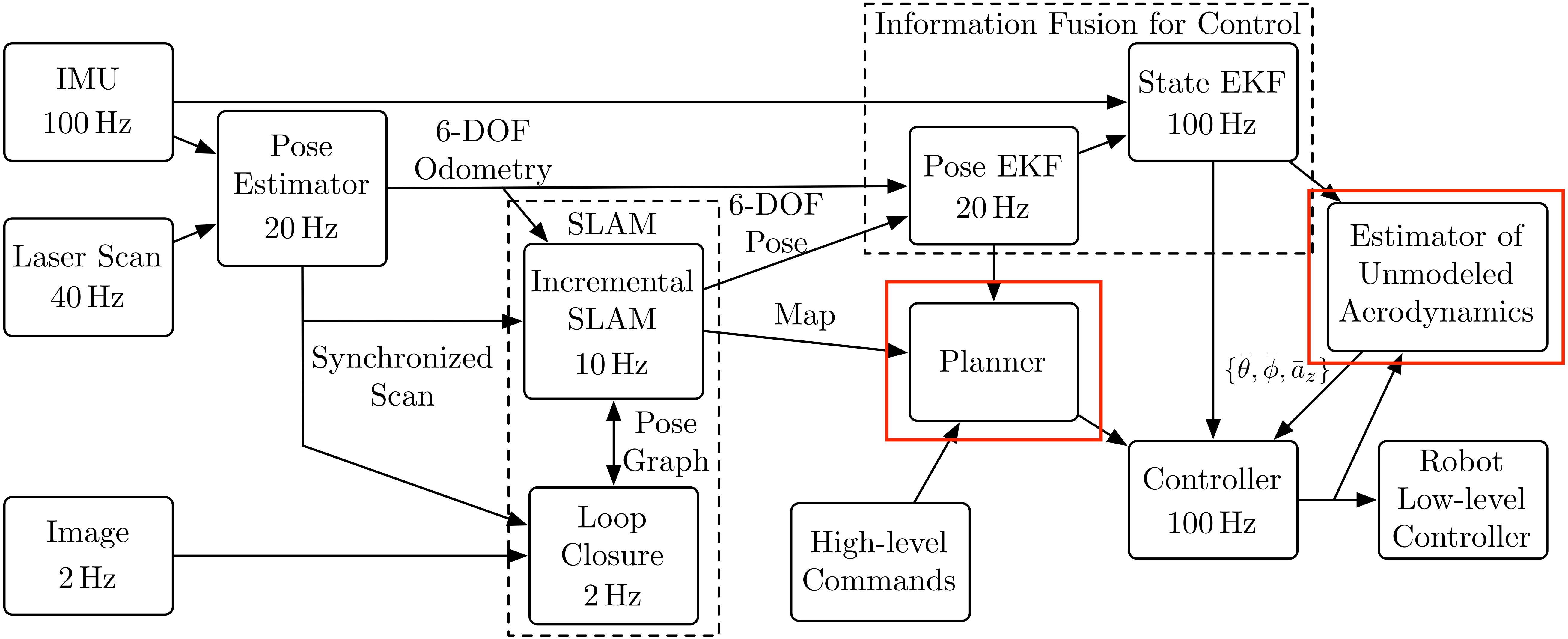


Incremental SLAM:

- Align incoming laser scans against the existing map
- Assumes 2.5D environment
- Detect stable floor transitions

Loop-Closure:

- Vision-based (SURF) features
- Bag-of-words methods
- Optimize pose graph using IEKF



Planner:

- Sampling-based methods (RRT)
- When RRT fails to find a solution (after timeout), system switches to A*
    - RRT typically fails when flying through closed or dense environments

Estimating Unmodeled Aerodynamic Effects and External Forces

IMU calibration and propeller model:

$$m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix} - \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$

Linearize and assume near hover:

Pitch offset

$$\begin{aligned} f_x/m &= g(\bar{\theta}\cos\psi + \bar{\phi}\sin\psi) \\ f_y/m &= g(\bar{\theta}\sin\psi - \bar{\phi}\cos\psi) \\ f_z/m &= \bar{a}_z \end{aligned}$$

Roll offset

Propeller model

Seek proportional term in model:

$$\text{Force from each prop} \longrightarrow f_i = \boxed{k_T}\,\omega_i^2 \longleftarrow \text{Prop speed (RPM)}$$

Estimating Unmodeled Aerodynamic Effects and External Forces

IMU calibration and propeller model:

$$m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix} - \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$

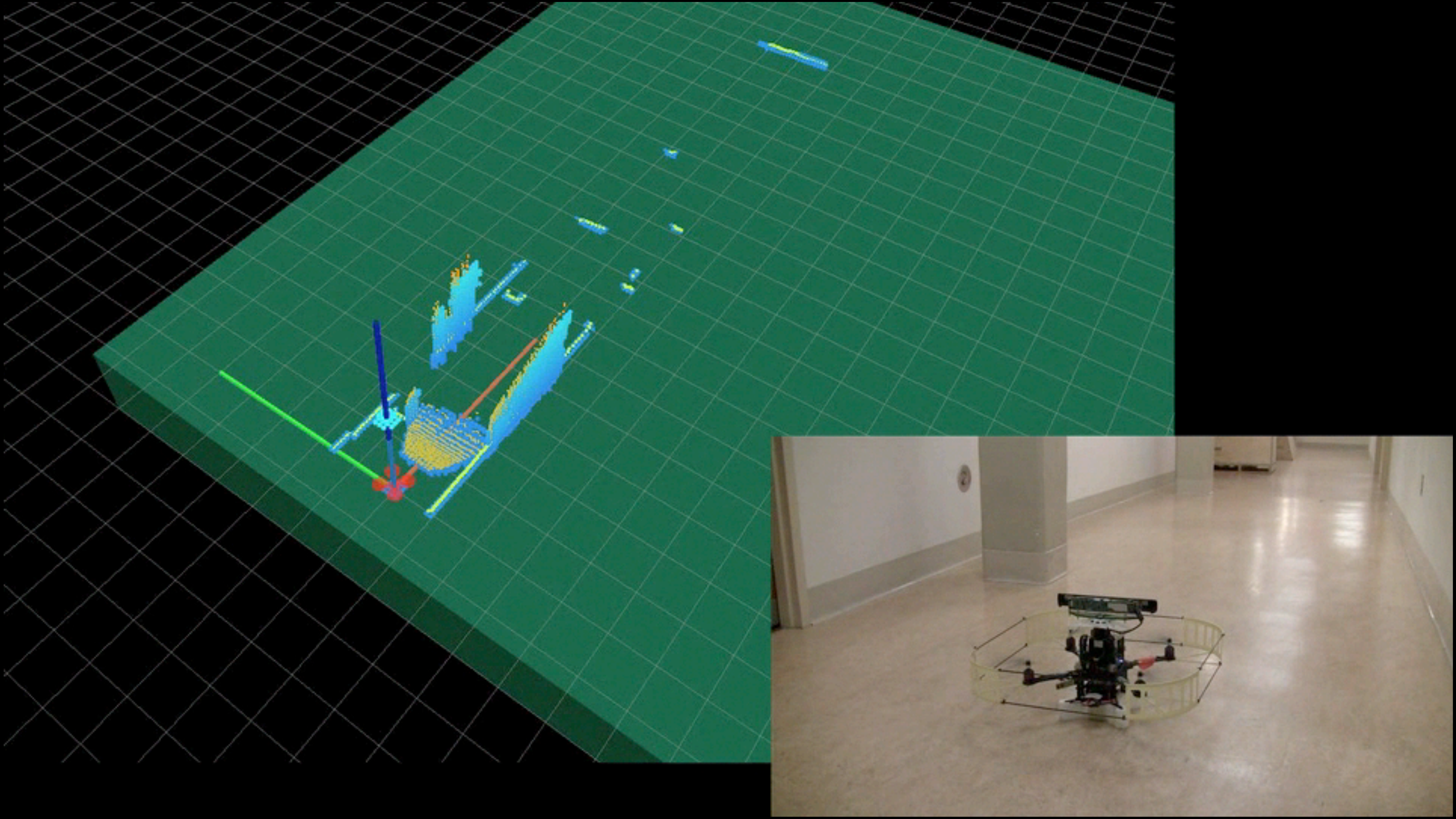
After establishing calibration and system parameters, run the estimator on the external force directly

Remarks:

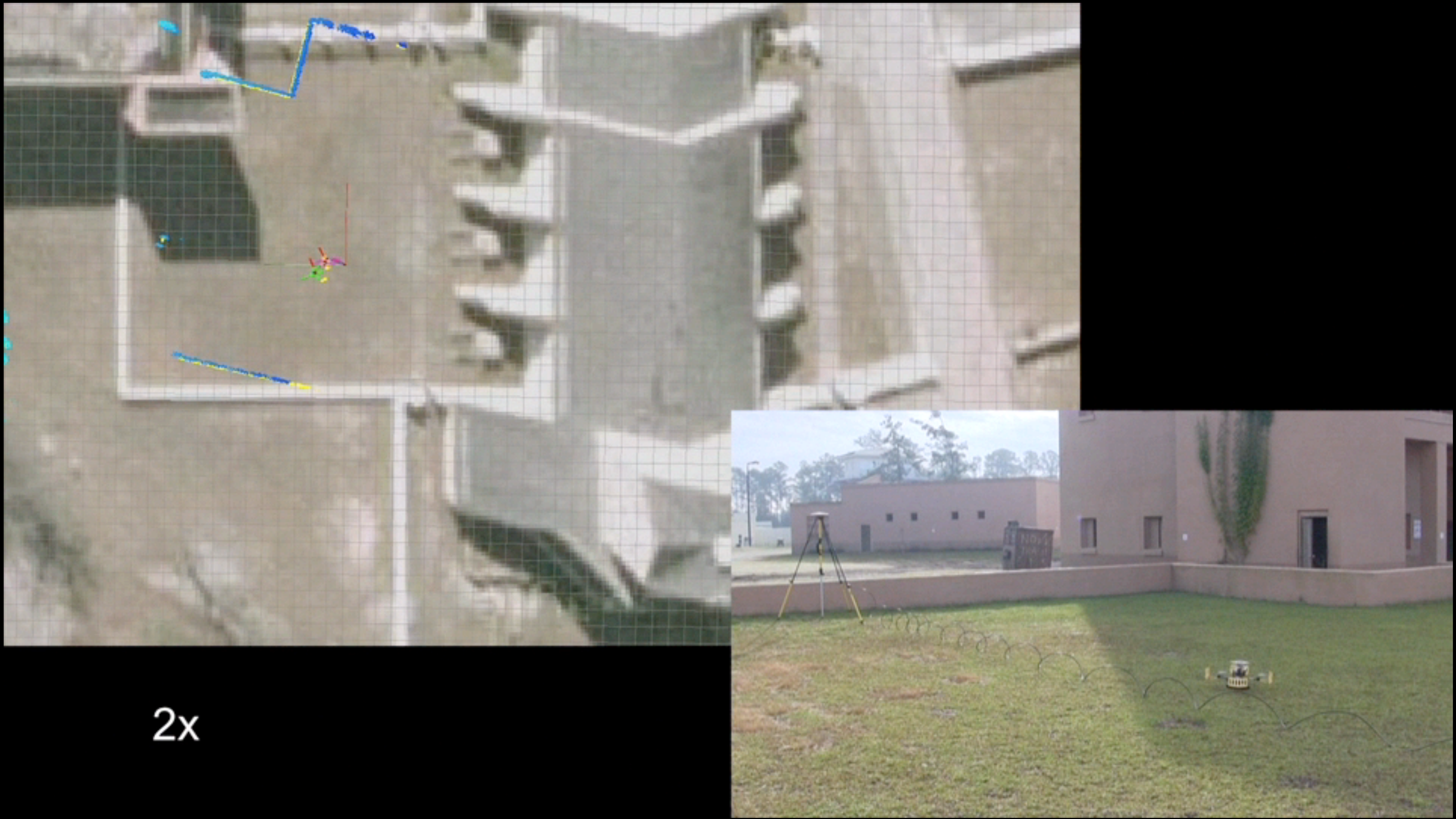
- IMU parameters are generally consistent on the same platform but differ between platforms
- Force model changes between runs due to propeller wear and tear
- Online calibration and force compensation is required for flight in confined spaces

Outline

- Quadrotor model and control
  - Aggressive maneuvers
  - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
  - Autonomous exploration
  - Application study: cooperative air-ground mapping
- Future research challenges



S. Shen, N. Michael, and V. Kumar. Autonomous indoor 3D exploration with a micro-aerial vehicle. In *Proc. of the IEEE Intl. Conf. on Robot. and Autom.*, pages 9-15, Saint Paul, MN, May 2012.

