Robot Planning in the Real World: Research Challenges and Opportunities
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Control and Planning for Agile Aerial Vehicles

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Acknowledgements
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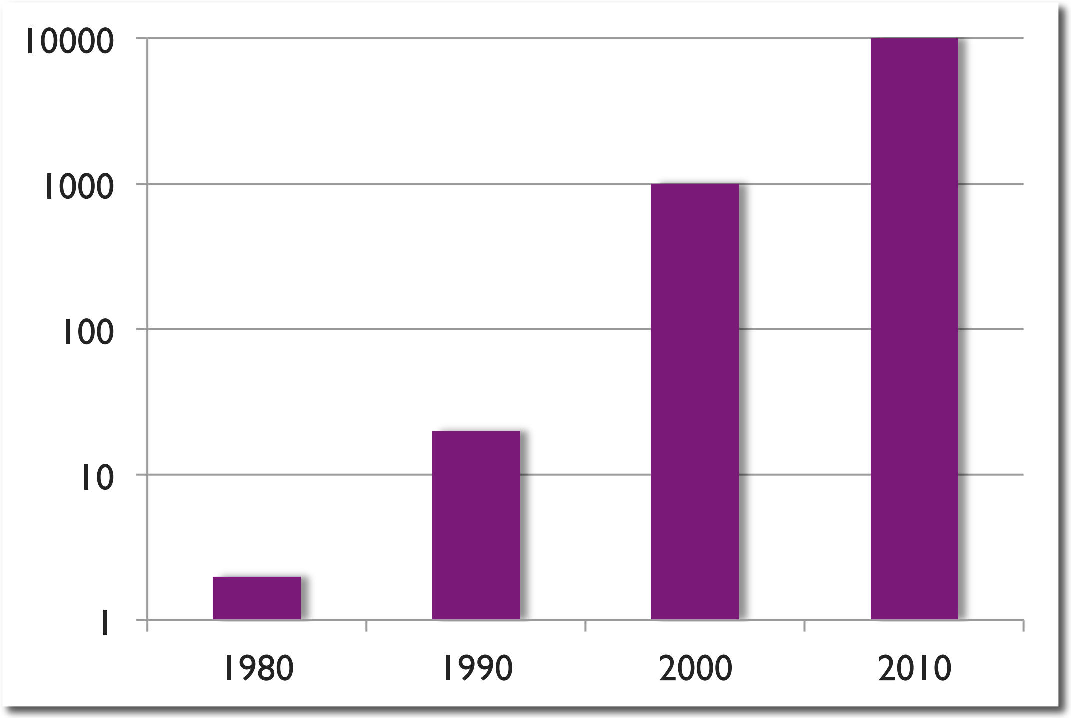
Unmanned Aerial Vehicles

Number of UAVs worldwide



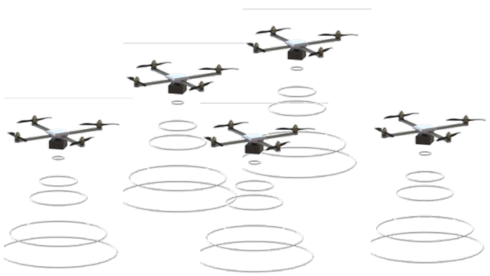
> $10B industry

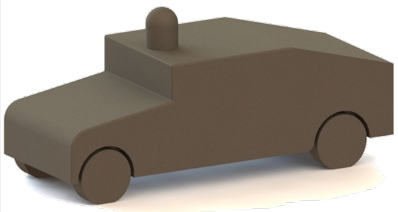
- Military: Surveillance, force protection, warfare (> 75 countries)
- Civilian commercial: Transport, environment
- Civilian private: DIY Drones

MATTERNET

SKYCATCH

HALO DROP





IDENTIFIED TECHNOLOGIES

KMel ROBOTICS

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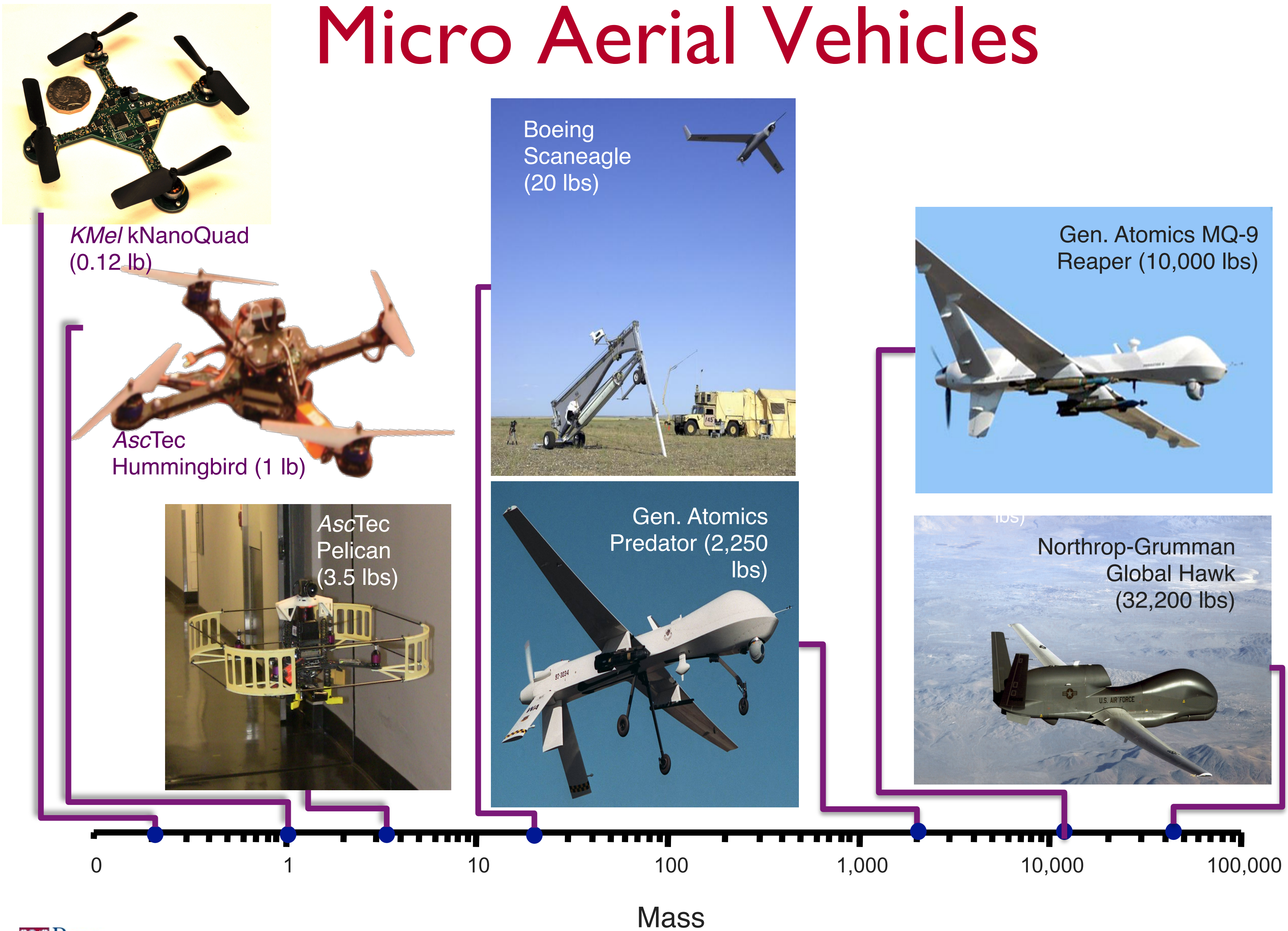
Micro Aerial Vehicles



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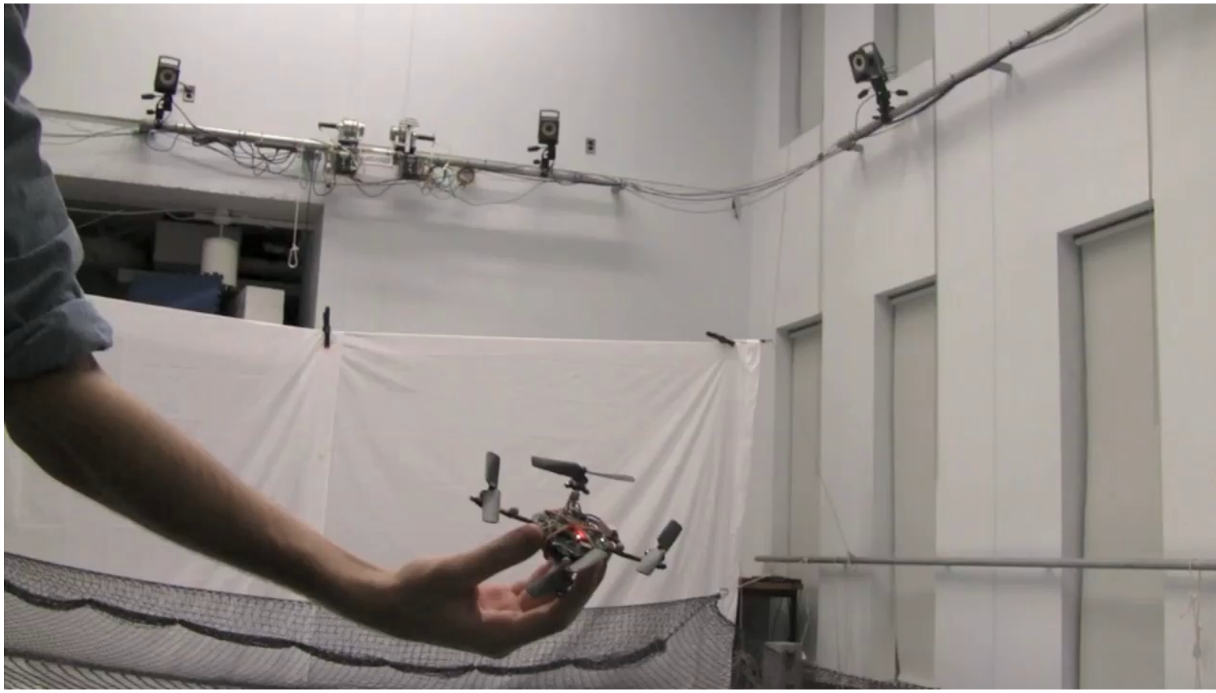
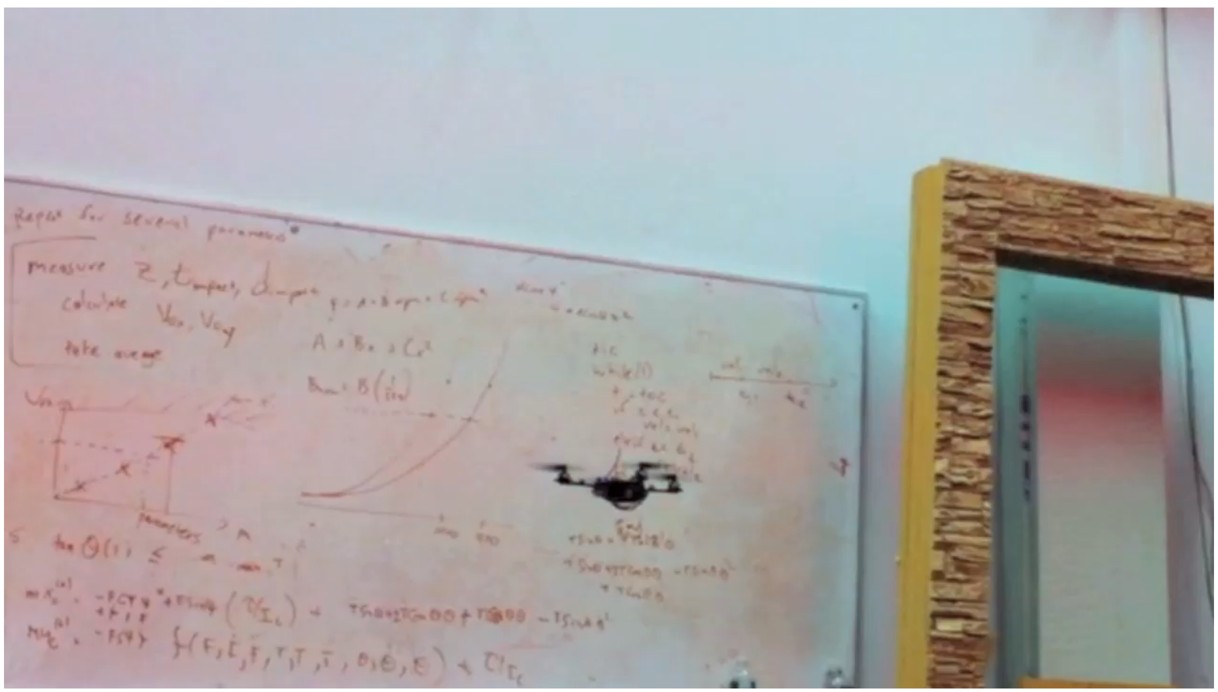
Images from www.af.mil





