Cooperative Surveillance in Aerial and Ground Robots

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Acknowledgements
ONR N00014-08-1-0696 (HUNT)
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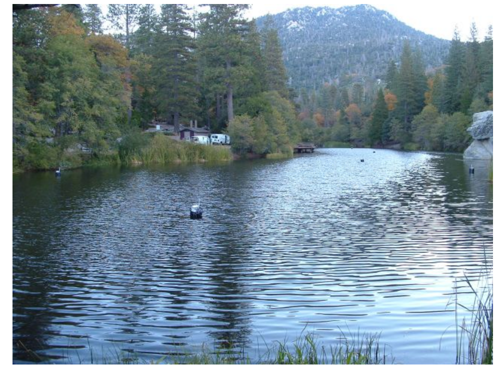
ONR N00014-09-1-1051 (ANTIDOTE)

Penn Engineering

Cooperating Robots

Robot networks

- Applications with large numbers of networked robots, embedded computers, high data rate sensors
  - ~ ¥200 Trillion industry, Network robot forum
- n ↑ (1-10 to 10's to 100's to 1,000,000's)



Acquatic Microbial Observatory (USC)

Exciting research

Communication, control and perception

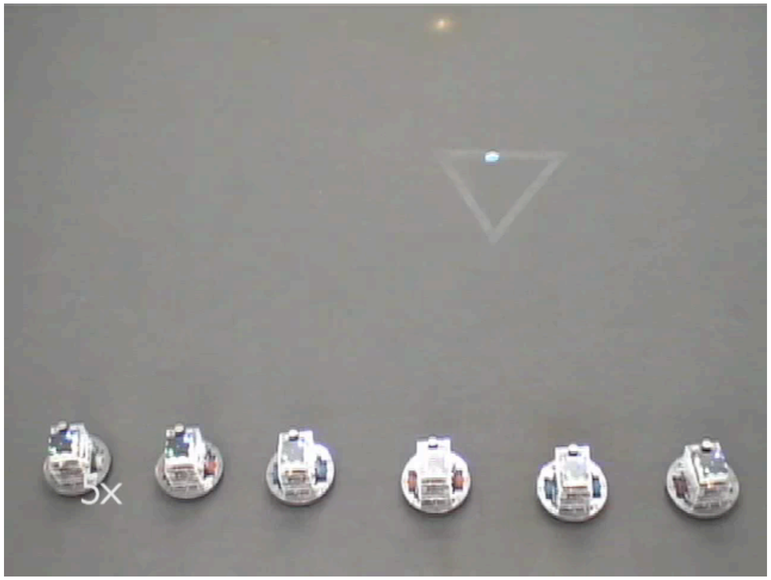
ABB

Kiva Systems

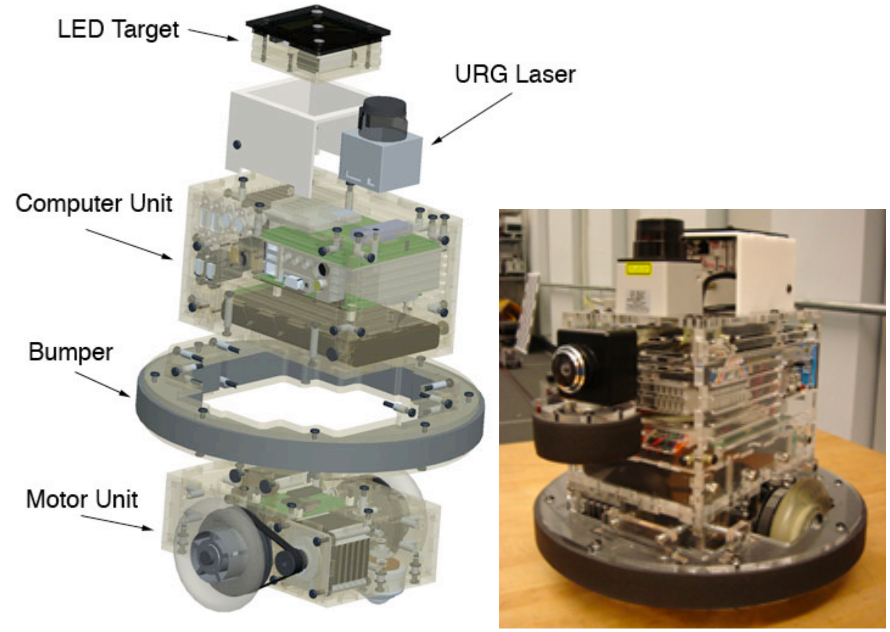
**Japanese Ministry of Internal Affairs and Communications, "Toward the Realization of Network Robots", 2003.*

Cooperative Retrieval

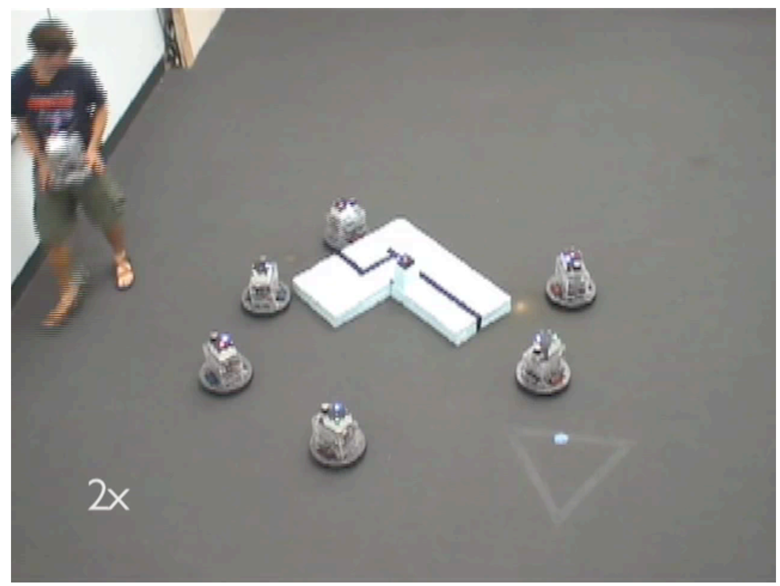
S. Berman, Q. Lindsey, M. S. Sakar, V. Kumar, and S. Pratt. *Study of group food retrieval by ants as a model for multi-robot collective transport strategies.* Robotics: Science and Systems (RSS) 2010.



Fink *et al*, RSS 07



Michael *et al*, RAM 08



Hsieh *et al*, ICRA 08

Outline

1. Micro Unmanned Aerial Vehicles

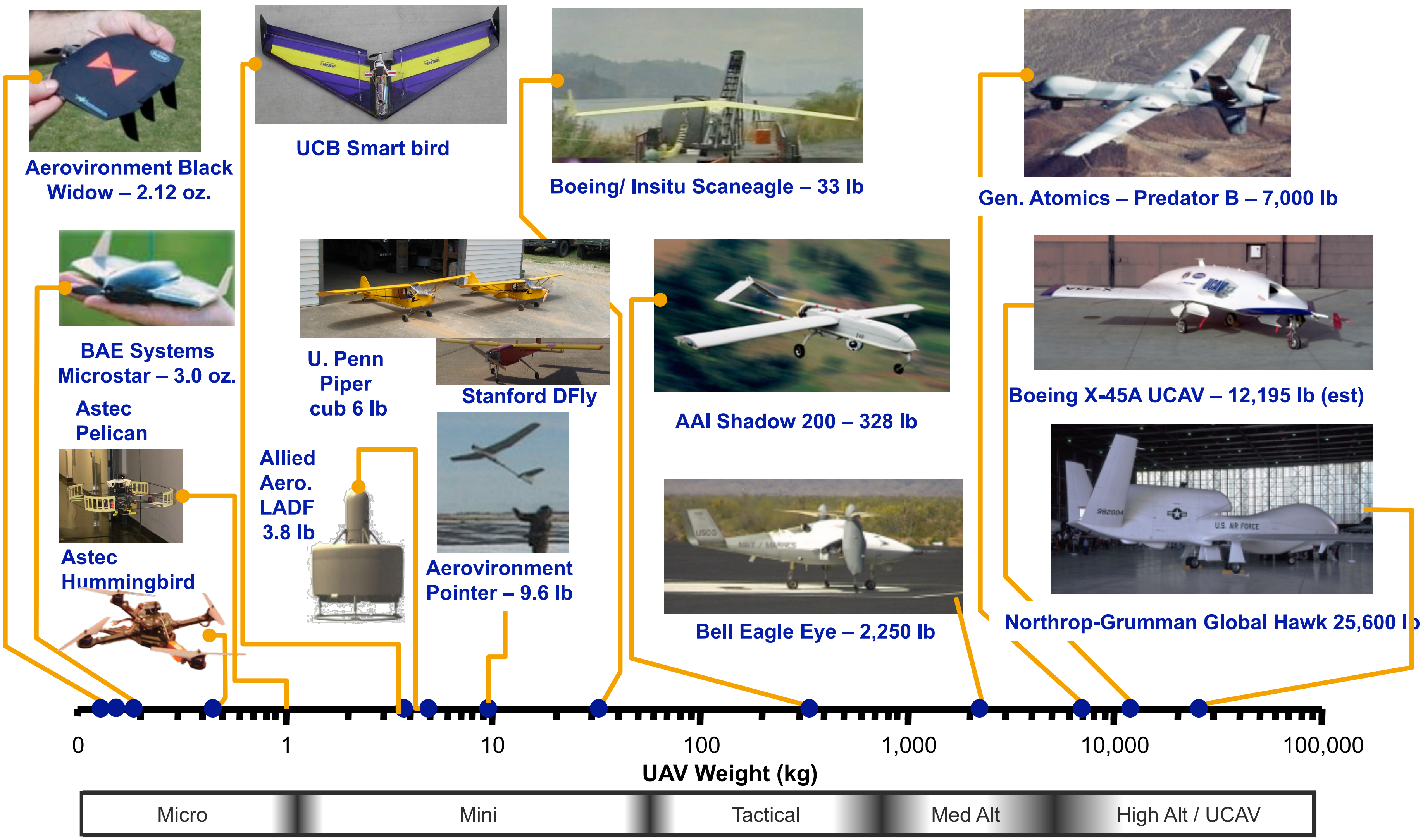
2. Control in Complex Environments

3. 3-D Perception and State Estimation

4. Coordinated Control for Exploration and Surveillance

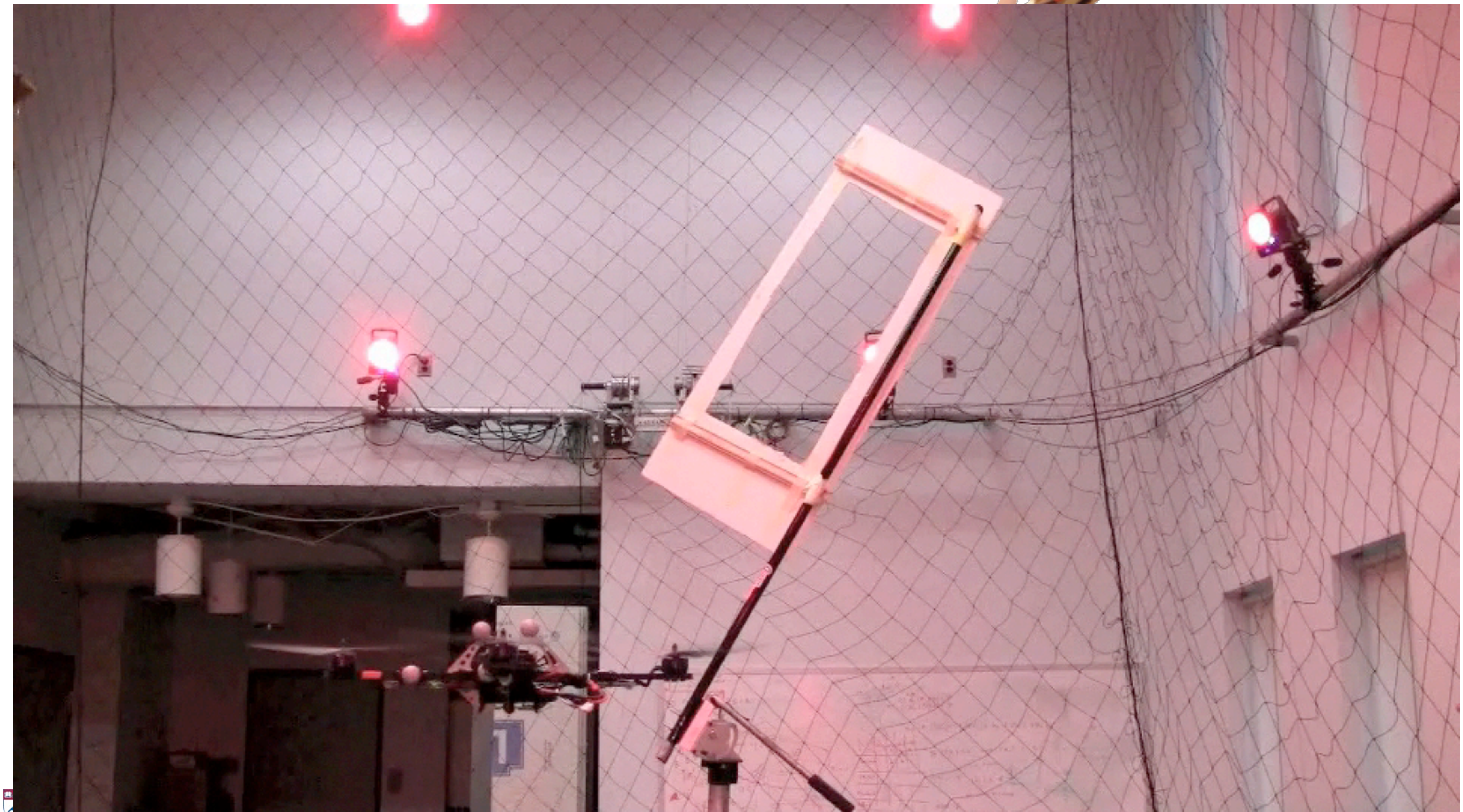
5. Establishing and Maintaining Communication Networks

