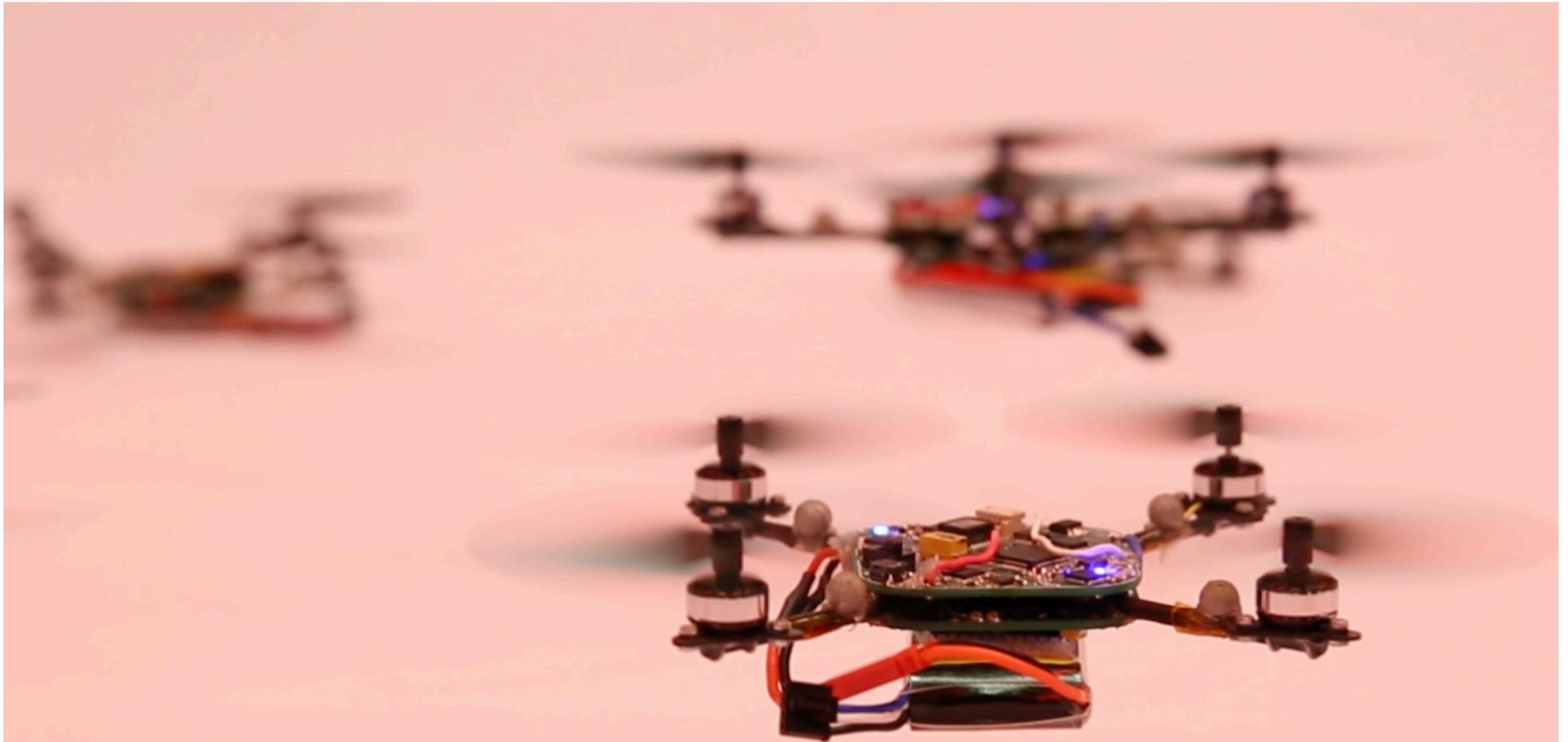


Aerial Robot Swarms



Vijay Kumar
University of Pennsylvania

CPS PI Meeting
Washington DC
November 7, 2014



all robots are cyber physical systems
even if not all robotics research is CPS research



Aerial Robot Swarms

Quadrotor





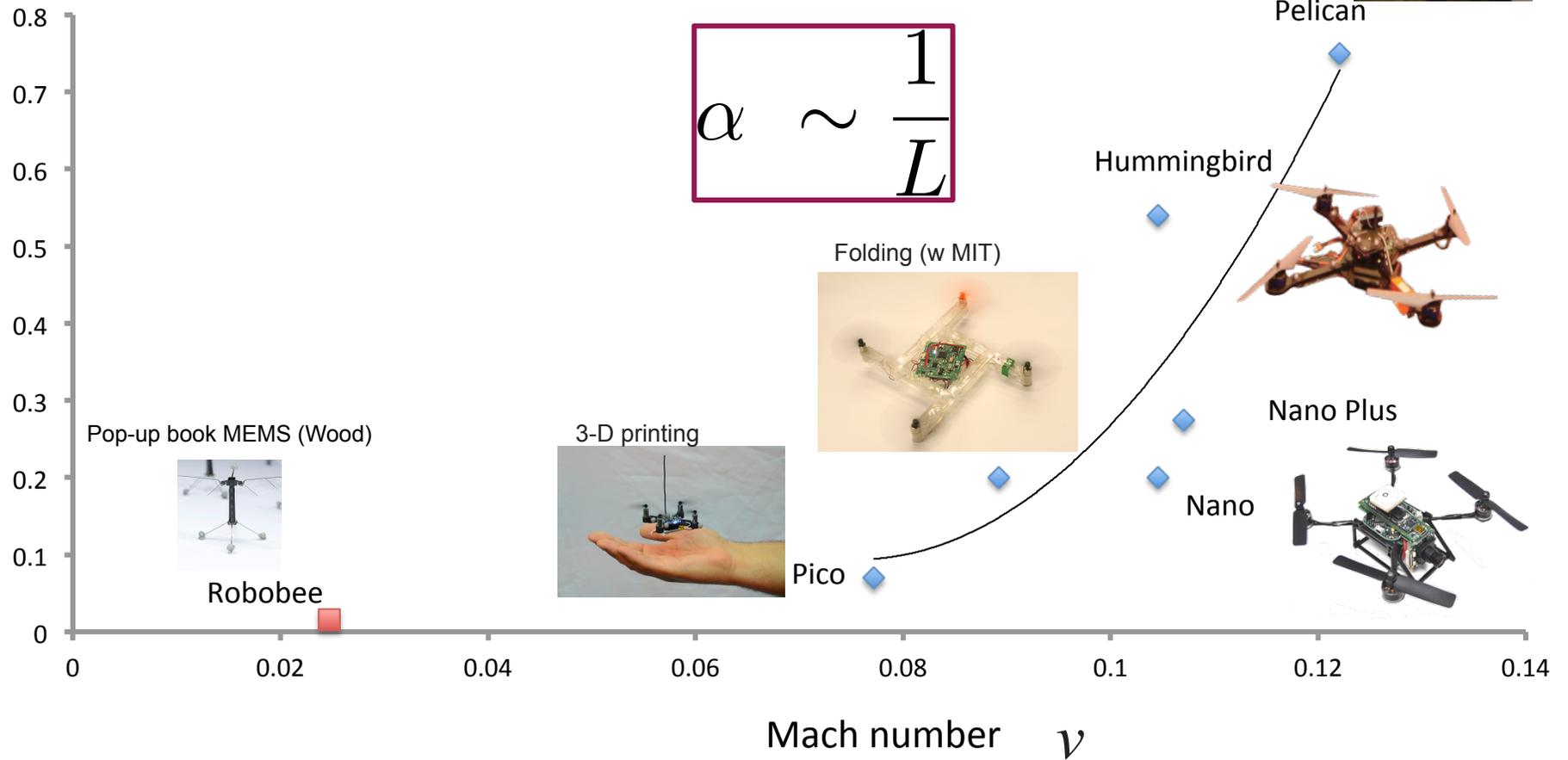
J. Bioinspiration and Biomimetics

Scaling Laws

L
Length (m)

$$v \sim \sqrt{L}$$

$$\alpha \sim \frac{1}{L}$$



Pico

11 cm

20 g,

6.5 Watts

Max speed 6m/s

Smaller

Safer

Smarter

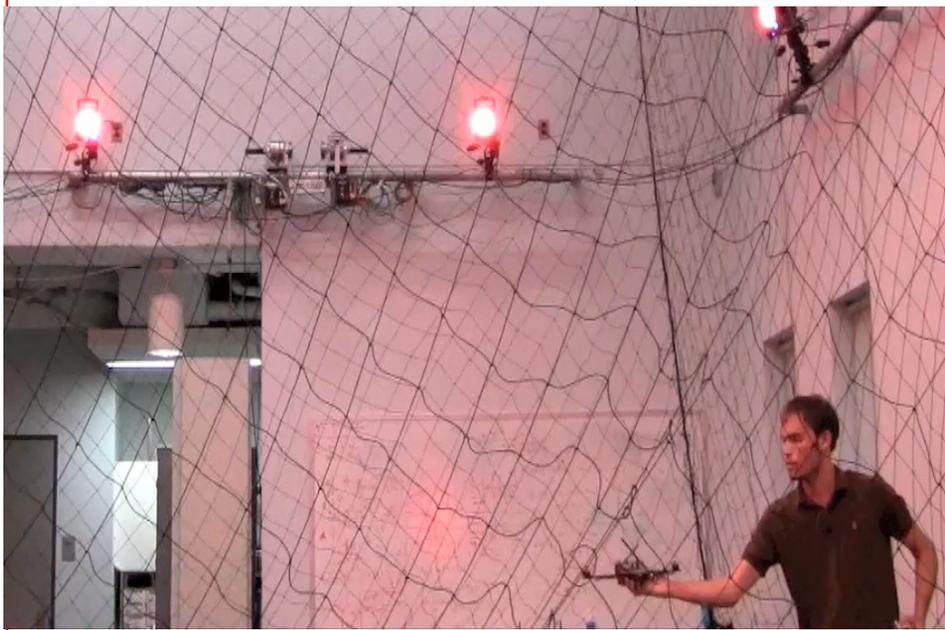


Small and safe



Recovery from mid air collisions

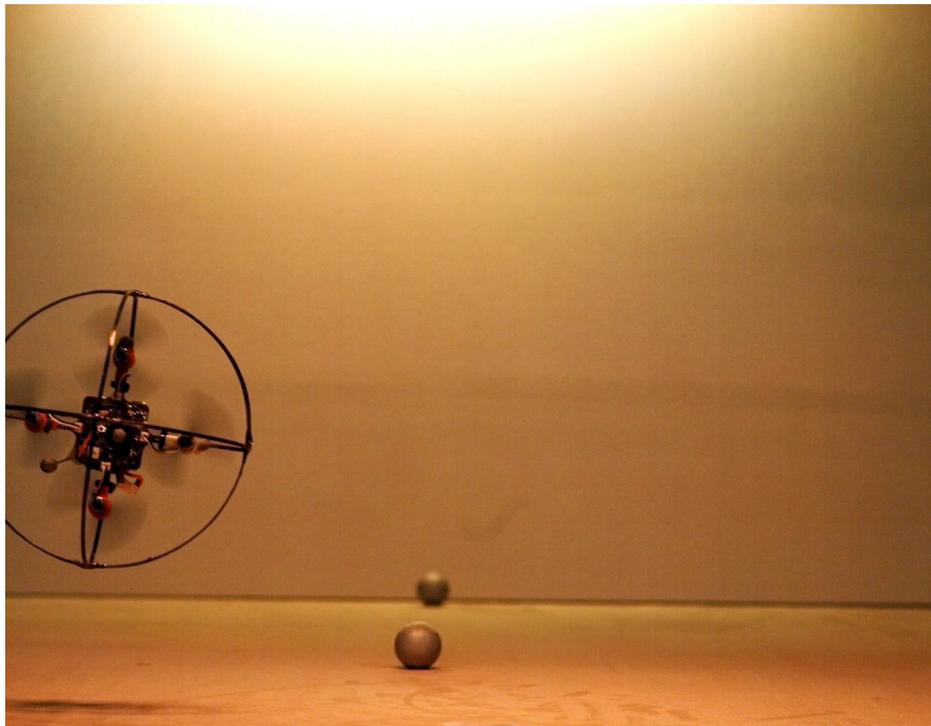




AscTec Hummingbird (Mellinger and Kumar, 2011)