[*Kushleyev, Mellinger and Kumar* 2012]

First Response

Operate indoors and outdoors

No GPS

Small, maneuverable

Agile, fast

Operate in teams

Outline

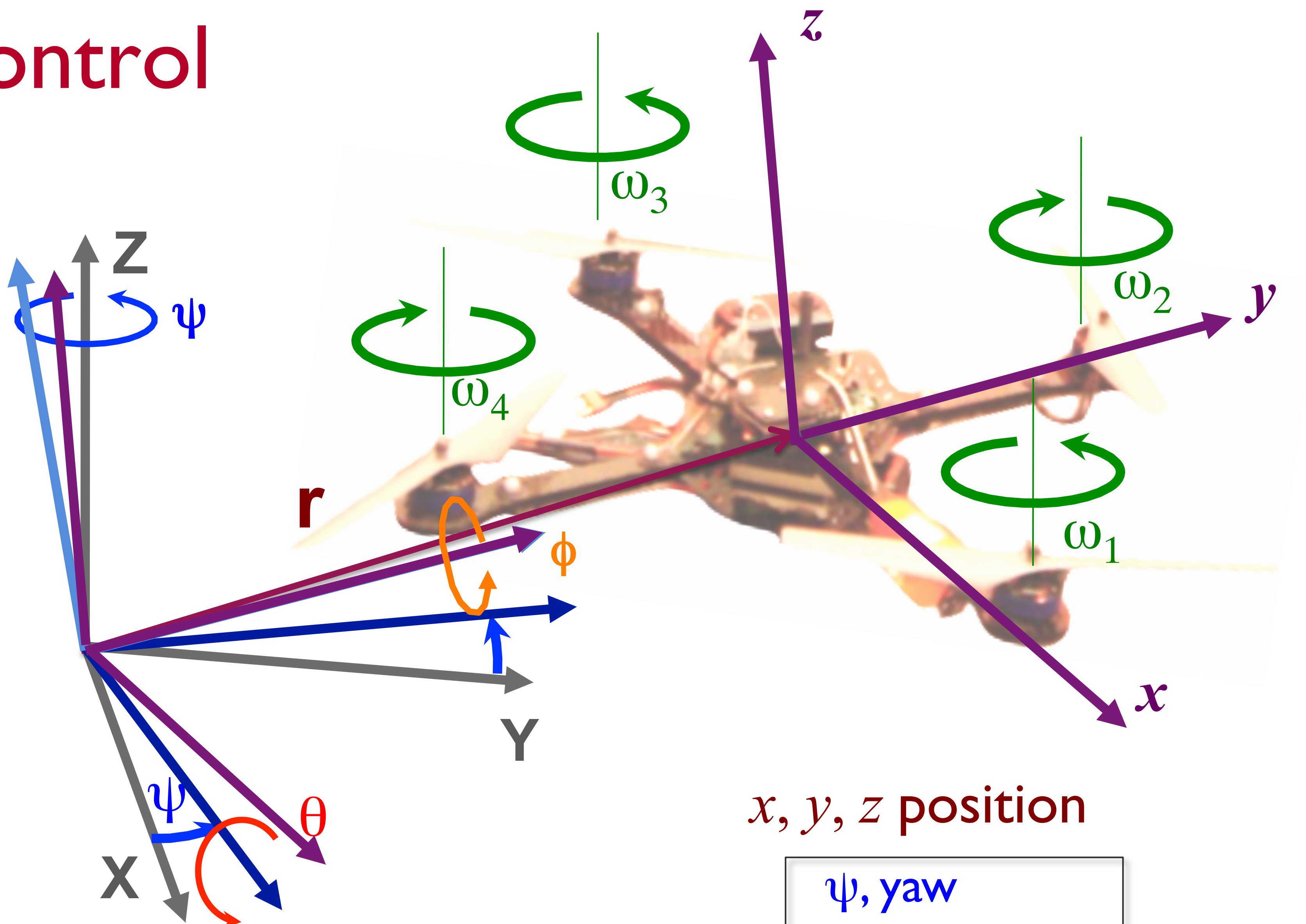
Single robot (non trivial dynamics)

- Completely known environment
- Partially known environment
- Uncertainties in state estimation

Multiple robots

- Labeled problem
- Unlabeled problem

Control



x, y, z position

ψ, yaw
θ, pitch
φ, roll

R

Underactuated

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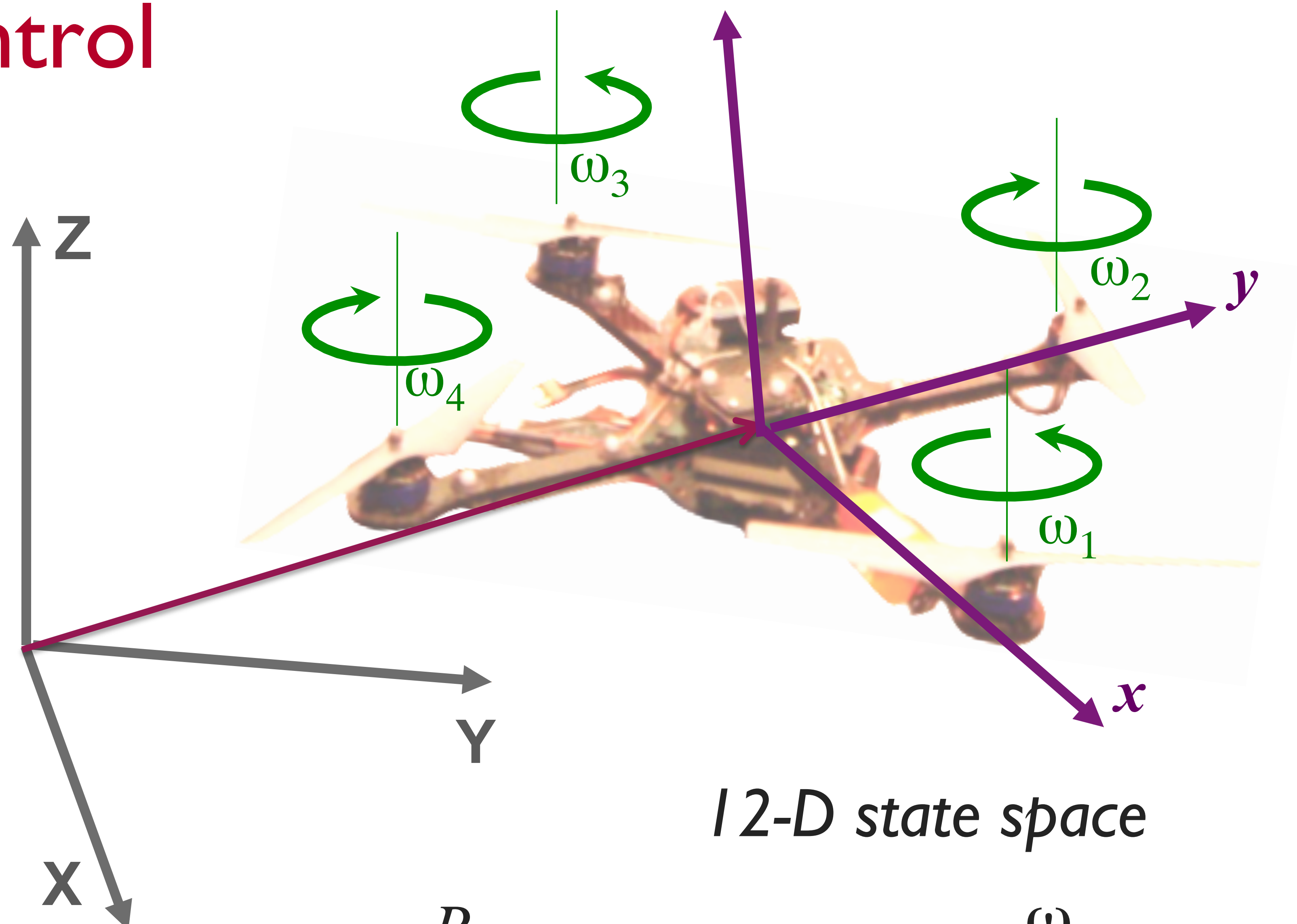
Control



12-D state space

$$\overbrace{}^{R}\qquad\qquad\overbrace{}^{\omega}$$

$$\left[x,\ y,\ z,\ \boxed{\theta,\ \phi,\ \psi,}\ \dot{x},\ \dot{y},\ \dot{z},\ \boxed{\dot{\theta},\ \dot{\psi},\ \dot{\phi}}\right]$$

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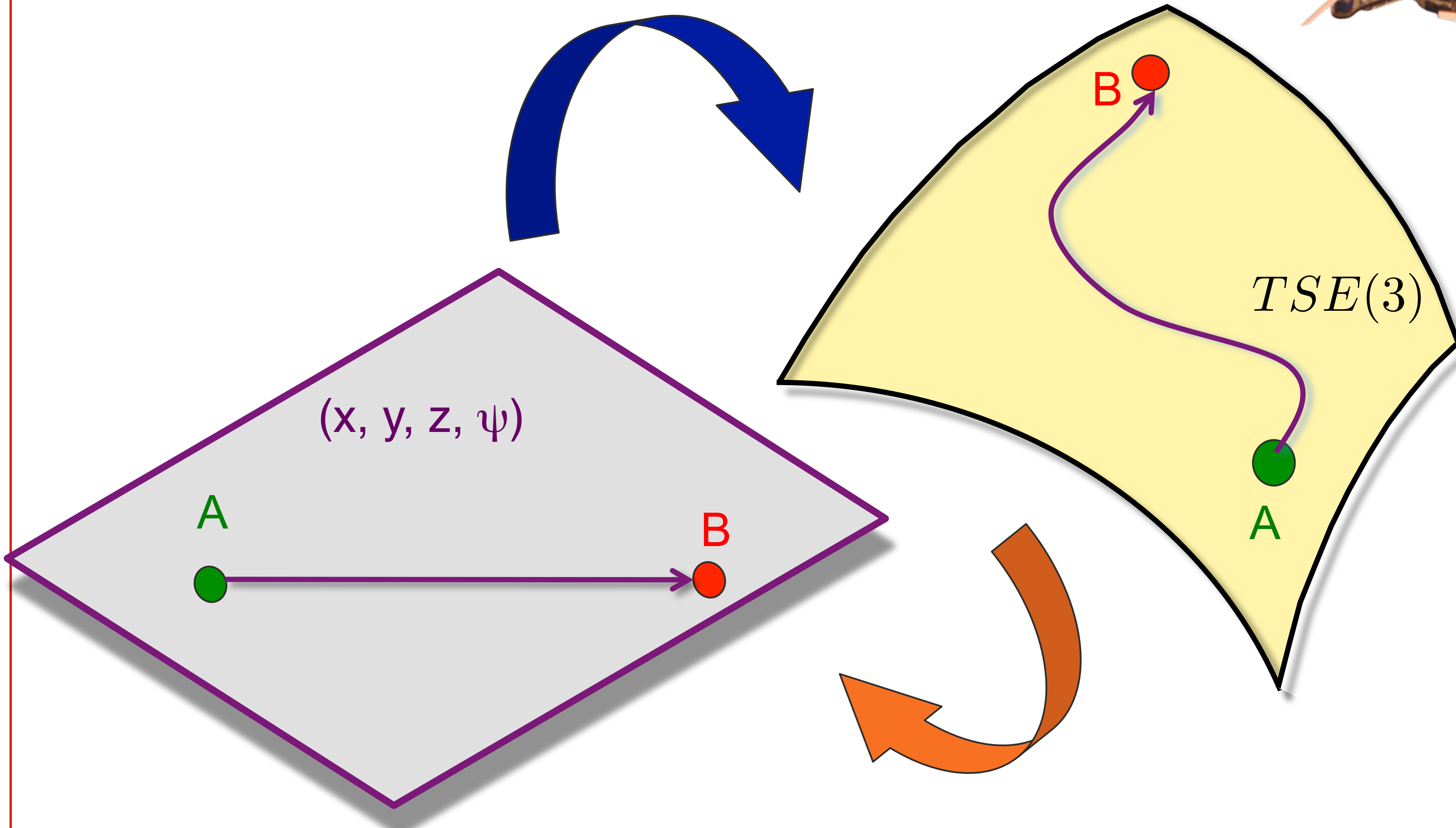
Abstraction