Unmanned Air Vehicles

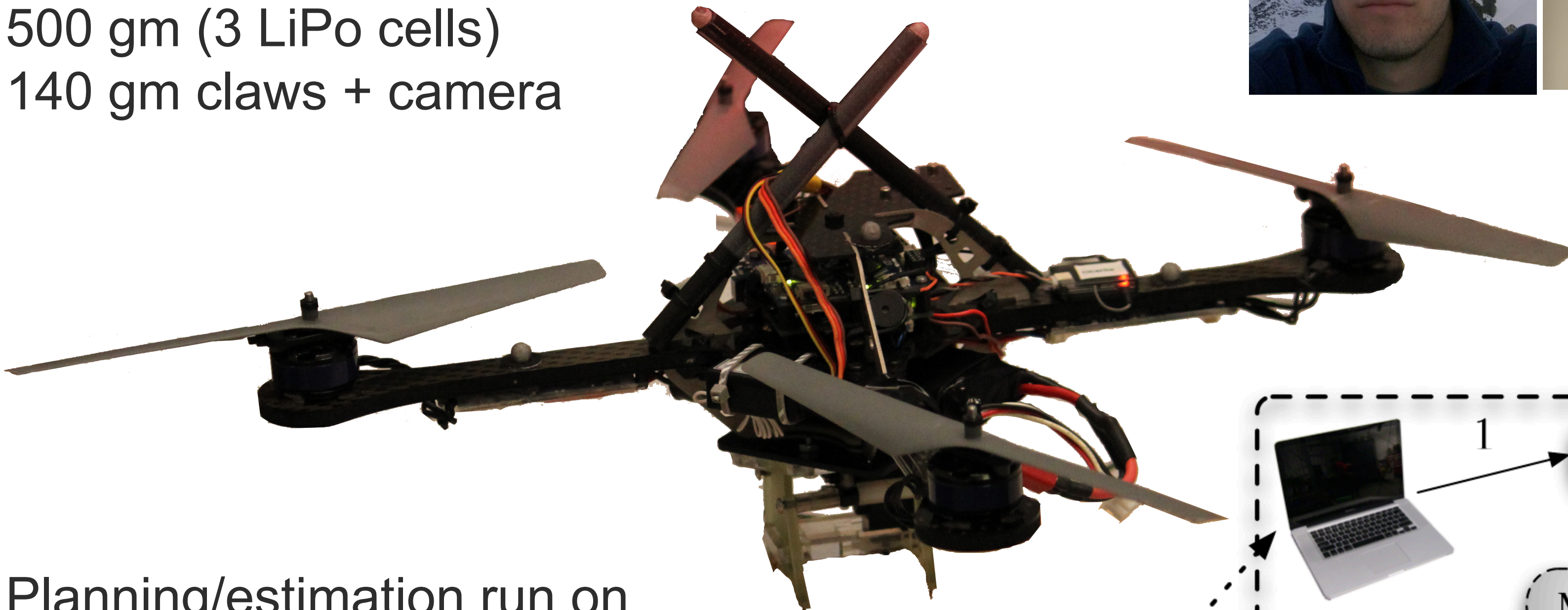


Multi-rotor micro UAVs

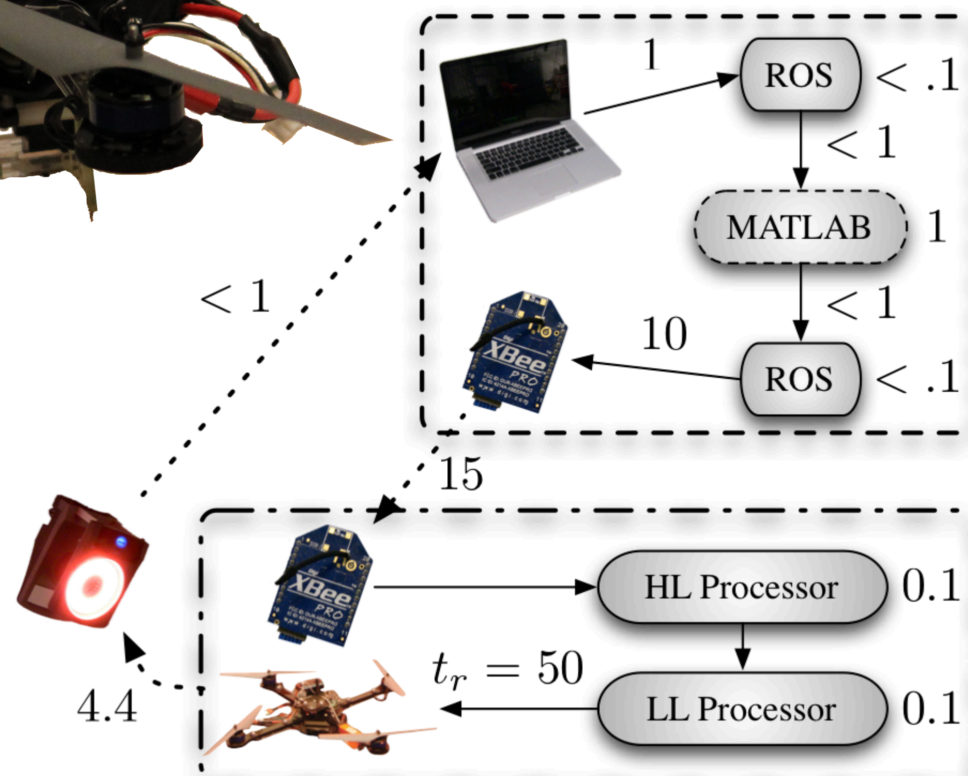
- Incredibly agile



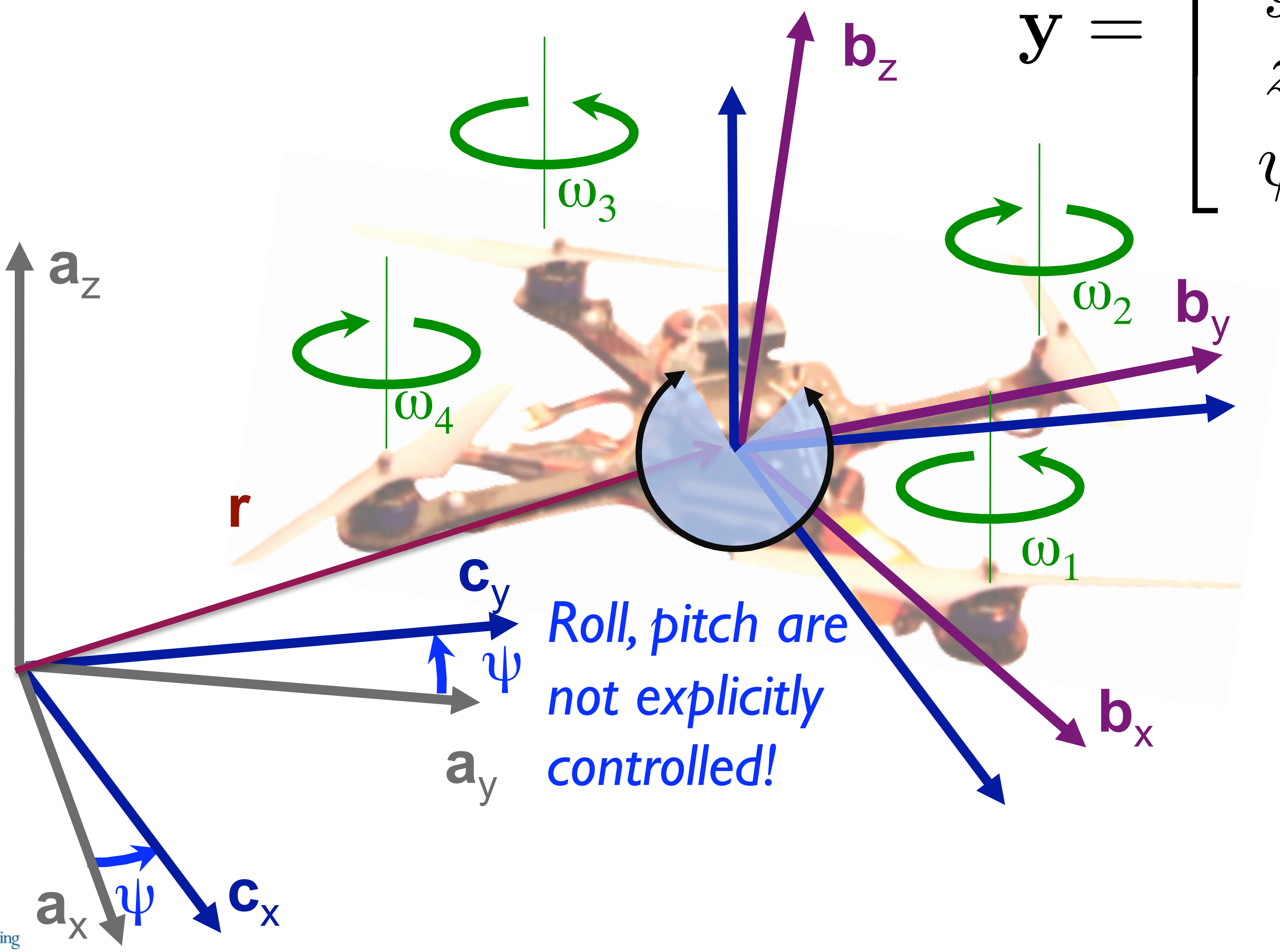
55 cm diameter
8 cm height
Carbon fiber, Mg frame
500 gm (3 LiPo cells)
140 gm claws + camera



Planning/estimation run on
MATLAB on a Macbook Pro

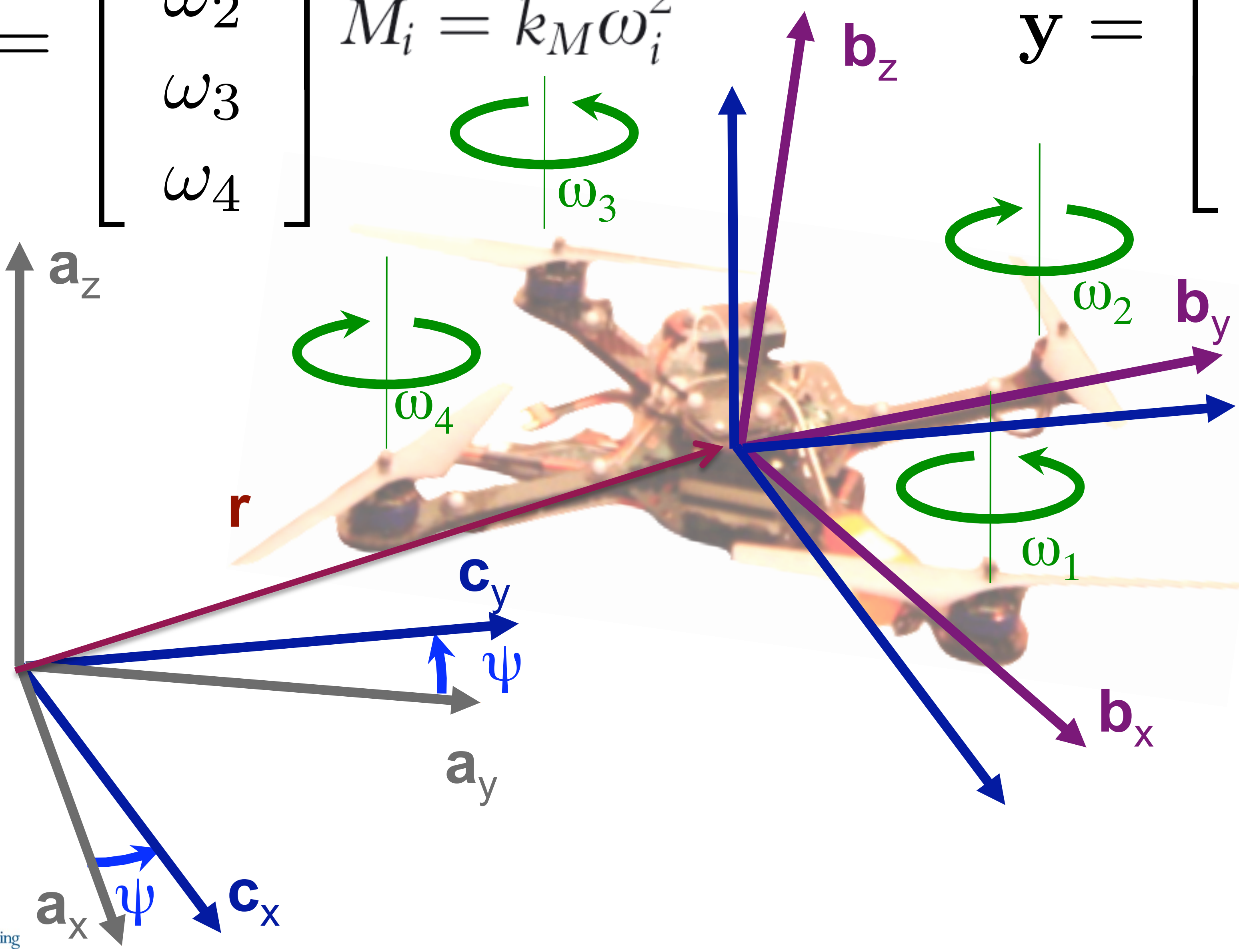


$$\mathbf{y} = \begin{bmatrix} x \\ y \\ z \\ \psi \end{bmatrix}$$



Roll, pitch are not explicitly controlled!