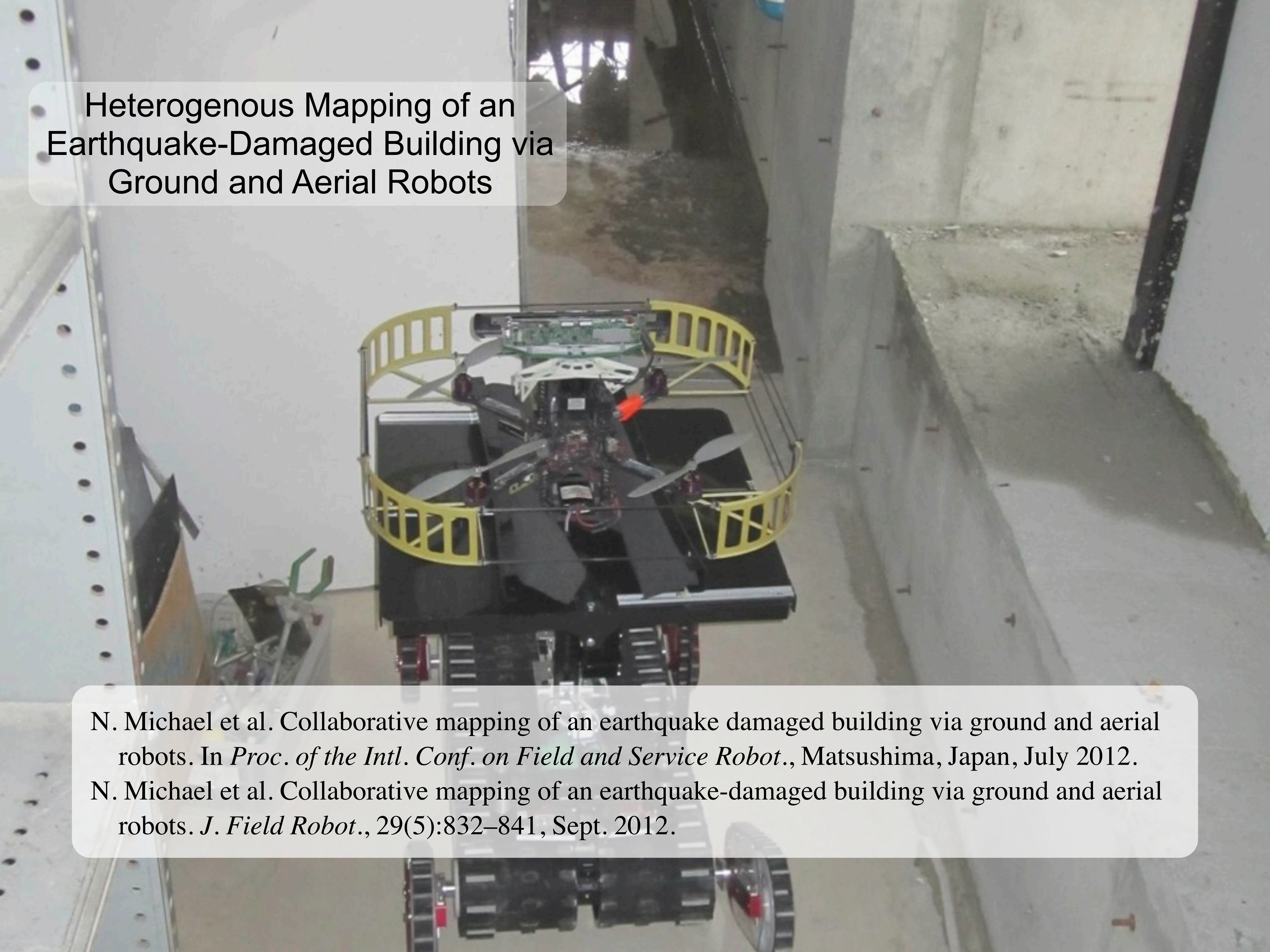


S. Shen and N. Michael. State estimation for indoor and outdoor operation with a micro-aerial vehicle. In *Proc. of the Intl. Sym. on Exp. Robot.*, Quebec City, Canada, June 2012.

Outline

- Quadrotor model and control
  - Aggressive maneuvers
  - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
  - Autonomous exploration
  - Application study: cooperative air-ground mapping
- Future research challenges

Heterogenous Mapping of an Earthquake-Damaged Building via Ground and Aerial Robots



N. Michael et al. Collaborative mapping of an earthquake damaged building via ground and aerial robots. In *Proc. of the Intl. Conf. on Field and Service Robot.*, Matsushima, Japan, July 2012.

N. Michael et al. Collaborative mapping of an earthquake-damaged building via ground and aerial robots. *J. Field Robot.*, 29(5):832–841, Sept. 2012.

Goals

- Construct maps of an earthquake-damaged building
- Leverage distinct ground and aerial robot capabilities
- Allow a remote human operator to directly interact with the robots
- Use autonomy to enable safe operation and reduce burden on operator

Location and Dates

Tohoku University
Sendai, Japan
July 29 - Aug. 1


HITACHI SUMITOMO

Not pictured: Prof. K. Yoshida, Prof. E. Takeuchi, Y. Okada, S. Kiribayashi, K. Otake

Prof. Vijay Kumar

Prof. Satoshi Tadokoro

Kartik Mohta

Shaojie Shen

Prof. Keiji Nagatani

Prof. Kazunori Ohno

Capability Comparison

Ground Robots

- Increased payload capacity:
  - Long mission durations
  - Can carry sensing, computation, and additional payload
  - Statically stable and able to support tethered communication
- Limited by terrain traversability

Aerial Robot

- Decreased payload capacity:
  - Short mission durations
  - Limited onboard sensing and computation
  - Stable flight requires closed-loop feedback control
- Maneuverable in 3D

Experiment Design

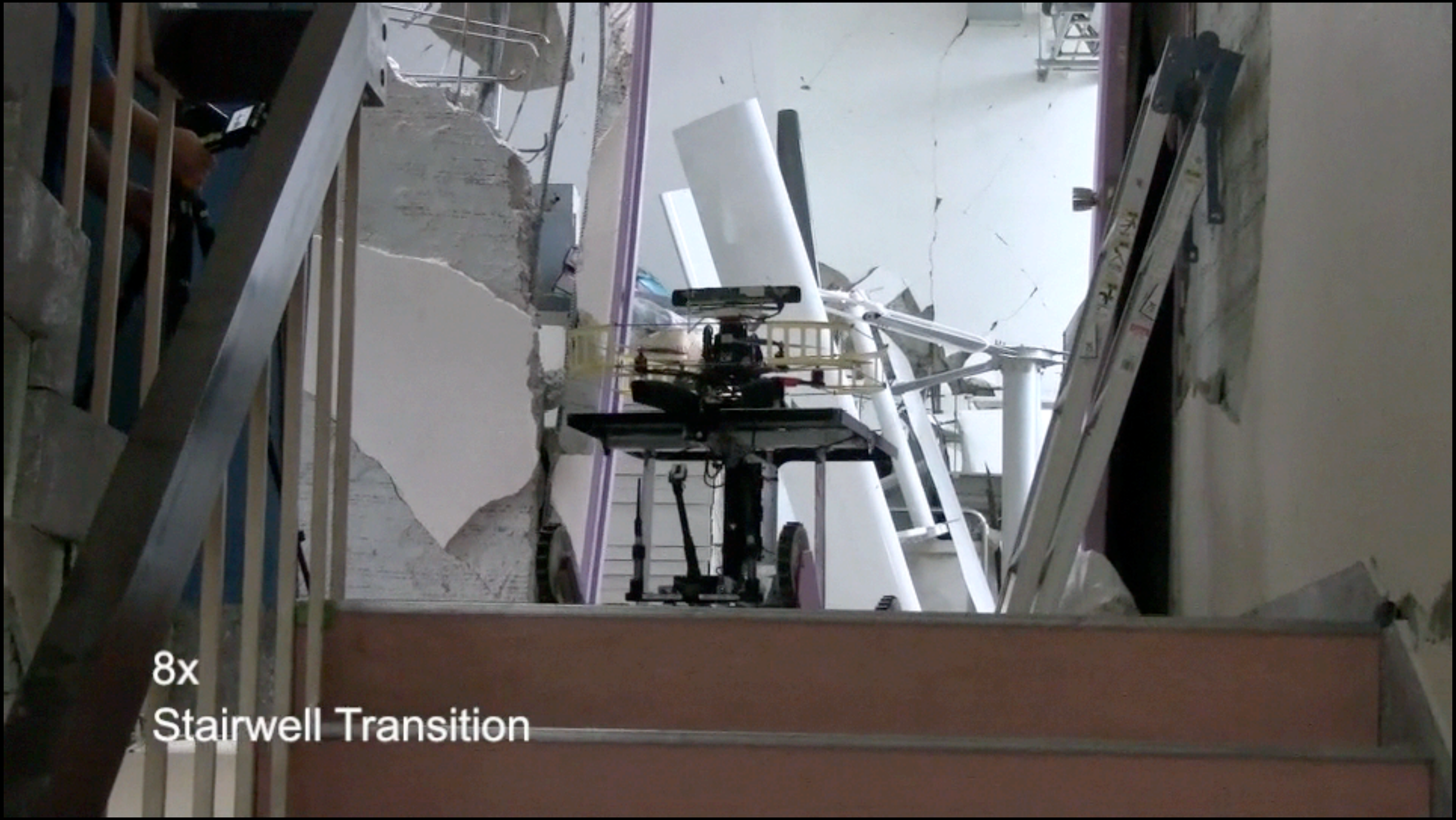
Phase 1:

Deploy a tele-operated ground robot (Kenaf) equipped with an onboard 3D laser scanner to generate a 3D map of the environment and identify locations inaccessible to the ground robot

Phase 2:

- Deploy a tele-operated ground robot (Quince) that carries an aerial robot (Pelican) to the inaccessible regions to complete the map
- Aerial robot autonomously takes-off and lands on an automated landing pad

Phase 1



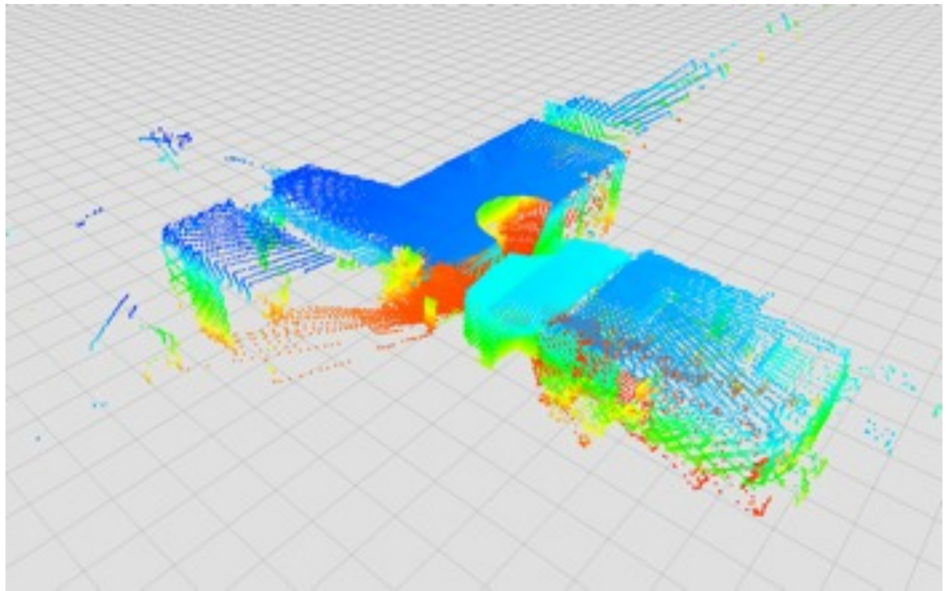
Phase 2

Robot Platforms

Kenaf

- Tracked ground platform
- Onboard sensing:
  - Rotating/panning laser scanner
    - 40 Hz scan with a 0.2 Hz cycle time
  - Odometry
  - IMU