$$\begin{bmatrix} x \\ y \\ z \\ \theta \\ \phi \\ \psi \\ \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\theta} \\ \dot{\psi} \\ \dot{\phi} \end{bmatrix}$$

$$\min_{\sigma(t)} \int_0^T \left(\alpha \| \ddddot{\mathbf{r}} \|^2 + \beta\alpha \| \ddot{\psi} \|^2 \right) dt$$

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Differential Flatness

Inputs

$u_1, \mathbf{u}_2$

$$u_1 = \sum_{i=1}^{4} F_i \qquad \mathbf{u}_2 = L \begin{bmatrix} 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ \mu & -\mu & \mu & -\mu \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$$

State

$(\mathbf{x}, \dot{\mathbf{x}})$

σ

jerk, snap, yaw

$$\begin{bmatrix} \mathbf{r} \\ \mathbf{v} \\ \mathbf{a} \\ \mathbf{j} \\ \mathbf{s} \\ \psi \\ \dot{\psi} \\ \ddot{\psi} \end{bmatrix} \longleftrightarrow \begin{bmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \\ u_1 \\ \dot{u}_1 \\ \ddot{u}_1 \\ \mathbf{u}_2 \end{bmatrix}$$

$$u_1 = m(a_3 - \mathbf{g}.\mathbf{b}_3)$$

$$\dot{u}_1 = m j_3$$

$$\ddot{u}_1 = m s_3 + u_1(q^2 + rp)$$

$$p = \frac{-m j_2}{u_1}$$

$$q = \frac{m j_1}{u_1}$$

Fleiss et al, 1995. Flatness and defect of nonlinear systems, Int. J. Control, 1995

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Trajectory Planning

Min. Snap Trajectory

$$\min_{\sigma(t)} \int_0^T \left(\alpha \| \ddddot{\mathbf{r}} \|^2 + \beta\alpha \| \ddot{\psi} \|^2 \right) dt$$

$$\sigma(0) = \sigma_0, \ \dot{\sigma}(0) = \dot{\sigma}_0, \ldots$$

$$\sigma(T) = \sigma_T, \ \dot{\sigma}(T) = \dot{\sigma}_T, \ldots$$

Parameterization

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

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

State/Input constraints

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

Solve

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

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

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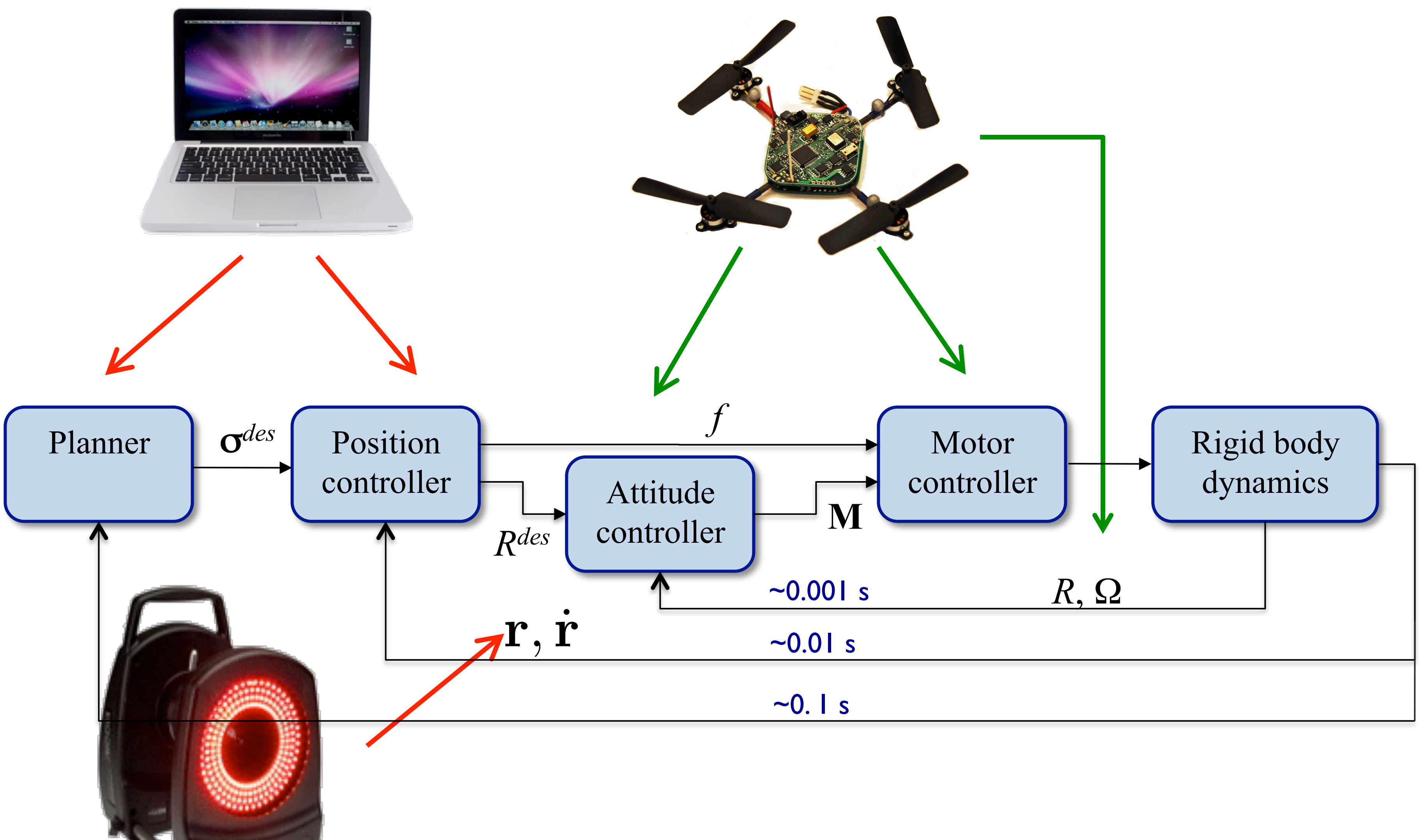
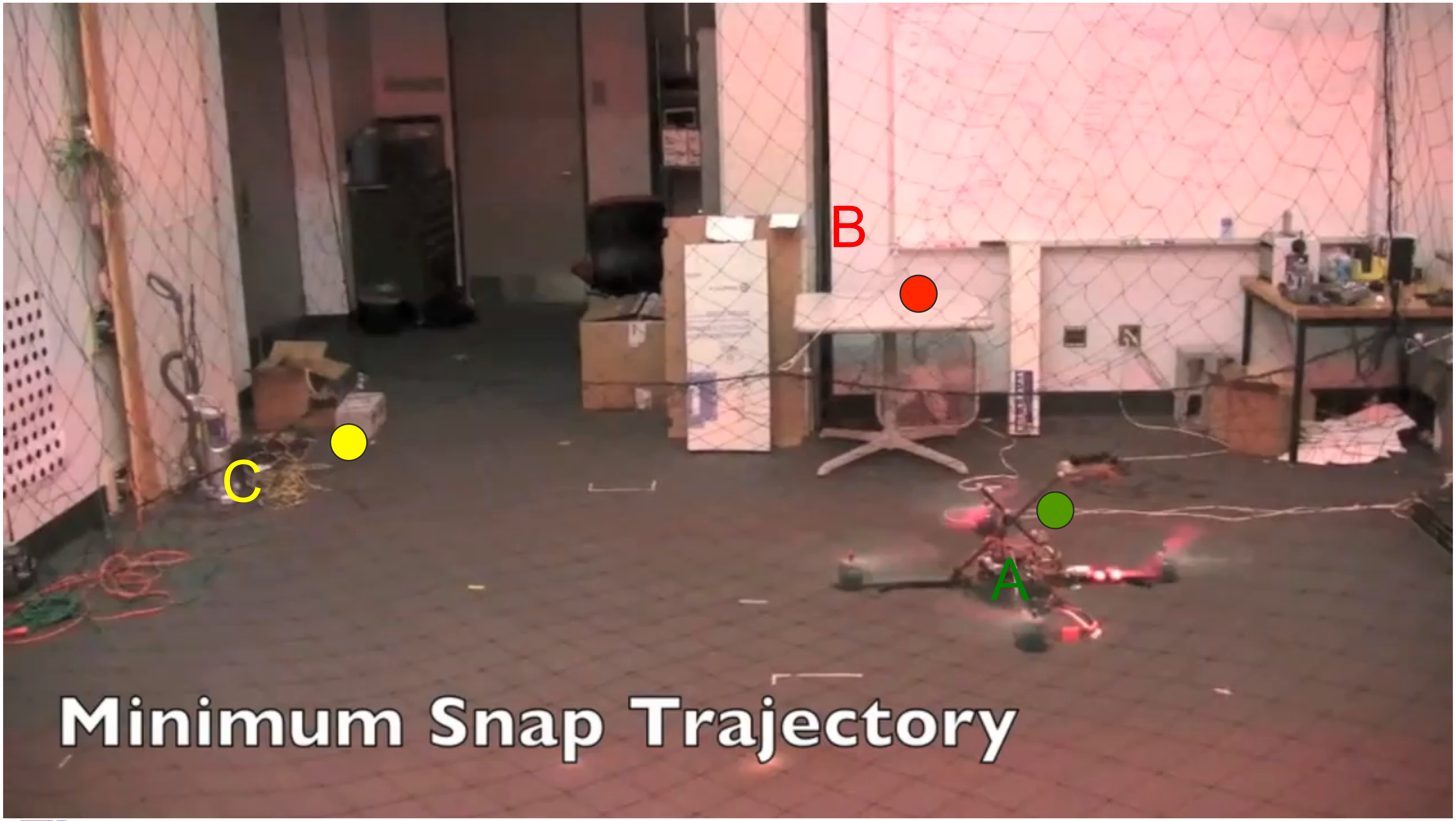
Control Software