$$\text{max ang. acceleration} \sim \frac{1}{L}$$

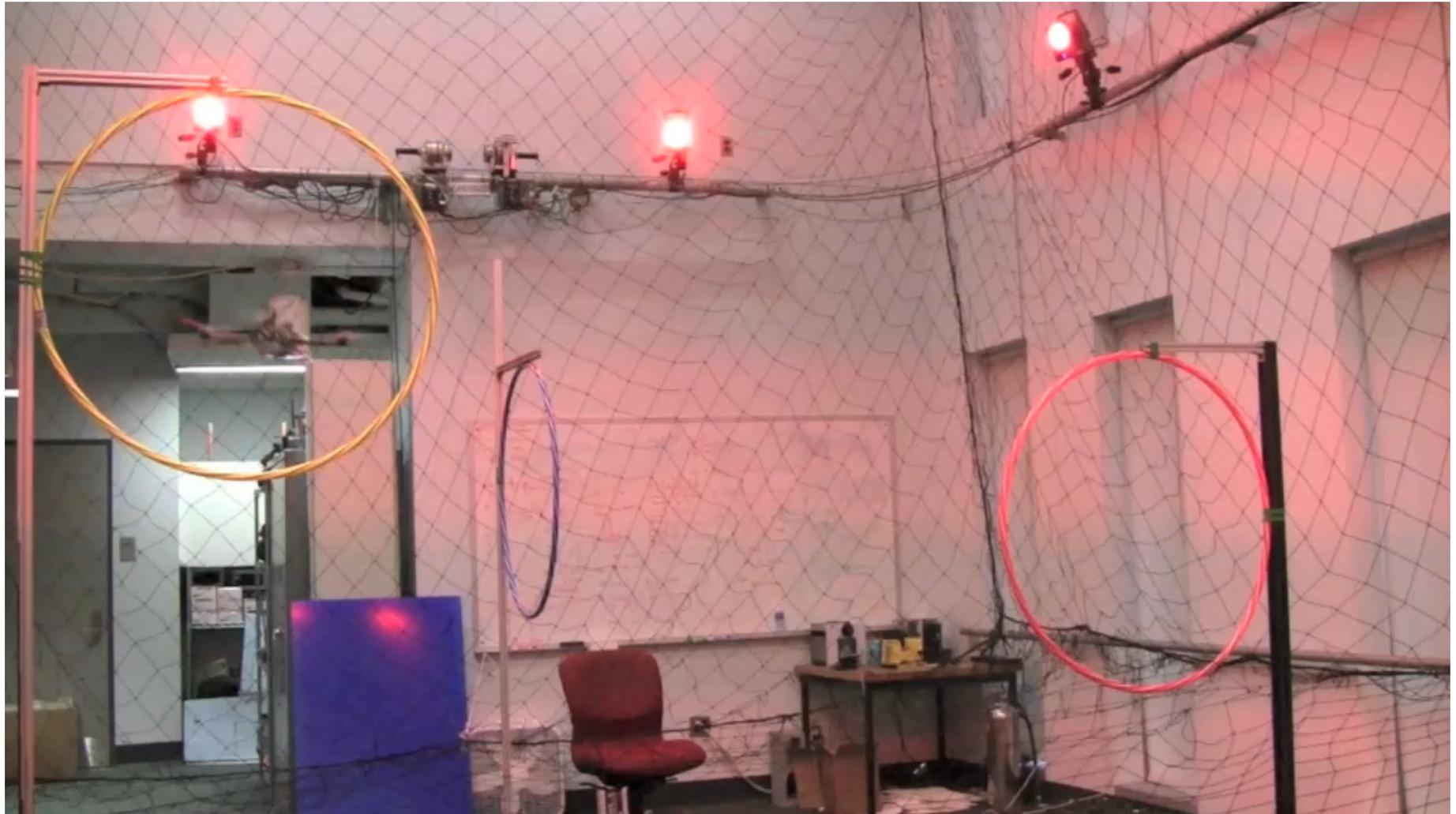
$$\text{basin of attraction} \sim \frac{1}{L^{\frac{5}{2}}}$$



Pico Quad (Mulgaonkar, Cross and Kumar, 2015)



Obstacle Avoidance



[Mellinger and Kumar, ICRA 2011]

Aerial Grasping and Manipulation

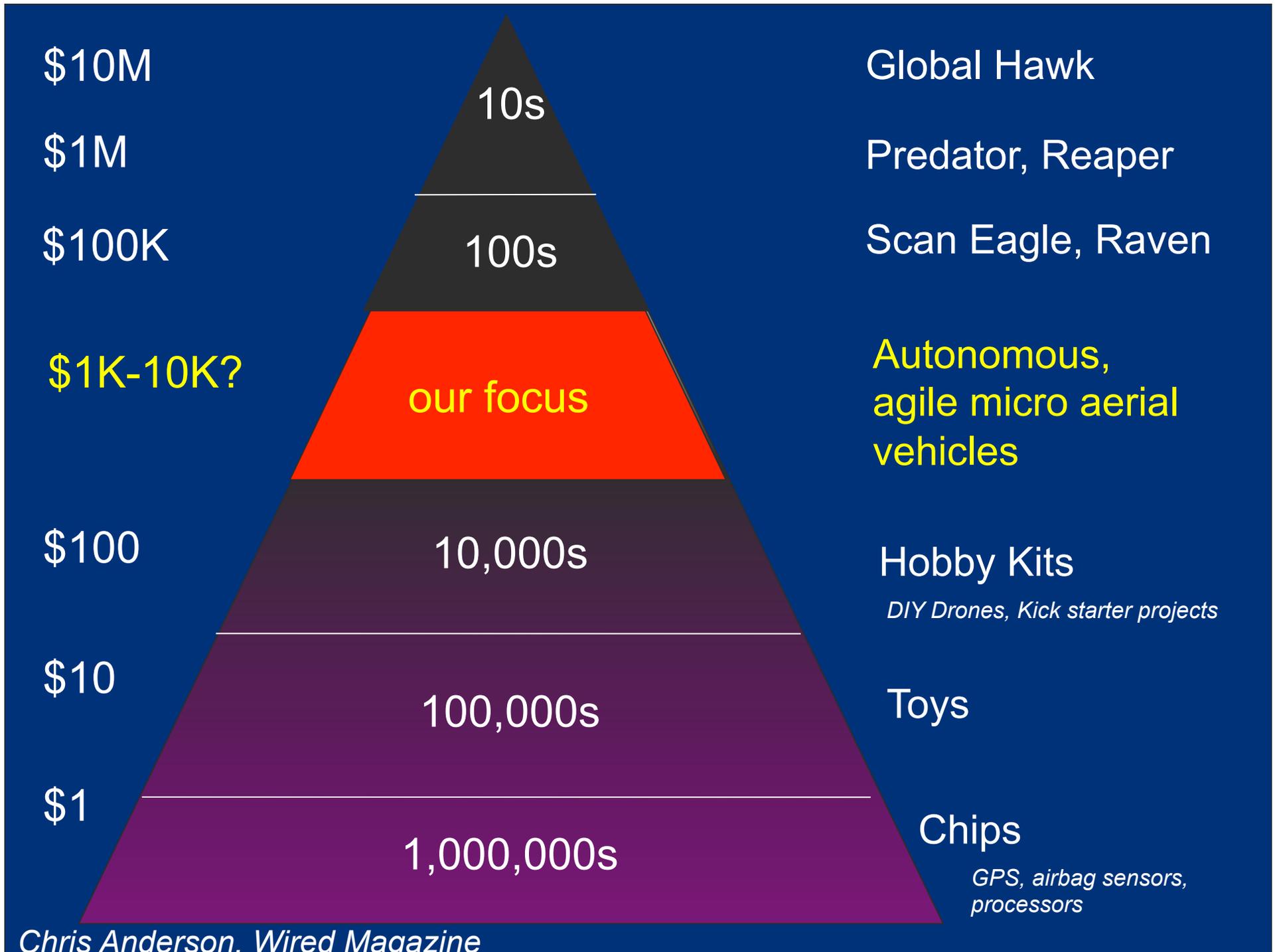


Transporting Suspended Payloads



3 Technological Trends





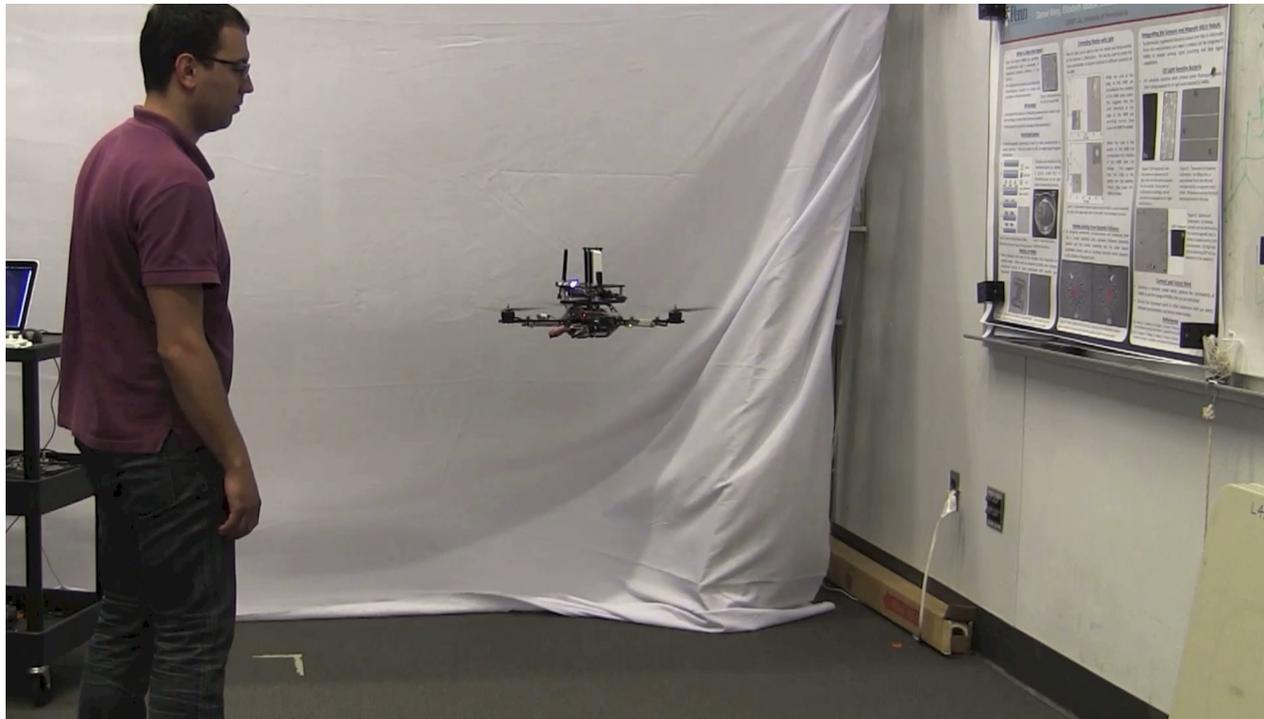
Chris Anderson, Wired Magazine

Robotics and the 3C Industry

Computers

Communication

Consumer (electronics)



Giuseppe Loianno, Gareth Cross, Yash Mulgaonkar, and Vijay Kumar, *IEEE Spectrum*, May 2014.

Lowered Barrier to Entry for Design



Yash Mulgaonkar and Matt Piccoli

Printable Robots: NSF Computing Expeditions (MIT, Penn, Harvard; Acknowledgement: I. Lee and

Moore's Law

Moshe Vardi (Editor, ACM Transactions)

“Is Moore's Party Over?” (2011)

“Moore's Law and the Sandheap Paradox (2014)”

Moore's After Party

Moshe Vardi (Editor, ACM Transactions)

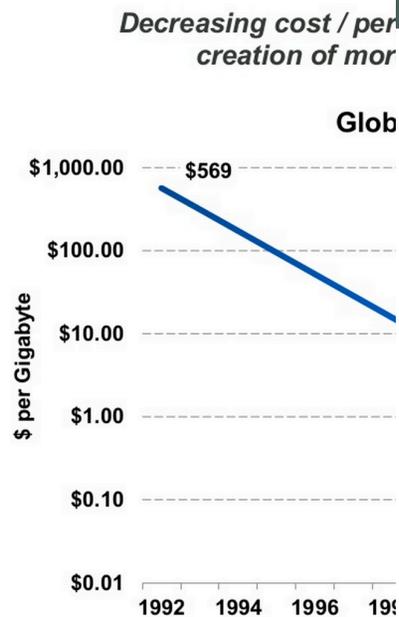
“Is Moore’s Party Over?” (2011)

“Moore’s Law and the Sandheap Paradox (2014)”

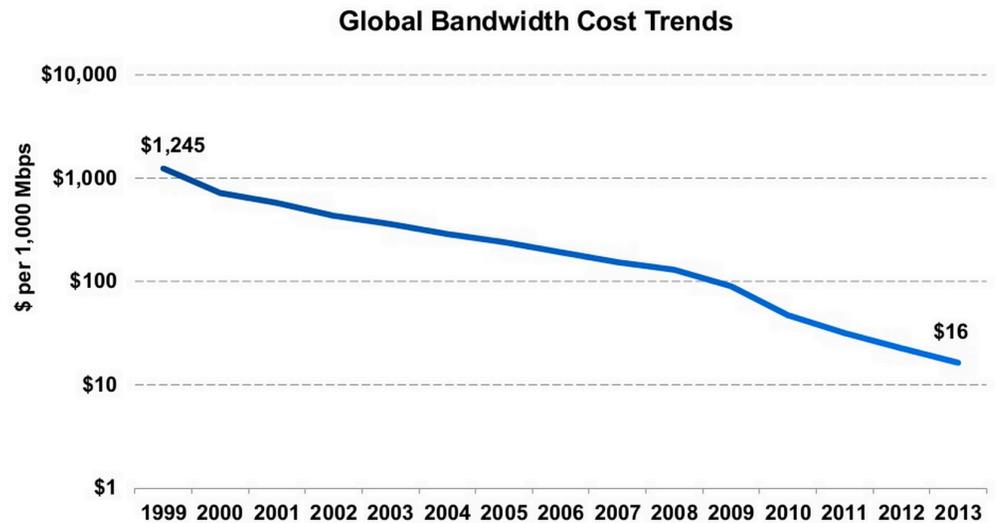
Compute Costs Declining = 33% Annually, 1990-2013...

...Storage Costs Declining = 33% Annually, 1990-2013...

...Bandwidth Costs Declining = 27% Annually, 1999-2013...



Declining cost / performance of bandwidth enables faster collection & transfer of data to facilitate richer connections / interactions...



@KPCB

Note: Y-axis on graph is logarithmic scale.
Source: John Hagel, Deloitte, 5/14.