Resulting body-frame registered
3D point cloud



Robot Platforms

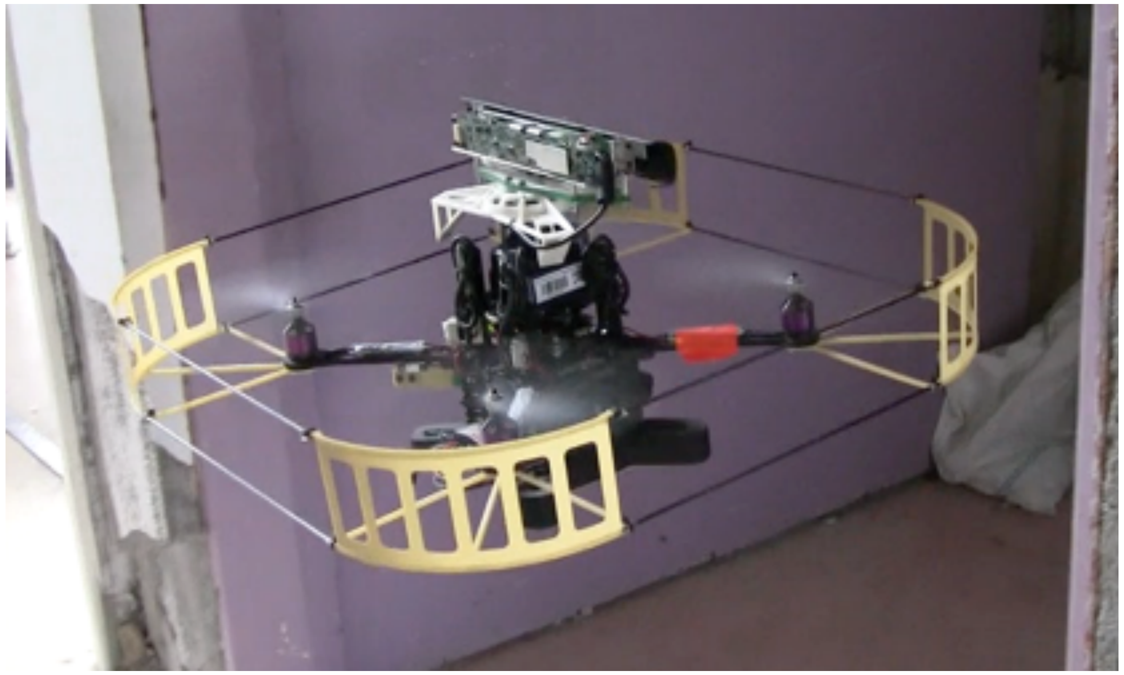
Quince

- Tracked ground platform
- Provides odometry information
- Equipped with aerial robot landing pad

Landing pad secures the aerial robot during the traversal of hallways and stairwells

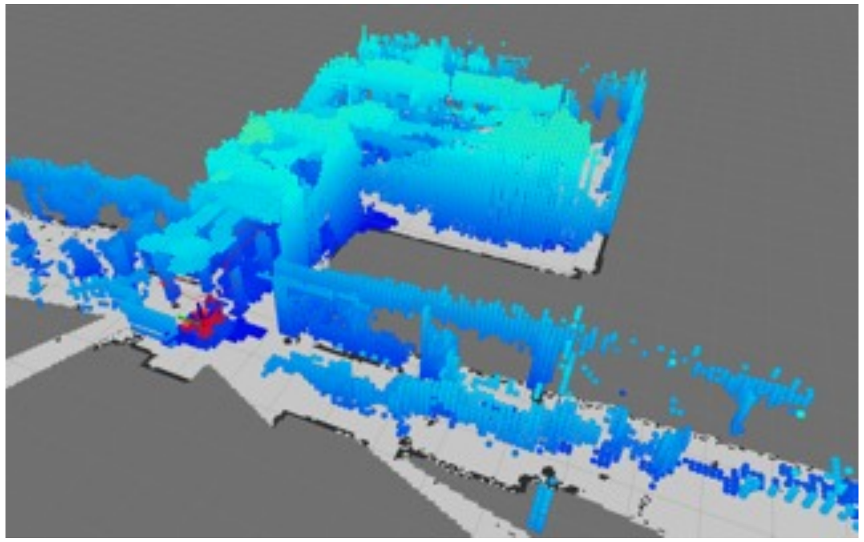
Robot Platforms

Pelican



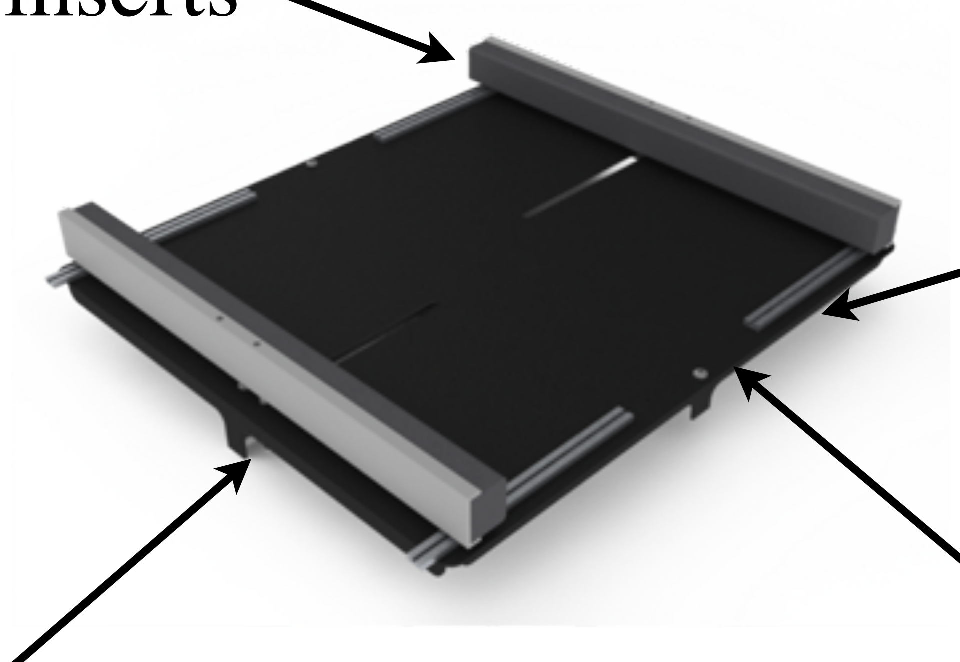
- Quadrotor platform
- Onboard sensing:
  - Laser
  - IMU
  - Kinect
- Limited onboard processing

Vehicle generates 3D voxel-grid based map of the environment; localizes, plans, and controls with respect to the map



Robot Platforms

Quince/Pelican Landing Pad



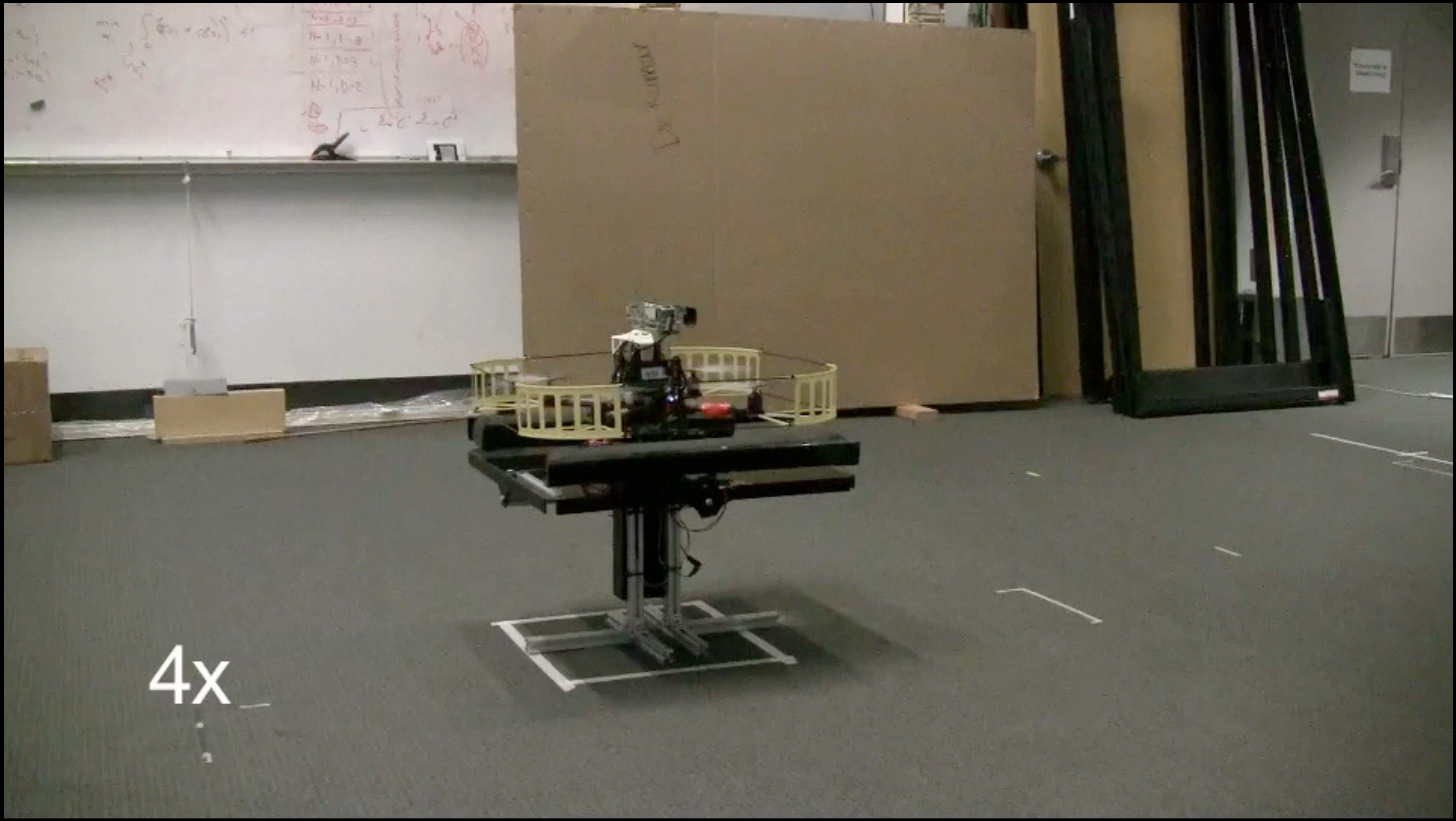
Dense foam inserts

Guidance rails

ABS plastic

Linear actuator with serial interface

Designed by Yash Mulgaonkar (Univ. of Penn.)


4x

Methodology

This work builds upon several previous results:

K. Nagatani, Y. Okada, N. Tokunaga, S. Kiribayashi, K. Yoshida, K. Ohno, E. Takeuchi, S. Tadokoro, H. Akiyama, I. Noda, T. Yoshida, and E. Koyanagi. Multirobot exploration for search and rescue missions: A report on map building in RoboCupRescue 2009. *J. Field Robot.*, 28(3):373–387, May 2011.

K. Nagatani, N. Tokunaga, Y. Okada, and K. Yoshida. Continuous acquisition of three-dimensional environment information for tracked vehicles on uneven terrain. In *Proc. of the IEEE Intl. Workshop on Safety, Security, and Rescue Robot.*, Sendai, Japan, Oct. 2008.

K. Ohno, S. Tadokoro, K. Nagatani, E. Koyanagi, and T. Yoshida. 3-D mapping of an underground mall using a tracked vehicle with four sub-tracks. In *IEEE Intl. Workshop on Safety, Security, and Rescue Robotics*, Denver, Colorado, Nov. 2009.

K. Ohno, S. Tadokoro, K. Nagatani, E. Koyanagi, and T. Yoshida. Trials of 3-D map construction using the tele-operated tracked vehicle Kenaf at Disaster City. In *Proc. of the IEEE Intl. Conf. on Robot. and Autom.*, pages 2864–2870, Anchorage, AK, May 2010.