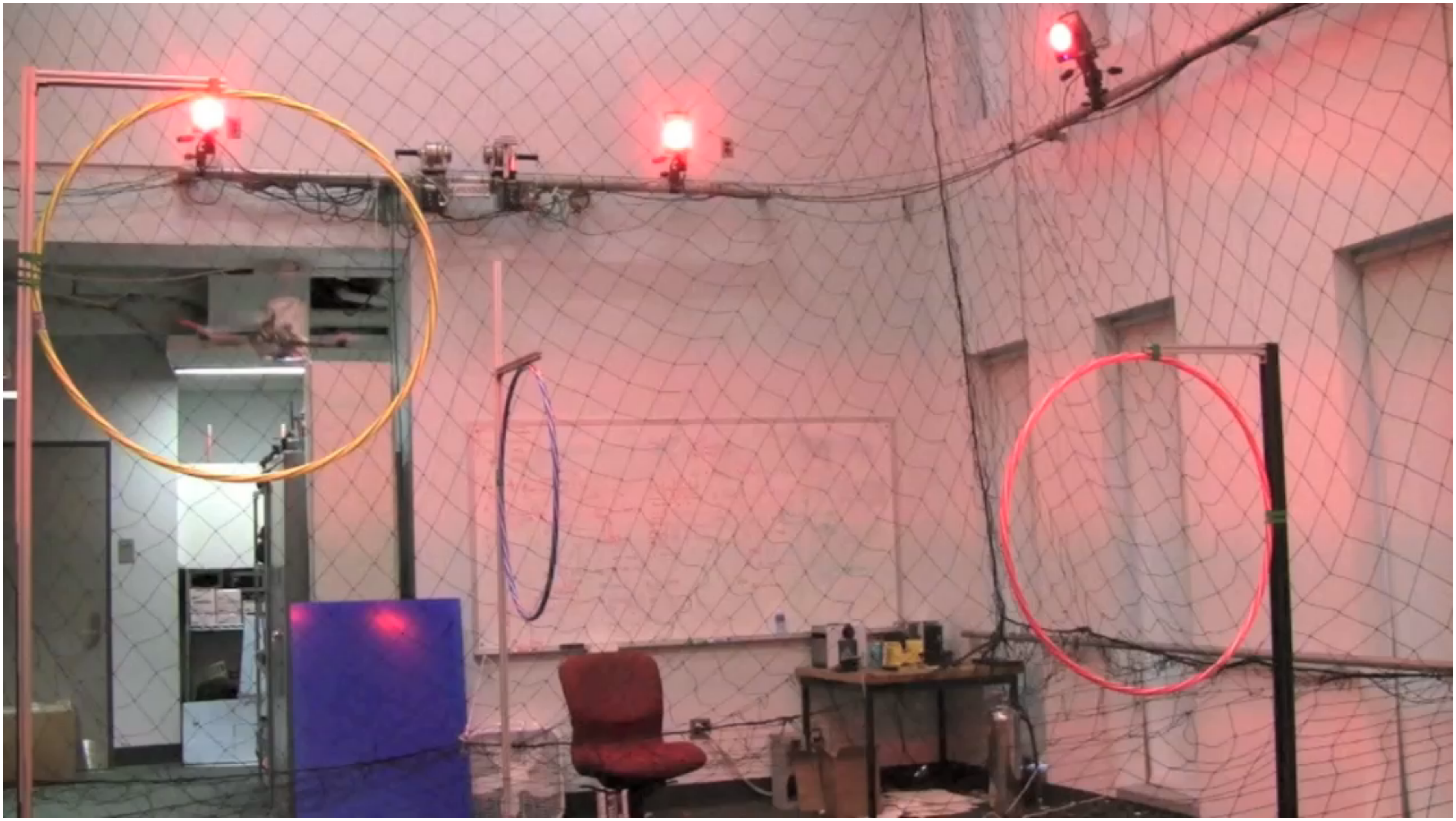
[Kraft 2003; Mellinger, Michael, and Kumar 2010; Mellinger and Kumar 2011]

Aggressive Maneuvering

[Mellinger and Kumar, ICRA 2011]



Real Time Planning



[Mellinger and Kumar, ICRA 2011]

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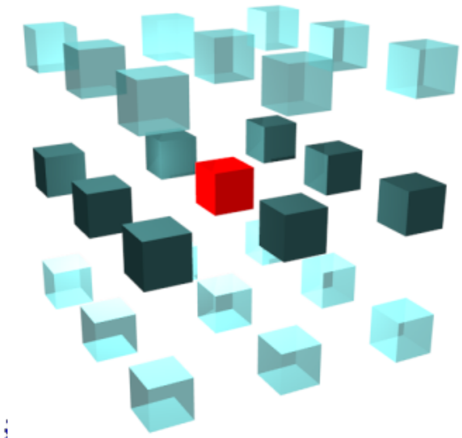
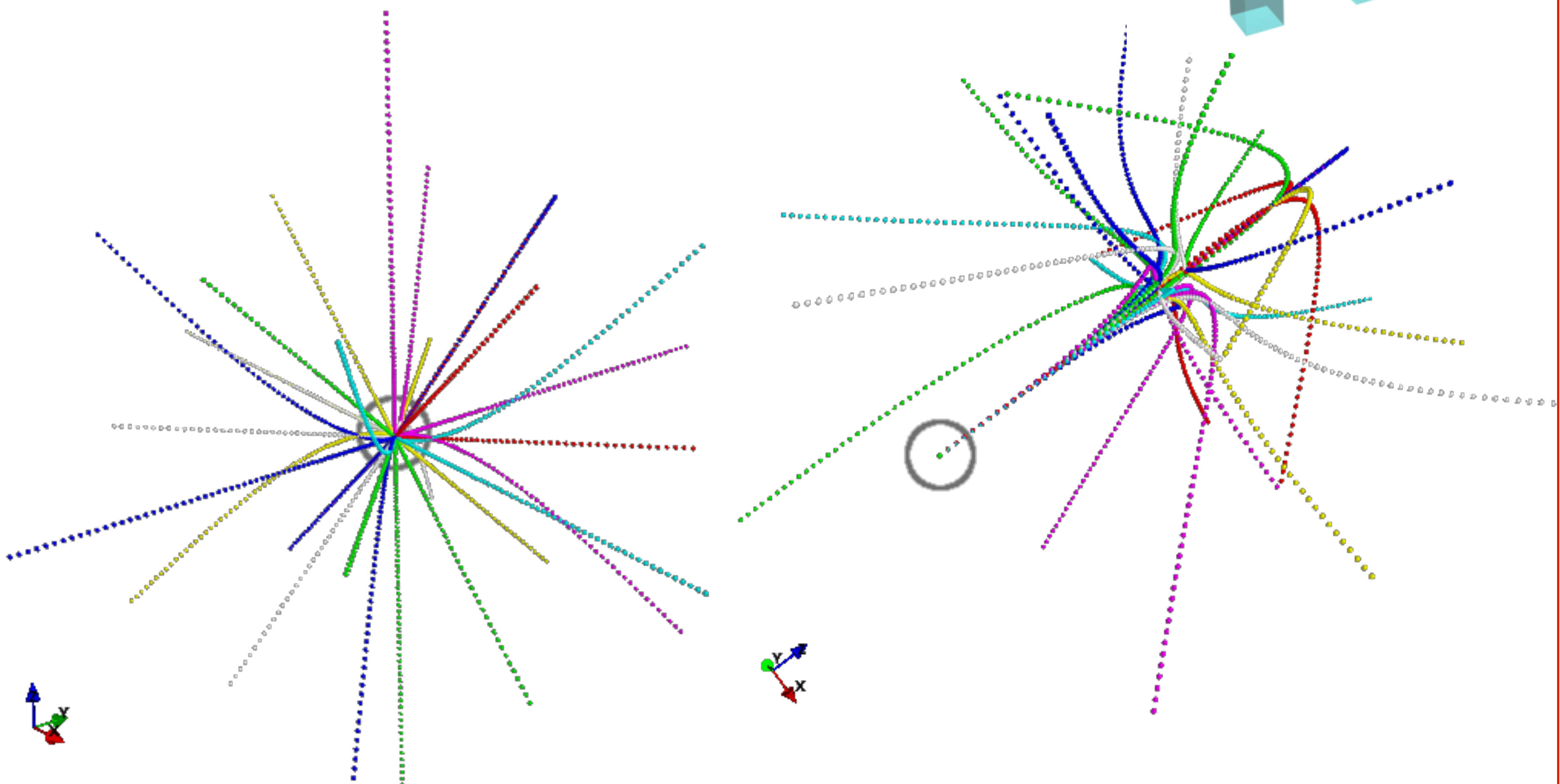
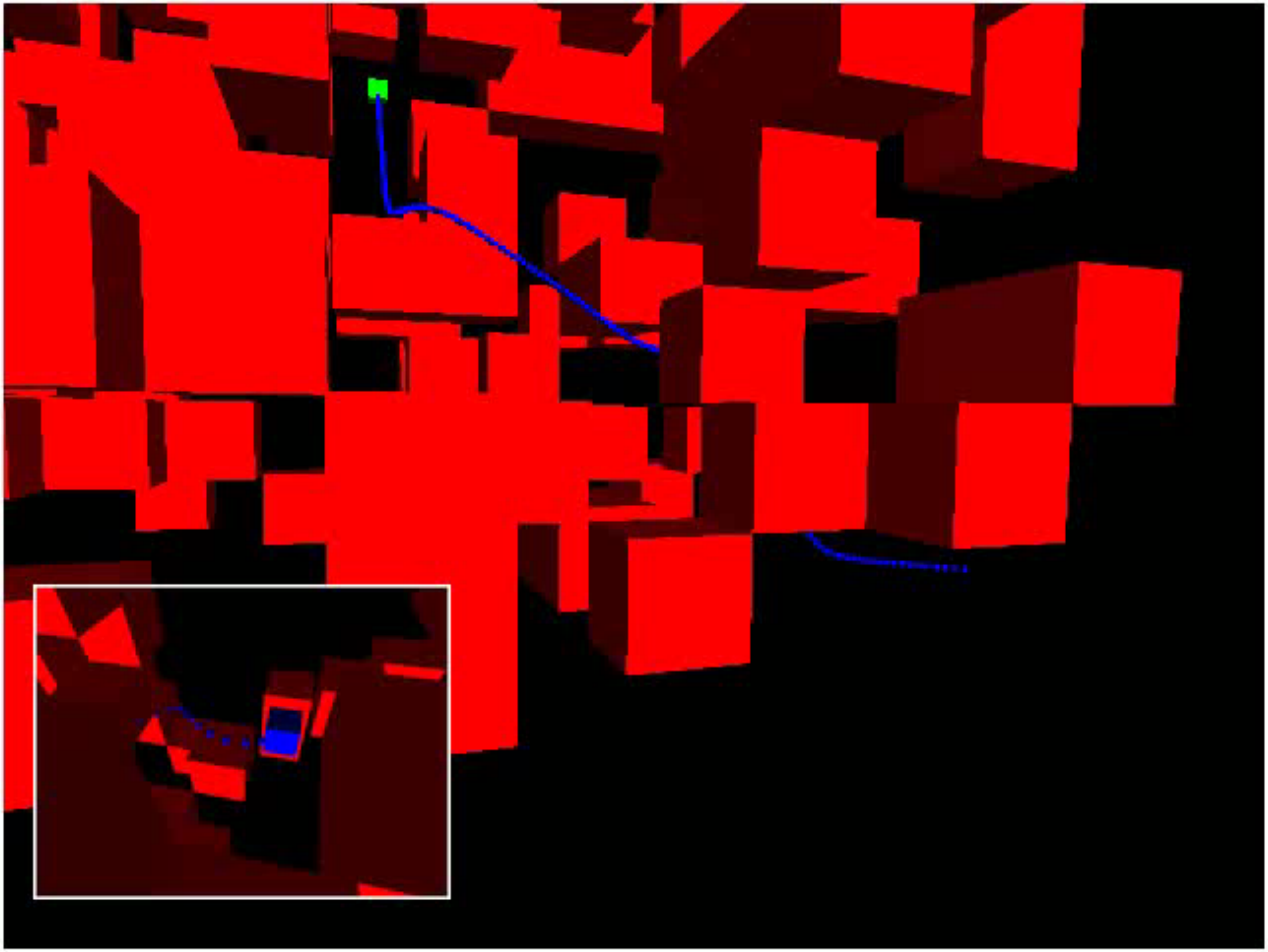
Composition of Motion Primitives