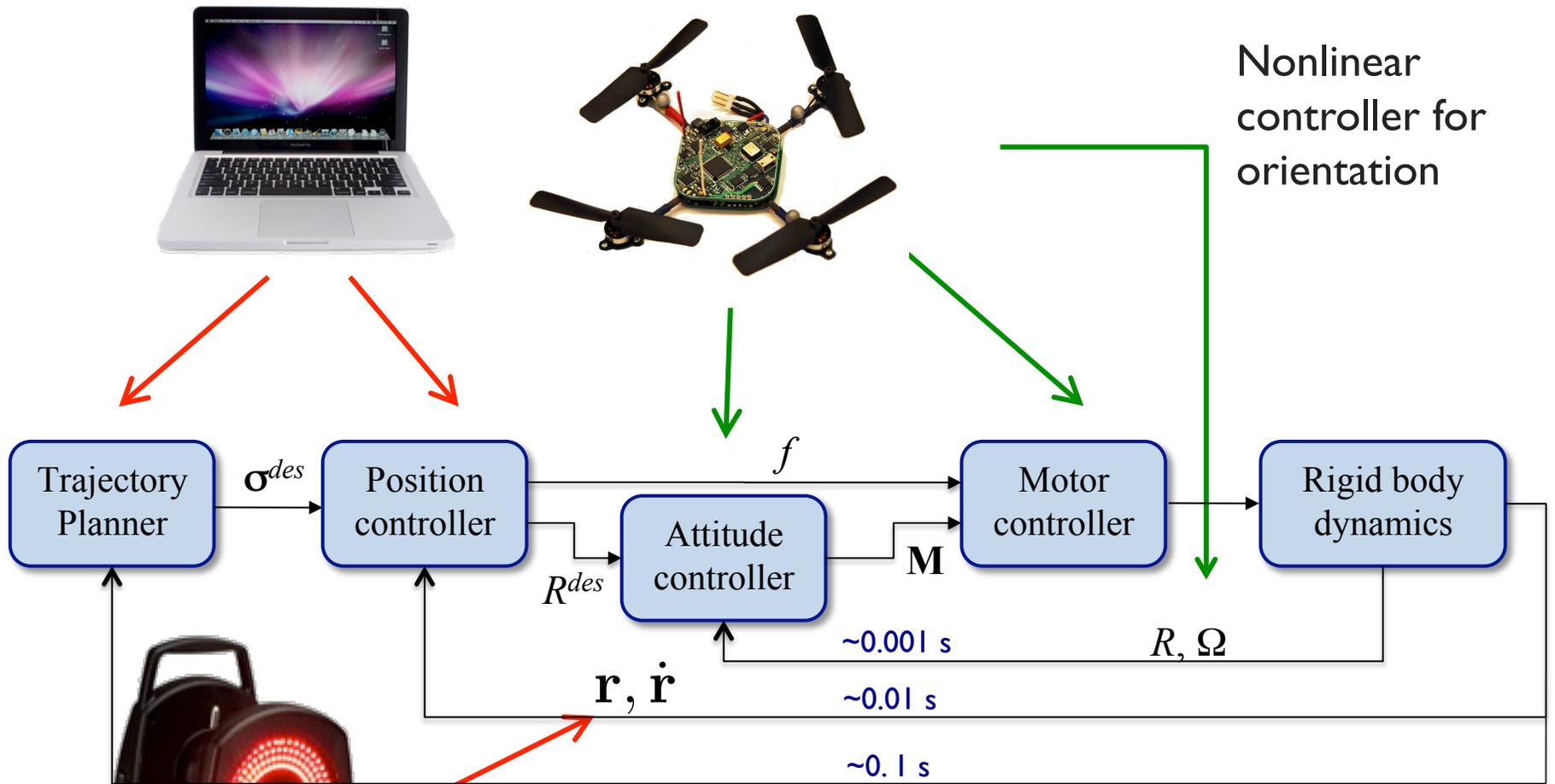
@KPCB

Note: Y-axis on graph is logarithmic scale.
Source: John Hagel, Deloitte, 5/14.

@KPCB

Note: Y-axis on graph is logarithmic scale.
Source: John Hagel, Deloitte, 5/14.

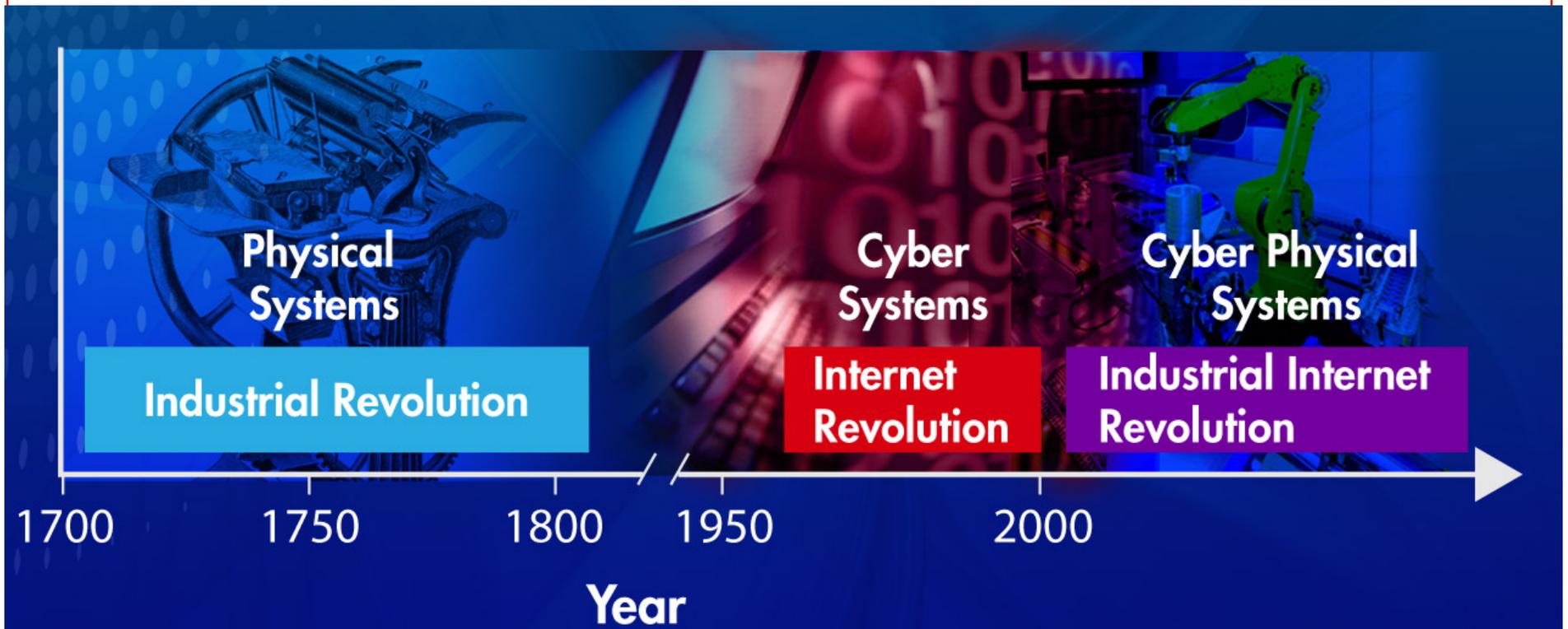
Software Architecture



N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar. The GRASP multiple micro UAV testbed. IEEE Robotics and Automation Magazine, Vol. 17, No. 3. 2010.

D. Mellinger and V. Kumar, "Minimum Snap Trajectory Generation and Control for Quadrotors," ICRA, Shanghai, China, May, 2011

The Industrial Internet and Robot Swarms





Reliable State Estimation for
Autonomous Operation

with power constraints (200 W/kg)

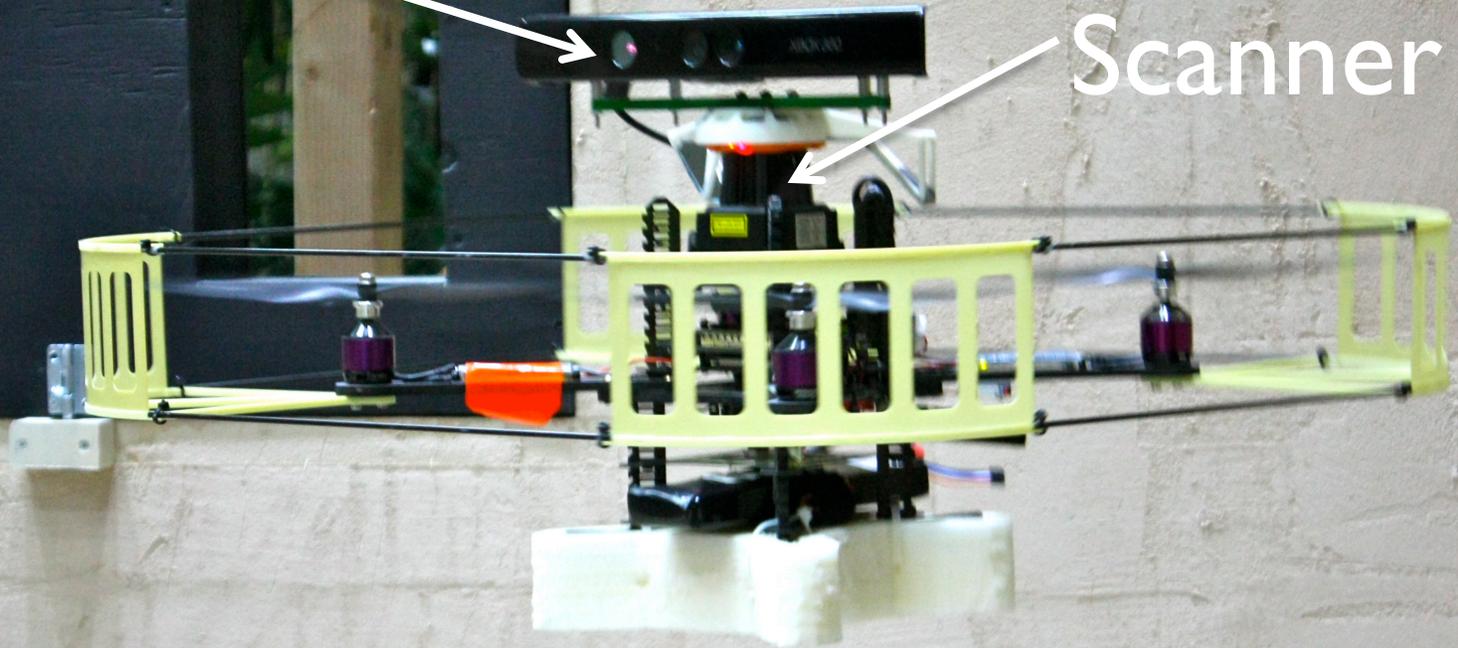
- 1.8 GHz Core i3 processor, 8 GB RAM
- u-blox LEA-6T GPS module
- Hokuyo UTM-30LX LiDAR
- 2 mvBlueFOX-MLC200w grayscale HDR cameras
(fisheye lenses, 752×480 , 25 Hz)
- IMU 100 Hz



Shaojie Shen, Yash Mulgaonkar, Nathan Michael and Vijay Kumar, "Multi-Sensor Fusion for Robust Autonomous Flight in Indoor and Outdoor Environments with a Rotorcraft MAV," *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, 2014

Microsoft
Kinect

Hokuyo
Laser
Scanner



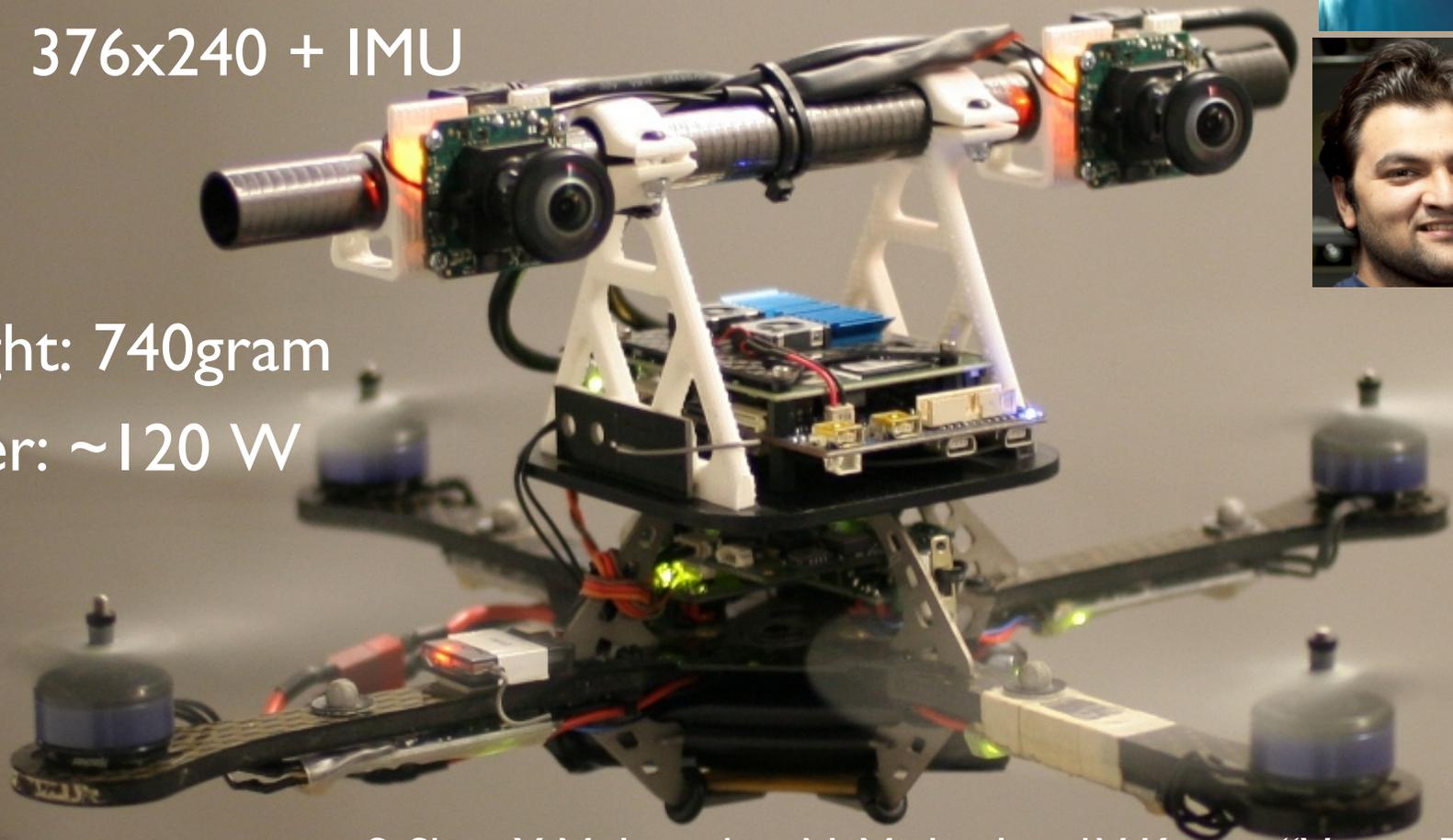
S. Shen, N. Michael, and V. Kumar, "Stochastic differential equation-based exploration algorithm for autonomous indoor 3D exploration with a micro-aerial vehicle," *Intl. J. Robot. Research*, Vol. 31, No. 12, pp. 1431-1444, 2012