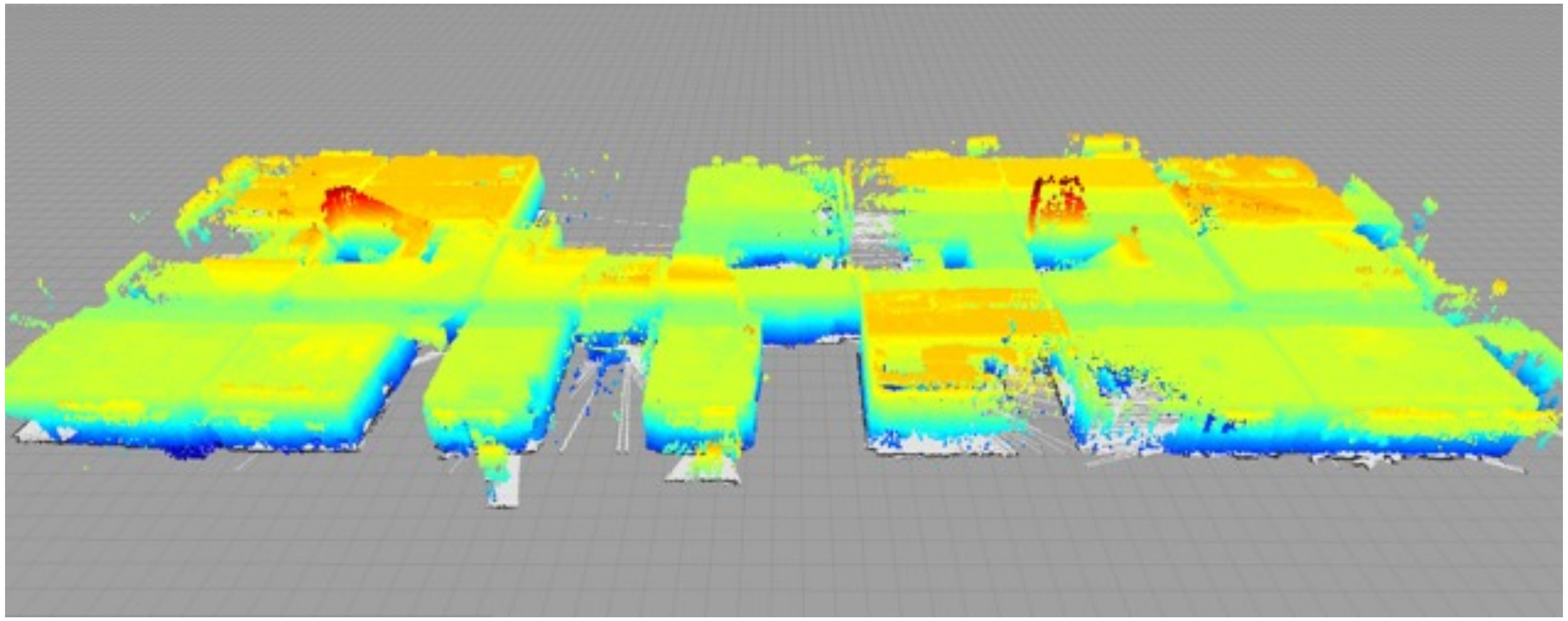
E. Rohmer, T. Yoshida, K. Ohno, K. Nagatani, S. Tadokoro, and E. Koyanagi. Quince: A collaborative mobile robotic platform for rescue robots research and development. In *Intl. Conf. on Adv. Mechatronics*, pages 225–230, Osaka, Japan, Oct. 2010.

S. Shen, N. Michael, and V. Kumar. Autonomous multi-floor indoor navigation with a computationally constrained MAV. In *Proc. of the IEEE Intl. Conf. on Robot. and Autom.*, pages 20–25, Shanghai, China, May 2011.

Methodology

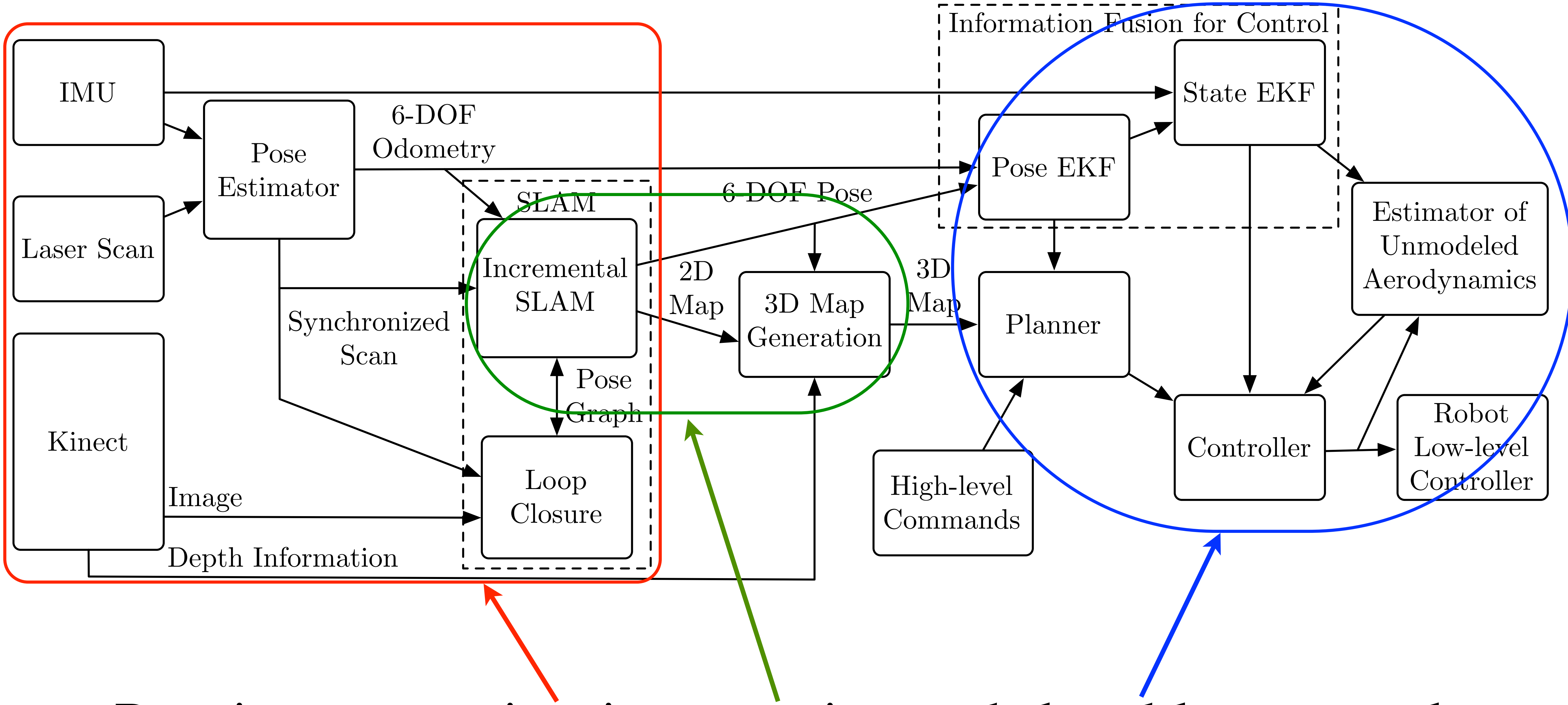
Kenaf

- Compute local incremental motion observed by 3D laser data via ICP
  - 3D ICP can converge to poor alignment solutions
    - On level terrain: ICP is based on 2D (fixed height) observations
    - On mixed terrain: Full 3D ICP
- Orientation error corrected based on IMU observations
- Graph-based SLAM formulation with consistency optimization



Methodology

Pelican



Requires state estimation, mapping, and closed-loop control

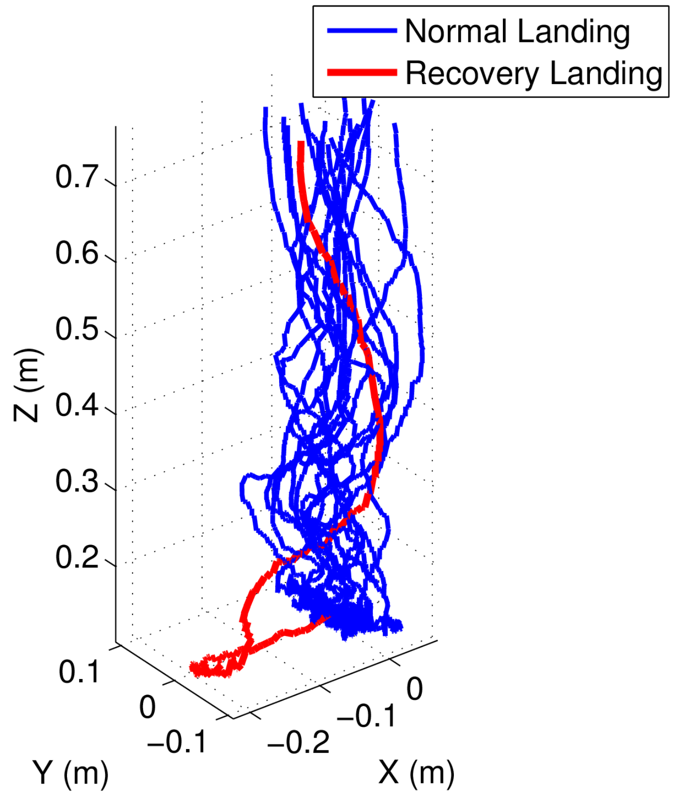
Methodology

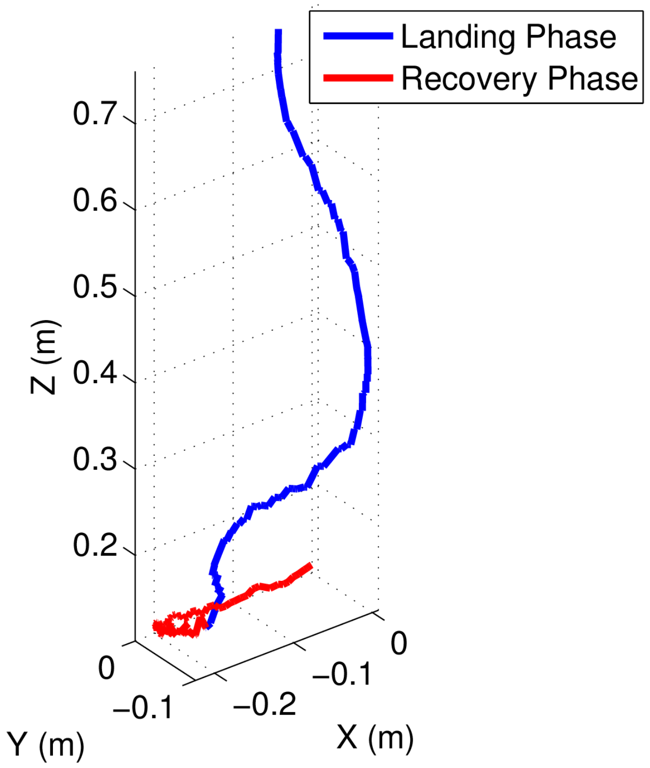
Autonomous Landing and Takeoff

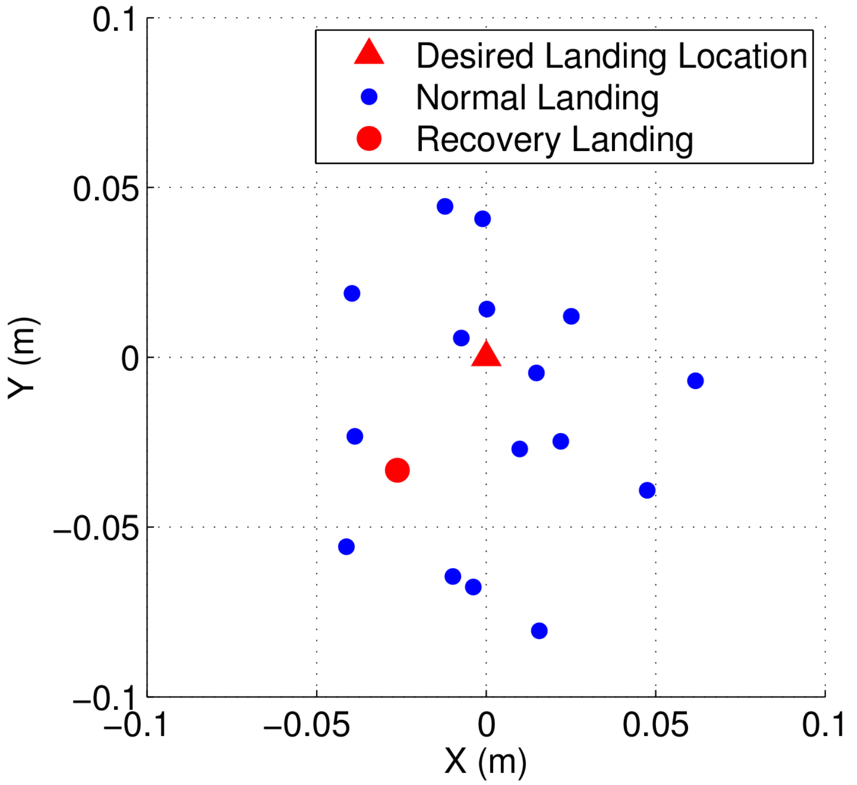
- Operator requests takeoff
  - Pelican and landing pad communicates via 802.15.4
  - Vehicle navigates to a fixed height above the landing pad
- Operator requests landing
  - Pelican navigates to above the starting position (open-loop)
  - Attempts to land, detects success or failure, and recovers if necessary

