Department of Mechanical and Aerospace Engineering
New York University

Dec 2, 2019

# Swarms of Small Flying Robots

Vijay Kumar
Professor and Nemirovsky Family Dean
University of Pennsylvania

Penn Engineering

# Acknowledgements

NSF · ARL · ONR (Department of the Navy, Science & Technology) · DARPA · USDA · NASA

Qualcomm · United Technologies · Lockheed Martin · intel · SRC Semiconductor Research Corporation · NVIDIA

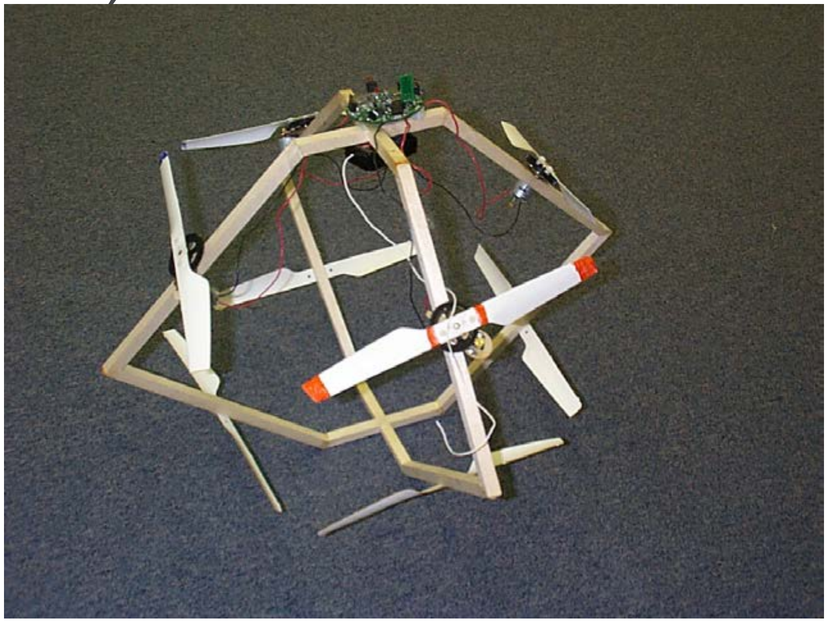
*Spin off companies*

*Non profit*

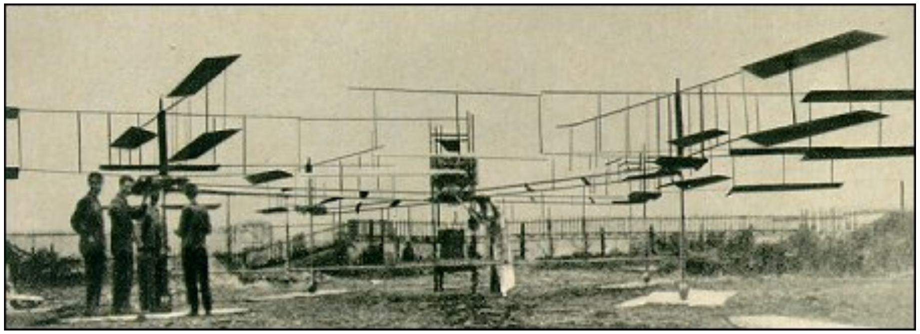
| KMel Robotics | Trefo.ai | Identified Technologies | exyn technologies | We Robotics |
| --- | --- | --- | --- | --- |
| *acquired by* Qualcomm, Penn Engineering | *applications to agriculture* | *aerial mapping* | *mining, asset mapping* | *health, disaster response* |

# A Brief History of Aerial Robotics

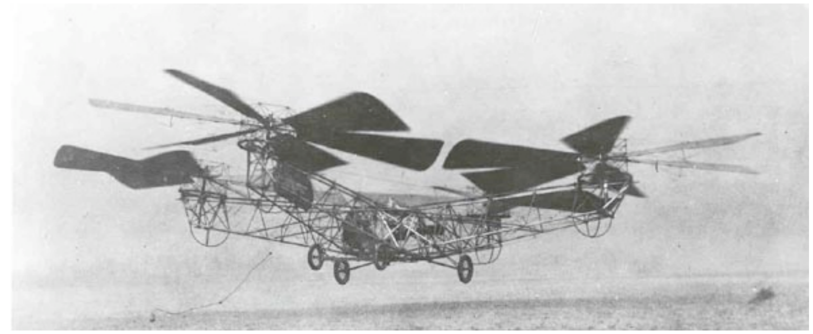
- International Aerial Robotics Competition (1991)
- Early work at GRASP (< 2000)



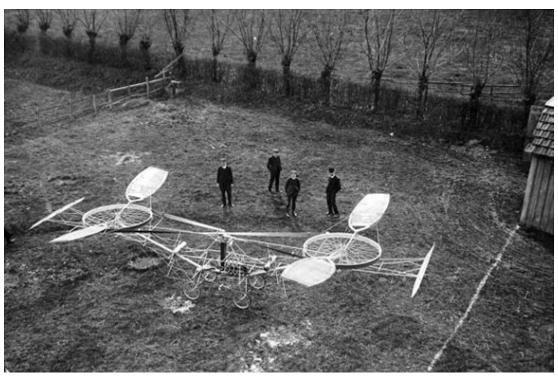
# There are no new ideas, only good ideas!