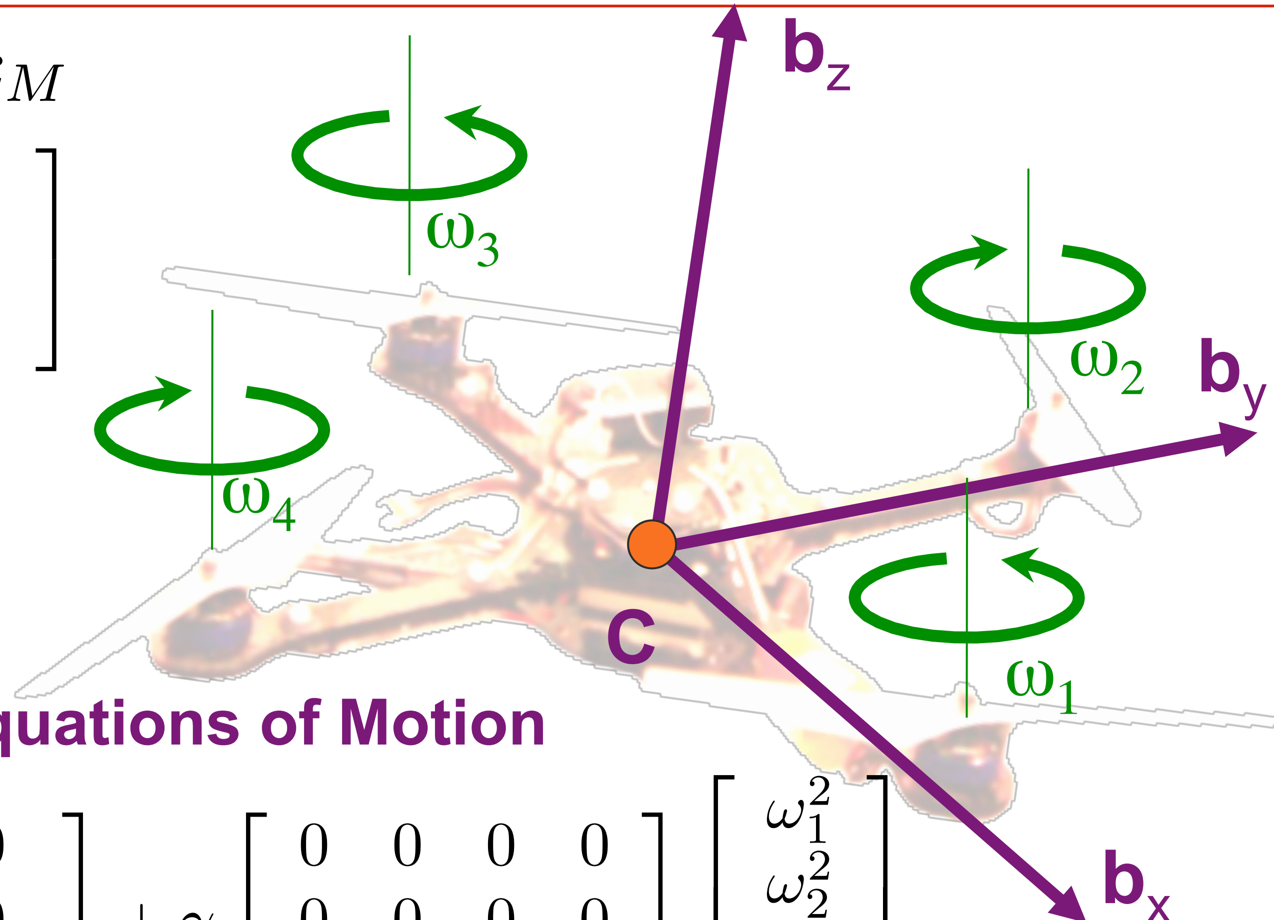
$$\mathbf{u} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \qquad F_i = k_F \omega_i^2 \qquad M_i = k_M \omega_i^2 \qquad \mathbf{y} = \begin{bmatrix} x \\ y \\ z \\ \psi \end{bmatrix}$$



$$\alpha = k_F L \quad \beta = k_M$$

$$\mathbf{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$$

$$\gamma = \frac{k_F}{m}$$

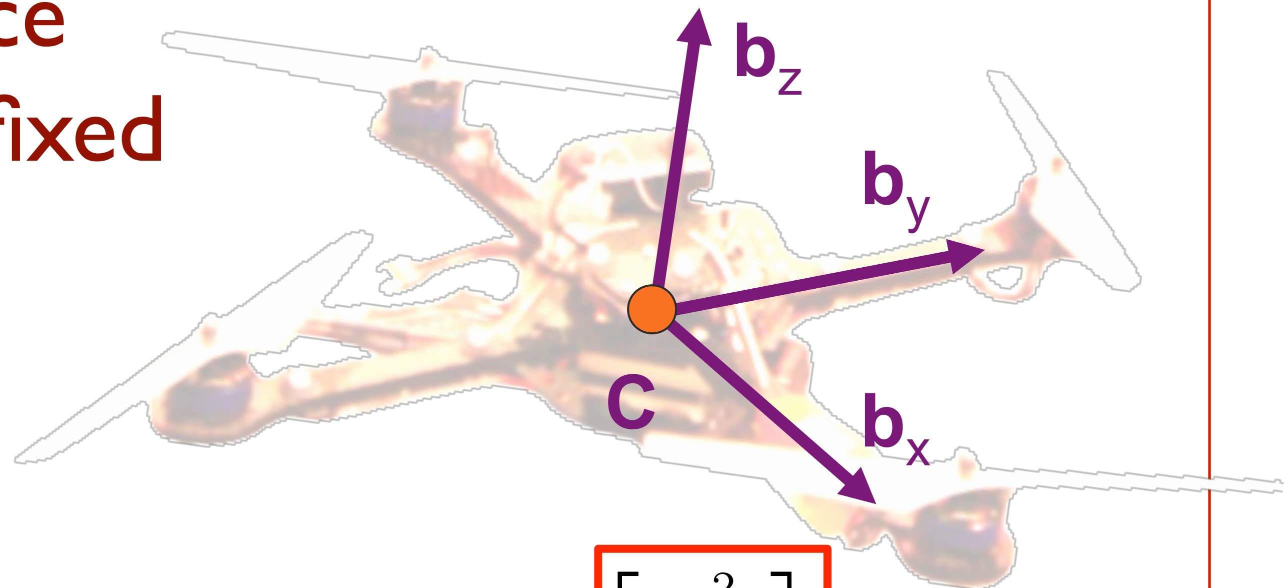


Newton – Euler Equations of Motion

$$\begin{bmatrix} a_{C,x} \\ a_{C,y} \\ a_{C,z} \end{bmatrix} = \mathbf{R}^T \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} + \gamma \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}$$

$$\mathbf{I} \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} + \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \times \mathbf{I} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 0 & \alpha & 0 & -\alpha \\ -\alpha & 0 & \alpha & 0 \\ \beta & -\beta & \beta & -\beta \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}$$

Can control force along the body-fixed z axis and all moments



$$\begin{bmatrix} a_{C,x} \\ a_{C,y} \\ a_{C,z} \end{bmatrix} = \mathbf{R}^T \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} + \underbrace{\gamma \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}}_{f}$$

$$\mathbf{I} \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} + \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \times \mathbf{I} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & \alpha & 0 & -\alpha \\ -\alpha & 0 & \alpha & 0 \\ \beta & -\beta & \beta & -\beta \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}}_{\mathbf{m}}$$

Control

Want $\mathbf{e}_r \rightarrow 0$

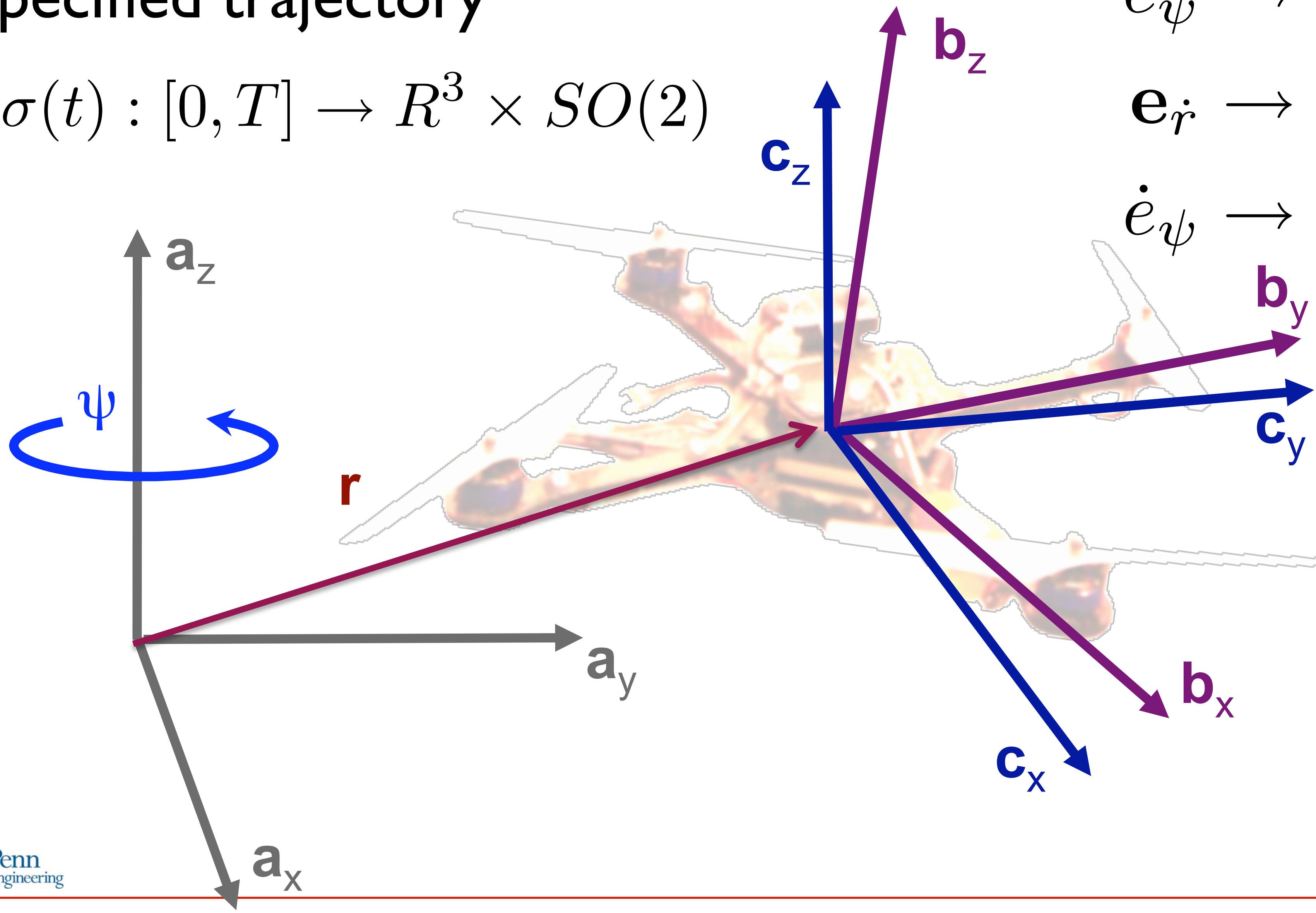
$e_\psi \rightarrow 0$

$\mathbf{e}_{\dot{r}} \rightarrow 0$

$\dot{e}_\psi \rightarrow 0$

Specified trajectory

$$\sigma(t) : [0, T] \rightarrow R^3 \times SO(2)$$

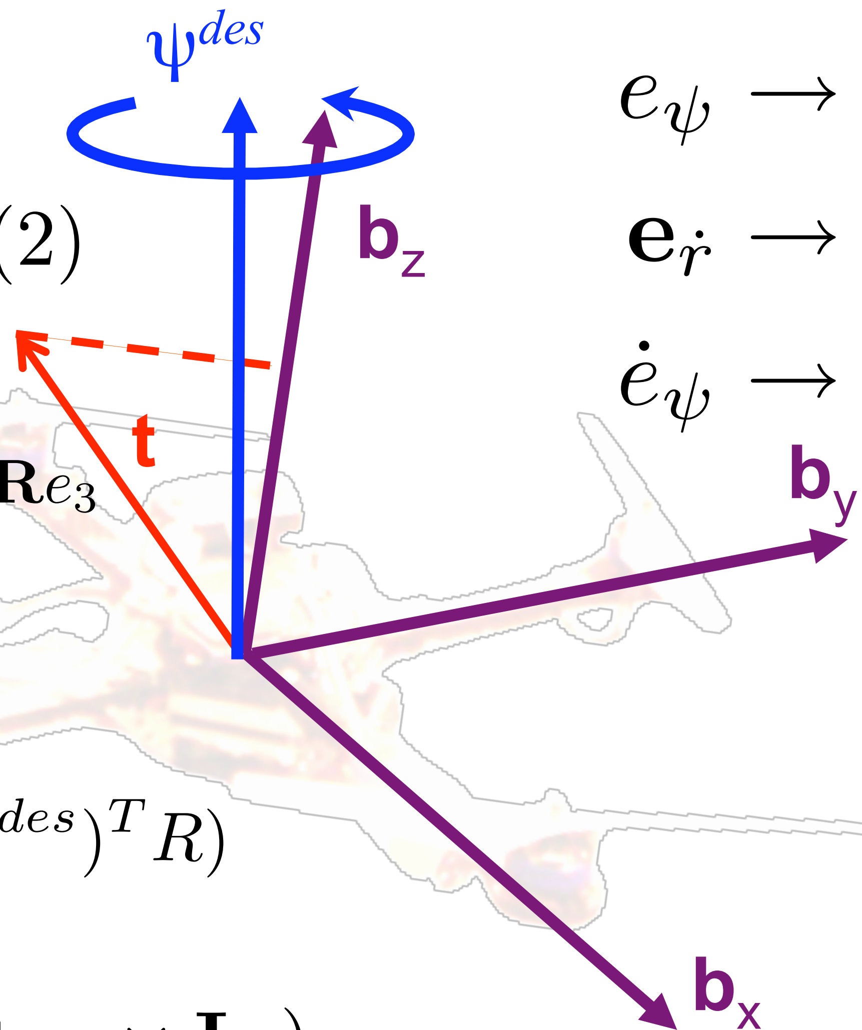


Control on SE(3)