Methodology

Autonomous Landing and Takeoff







Performance repeatability

Methodology

Operator Input

- Kenaf and Quince robots are tele-operated
- Pelican responds to two types of input:
  - Point-model velocity control (position and heading)
  - Waypoint control where operator clicks on points in the map and vehicle plans and controls to the location

Implementation Notes

Tethered communication is possible

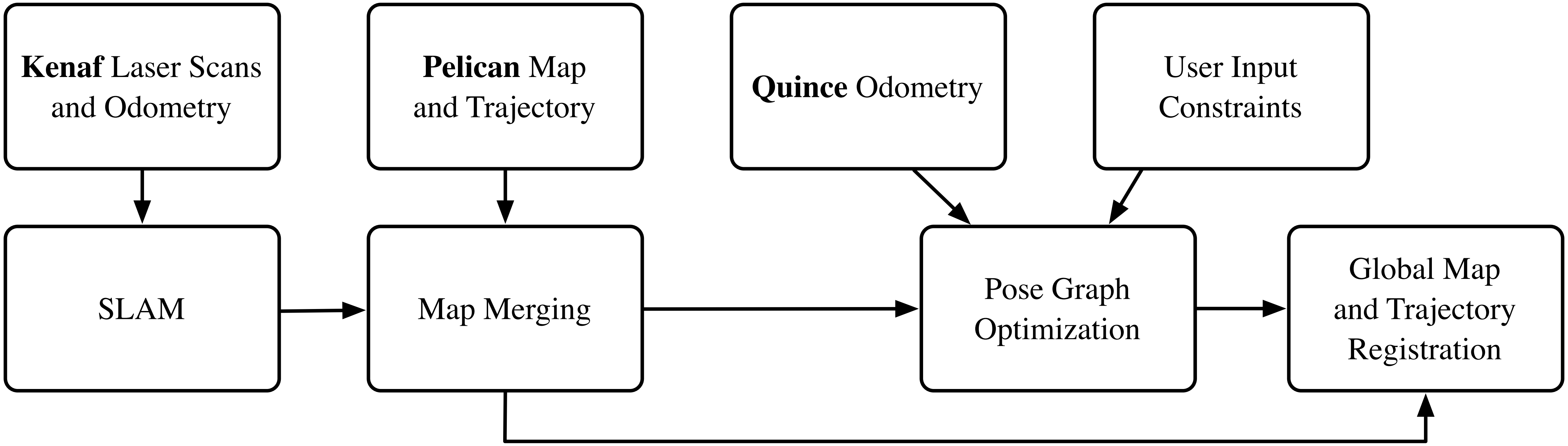
- Kenaf maps are generated off-line
- Kenaf and Quince communicate with operator via 802.11
- Pelican communicates with operator via 802.11 (with AP on Quince)
- Pelican batteries are manually replaced during experimentation

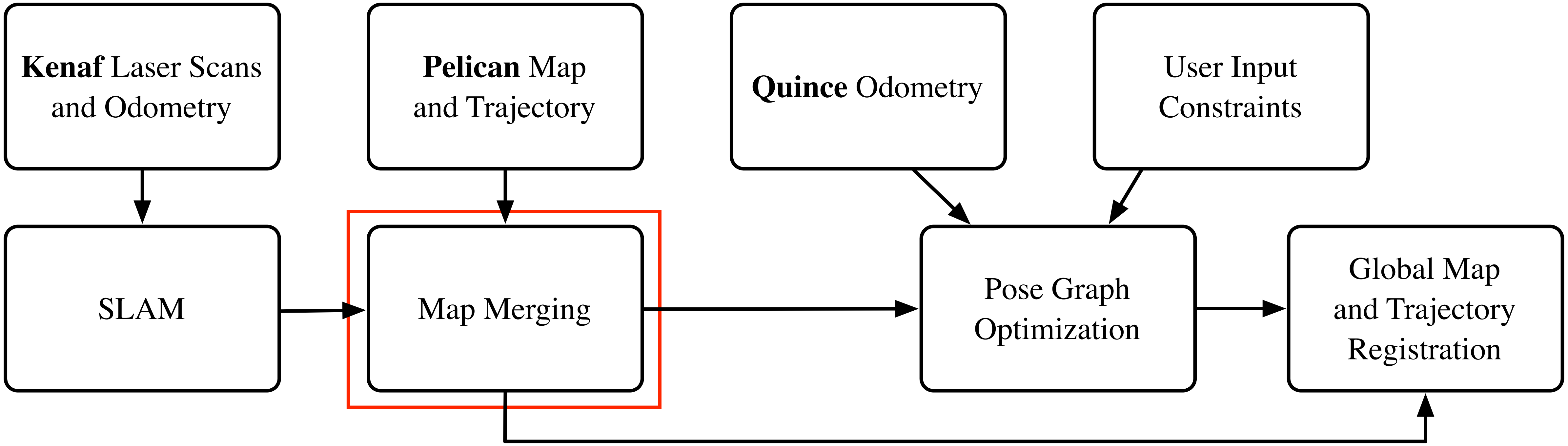
Autonomous recharging is possible

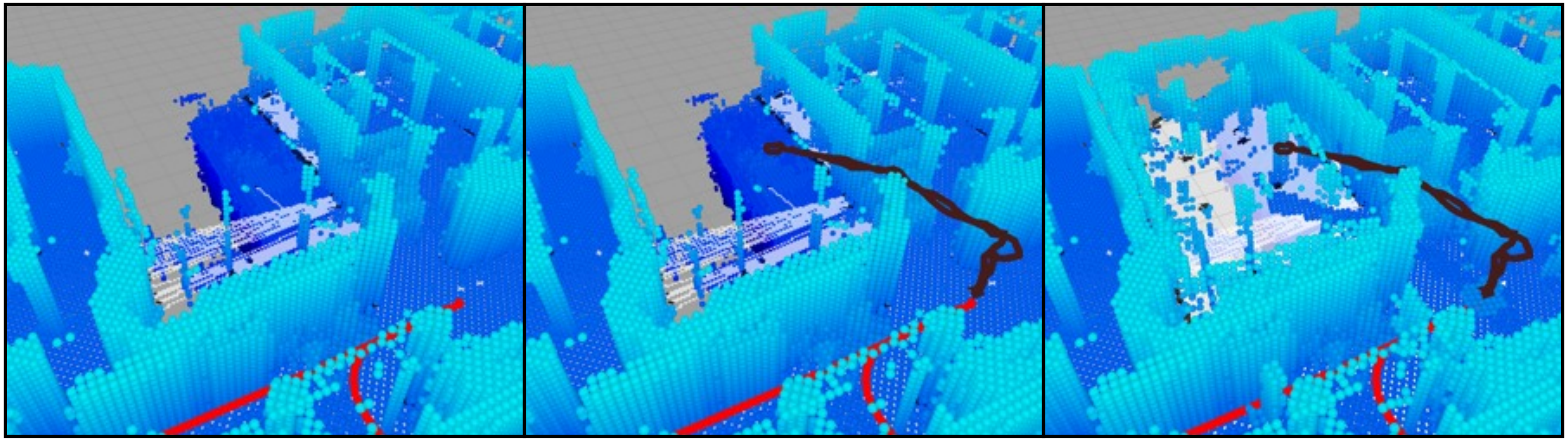

4x

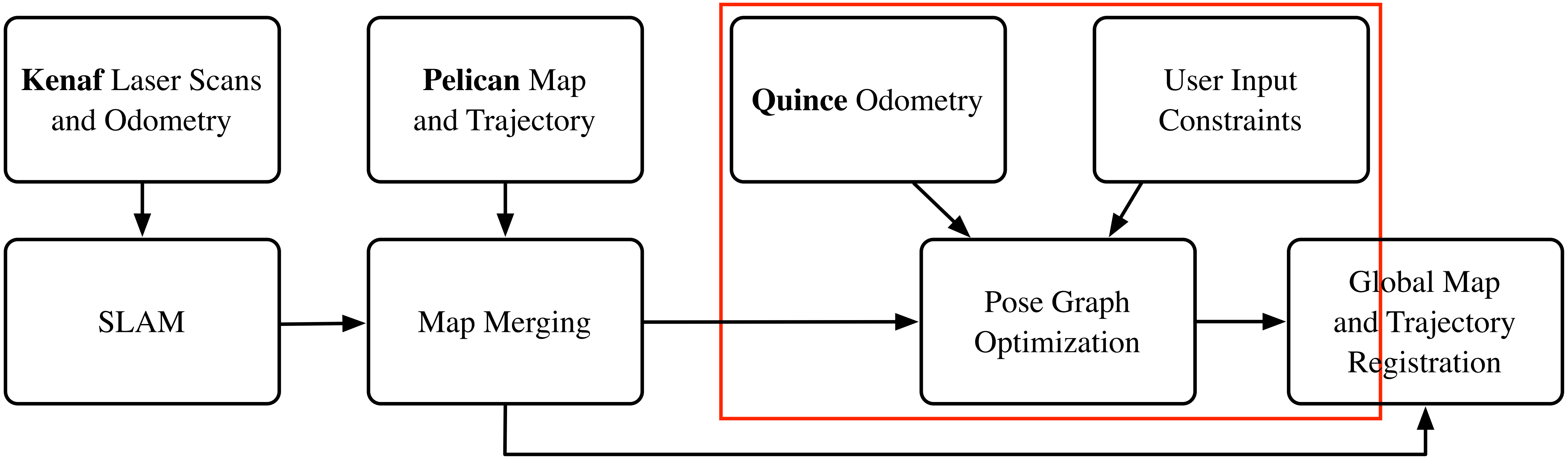
Methodology

Merging Observations and Maps Across Platforms




Kenaf Laser Scans and Odometry
Pelican Map and Trajectory
Quince Odometry
User Input Constraints
SLAM
Map Merging
Pose Graph Optimization
Global Map and Trajectory Registration