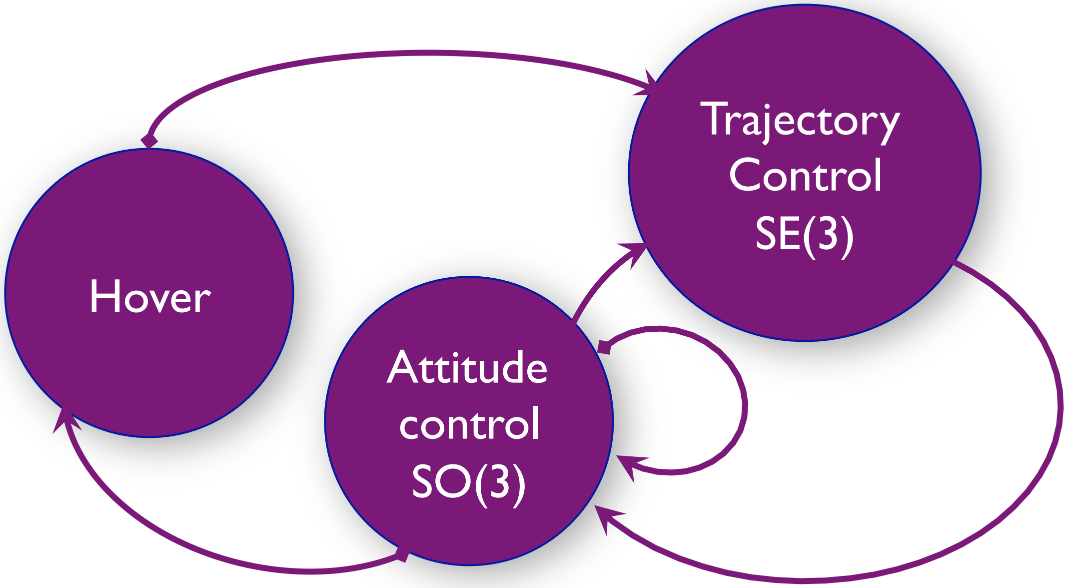


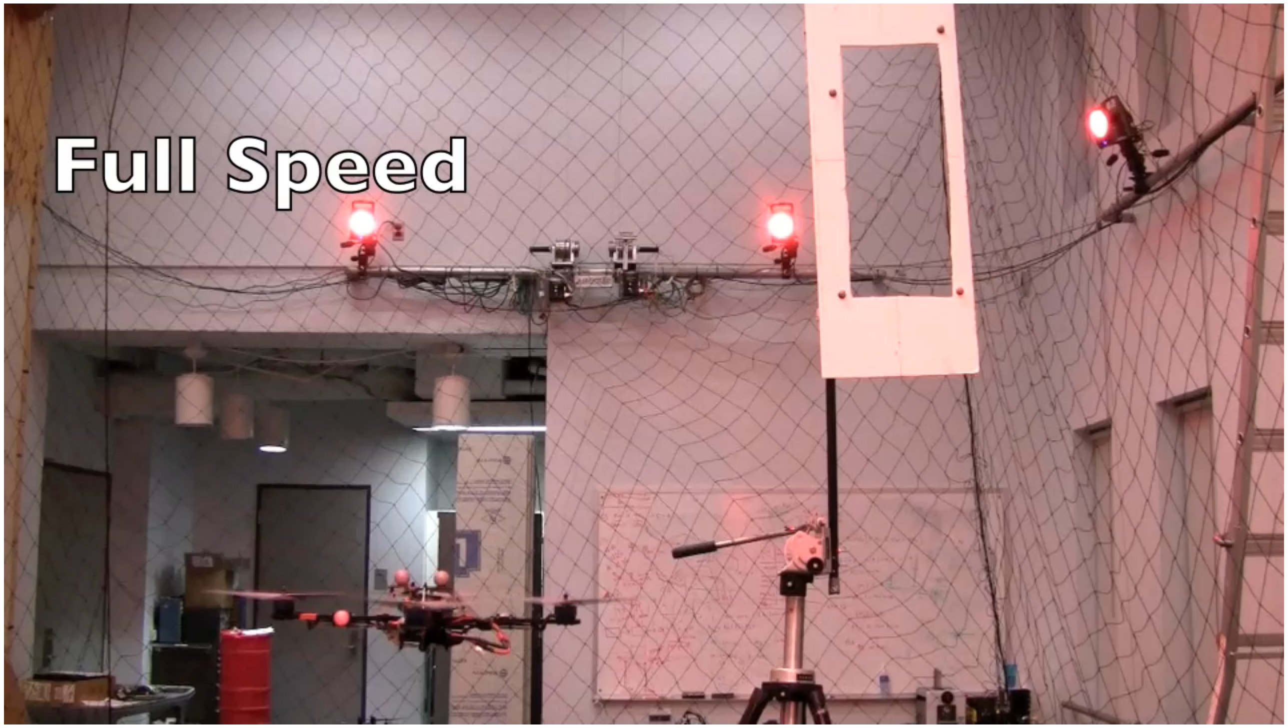


[Pivtaraiko, Mellinger and Kumar, 2013]

Sequential Composition

Mellinger, Michael and Kumar IJRR 2011





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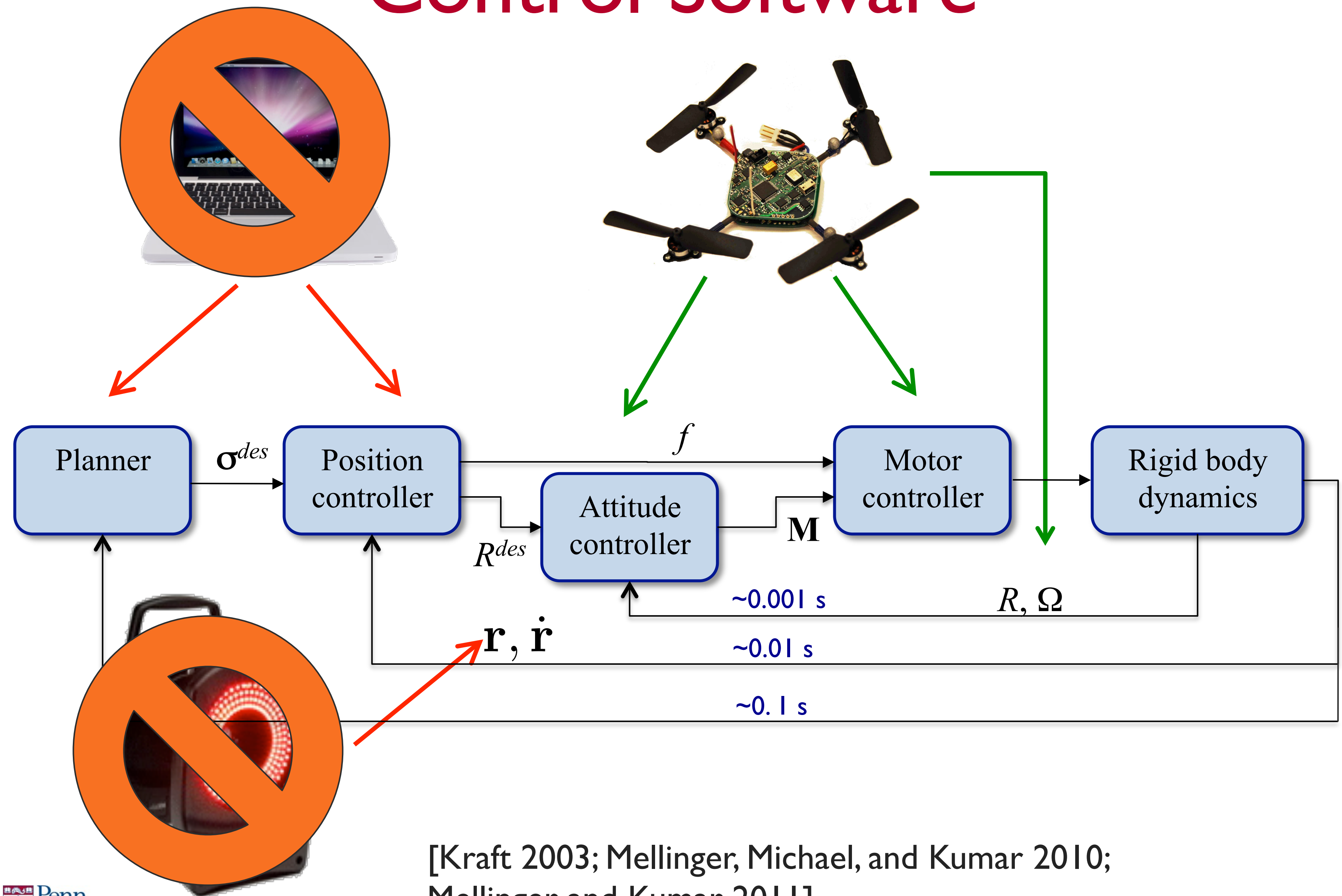
Control Software



[Kraft 2003; Mellinger, Michael, and Kumar 2010; Mellinger and Kumar 2011]

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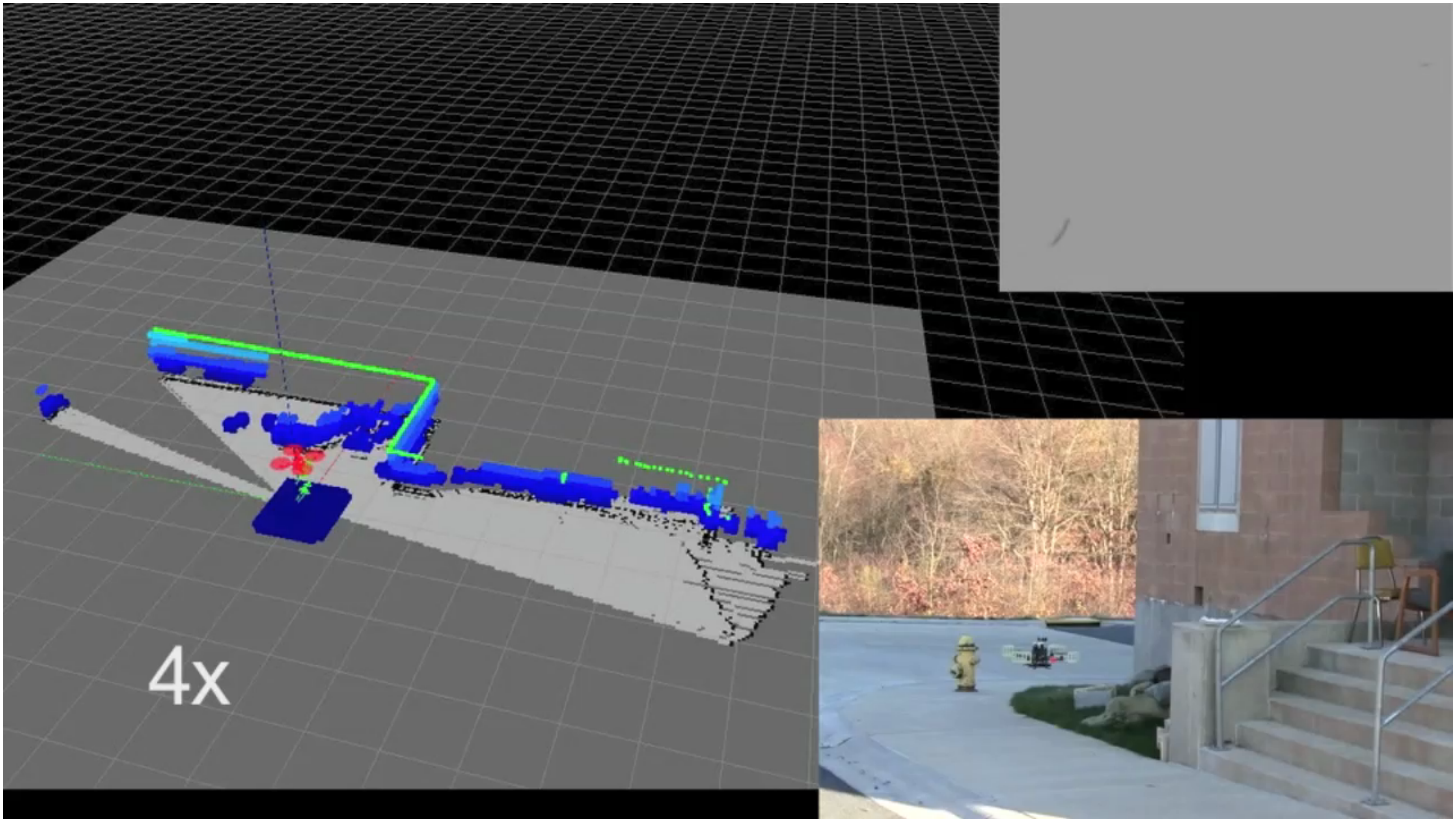
Hokuyo
Laser
Scanner
August 2010
[Shen, Michael, and Kumar 2011]