Want
$$\mathbf{e}_r \rightarrow 0$$
$$e_\psi \rightarrow 0$$
$$\mathbf{e}_{\dot{r}} \rightarrow 0$$
$$\dot{e}_\psi \rightarrow 0$$

Specified trajectory

$$\sigma(t) : [0,T] \rightarrow R^3 \times SO(2)$$



t

$$f = \boxed{\left(\ddot{\mathbf{r}}^{des} + K_v \mathbf{e}_{\dot{r}} + K_p \mathbf{e}_r + g e_3\right)} . \mathbf{R} e_3$$

$$\boxed{\begin{aligned} \mathbf{R}^{des} e_3 &= \frac{\mathbf{t}}{\|\mathbf{t}\|} \\ \psi &= \psi^{des} \end{aligned}}$$

$$R^{des} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$e_R = log((R^{des})^T R)$$

$$M = -\mathbf{I}\left(-k_R e_R - k_\omega e_\omega + \omega \times \mathbf{I}\omega\right)$$

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Convergence

- Large basin of attraction

$$tr[I - (R^{des})^T R] < 2 \qquad \|e_\omega(0)\|^2 \leq \frac{2}{\lambda_{min}(I)} k_R \left(1 - \frac{1}{2} tr\left[I - (R^{des})^T R\right]\right)$$

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Trajectory Planning

Need to specify trajectory

$$\sigma(t) : [0, T] \to R^3 \times SO(2)$$

Constraints on state and input variables can be expressed as algebraic functions of the *independent* trajectory variables and its derivatives

$$\sigma = \begin{bmatrix} \mathbf{r} \\ \psi \end{bmatrix} \Rightarrow$$

$$\mathbf{v} = \dot{\mathbf{r}}$$

$$\mathbf{a} = \ddot{r}$$

$$\mathbf{R}_{12}\mathbf{e}_3 = \frac{1}{f}(mg\mathbf{e}_3 + m\mathbf{a})$$

$$\mathbf{R} = \mathbf{R}_{12}\mathbf{R}_\psi$$

...

$$f = \|(mg\mathbf{e}_3 + m\mathbf{a})\|$$

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Trajectory Planning

Trajectory

$$\sigma(t) : [0, T] \to R^3 \times SO(2)$$

Optimization

$$\min_{\sigma(t)} \int_0^T \alpha \| \dddot{\mathbf{r}}^{des}(t) \|^2 + \beta \ddot{\psi}(t)^2 \, dt$$

Parameterization

$$\mathbf{r}^{des}(t) = \sum_{i=0}^{n} \mathbf{r}_i \, t^i$$

$$\psi^{des}(t) = \sum_{i=0}^{m} \psi_i \, t^i$$

Constraints

$$f(\mathbf{r}^{des}(t), \dot{\mathbf{r}}^{des}(t), \mathbf{R}^{des}(t), \omega^{des}(t)) \leq 0$$

Discretization

$$\{0, t_1, t_2, \ldots, T\}$$

Solve

$$\min_{\mathbf{x}=\{\mathbf{r}_i, \psi_i\}} \mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{p}^T \mathbf{x}$$

$$\text{s.t.} \quad \mathbf{A}^T \mathbf{x} \leq \mathbf{b}$$

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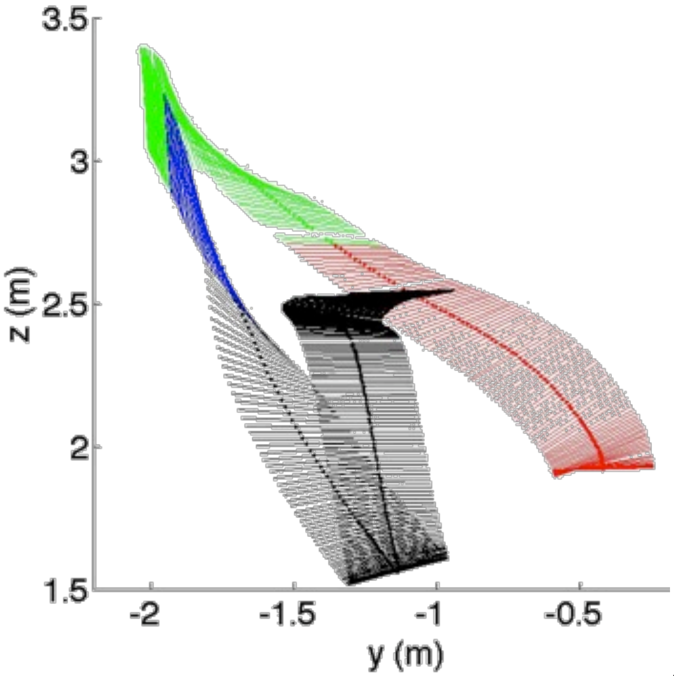
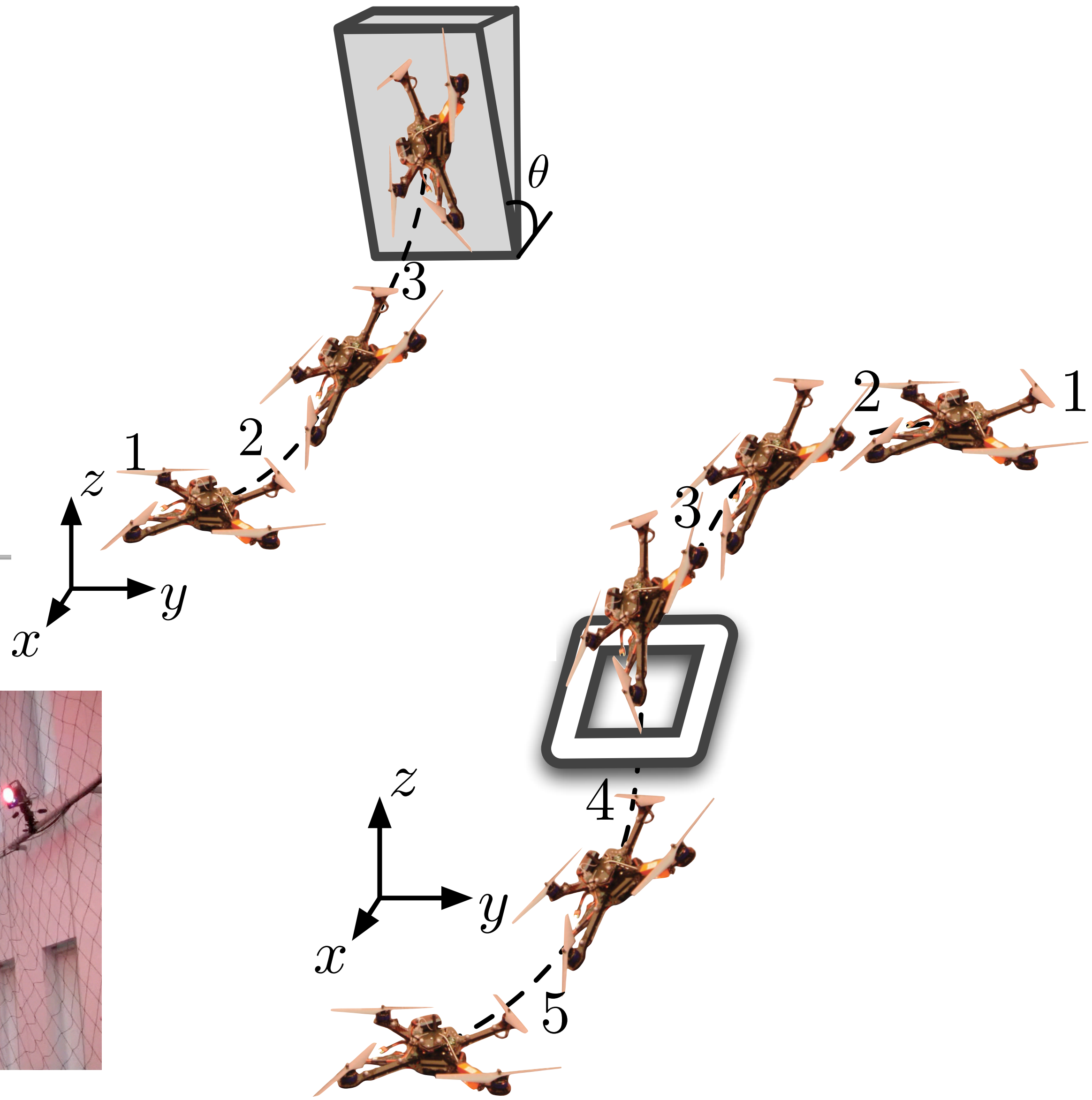
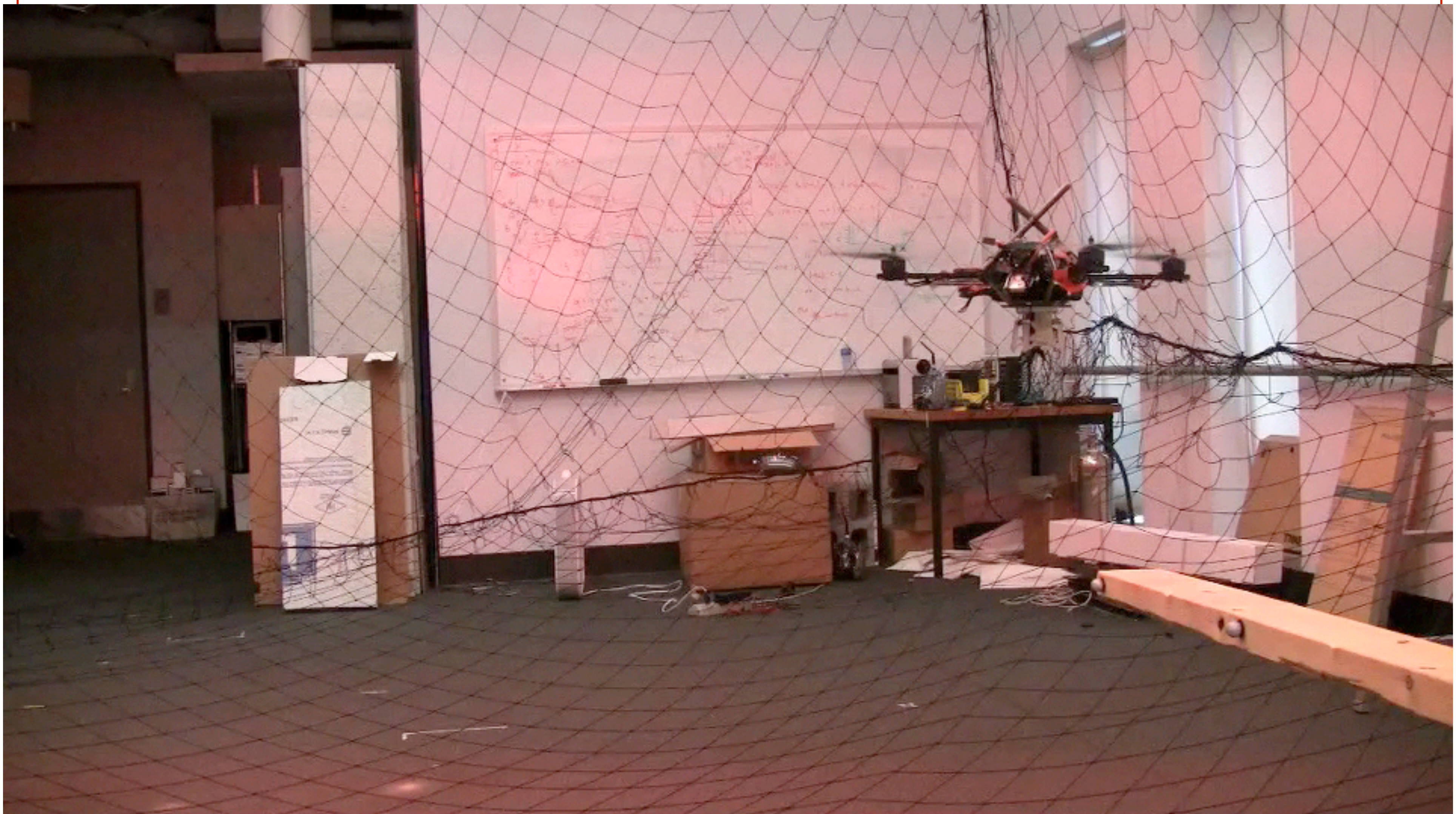
Composite Trajectories