Kenaf Laser Scans and Odometry

Pelican Map and Trajectory

Quince Odometry

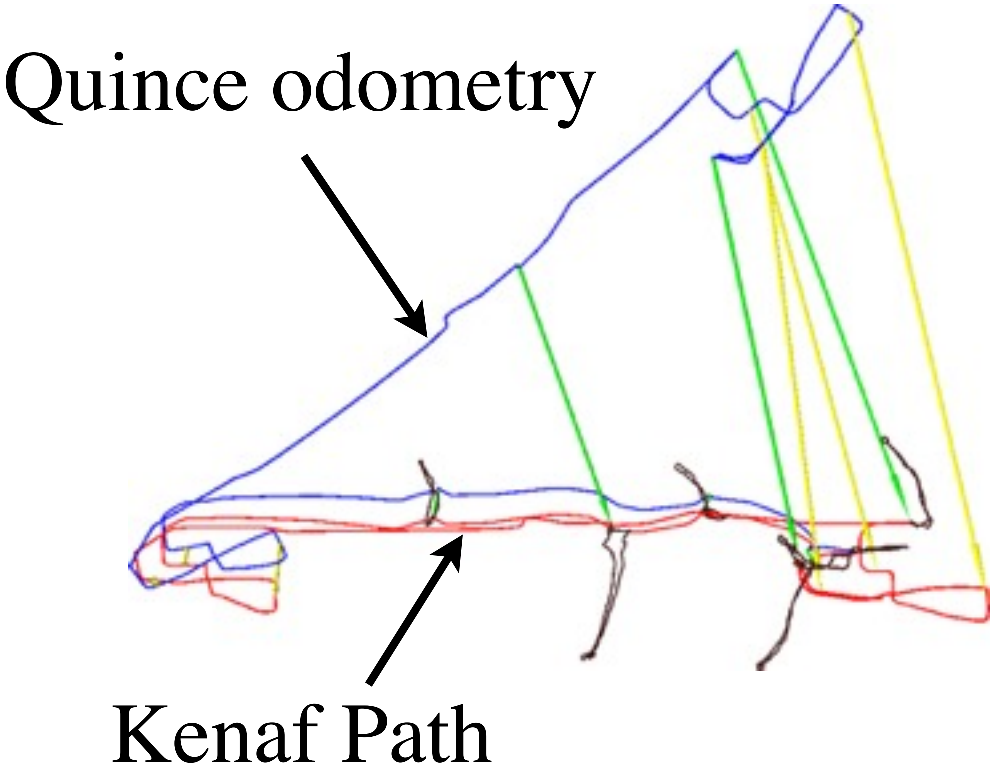
User Input Constraints

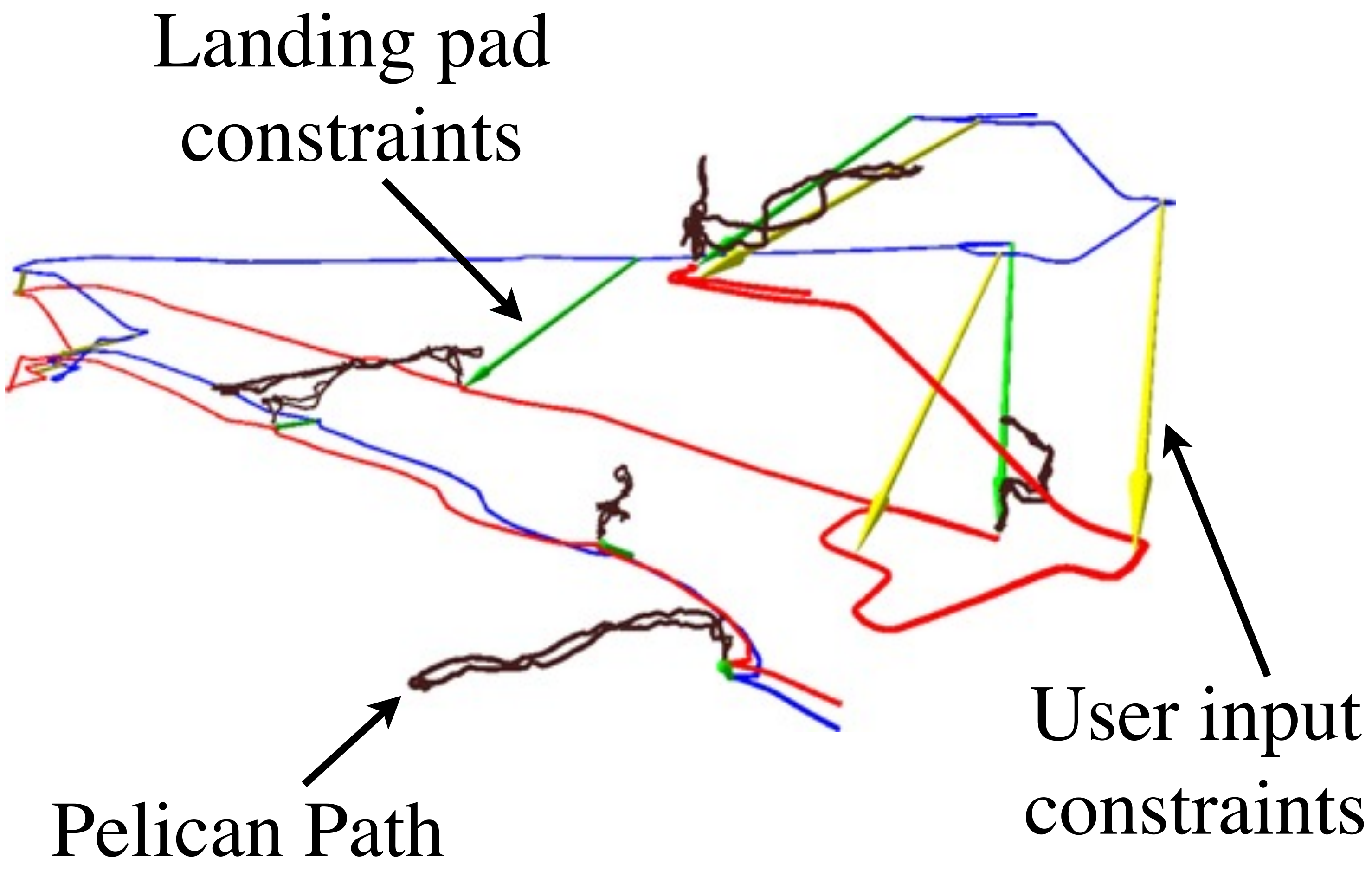
SLAM

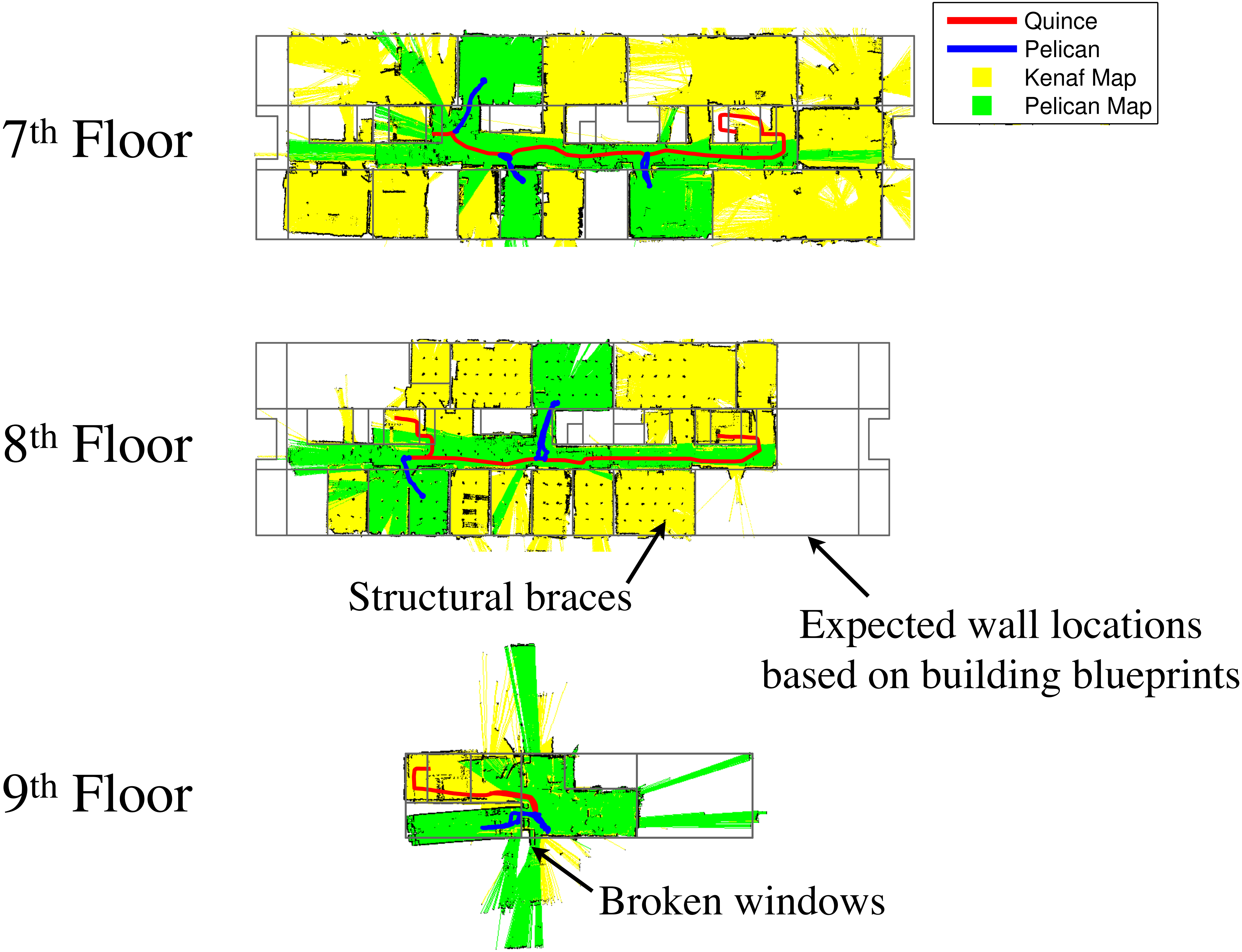
Map Merging

Pose Graph Optimization

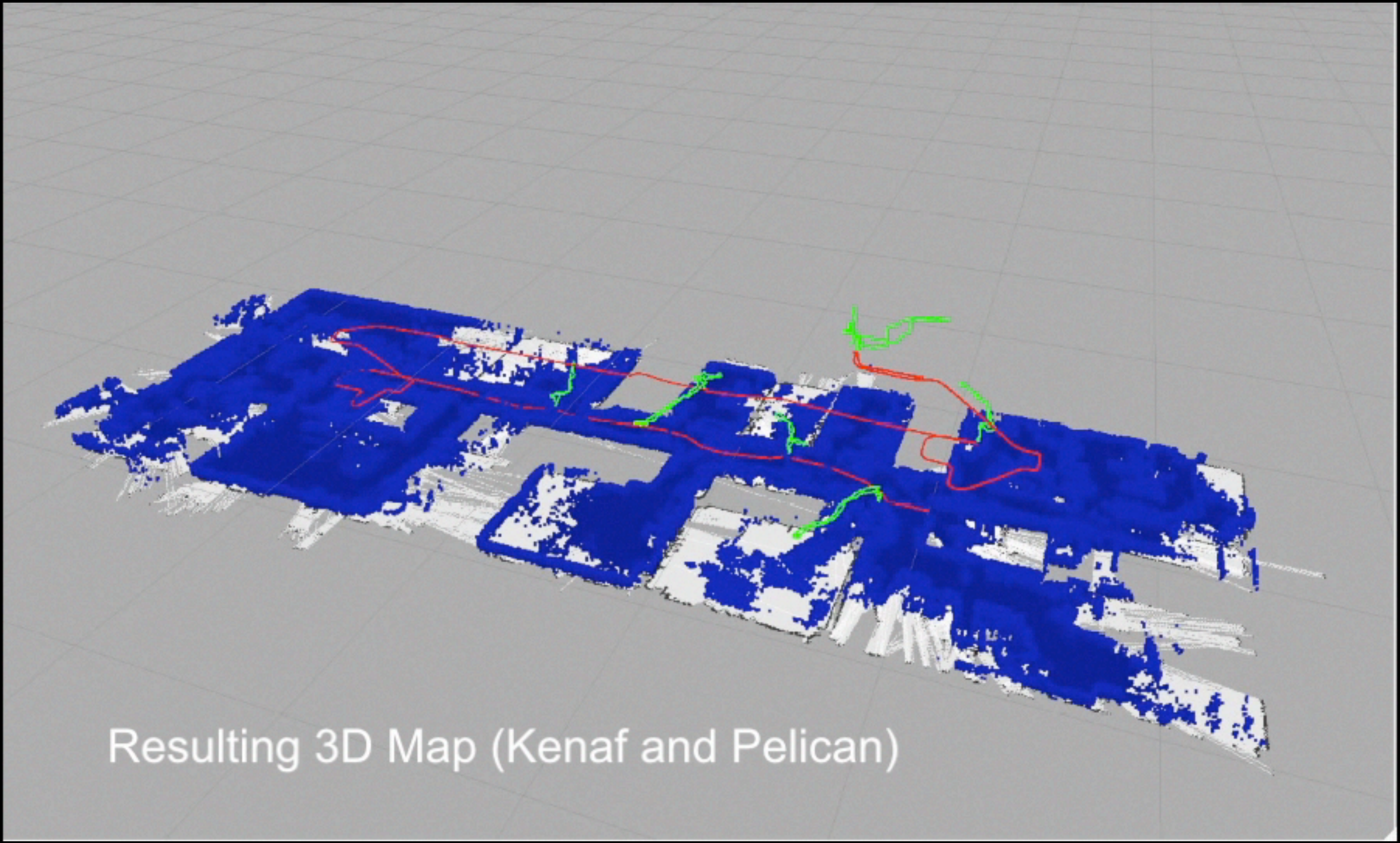