CPU: Intel Atom Processor, 1.6 GHz, 1 GB Ram

Sensing: 2 grayscale Matrix Vision cameras,
376x240 + IMU

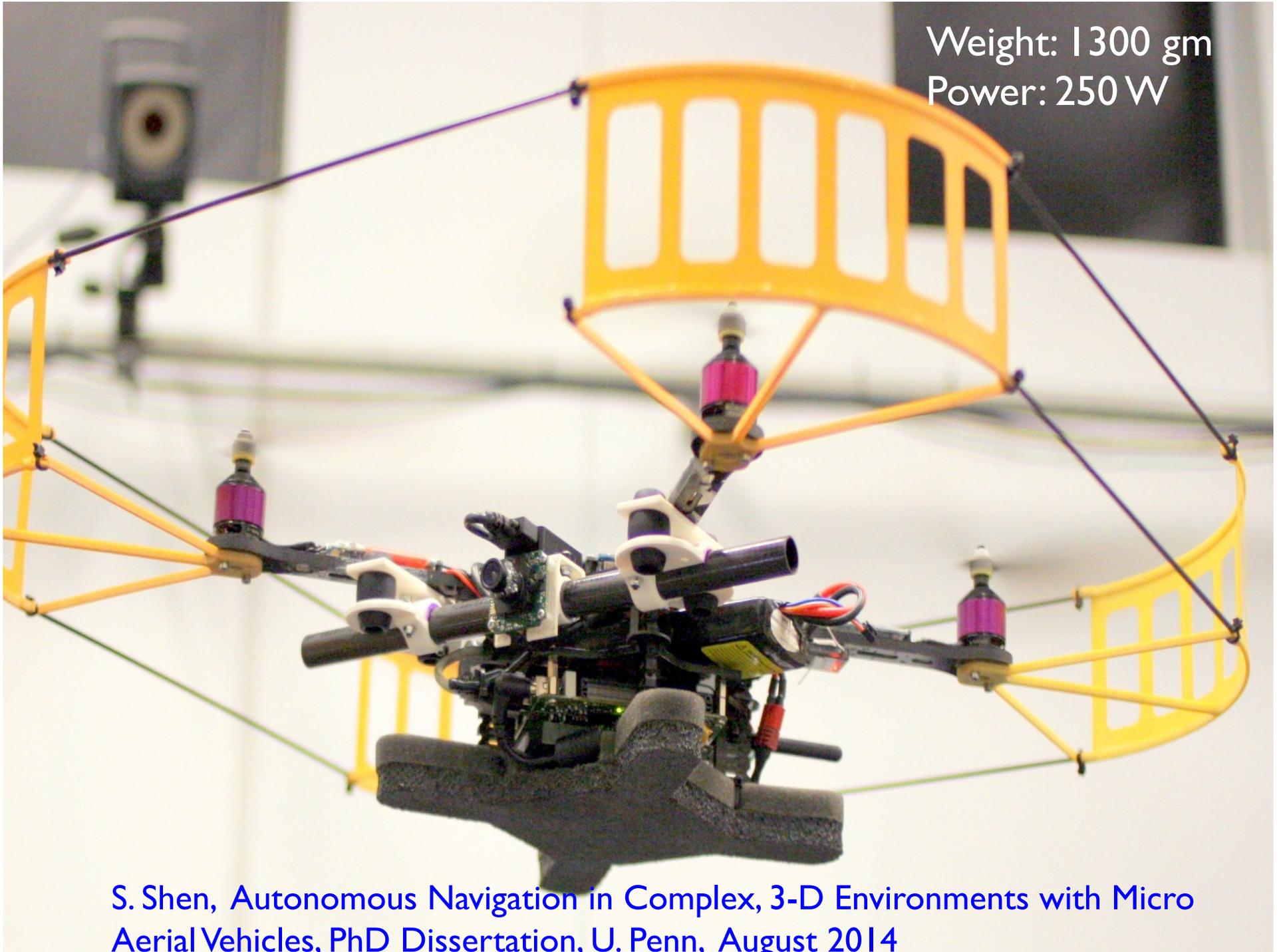
Weight: 740gram

Power: ~120 W



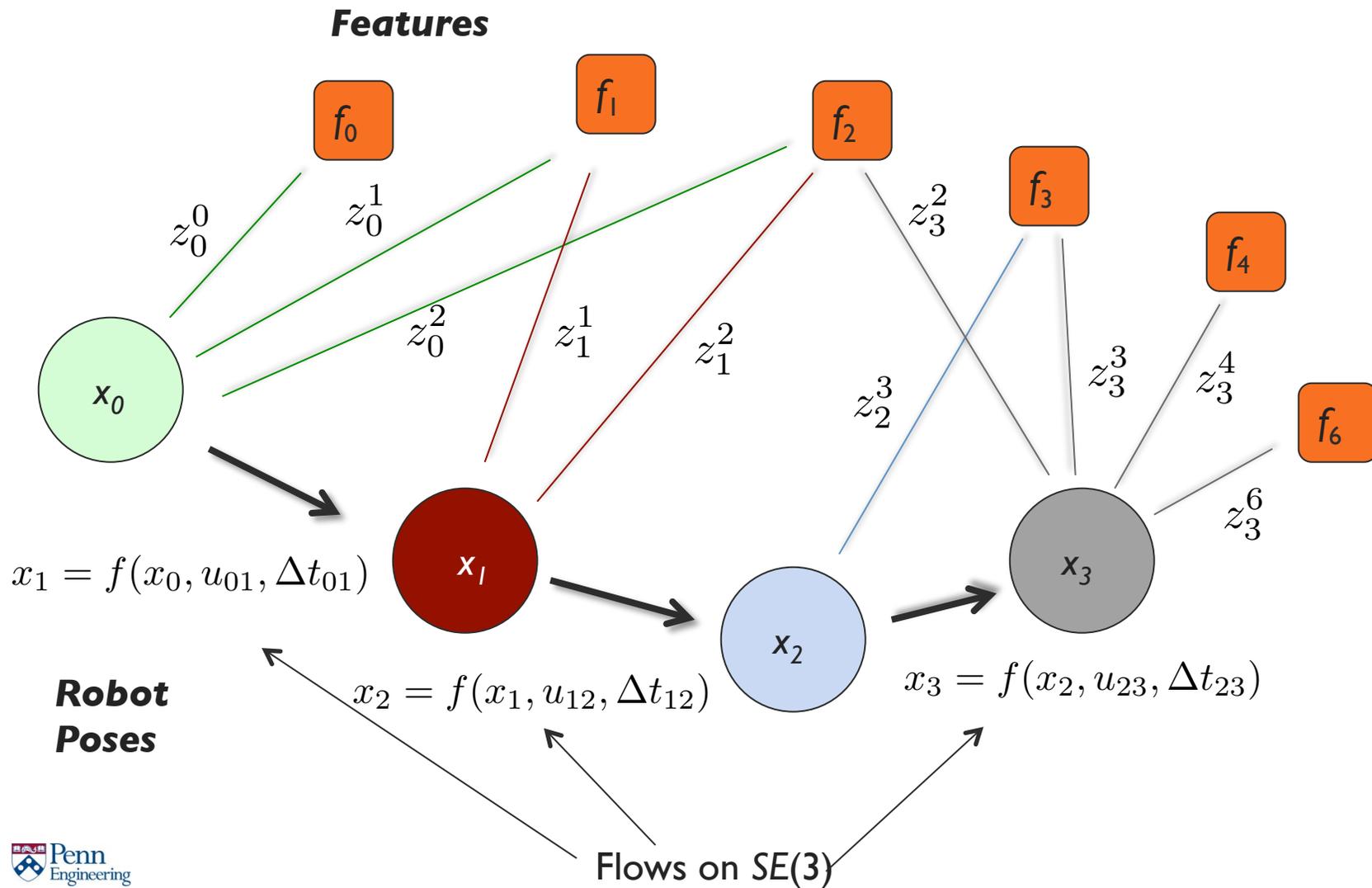
S. Shen, Y. Mulgaonkar, N. Michael and V. Kumar, "Vision-Based State Estimation and Trajectory Control Towards Aggressive Flight with a Quadrotor," Robotics: Science and Systems (RSS) June 2013.

Weight: 1300 gm
Power: 250 W

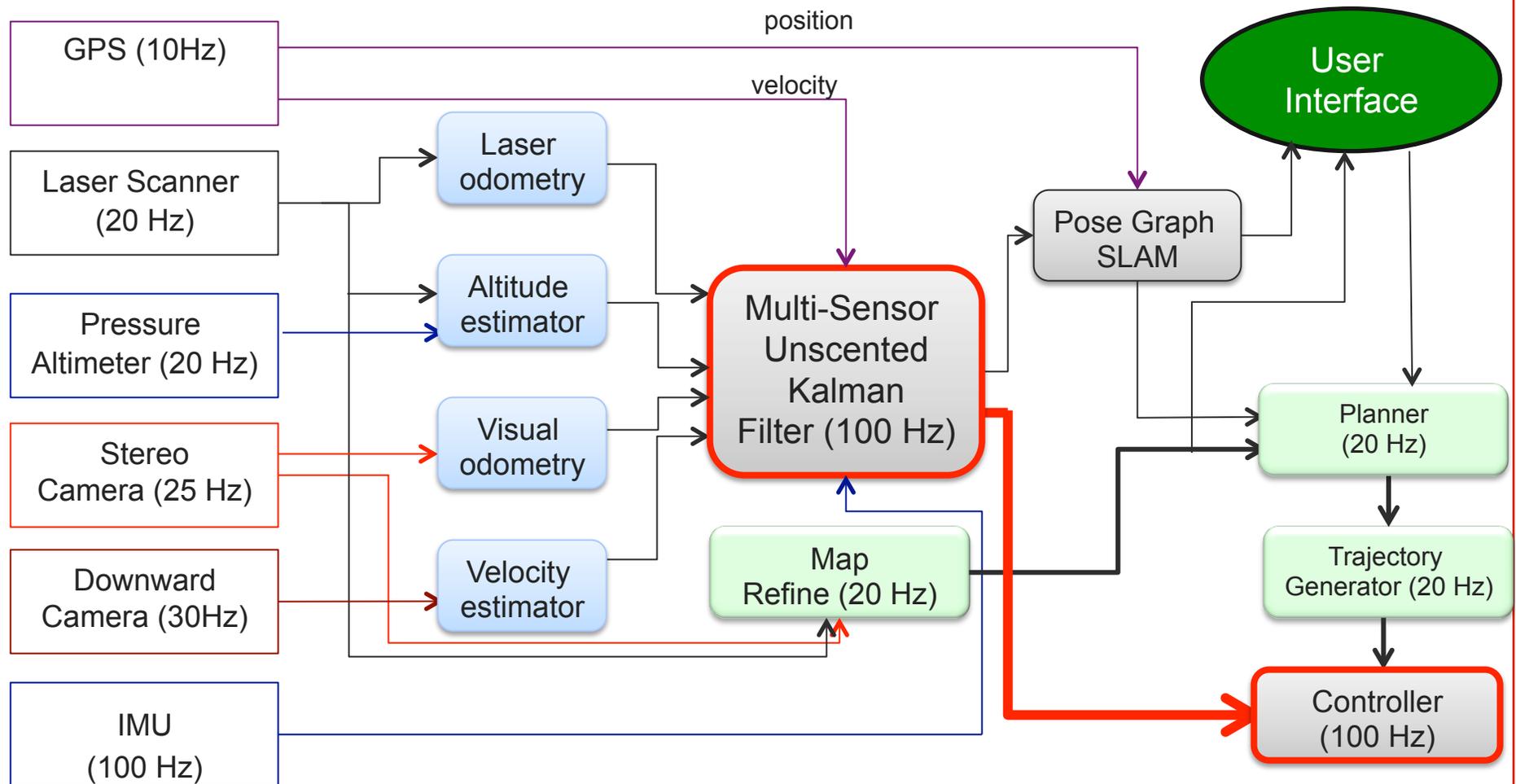


S. Shen, Autonomous Navigation in Complex, 3-D Environments with Micro Aerial Vehicles, PhD Dissertation, U. Penn, August 2014