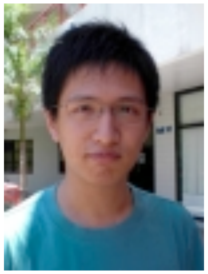


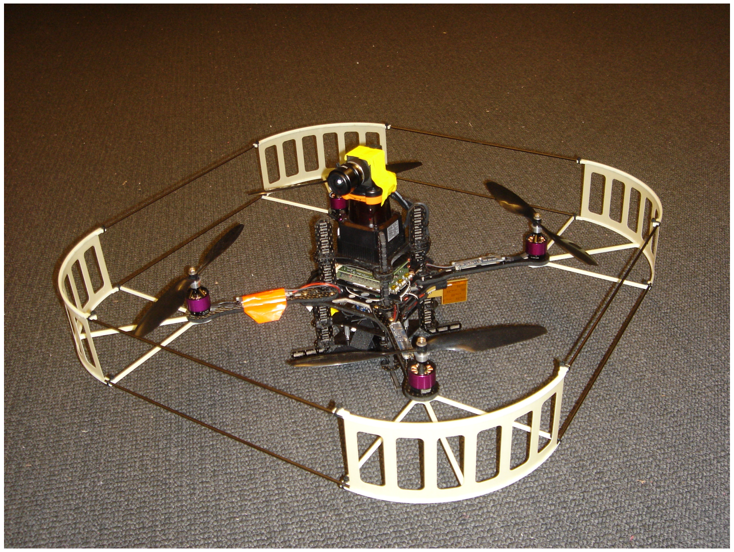


Fault tolerance



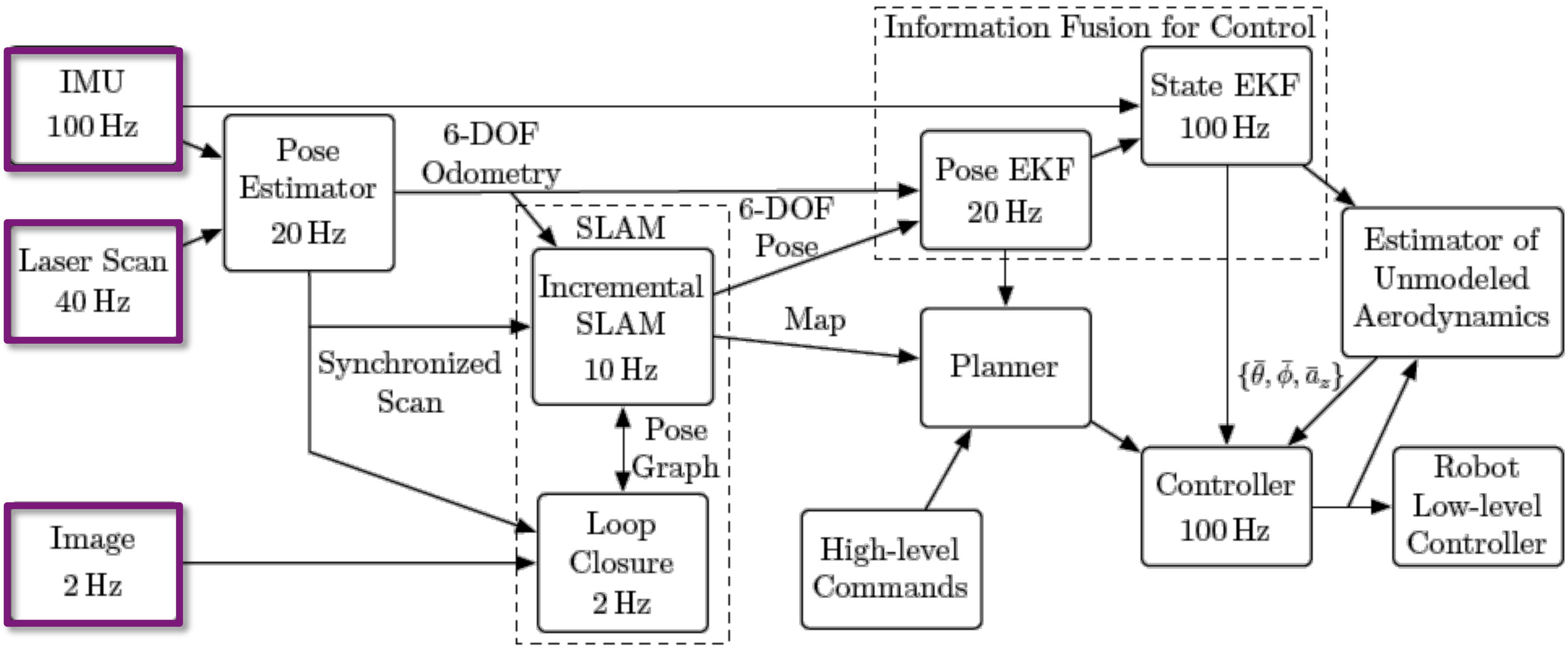
3-D Perception and State Estimation

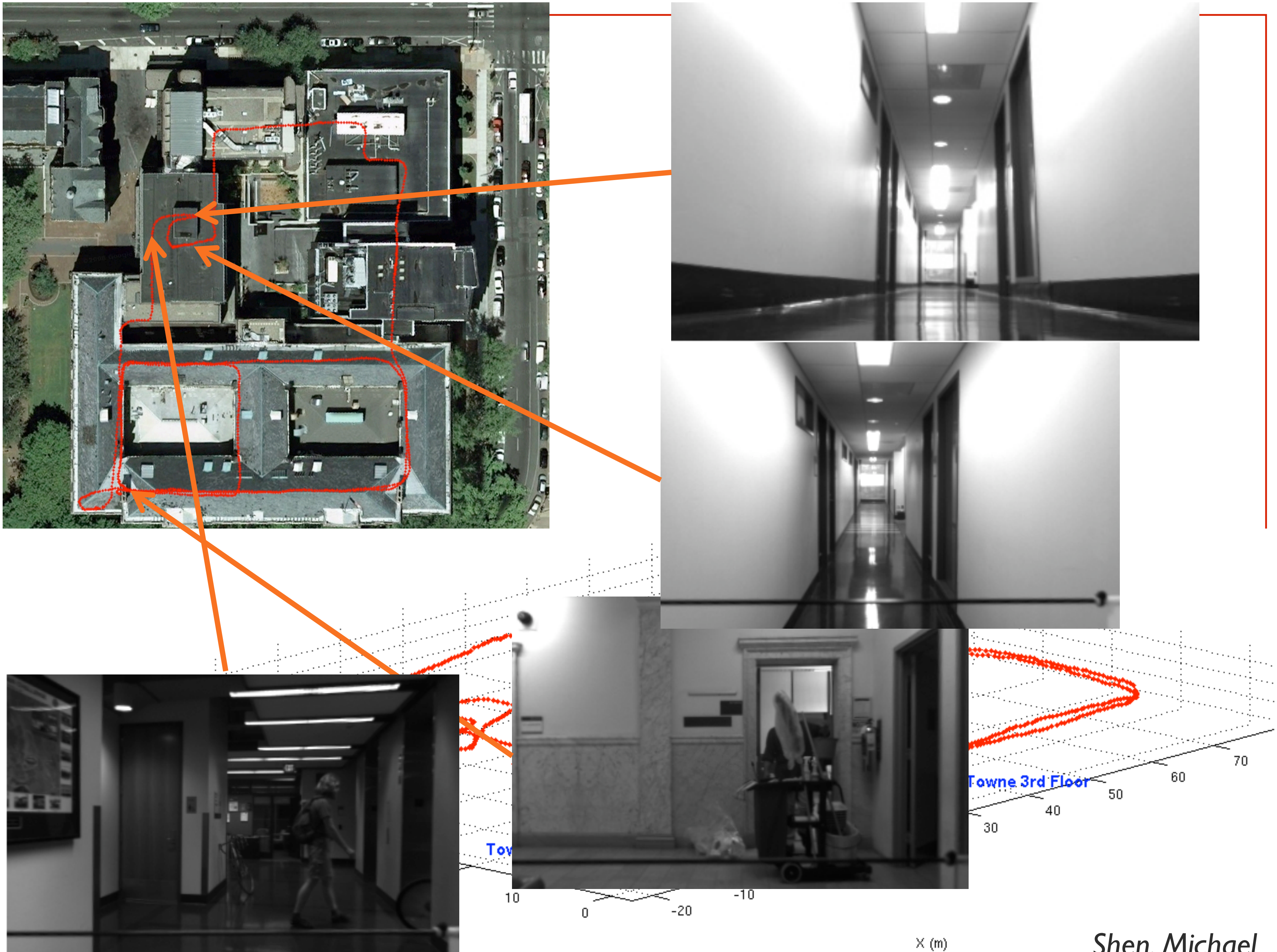




Camera
Hokuyu UTM-30LX
Atom X86 processor

3-D Perception and State Estimation





Shen, Michael

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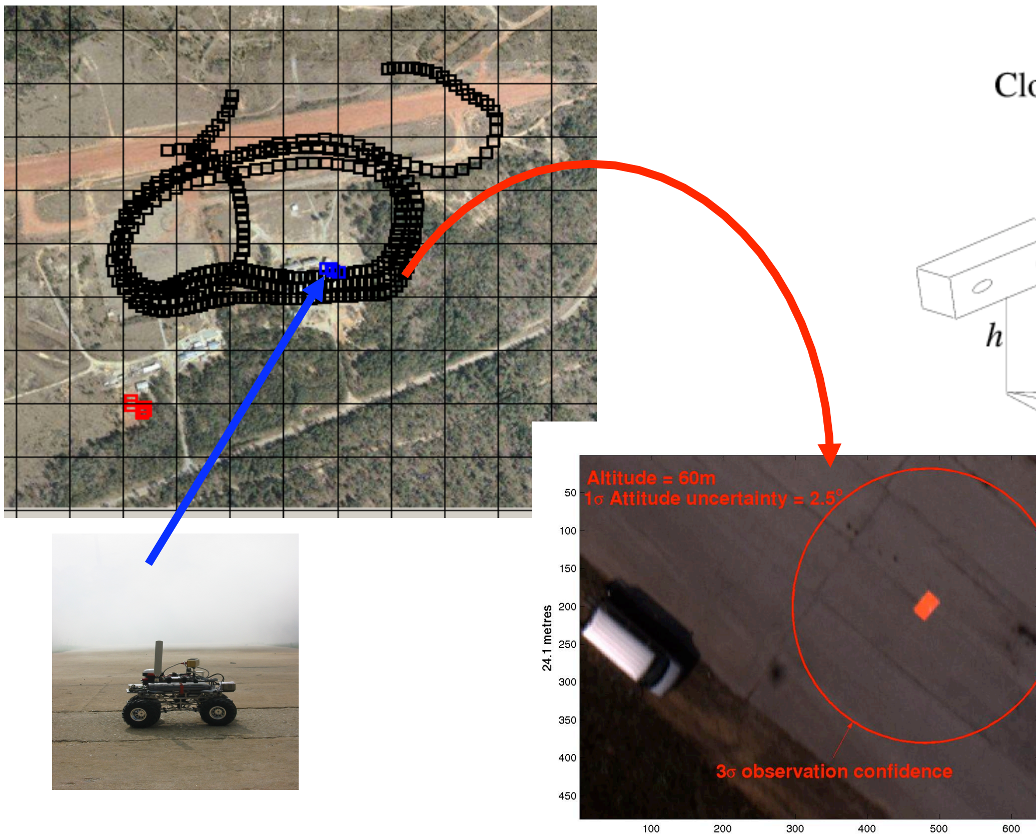
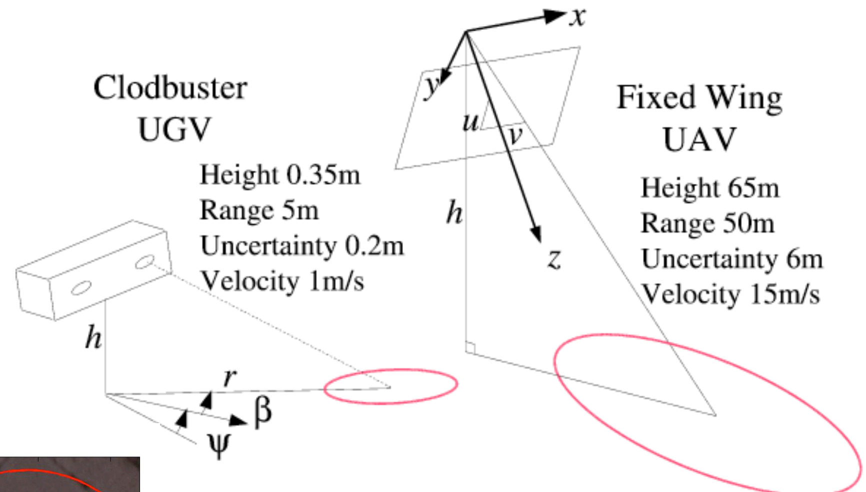
Problem Definition

- *N* robots **explore** an unknown (or partially known) environment
- Achieve **coverage** of the environment
- **Track** detected targets during coverage
- **Share tasks** in a fair manner
- From localization and tracking targets to mapping unknown environments
- Decentralization, anonmity