Global Map and Trajectory Registration



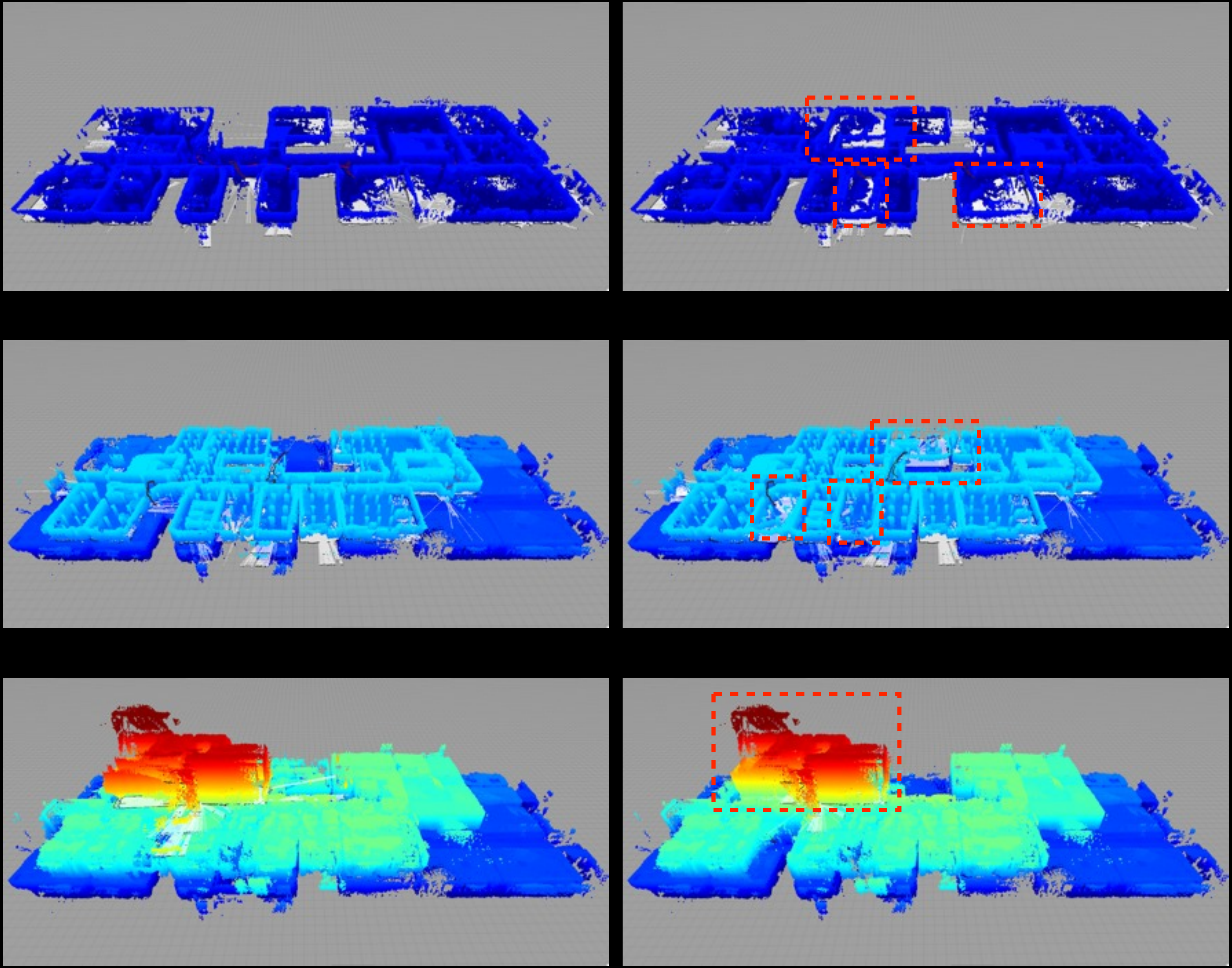


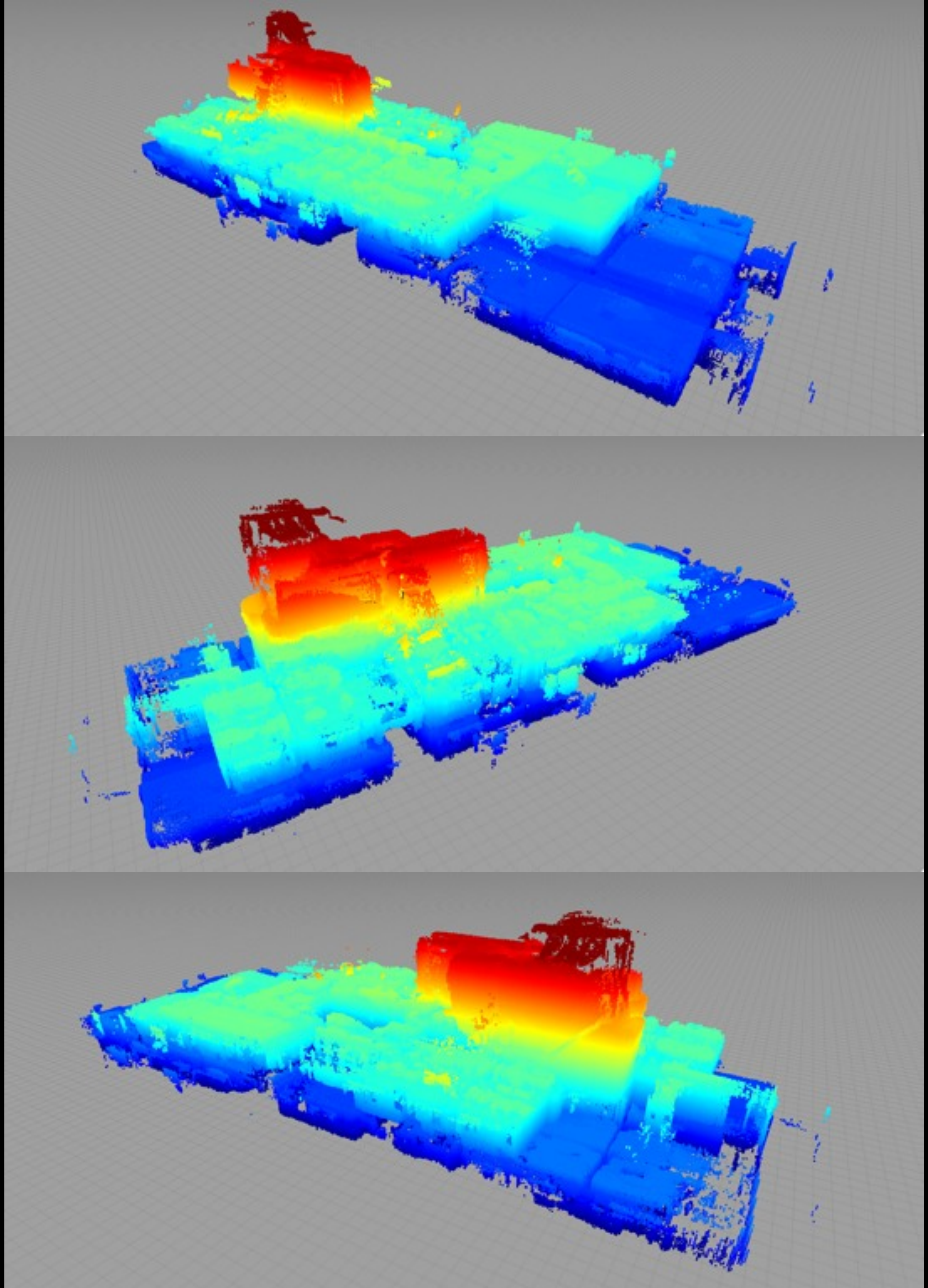


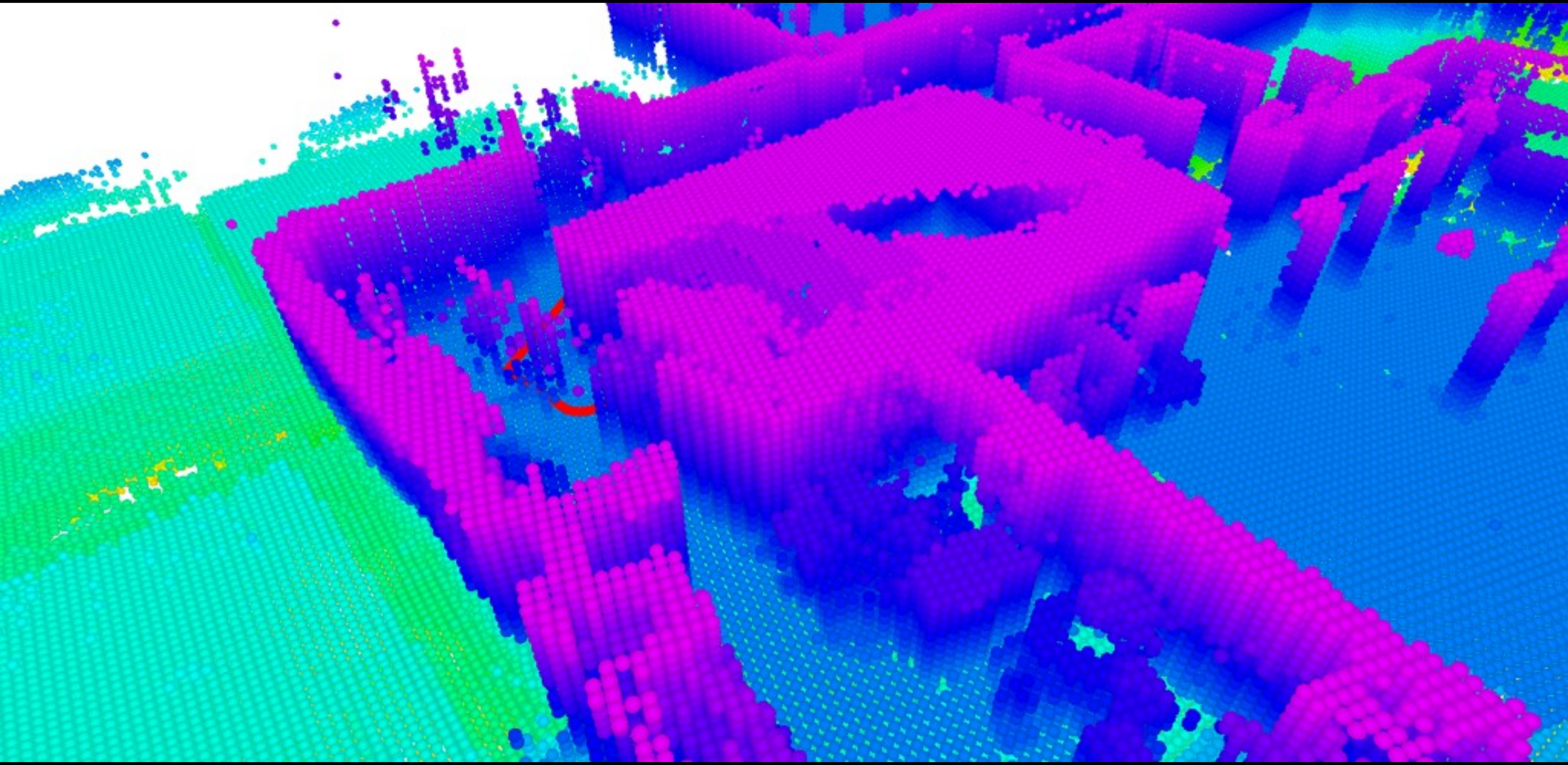
Quince
Pelican
Kenaf Map
Pelican Map
7th Floor
8th Floor
Structural braces
Expected wall locations based on building blueprints
9th Floor
Broken windows