Simultaneous Localization and Mapping

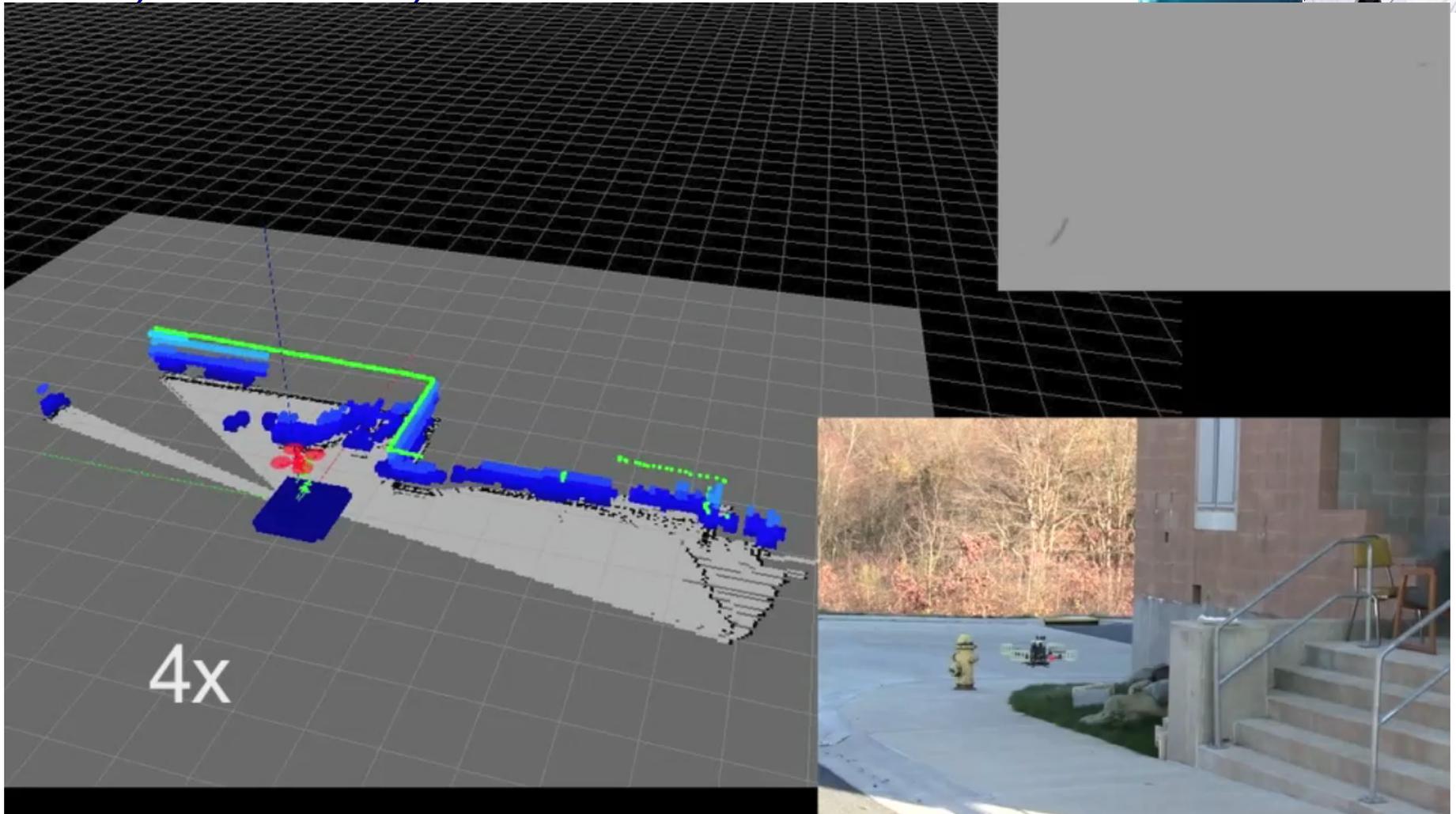
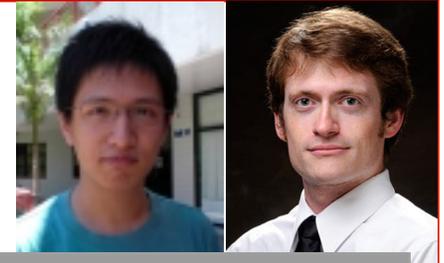


Estimation and Control Architecture

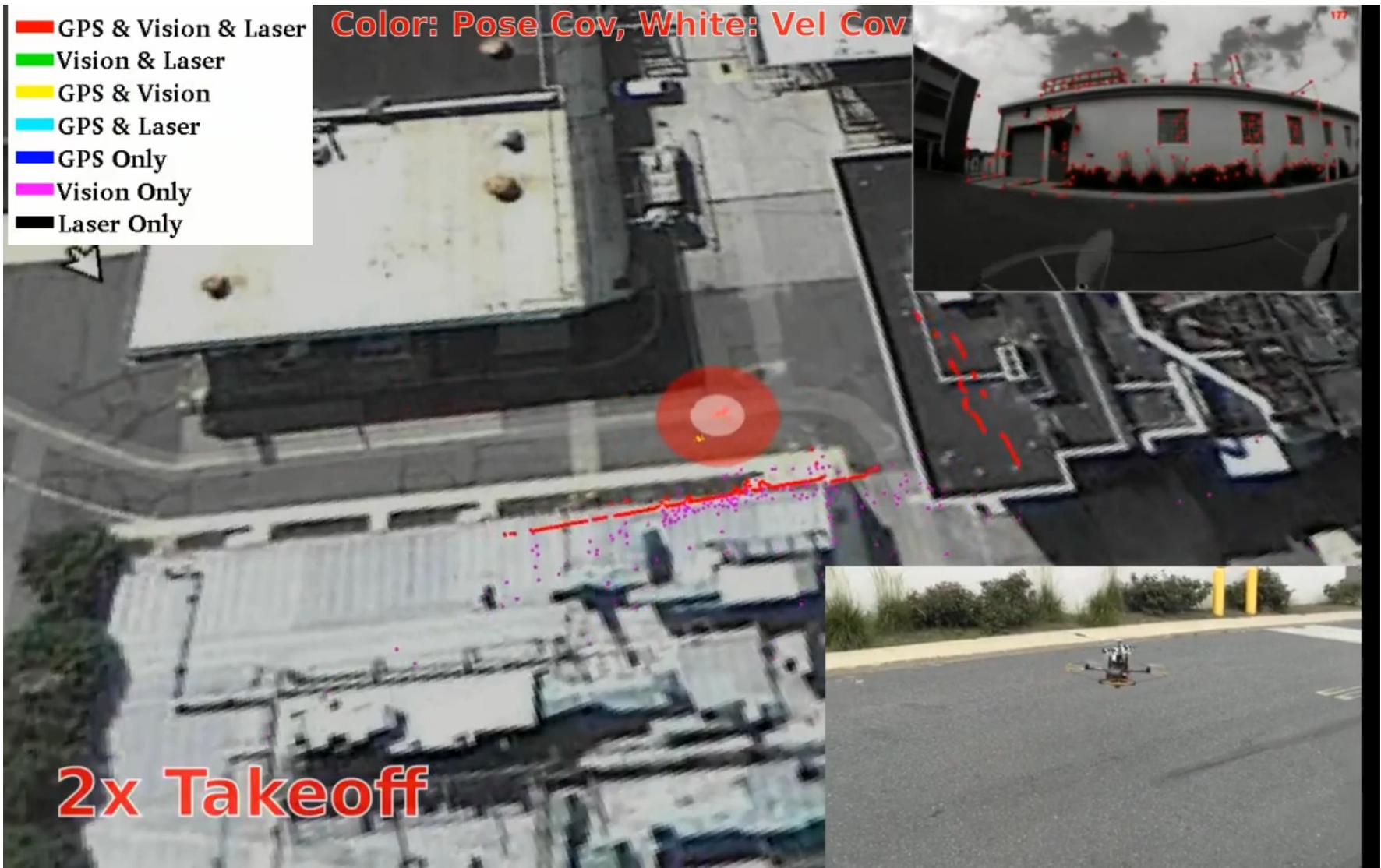


Onboard State Estimation

IMU, Laser scanner, and camera



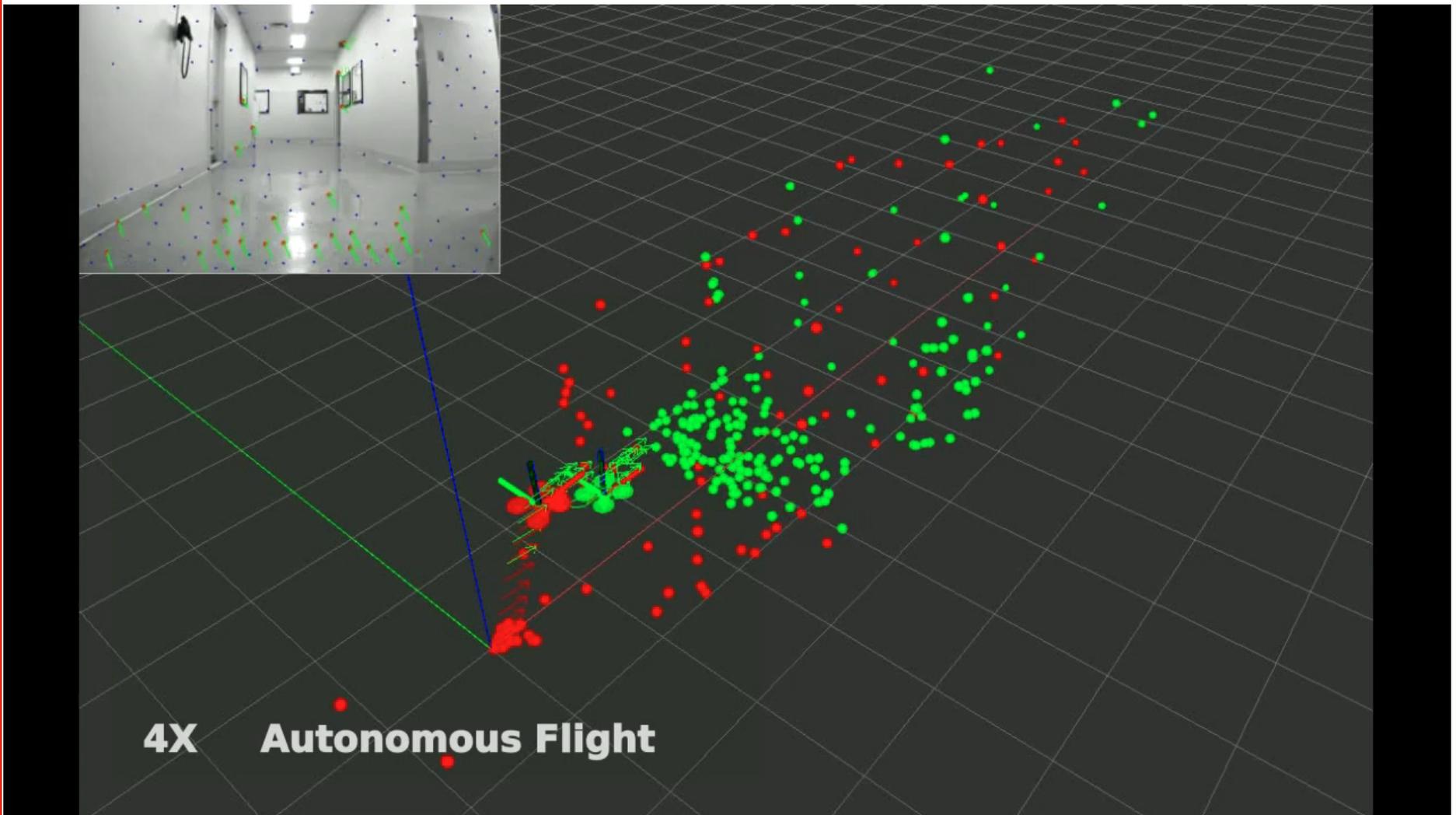
 S. Shen, N. Michael and V. Kumar, "Autonomous navigation in confined indoor environments with a micro-aerial vehicle," IEEE Robotics and Automation Magazine, 2013²⁹



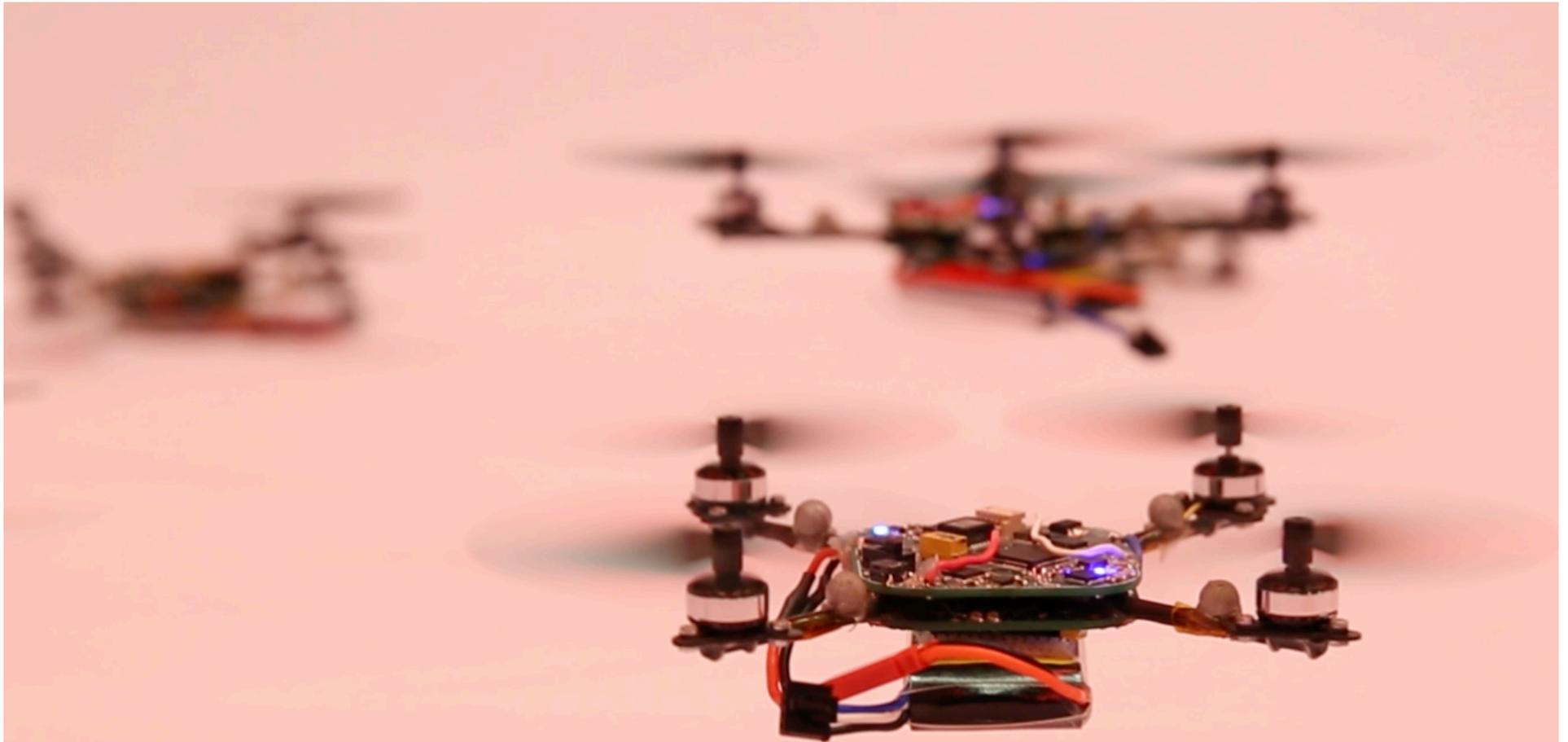
1/2 km, 1.5 m/s, indoor/outdoor

Shaojie Shen, Yash Mulgaonkar, Nathan Michael and Vijay Kumar, "Multi-Sensor Fusion for Robust Autonomous Flight in Indoor and Outdoor Environments with a Rotorcraft MAV," *Proc. IEEE Int. Conference on Robotics and Automation (ICRA), 2014*