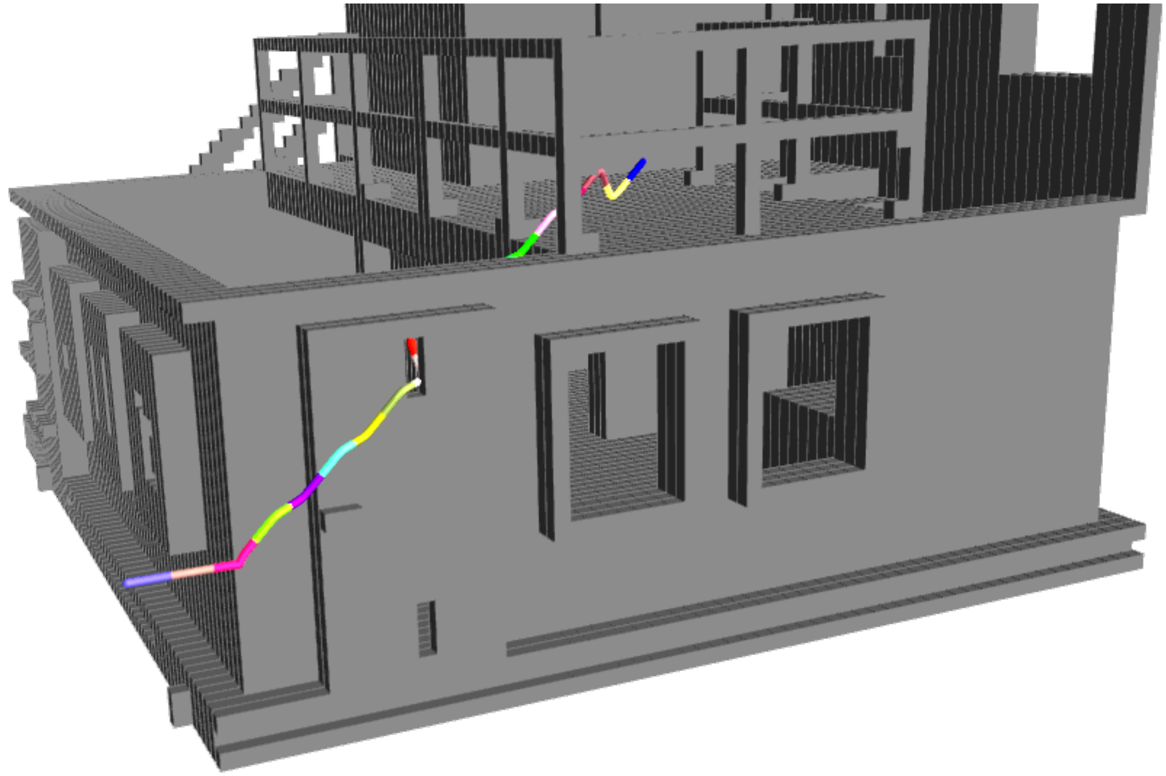
Onboard State Estimation

IMU, Laser scanner, and camera

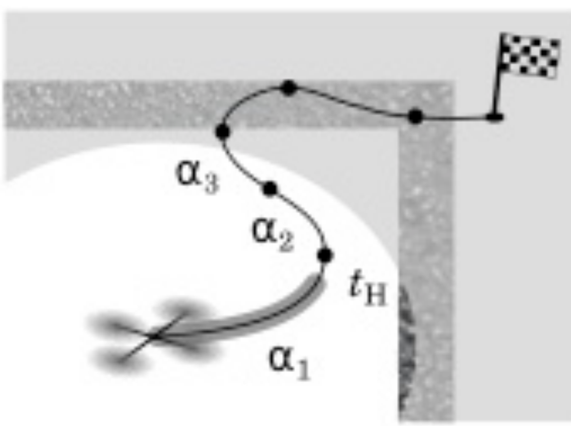


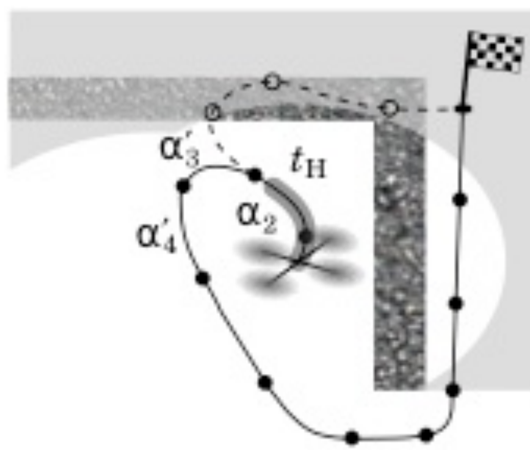
[Shen, Michael, and Kumar 2011]