Resulting 3D Map (Kenaf and Pelican)



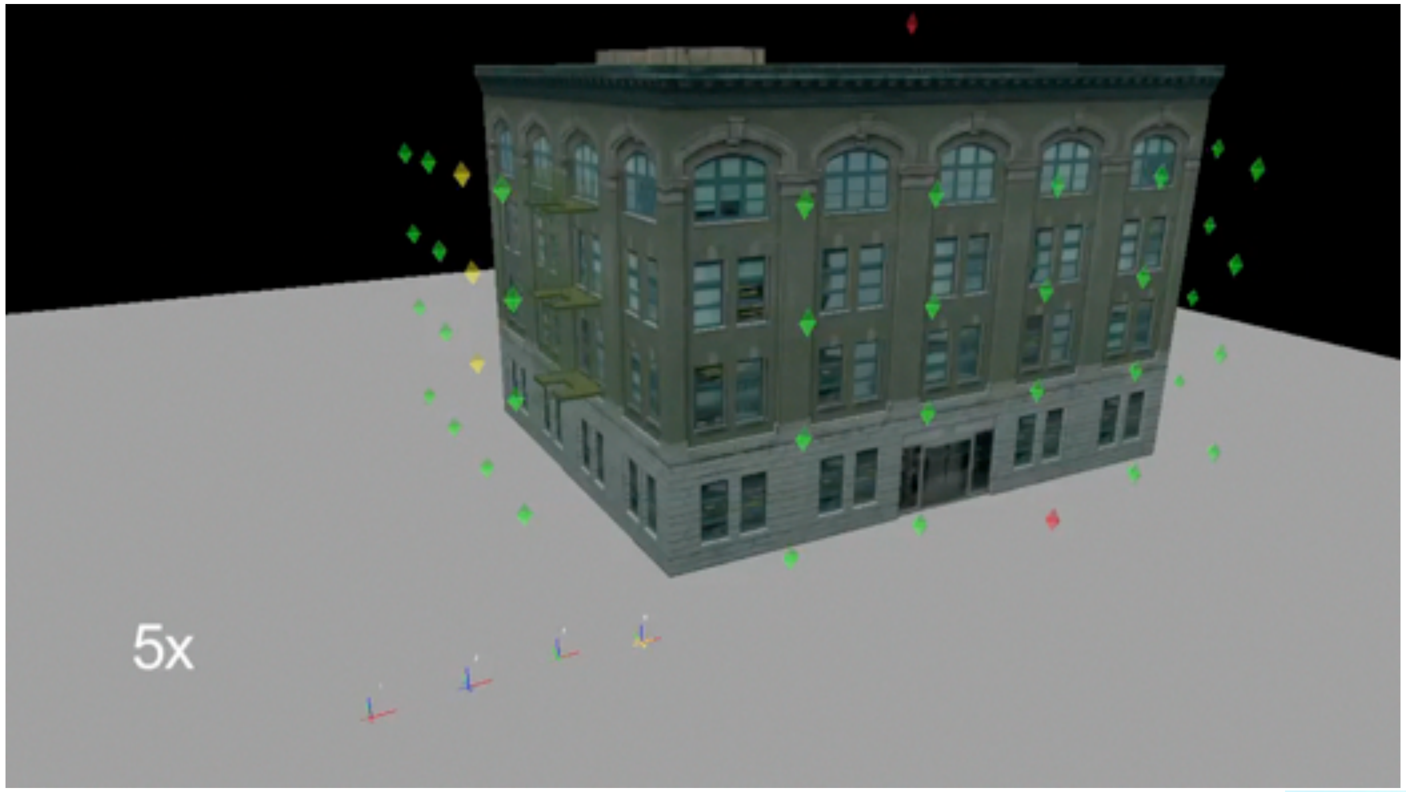




Outline

- Quadrotor model and control
  - Aggressive maneuvers
  - Multi-robot formation control
- Quadrotor state estimation, mapping, and localization
  - Autonomous exploration
  - Application study: cooperative air-ground mapping
- Future research challenges

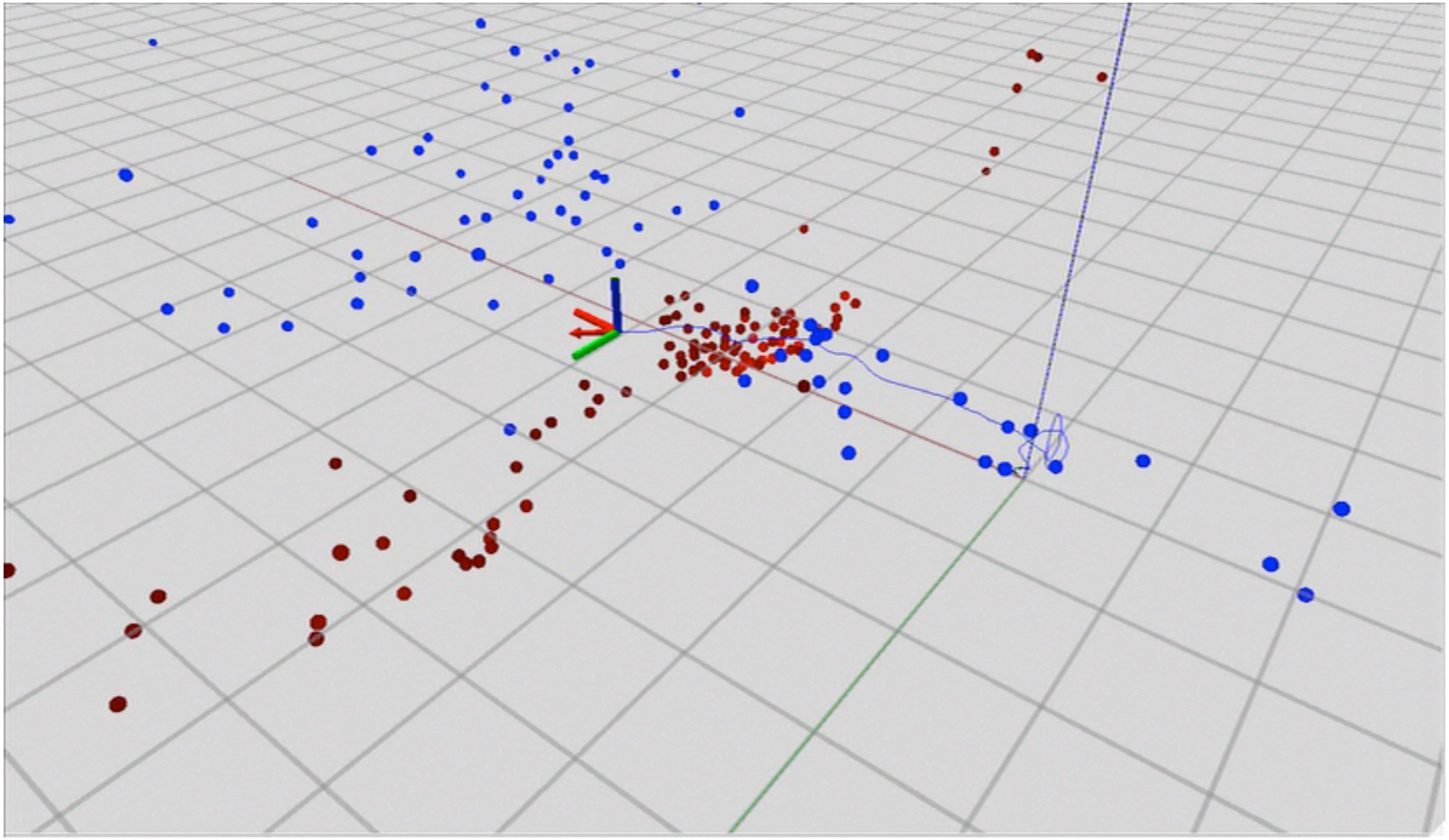
Future Research Challenges



Intermittent connectivity

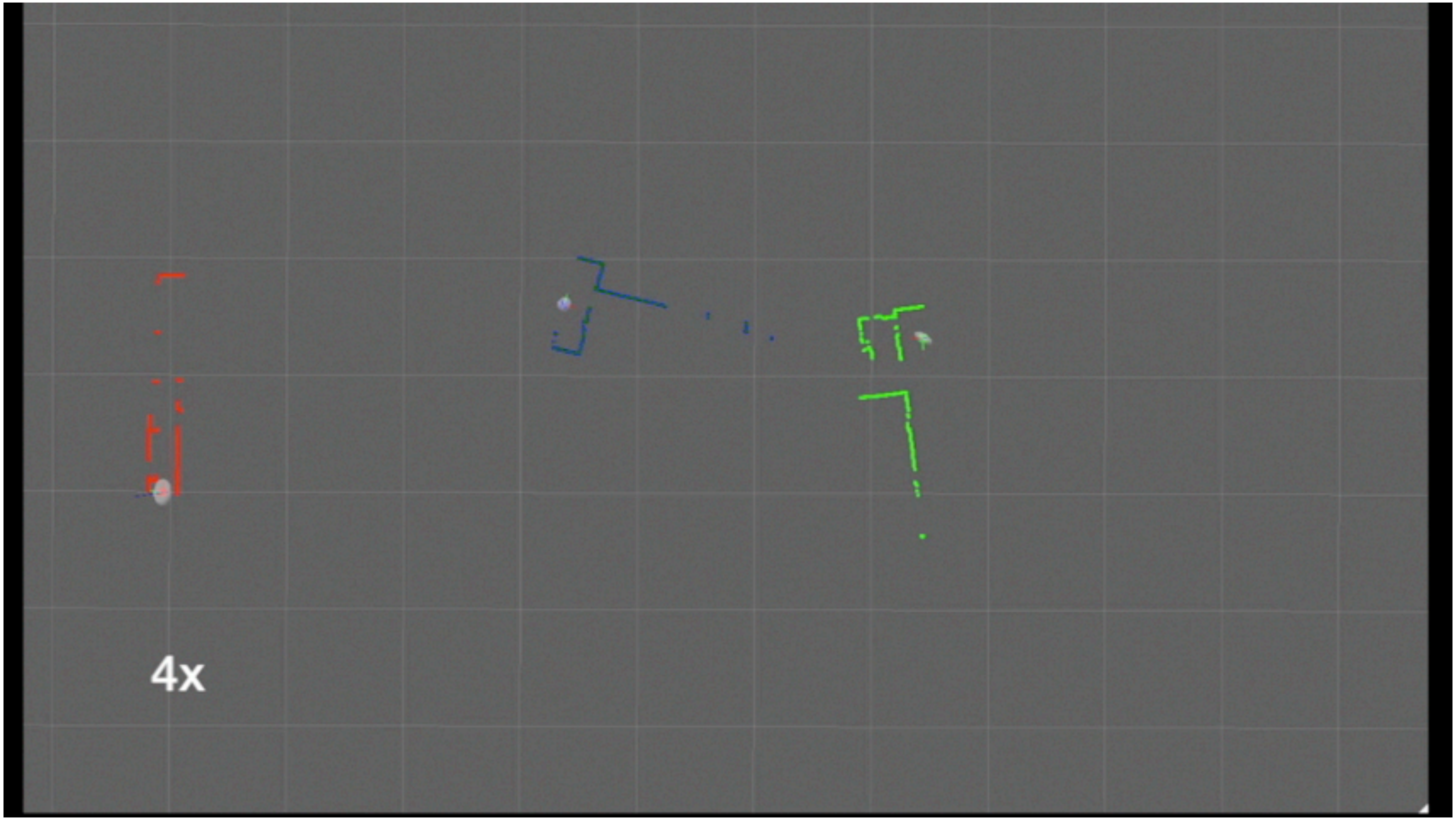
Networking delays in
cooperative planning and control

Future Research Challenges



Mapping, planning, and control in vision-based representations

Future Research Challenges



Cooperative mapping and exploration

Acknowledgement

Collaborators and Students (Penn):

- Prof. Vijay Kumar
- Dr. Daniel Mellinger
- Matthew Turpin
- Shaojie Shen
- Kartik Mohta

Funding:

National Science Foundation

Army Research Laboratory

Office of Naval Research