Autonomous Indoor Flight with Vision Based Control



S. Shen, Y. Mulgaonkar, N. Michael, and V. Kumar, "Initialization-free monocular visual-inertial estimation with application to autonomous MAVs," *International Symposium on Experimental Robotics (ISER)*, Morocco, 2014



Coordination, Cooperation and Collaboration in Large Teams

Collaboration in Small Teams



Quentin Lindsey, Daniel Mellinger and Vijay Kumar, "Construction with quadrotor teams," *Autonomous Robots*, 33, (3), 2012

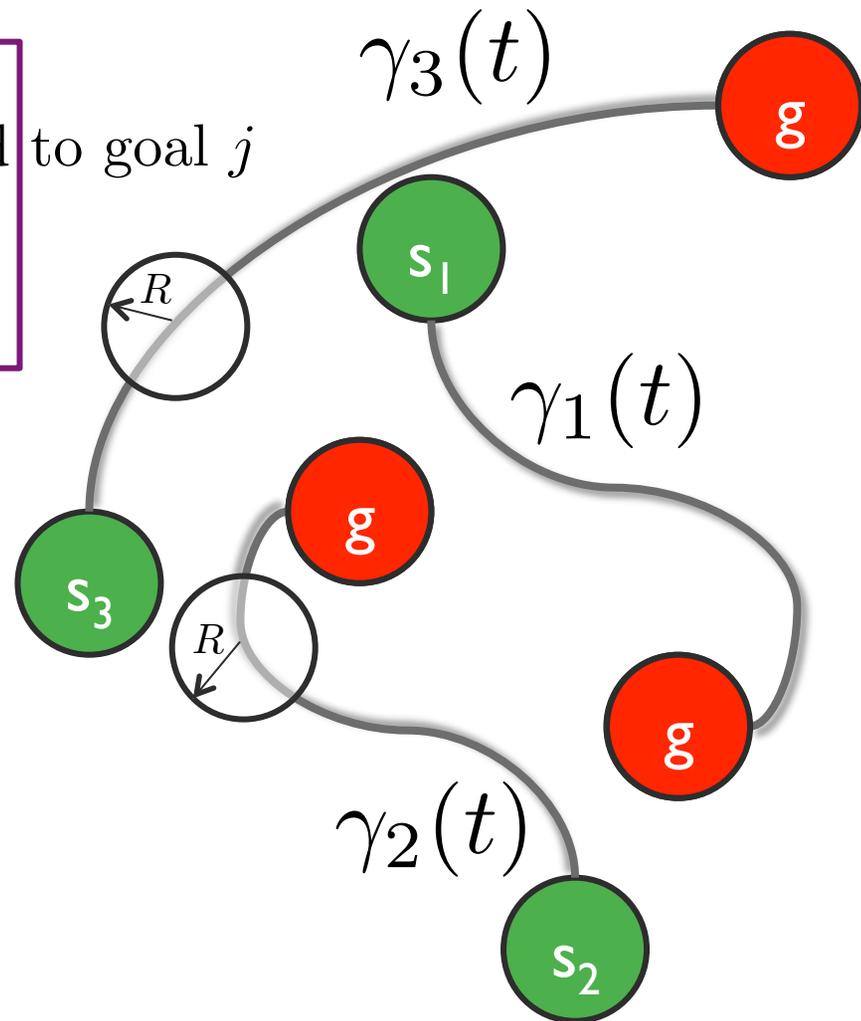
Assignment of robots to goals

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

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

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

Increase in Complexity with Swarm Size

n robots, m obstacles

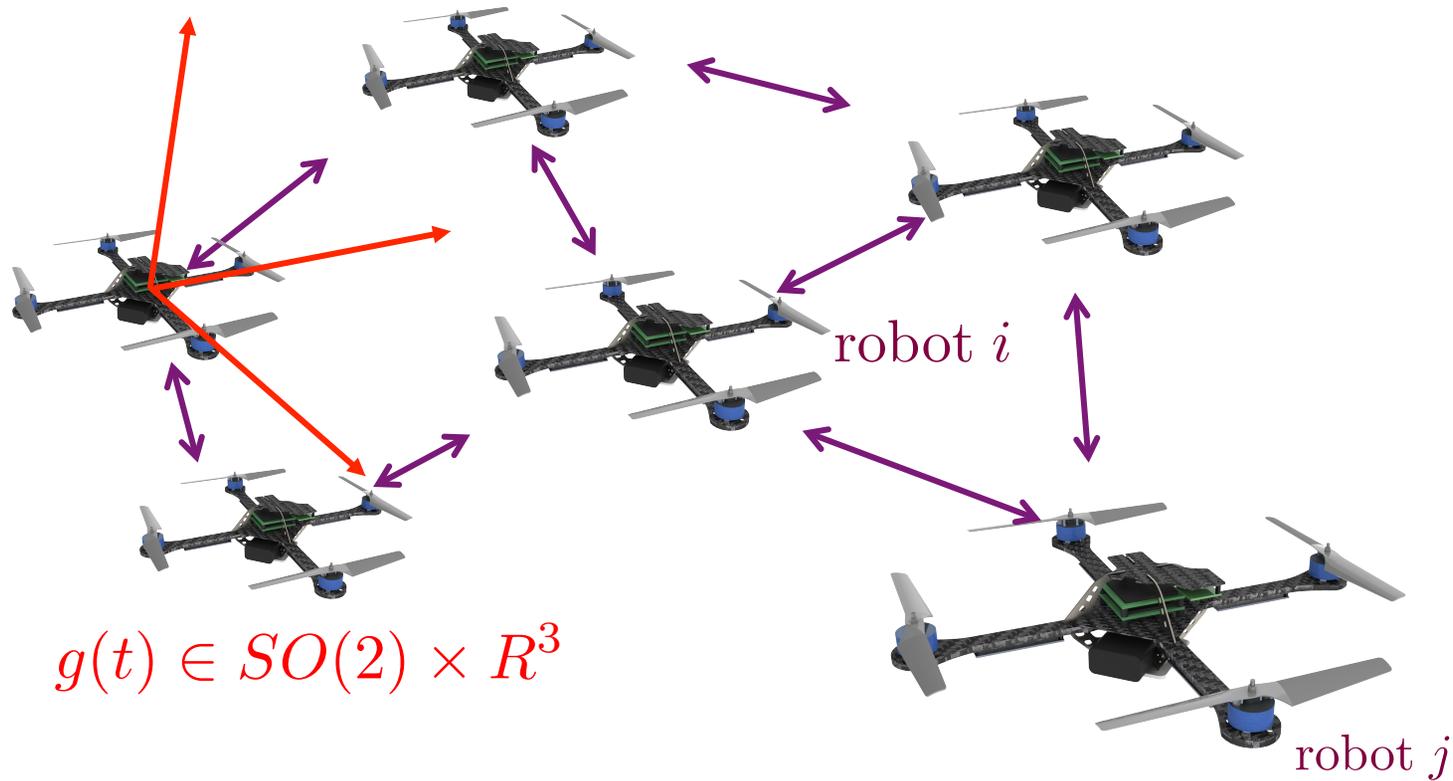
- Dimensionality of the space increases linearly with n $O(\Delta^n)$

- Number of potential interactions with neighbors increases as n^2 $O(mn+n^2)$

- Number of potential interactions with obstacles increases as mn

- Number of assignments of robots to goal positions $O(n!)$

I Leader-Follower Networks



$$g(t) \in SO(2) \times R^3$$

$$\mathbf{s}_{i,j}(t) = \mathbf{x}_j(t) - \mathbf{x}_i(t)$$

Leader-Follower Networks



2 Anonymity (unlabeled robots)



3 Control of Formation Shape and Group Motion



ROS

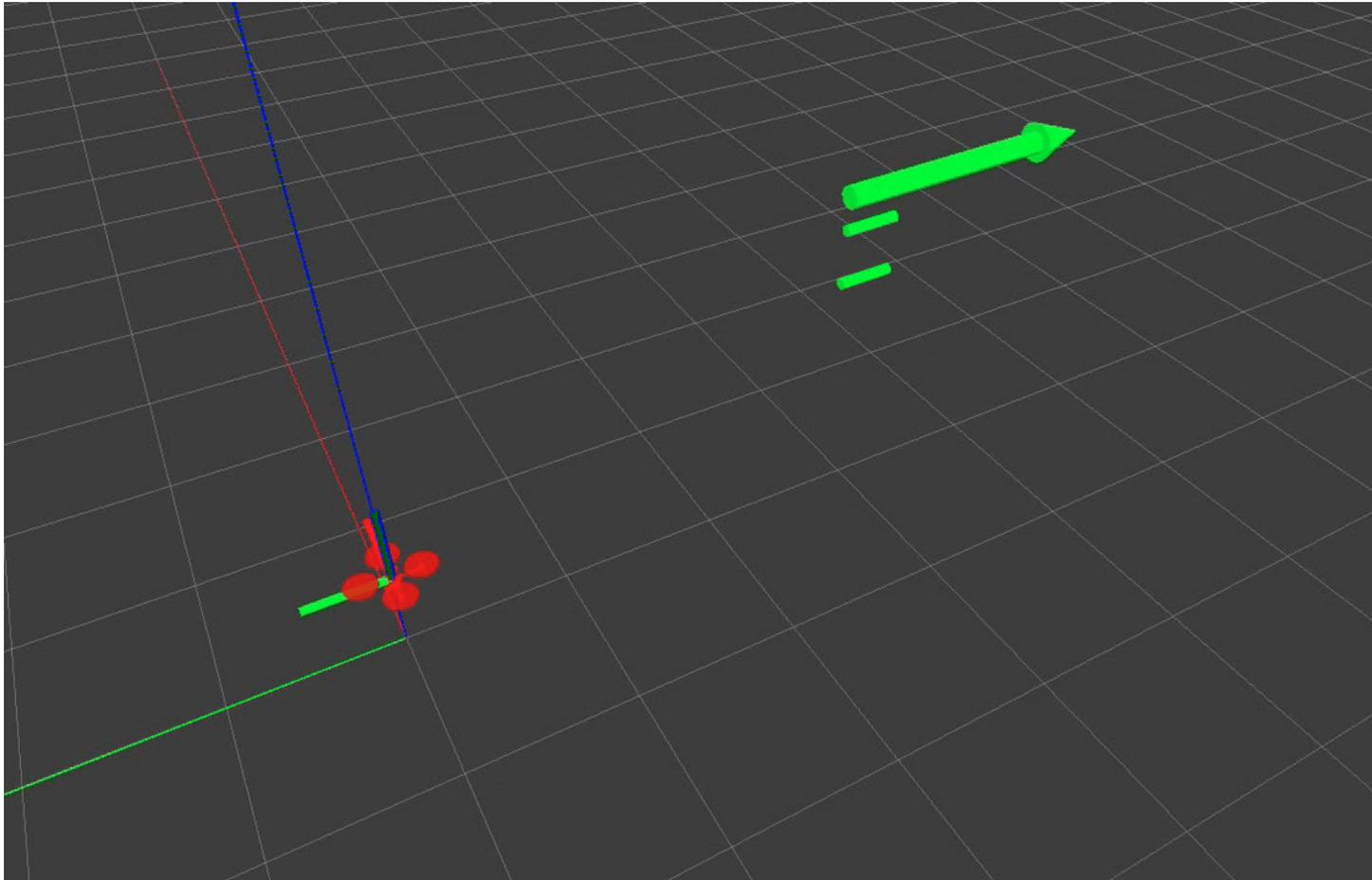
www.ros.org

- Middleware
- Standards for nodes and messages
- Formal descriptions of robots
- Abstractions for hardware
- Software libraries
 - rqt, rviz, pcl