Known Environment



Partially Known Environment





$$\frac{R}{H}$$

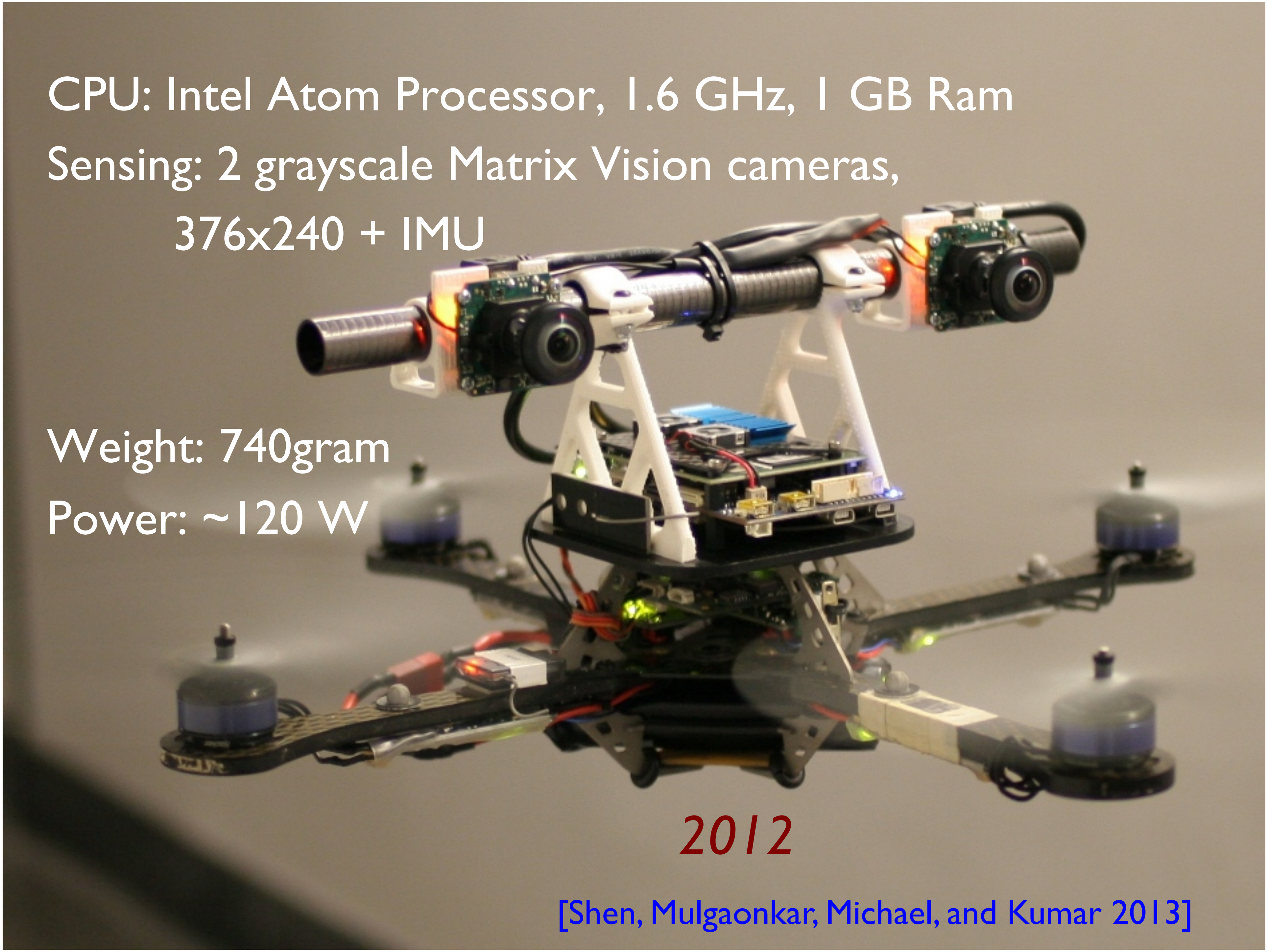
R: sensing range

H: horizon

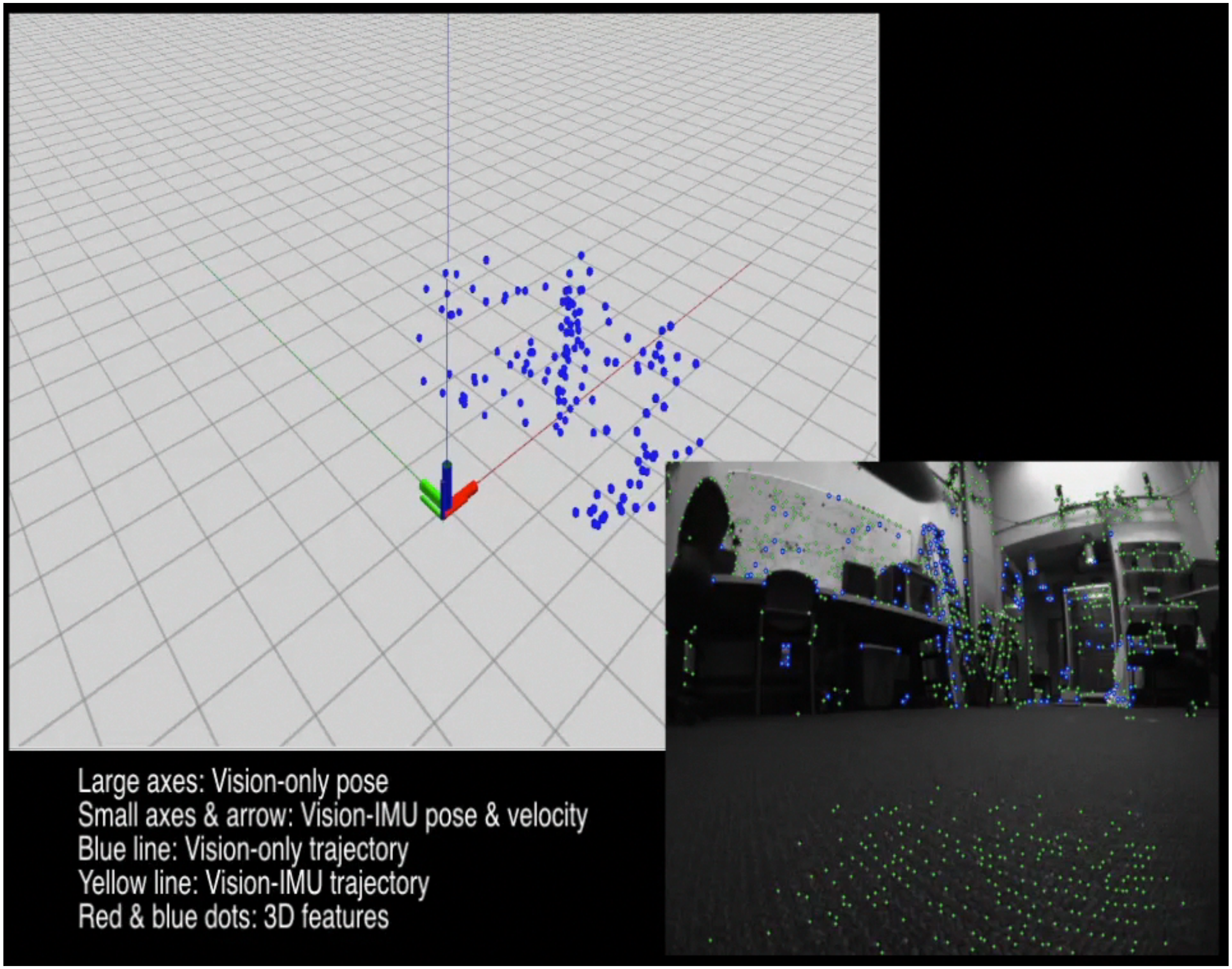
$$\frac{VT}{H}$$

VT: characteristic speed

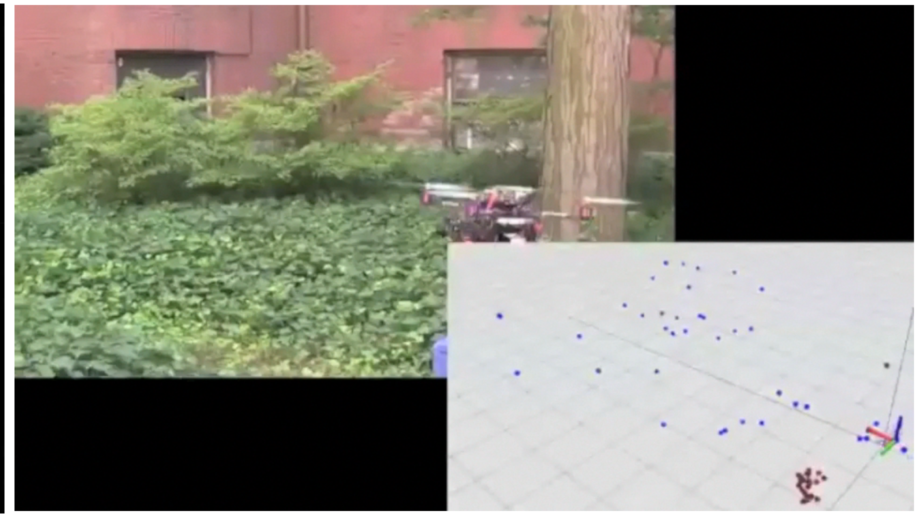
H: time scale of dynamics


CPU: Intel Atom Processor, 1.6 GHz, 1 GB Ram
Sensing: 2 grayscale Matrix Vision cameras,
376x240 + IMU
Weight: 740gram
Power: ~120 W
2012
[Shen, Mulgaonkar, Michael, and Kumar 2013]

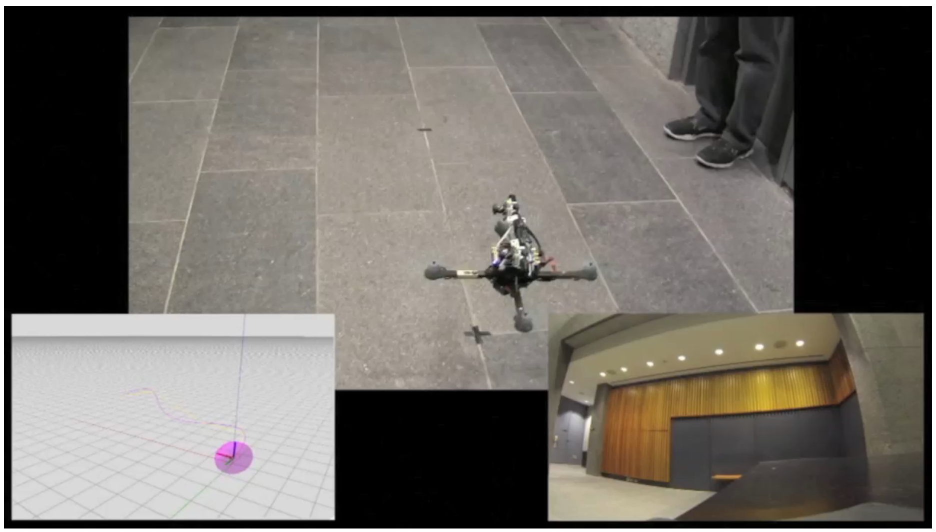
Vision + IMU State Estimation



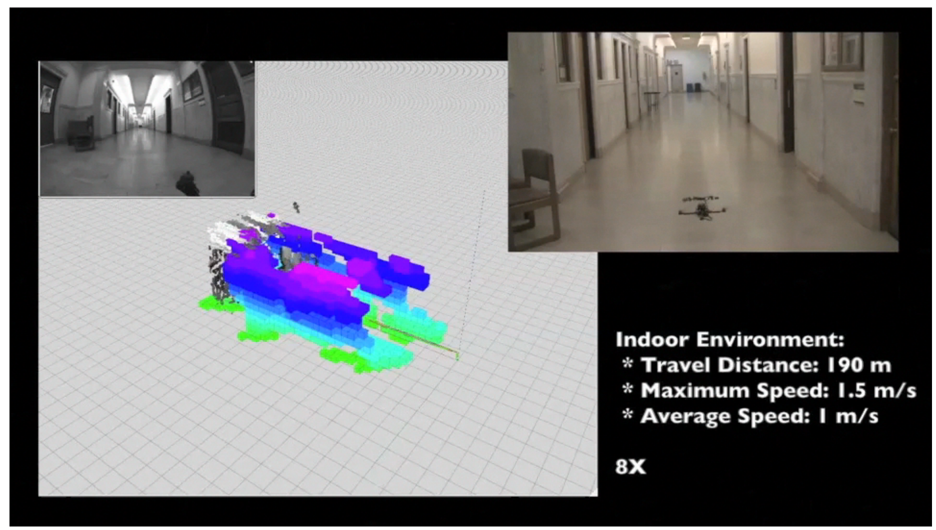
Fast (4 m/s), Indoor



Outdoor, foliage



Indoor, 3-D



Indoor/outdoor, visual SLAM

(Shen, Mulgaonkar, Michael, and Kumar, 2013)

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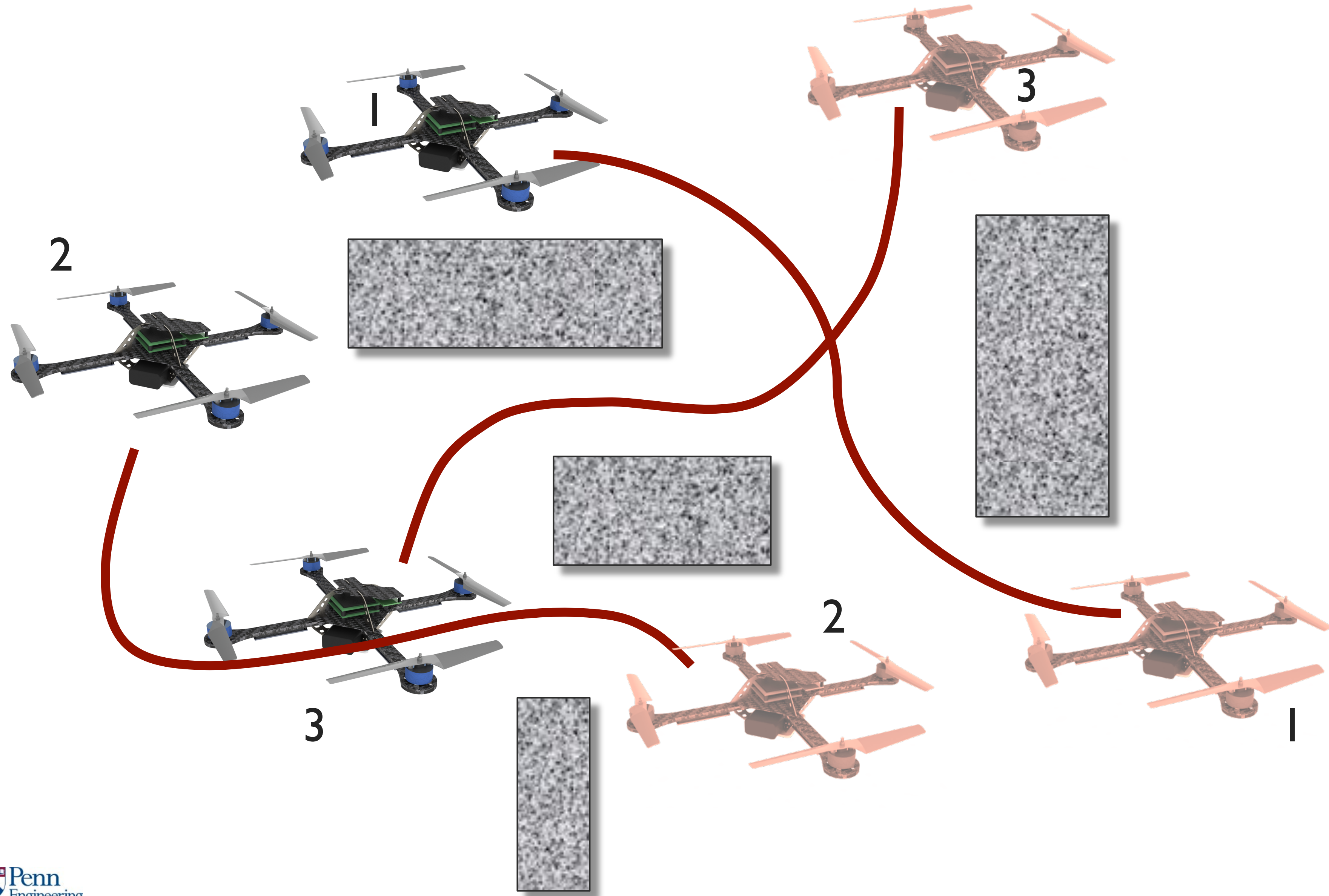
Labeled robots



Mixed Integer Quadratic Program

Dimensionality

$$3n_w n_p n_q$$

Binary variables

$$n_b = n_w n_k n_q \prod_{o=1}^{n_o} n_f(o) + 3n_w n_k n_q(n_q - 1)$$

n_w	no. intermediate waypoints
n_p	no. basis functions
n_q	no. quadrotors
$n_f(o)$	no. of faces for obstacle o
n_k	no. time points