Breguet-Richet Gyroplane No.1, 1907



George de Bothezat's Quadrotor, 1922



1907, Paul Cornu: First to Hover?

Flying windmill, 2007

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Wired Magazine, *A hundred years of hovering*, 2007

# A Brief History of Aerial Robotics

- International Aerial Robotics Competition (1991)
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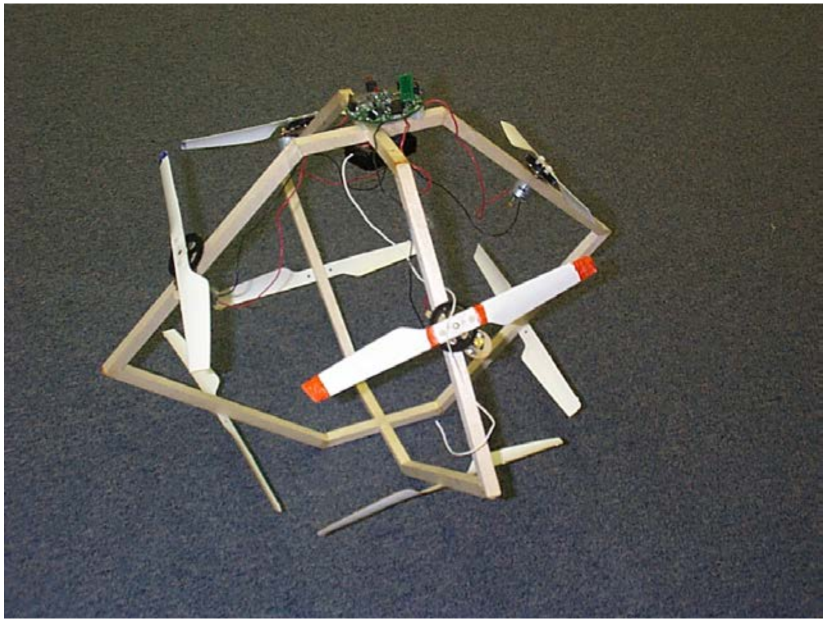


# Inertial Measurement Units

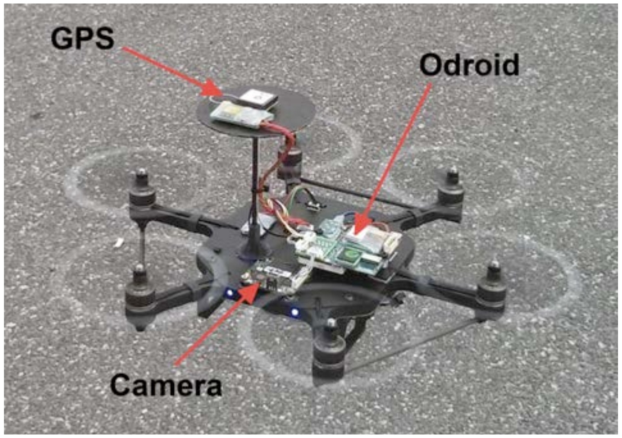
- Accelerometer, airbag sensors (Analog Devices), 1993
- MEMS gyros for electronic stability control (Bosch), 1997
- 3-axis accelerometers for Nintendo Wii, 2006
- 3-axis accelerometer, iPhone (Apple), 2007
- 3-axis accelerometer, 3-axis gyro, 3-axis magnetometer, iPhone 4 (Apple), 2010