ROS Simulator

Test controllers, estimators, planners

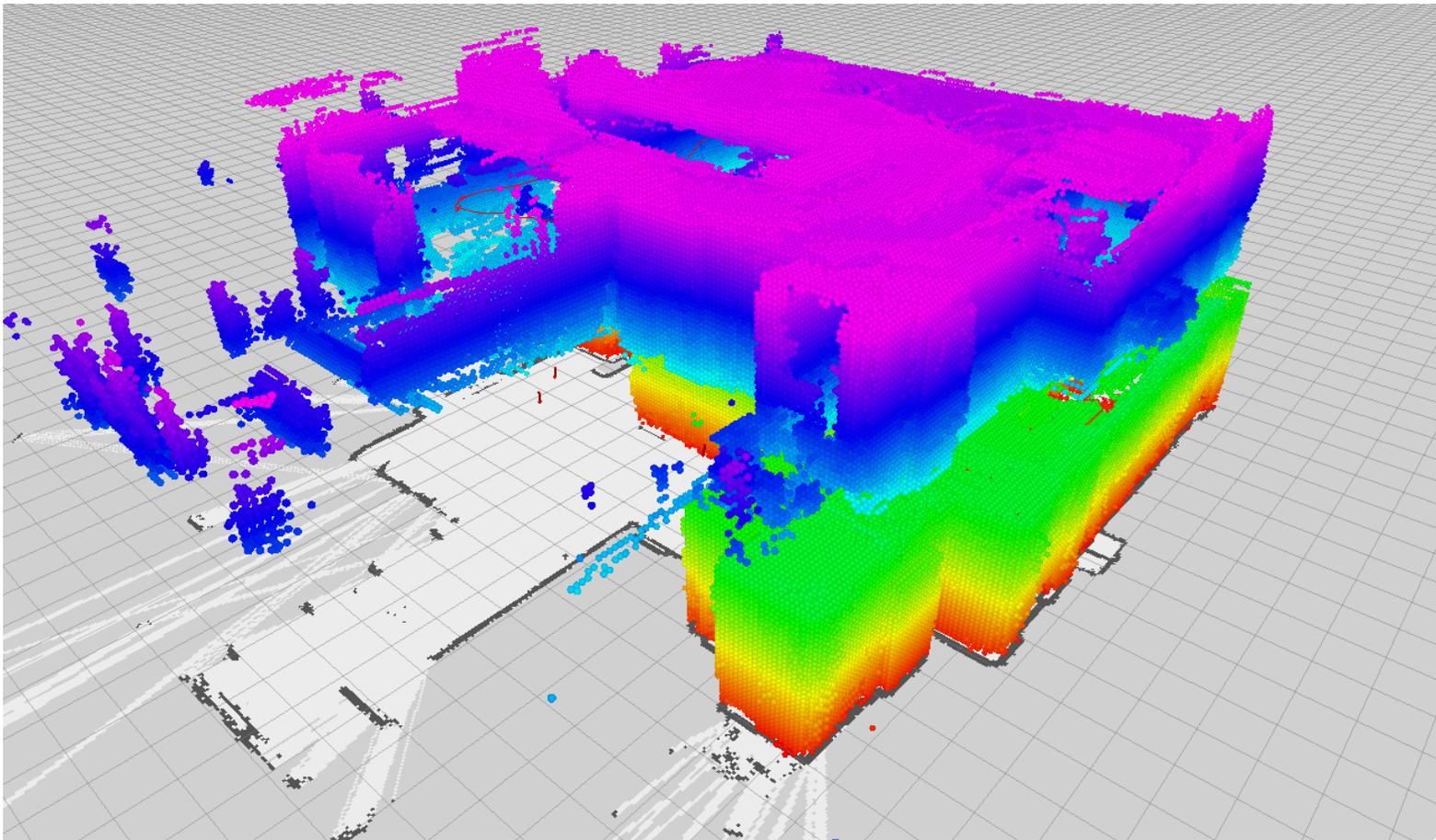
- Dynamics (rigid body, aerodynamics, motor dynamics)
- Sensors (gyros, accelerometers), laser scanner, cameras

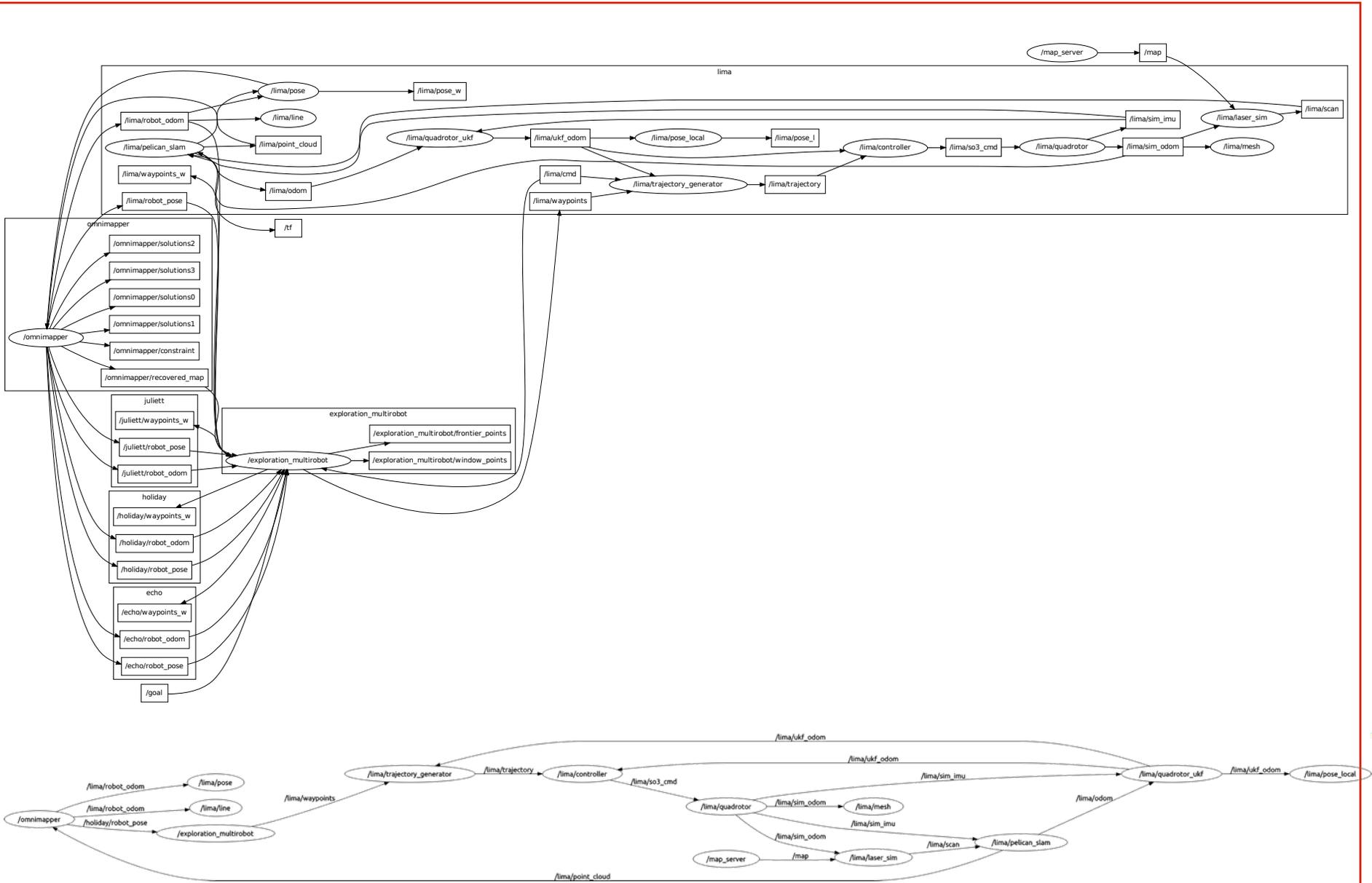


ROS Simulator

Test controllers, estimators, planners

- Dynamics (rigid body, aerodynamics, motor dynamics)
- Sensors (gyros, accelerometers), laser scanner, cameras





CPS for Autonomous Systems

ROS

State of the Art

Limitations

Software abstractions

Formal semantics

Perception-action loops

Real-time guarantees

Tools

Ease of use

Graph representation
of architecture

Nested, hierarchical
representations

Support for co-design

CPS for Swarms

ROS

Advantages

Software abstractions

Perception-action loops

Tools

Graph representation
of architecture

Distributed

Limitations

Formal semantics

Real-time guarantees

Ease of use

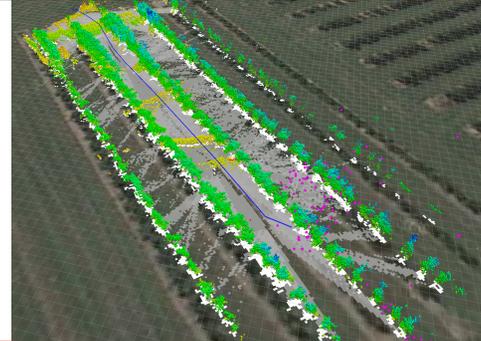
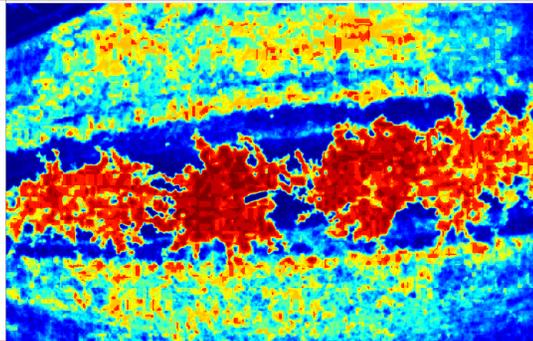
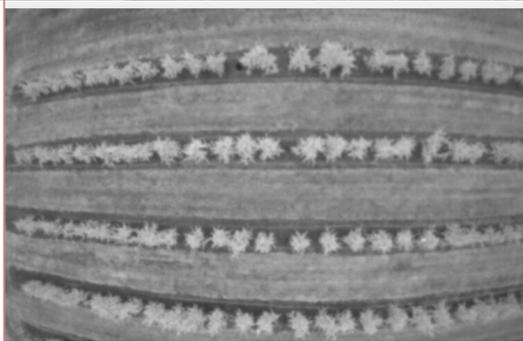
Nested, hierarchical
representations