Cooperative search, identification, and localization





with decentralized control and anonymous sensors

Grocholsky, B., Keller, J., Kumar, V. and Pappas, G. "Cooperative Air-Ground Surveillance," *IEEE Robotics and Automation Magazine*, Vol. 13 (3), 2006: 16-25

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Information Model: Shared

Approximate model

$$\begin{bmatrix} x^R_{k+1} \\ x^T_{k+1} \end{bmatrix} = \begin{bmatrix} x^R_k \\ x^T_k \end{bmatrix} + \begin{bmatrix} u_{k+1} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z^R_k \\ z^T_k \end{bmatrix} = \begin{bmatrix} x^R_k \\ h(x^T_k) \end{bmatrix} + \begin{bmatrix} 0 \\ v_k \end{bmatrix}$$

No noise

$$v_k \sim N(0, R_k)$$

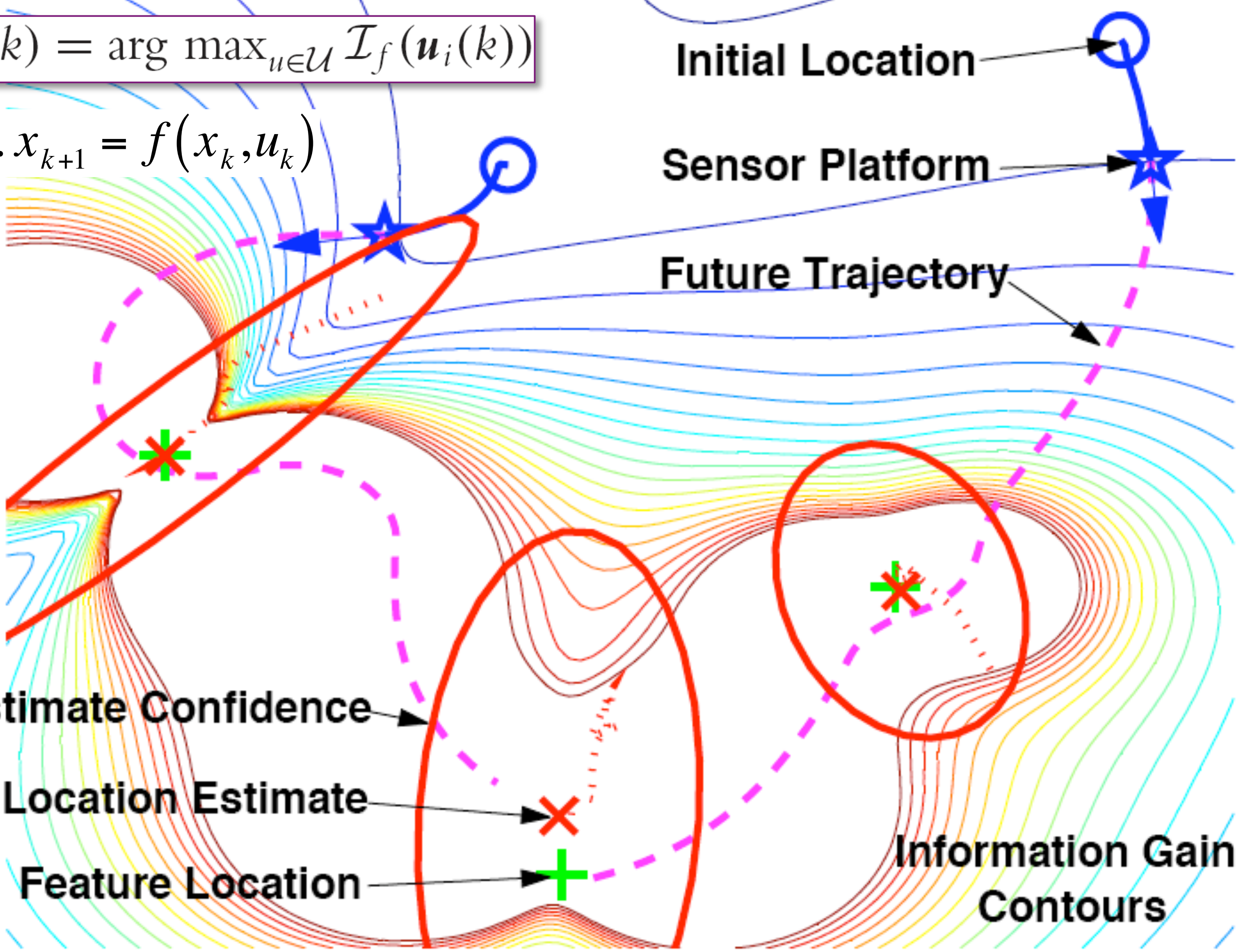
$$P_k = E(x_k x'_k) \qquad Y_k = P_k^{-1}$$

$$Y_{k+1} = Y_k + I_k \qquad I_k = H_k^T R_k^{-1} H_k$$

Locally Optimal Controller

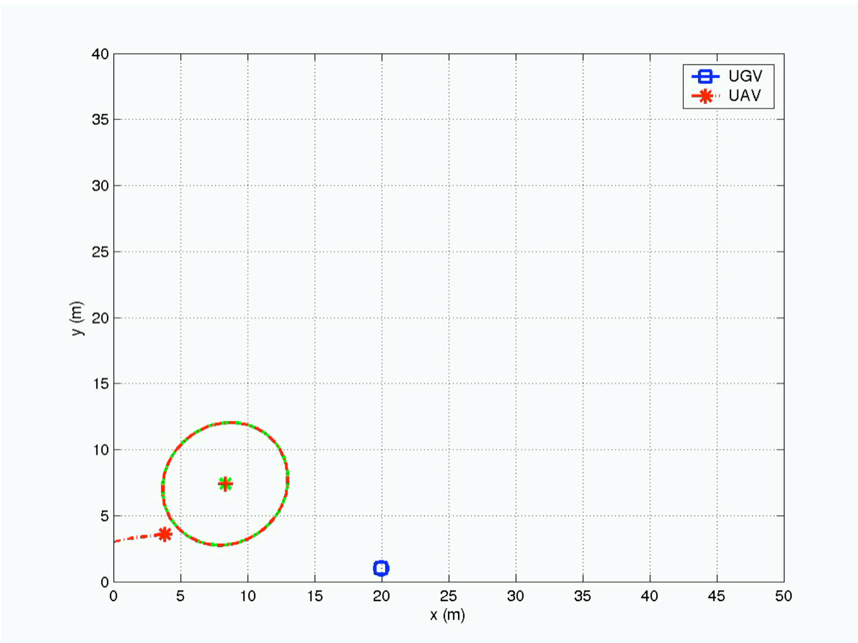
$$\boldsymbol{u}_i(k) = \arg\max_{u \in \mathcal{U}} \mathcal{I}_f(\boldsymbol{u}_i(k))$$

$$s.t.\ x_{k+1} = f(x_k, u_k)$$

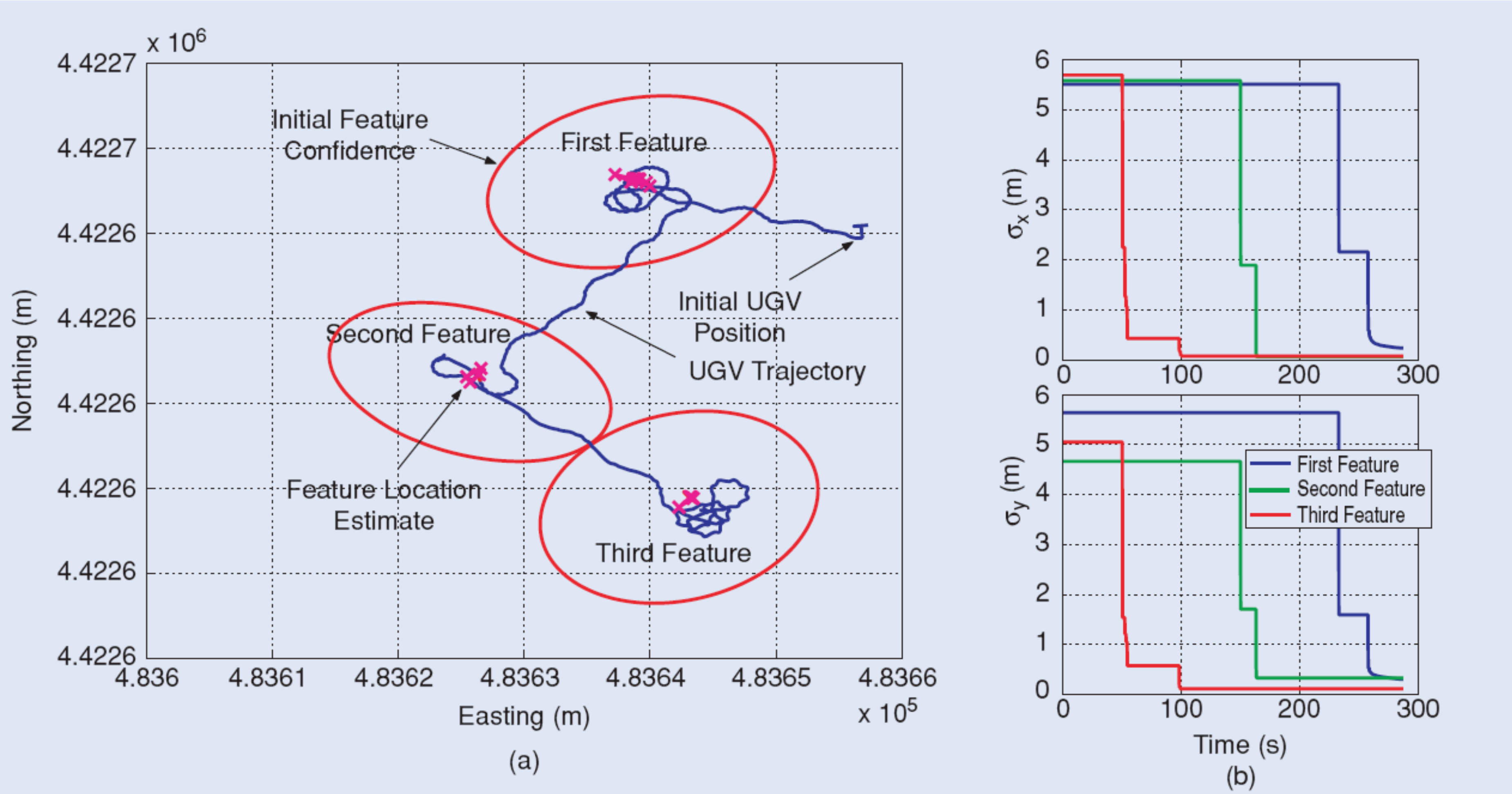


UAV search pattern

UGV identification and localization of potential targets



Localization of Targets



Grocholsky, B., Keller, J., Kumar, V. and Pappas, G. “Cooperative Air-Ground Surveillance,” *IEEE Robotics and Automation Magazine*, Vol. 13 (3), 2006: 16-25

Locational Optimization: A Framework for Allocating Tasks

$$\mathcal{H}(P) = \boxed{\int_Q} \boxed{\min_{i \in \{1,\ldots,n\}}} \boxed{f(d(\mathbf{q}, \mathbf{p}_i))} \phi(\mathbf{q}) d\mathbf{q}$$

Density Function

Integral across the environment Q

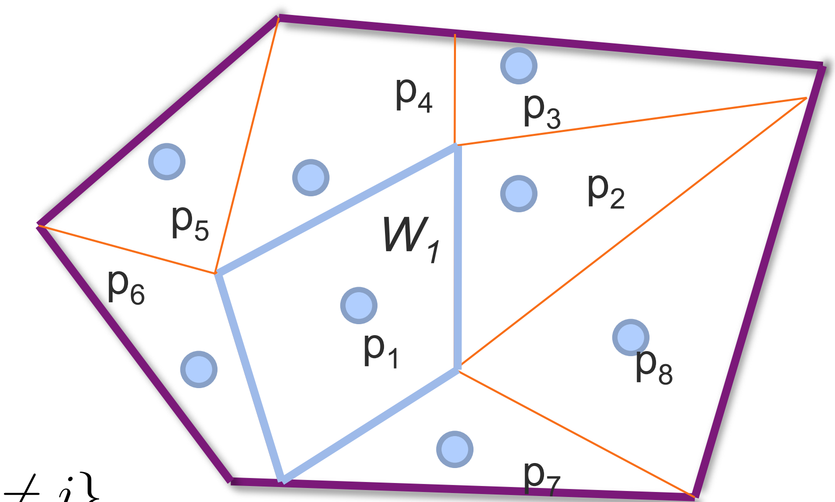
Sensor that has most influence on location q

Monotonically increasing function of distance

$$\mathcal{H}(P, W) = \sum_{i=1}^{n} \int_{W_i} f(d(\mathbf{q}, \mathbf{p}_i)) \phi(\mathbf{q}) d\mathbf{q}$$

$$V(P) = \underset{W}{\text{argmin}}\, \mathcal{H}(P, W)$$

Voronoi Tesselation



$$V_i(P) = \{\mathbf{q} \in Q \mid d(\mathbf{q}, \mathbf{p}_i) \leq d(\mathbf{q}, \mathbf{p}_j), \forall j \neq i\}$$

L. Pimenta, M. Schwager, Q. Lindsey, V. Kumar, and D. Rus. Simultaneous coverage and tracking (SCAT) of moving targets with robot networks. *8th Int. Workshop on the Algorithmic Foundation of Robotics*, Guanajuato, Mexico, December 2008.