*inflexion point*

# A Brief History of Aerial Robotics

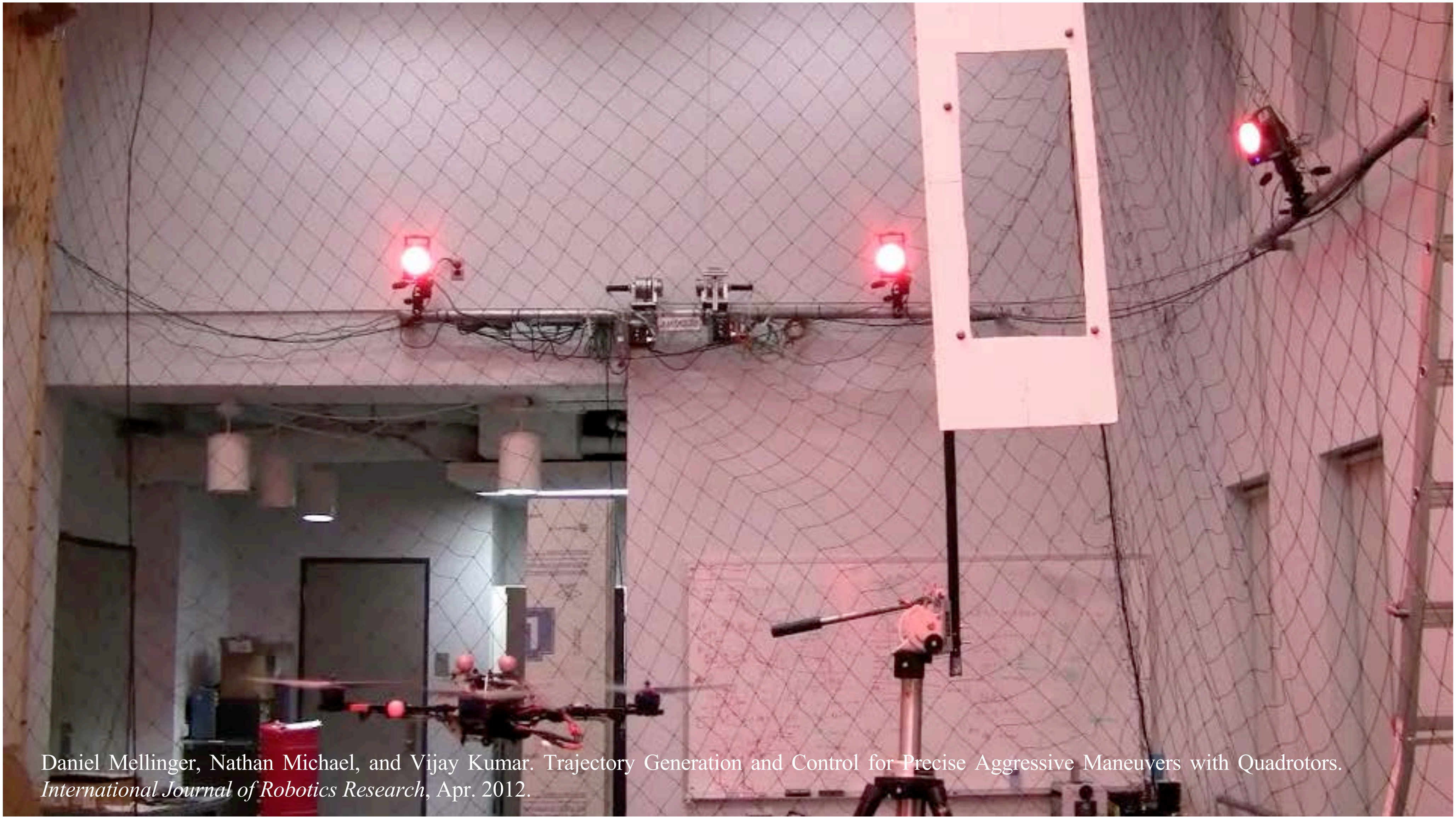
- International Aerial Robotics Competition (1991)
- Early work at GRASP
- 2008-9 – small multi rotor aircrafts become practical

Ascending Technologies




KMel Robotics

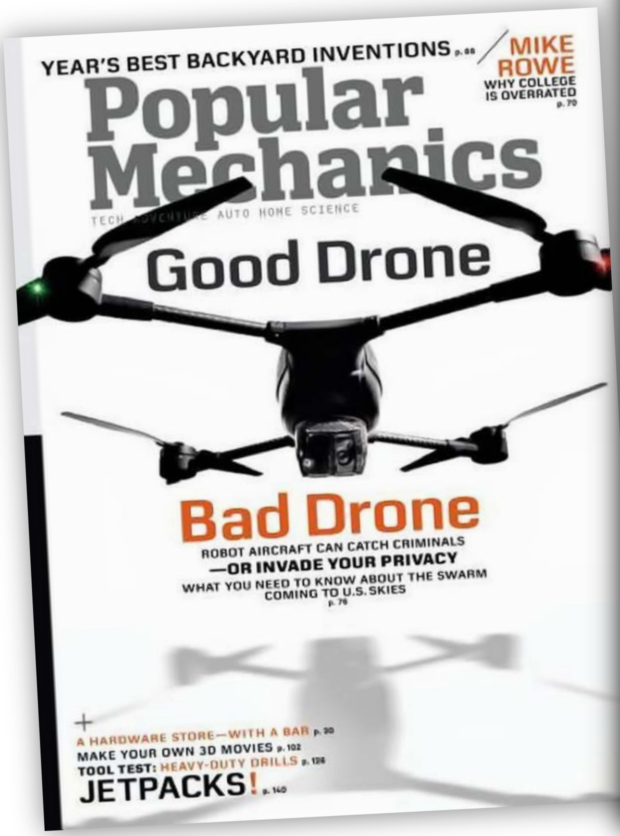
Daniel Mellinger and Alex Kushleyev



Daniel Mellinger, Nathan Michael, and Vijay Kumar. Trajectory Generation and Control for Precise Aggressive Maneuvers with Quadrotors. *International Journal of Robotics Research*, Apr. 2012.