**Communication, no
global clock**

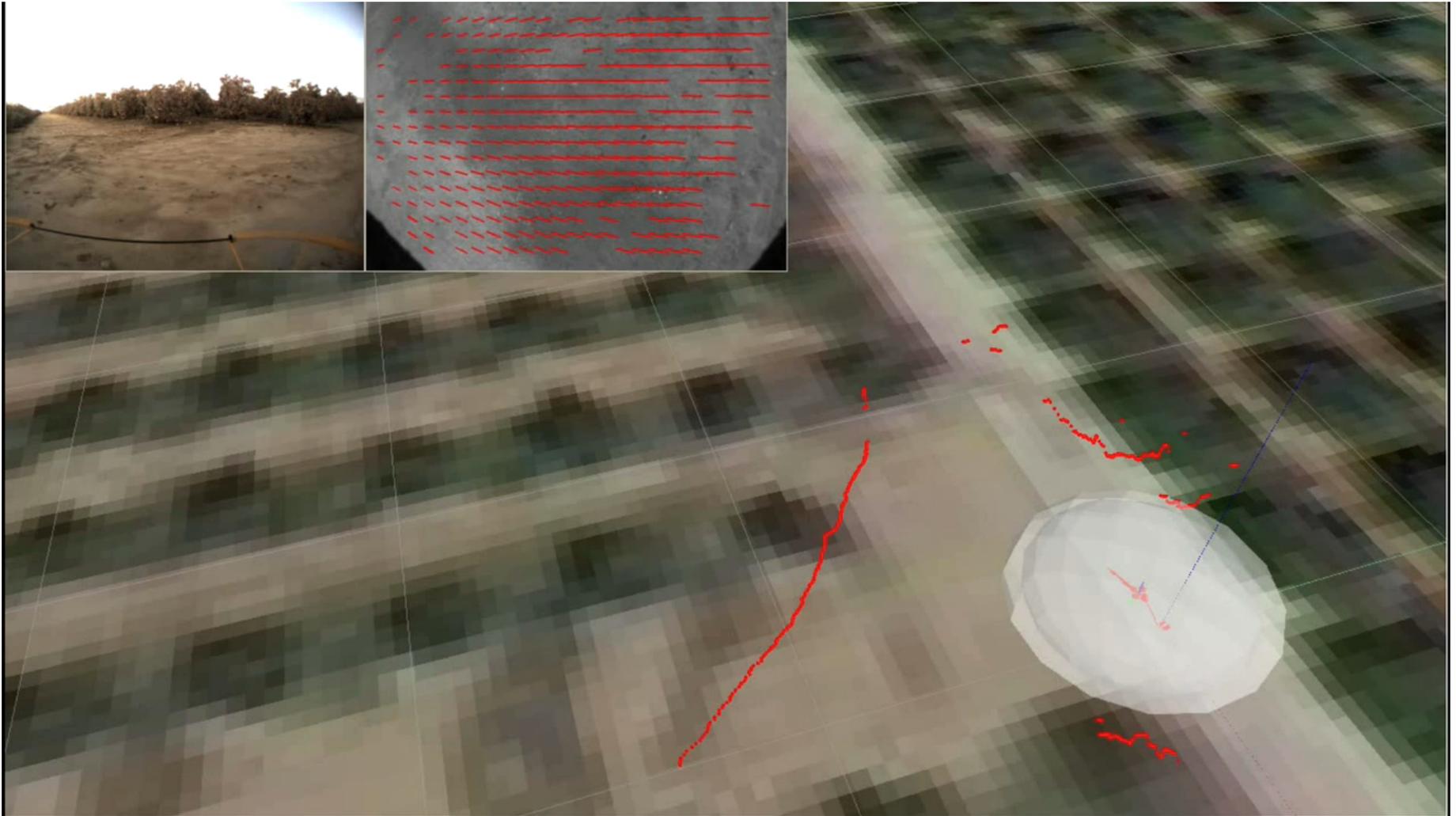


Applications

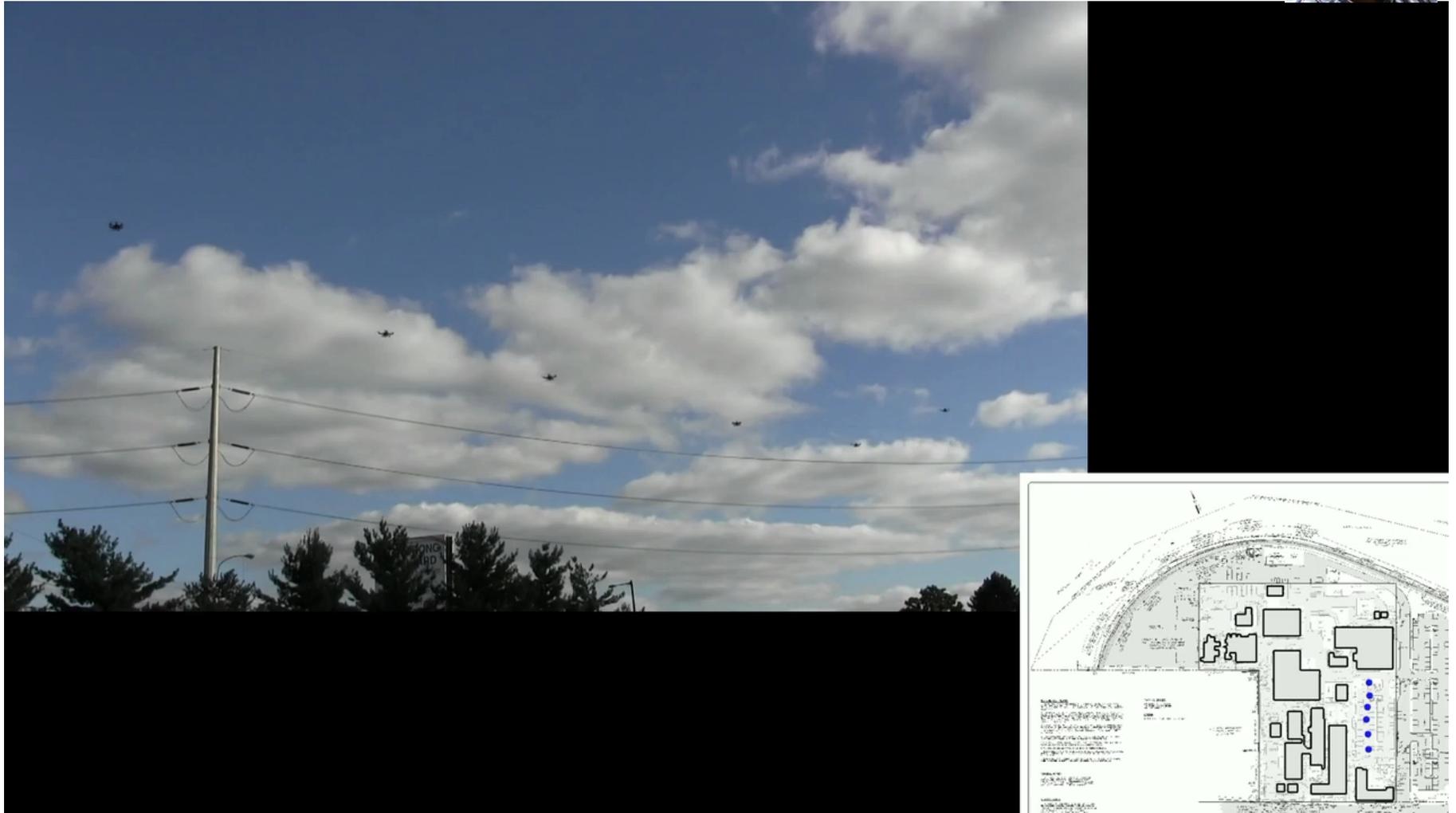
Precision Farming



Precision Farming



Security and First Response



Kartik Mohta, Matthew Turpin, Alex Kushleyev, Daniel Mellinger, Nathan Michael, and Vijay Kumar, "QuadCloud: A Rapid Response Force with Quadrotor Teams," *International Symposium on Experimental Robotics (ISER)*, Morocco, 2014.

Search and Rescue

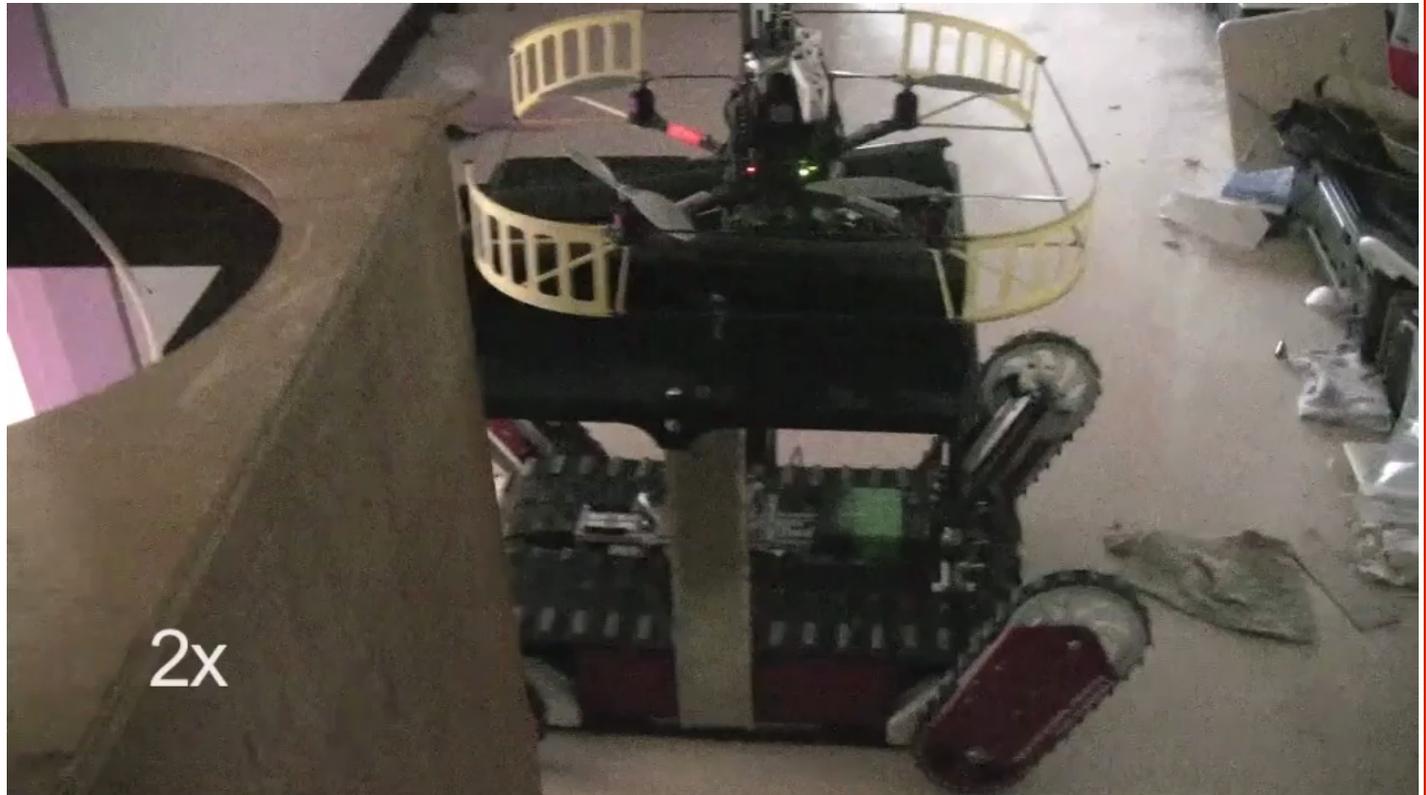


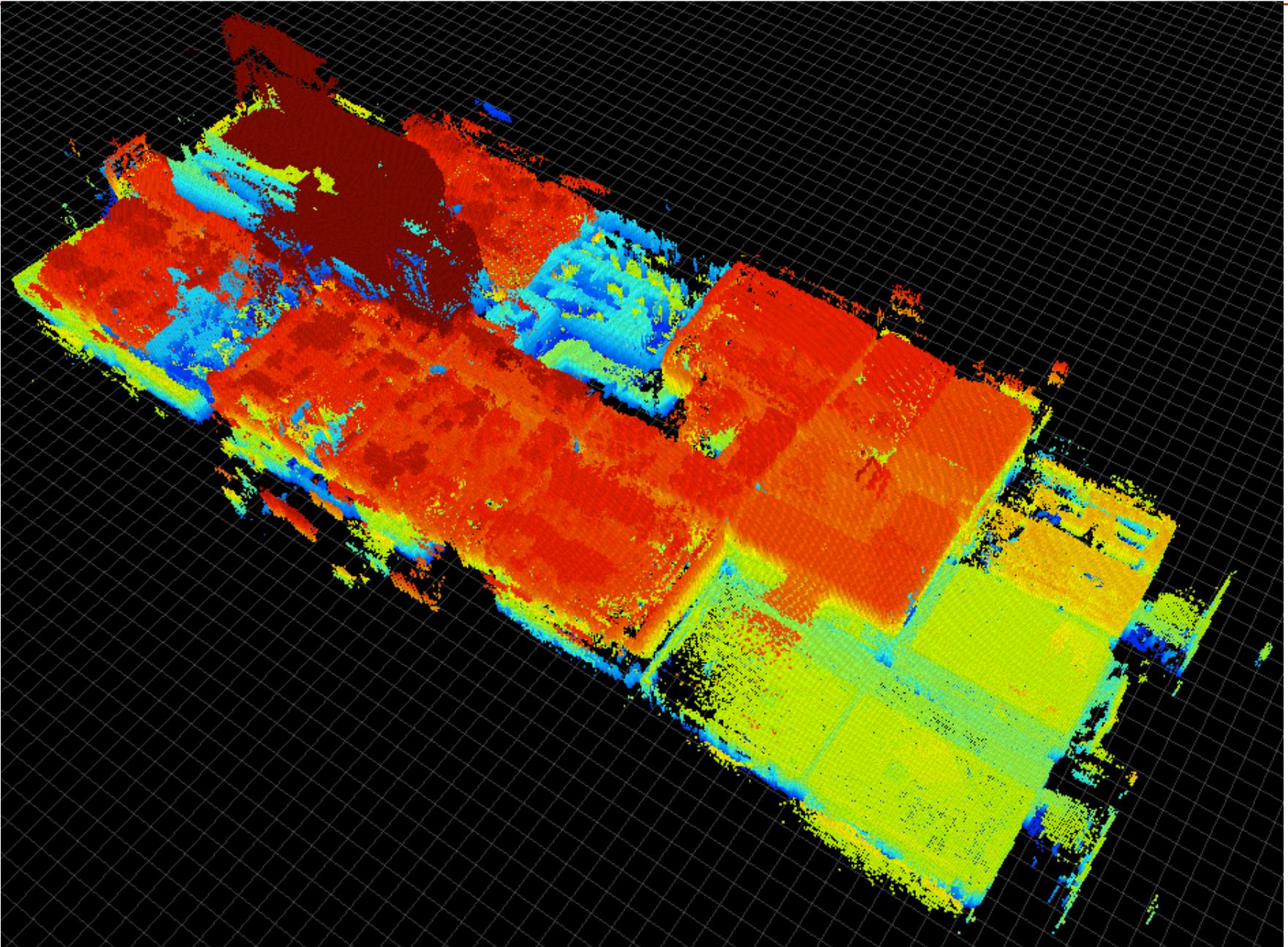
N. Michael, S. Shen, K. Mohta, Y. Mulgaonkar, V. Kumar, K. Nagatani, Y. Okada, S. Kiribayashi, K. Otake, K. Yoshida, K. Ohno, E. Takeuchi, and S. Tadokoro, "Collaborative mapping of an earthquake-damaged building via ground and aerial robots," *J. Field Robotics*, vol. 29, no. 5, pp. 832–841, 2012.

Search and Rescue



N. Michael, S. Shen, K. Mohta, Y. Mulgaonkar, V. Kumar, K. Nagatani, Y. Okada, S. Kiribayashi, K. Otake, K. Yoshida, K. Ohno, E. Takeuchi, and S. Tadokoro, "Collaborative mapping of an earthquake-damaged building via ground and aerial robots," *J. Field Robotics*, vol. 29, no. 5, pp. 832–841, 2012.





7th, 8th, and 9th floors

AMAZING IN MOTION

SWARM



'Swarm' is a project that set out to explore the intersection of design, technology and movement. The story unfolds as a swarm of amazing quadrotors come out to play and explore the world while we sleep.



WATCH 'SWARM'

Its size...is immeasurable.

Its power... is limitless.

Its enemy...is man!

THE SWARM

is coming!

Warner Brothers Pictures Presents Irwin Allen's Production of "THE SWARM"
Starring MICHAEL CAPE KATHARINE FOSS RICHARD WIDMARK RICHARD CHAMBERLAIN
OLYVA DAVYDLAND BEN JOHNSON LEE GRANT JOSE FERRER PATTY DUXE ASTIN
SAM FICKDHS BRADFORD DELMAH with FRED MACMURRAY and HENRY FONDA as Dr. Eric
Music by JERRY GOLDSMITH Screenplay by STERLING SILLPHANT
Produced and Directed by IRWIN ALLEN

PG PARENTS STRONGLY CAUTIONED
Some Material May Be Inappropriate for Children Under 13

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