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Unlabeled robots

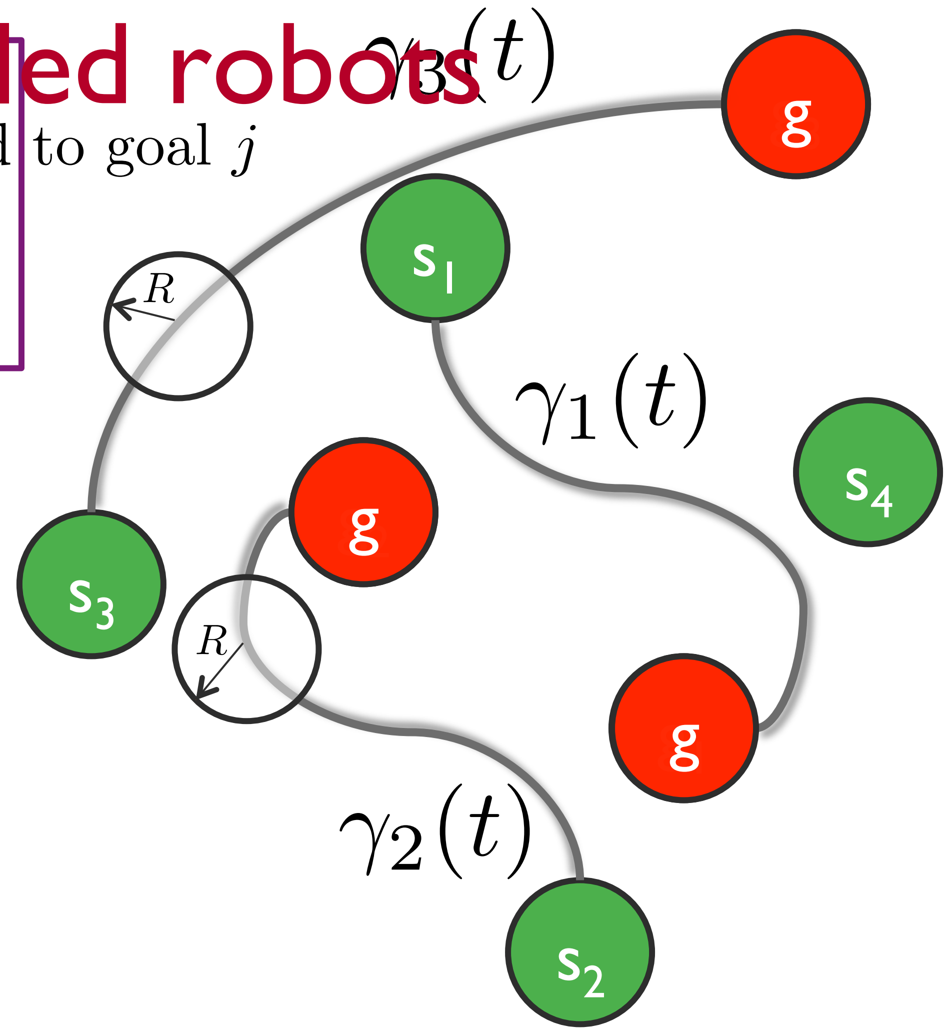
Assignment of robots to goals

$$\phi_{i,j} = \begin{cases} 1 & \text{if robot } i \text{ is assigned to goal } j \\ 0 & \text{otherwise} \end{cases}$$

Planning trajectories

$$\mathbf{X}(t) = \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \dots \\ \mathbf{x}_N(t) \end{bmatrix}$$

$$\gamma(t) : [t_0, t_f] \rightarrow \mathbf{X}(t)$$



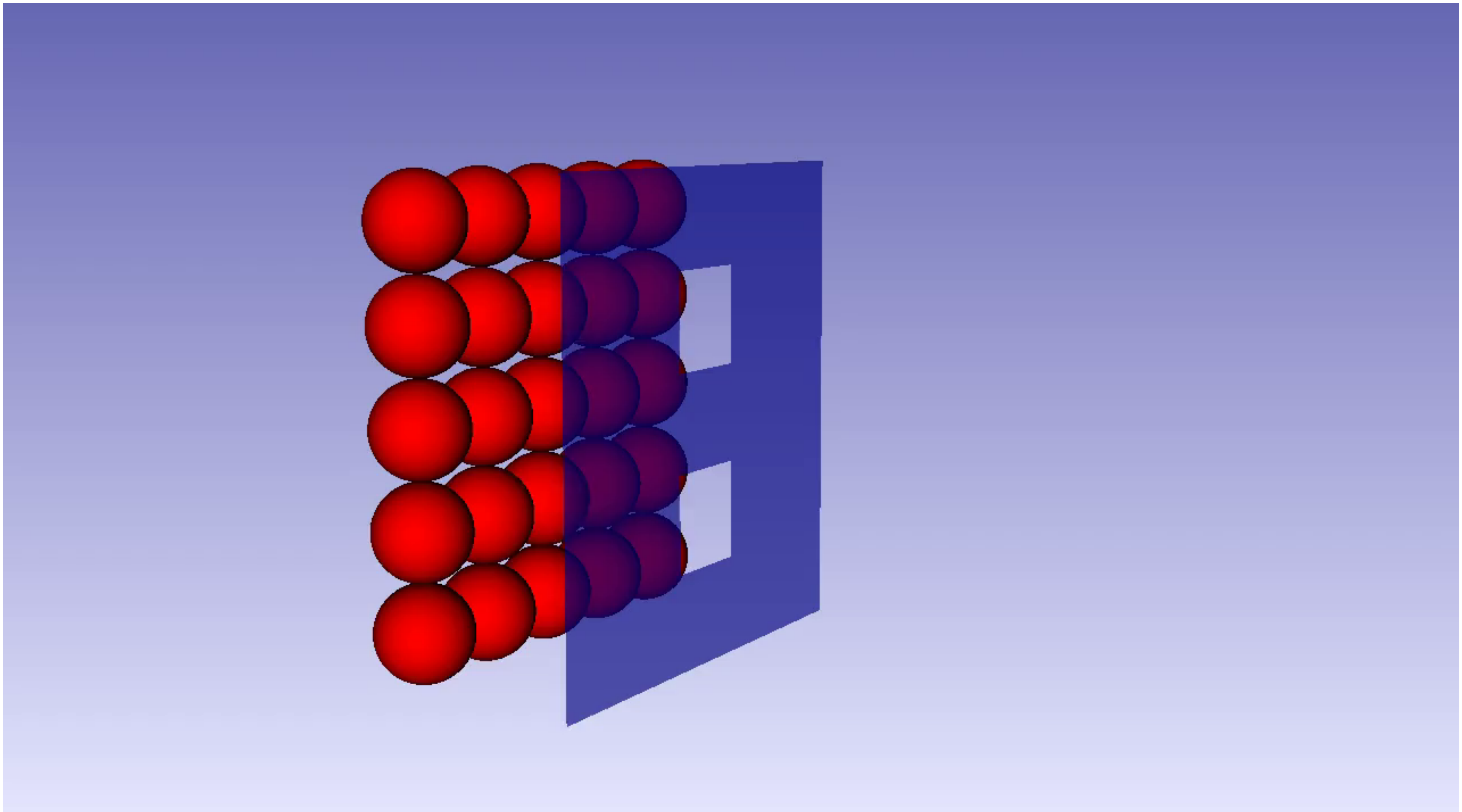
Safety

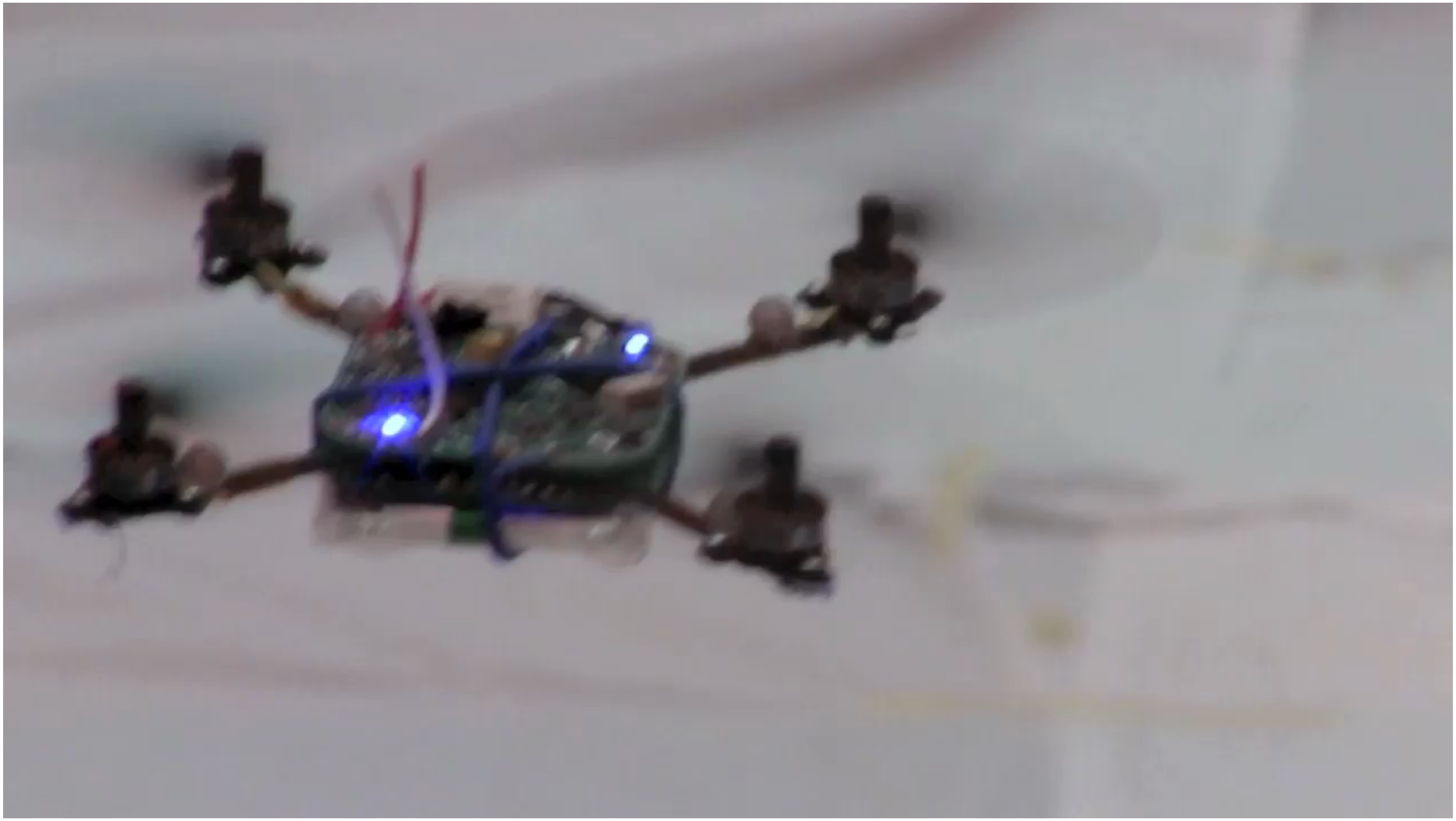
$$\left[\inf_{i \neq j \in \mathcal{I}, t \in [t_0, t_f]} ||\mathbf{x}_i(t) - \mathbf{x}_j(t)|| - 2R \right] > 0$$

Optimality

$$\gamma^\star(t) = \underset{\gamma(t)}{\operatorname{argmin}} \int_{t_0}^{t_f} L(\gamma(t))dt$$

[*Turpin et al*, RSS 2013]





[*Kushleyev, Mellinger and Kumar RSS* 2012]

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Challenges for Agile Robots

- Uncertainty (integration over belief space and over the set of possible measurements) and risk
- Model predictive control or receding horizon control with completeness and convergence guarantees
- Ability to plan with multimodal, nested perception-action loops