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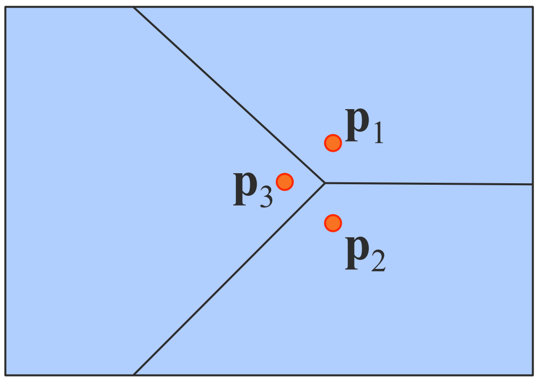
Previous work by Bullo, Cortez, Martinez

Assignment for Exploration and Coverage (*known environment*)

Voronoi Tesellation:

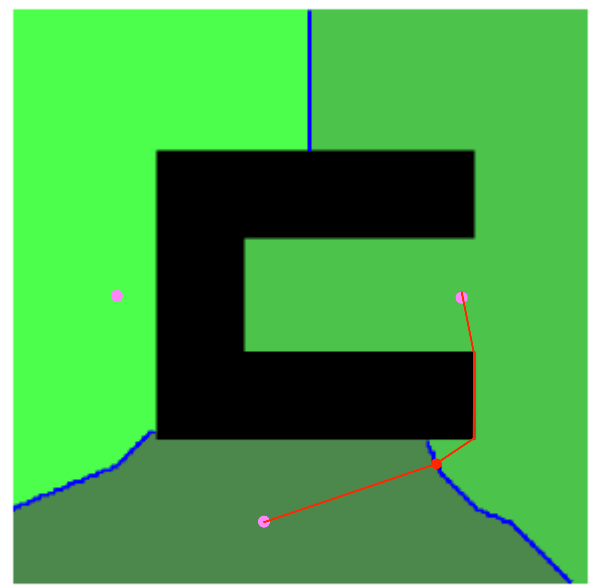


Ω

$$V_i(P) = \{\mathbf{q} \in \Omega \,|\, d(\mathbf{q}, \mathbf{p}_i) \leq d(\mathbf{q}, \mathbf{p}_j), \forall j \neq i\}$$

In non-convex environments:

d is the *Geodesic* Distance



L. Pimenta, V. Kumar, R, Mesquita and G. Pereira, Sensing and Coverage for a Network of Heterogeneous Robots, Proceedings of the 47th IEEE International Conference on Decision and Control (CDC'08). Dec 9-11, Cancun, Mexico.

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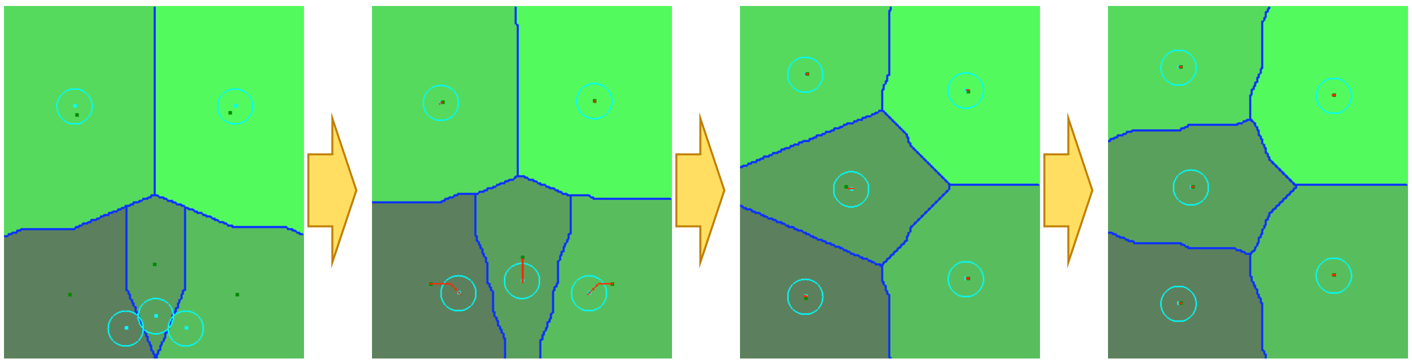
Continuous time Lloyd's Algorithm

$$min \quad \mathcal{H}(P, V(P)) = \sum_{i=1}^{n} \int_{V_i} f(d(\mathbf{q}, \mathbf{p}_i))\phi(\mathbf{q})d\mathbf{q}$$



$$\mathbf{u}_i = k(\mathbf{C}_{V_i} - \mathbf{p}_i) \qquad \mathbf{C}_{V_i} = \frac{\int_{V_i} \mathbf{q}\phi(\mathbf{q})d\mathbf{q}}{\int_{V_i} \phi(\mathbf{q})d\mathbf{q}}$$

Follow gradient of $\mathcal{H}$

$$\frac{\partial \mathcal{H}}{\partial \mathbf{p}_i} = \int_{V_i(P)} \frac{\partial}{\partial \mathbf{p}_i} f(d(\mathbf{q}, \mathbf{p}_i))\phi(\mathbf{q})d\mathbf{q}$$

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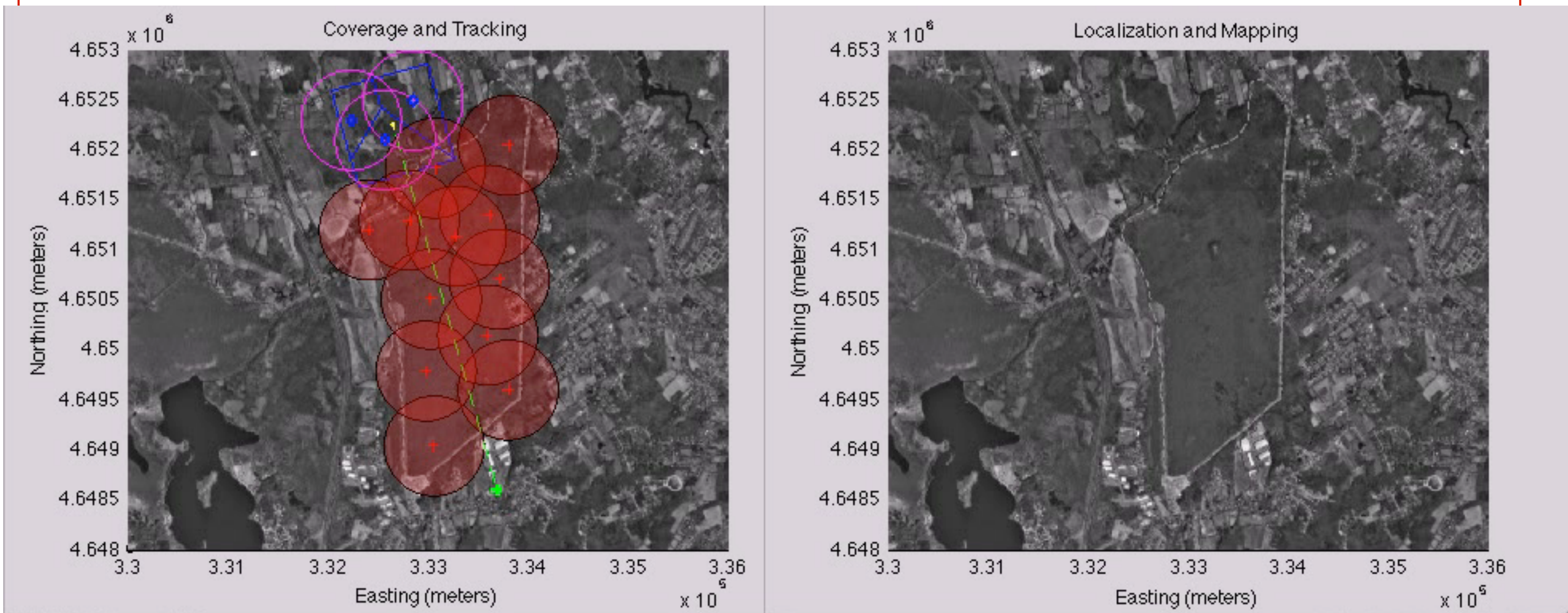
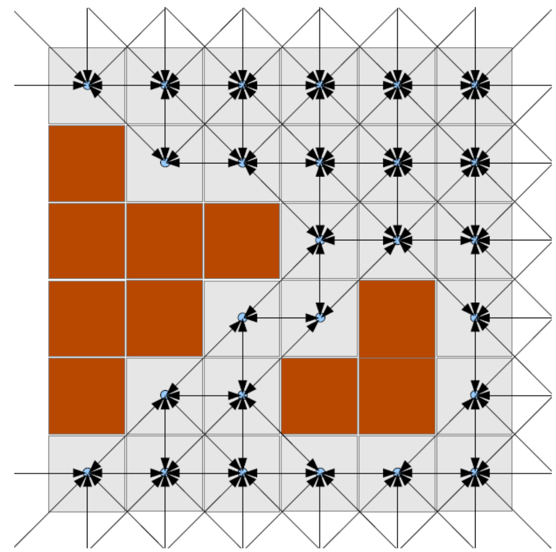
Coverage and Tracking



L. Pimenta, M. Schwager, Q. Lindsey, V. Kumar, and D. Rus. Simultaneous coverage and tracking (SCAT) of moving targets with robot networks. *8th Int. Workshop on the Algorithmic Foundation of Robotics*, Guanajuato, Mexico, December 2008.

Unknown Environments



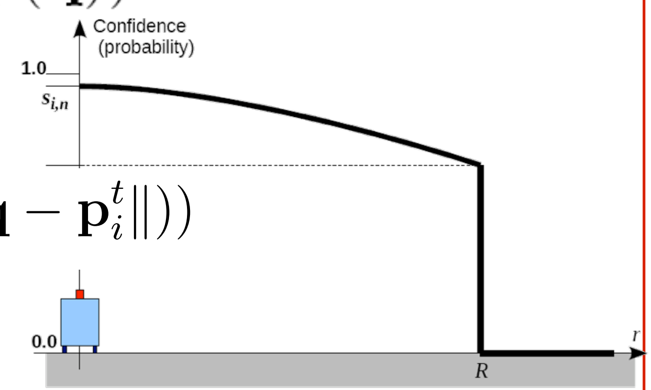
Discretize the environment

Geodesic metric

$$V_i = \{\mathbf{q} \in \mathcal{V}(\mathcal{G}_\Omega) \mid g_i(\mathbf{q}) \leq g_j(\mathbf{q}), \forall j \neq i\}$$

Entropy of the occupancy grid

$$e(\mathbf{q}) = p(\mathbf{q}) \ln(p(\mathbf{q})) + (1 - p(\mathbf{q})) \ln(1 - p(\mathbf{q}))$$



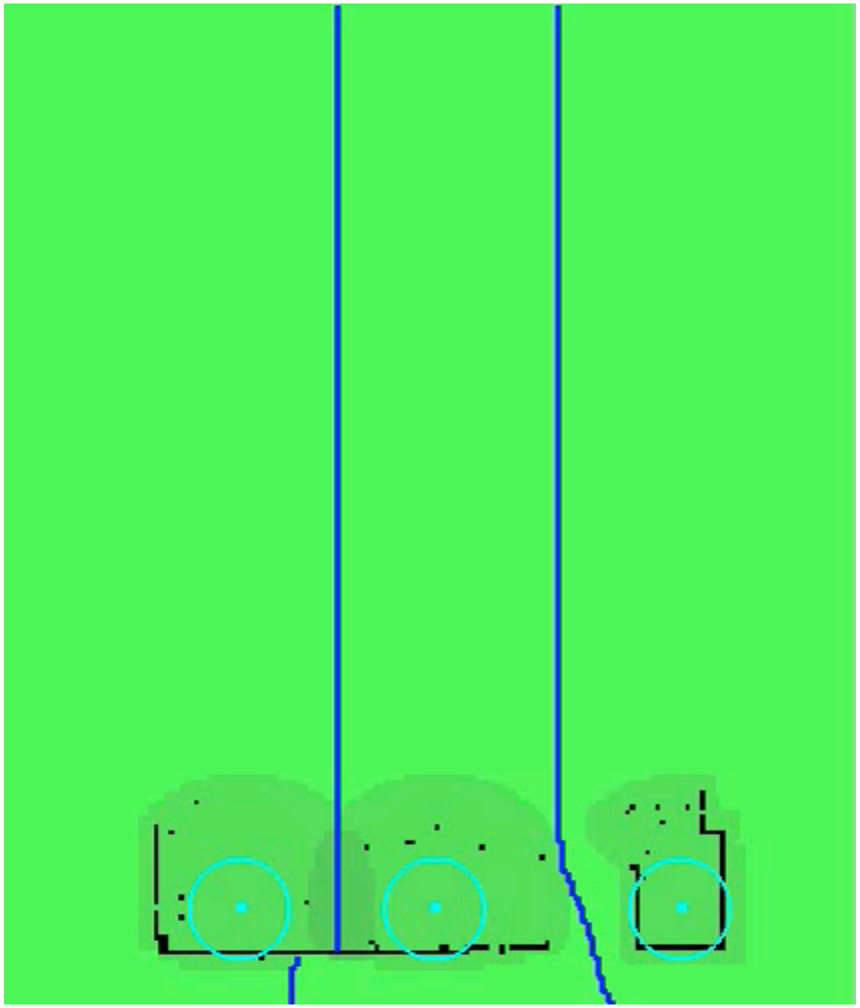
Sensor model

$$p_i^t(\mathbf{q}) = z_i^t(\mathbf{q})\, s_i(\|\mathbf{q} - \mathbf{p}_i^t\|) + (1 - z_i^t(\mathbf{q}))(1 - s_i(\|\mathbf{q} - \mathbf{p}_i^t\|))$$

Time-varying density function

$$\phi(\mathbf{q}, t) = e(\mathbf{q}, t) = p^t(\mathbf{q}) \ln(p^t(\mathbf{q})) + (1 - p^t(\mathbf{q})) \ln(1 - p^t(\mathbf{q}))$$

Representative Example



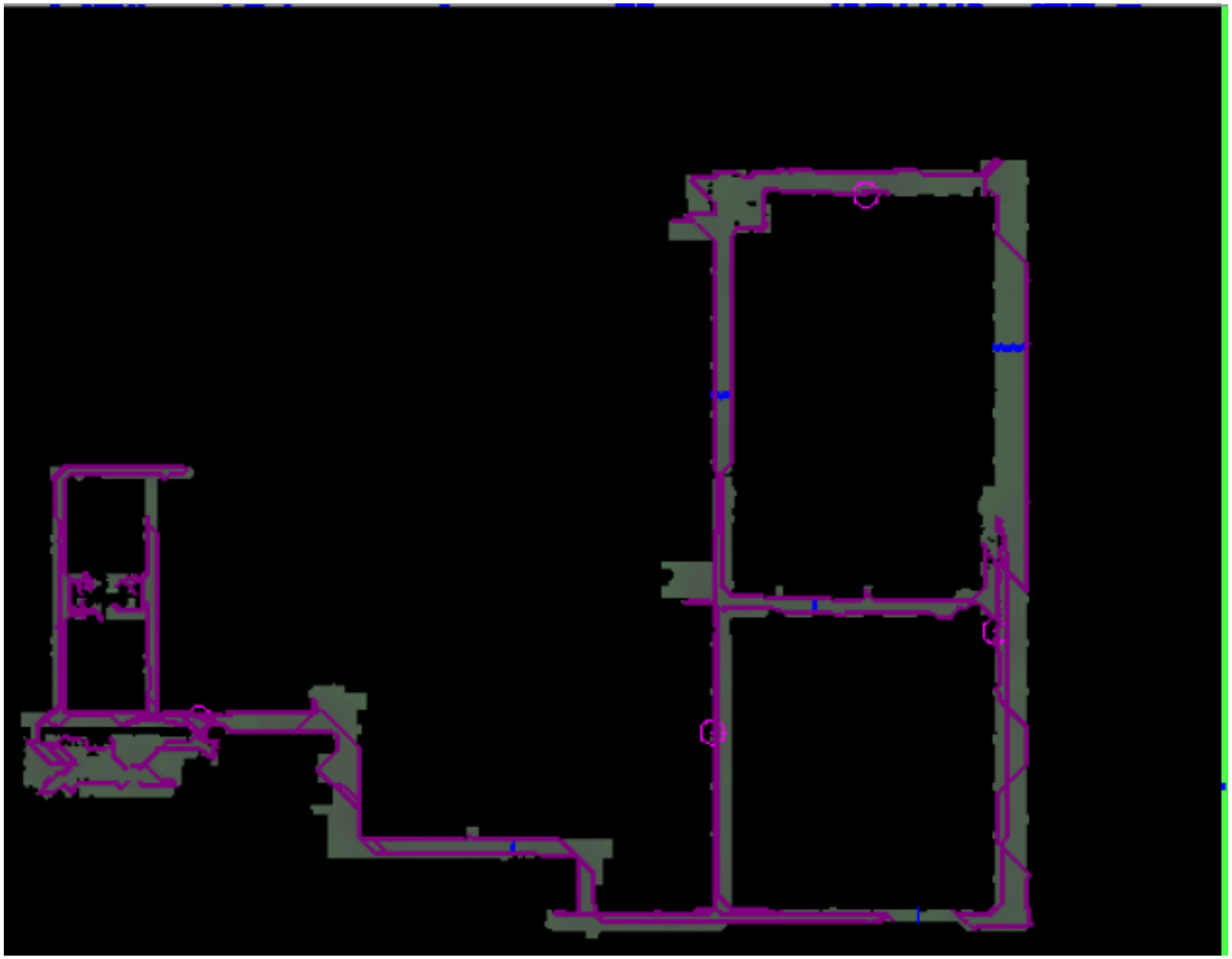
3 robots

Convergence to a state where the entropy of each reachable cell is below τ

Each iteration (time-step) takes about 0.1 s for each robot

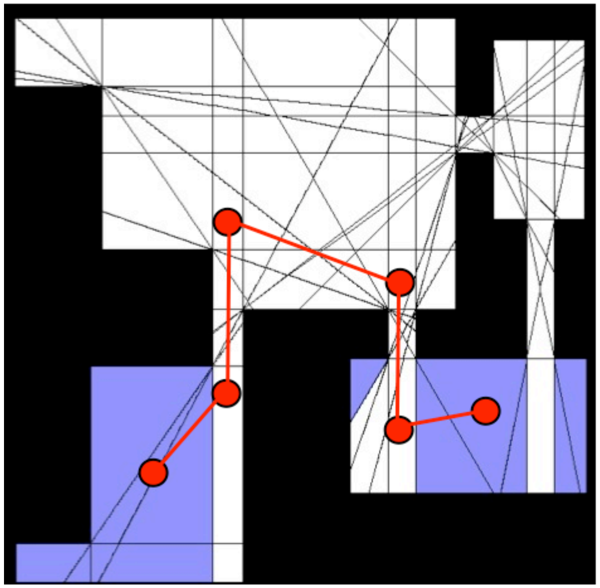
S. Bhattacharya, N. Michael and V. Kumar, "Distributed Coverage and Exploration in Unknown Non-Convex Environments," *10th International Symposium on Distributed Autonomous Robots*, Lausanne, Switzerland, Nov 1-3, 2010.

Mapping three interconnected buildings

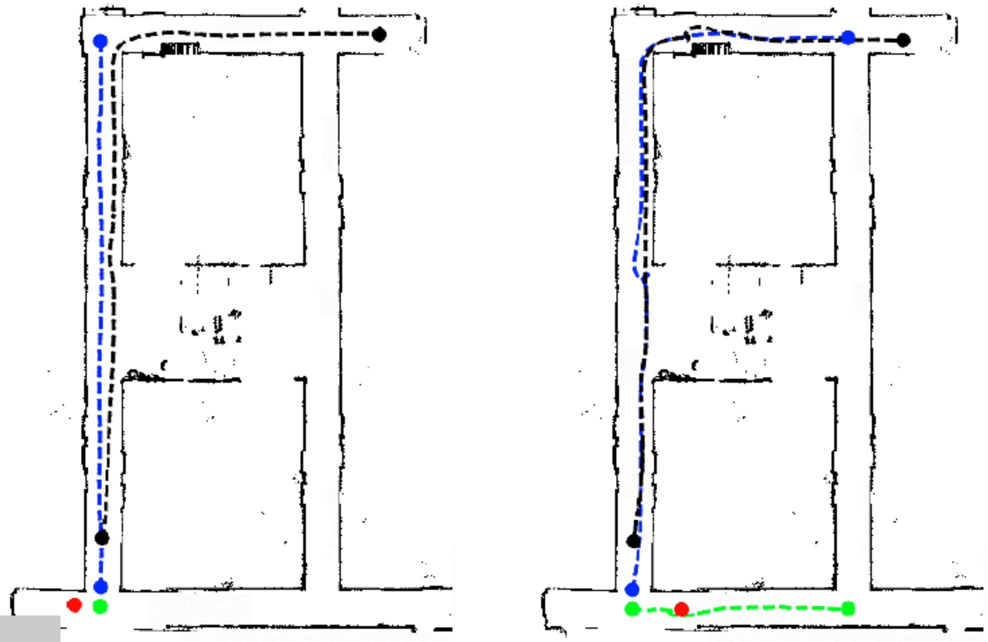


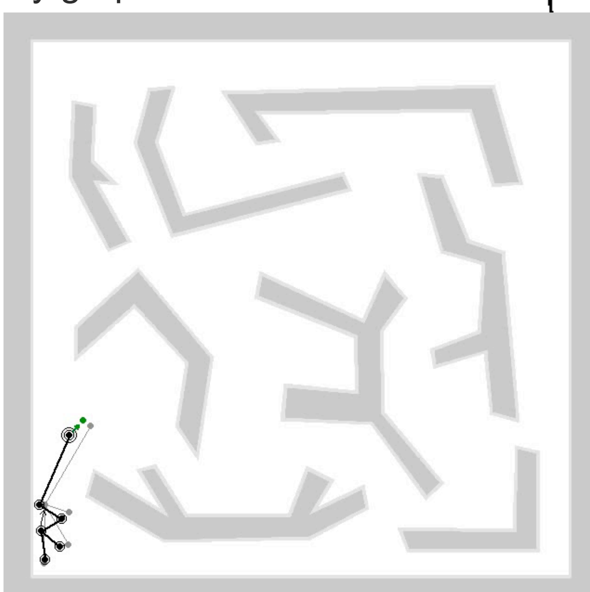
t = 2800

Visibility-Based Communication

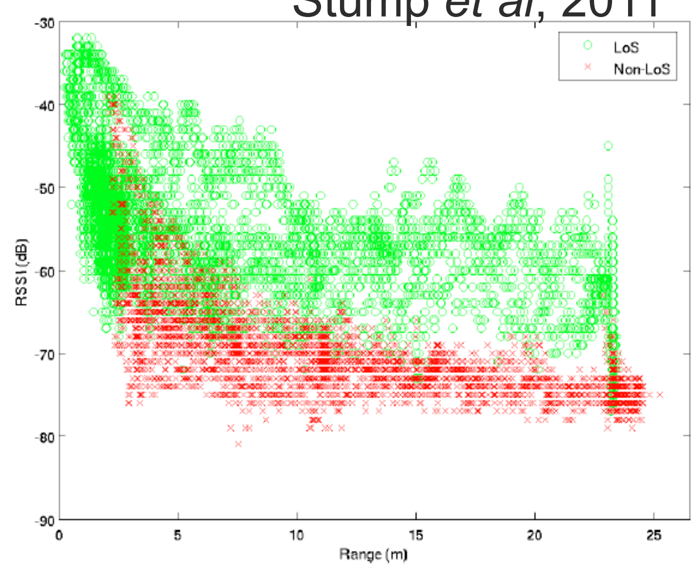


Mutual visibility graphs for line of sight control



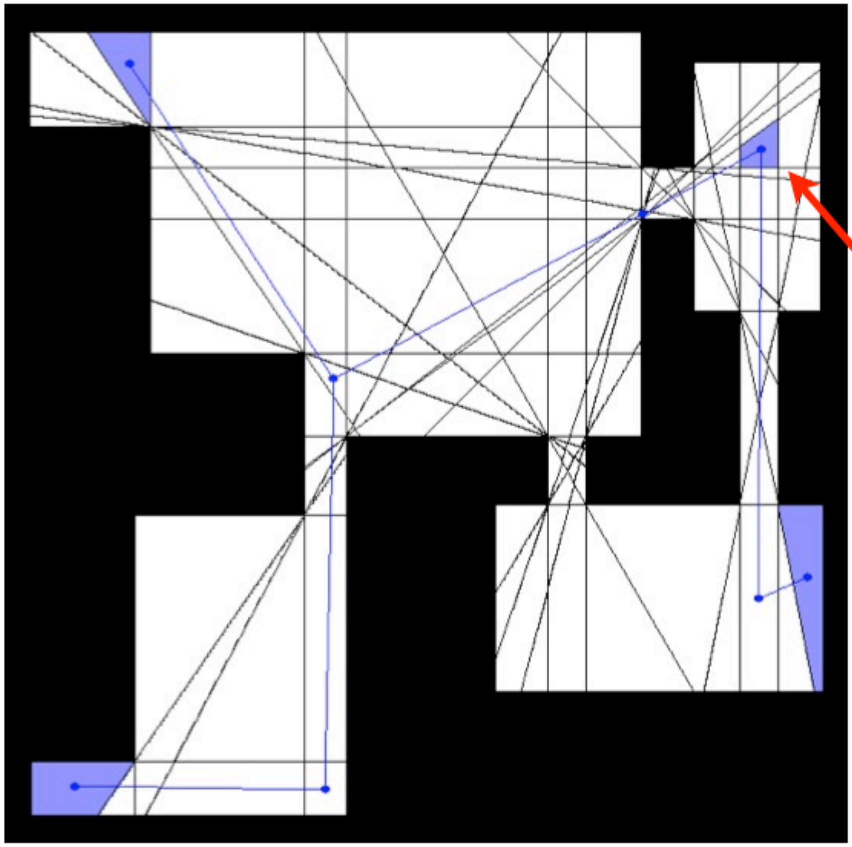


Stump *et al*, 2011



Line-of-sight connectivity

Approximating Steiner Trees



Terminal is not a leaf

Steiner count = 4 (N = 9)

E. Stump, Control for Localization and Connectivity Maintenance, *PhD dissertation*, University of Pennsylvania, 2009.

Conclusion

- Ability to create/control agile, micro UAVs
- 3-D state estimation, mapping is challenging
- Exploration, persistent surveillance require decentralized algorithms for coverage, mapping, localization and tracking
- Concurrent control of routing and mobility to enable cooperative surveillance