Daniel Mellinger, and Vijay Kumar. “Minimum Snap Trajectory Generation and Control for Quadrotors,” Proc. IEEE International Conference on Robotics and Automation. Shanghai, China, May, 2011.

# 2015 – Drones everywhere!



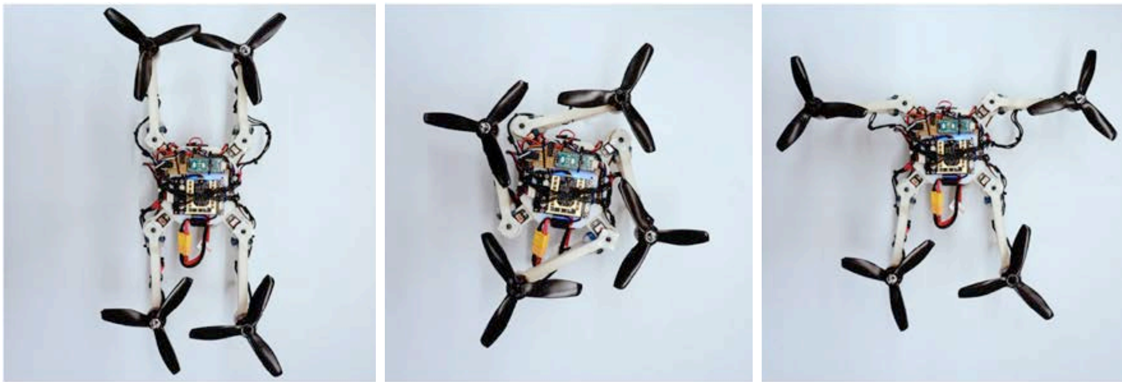


# Drone Racing

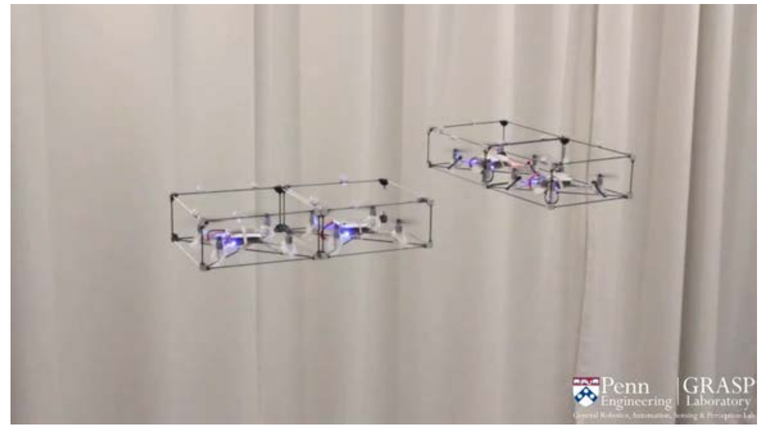

Yash Mulgaonkar

*Drone Nationals*, New York City, 2016

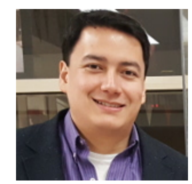
# Beyond Quadrotors



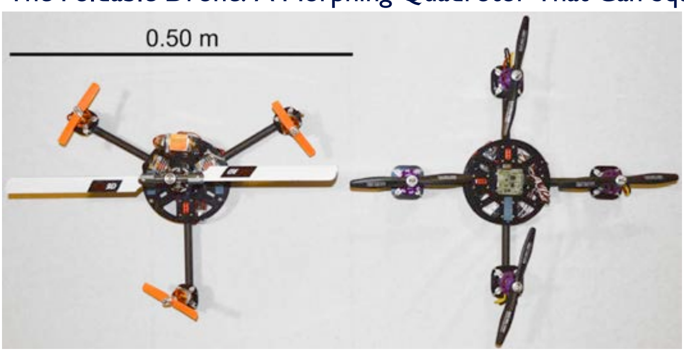
Davide Falanga , Kevin Kleber, Stefano Mintchev , Dario Floreano , and Davide Scaramuzza, “The Foldable Drone: A Morphing Quadrotor That Can Squeeze and Fly,” 2019.



David Saldana, Bruno Gabrich, Guanrui Li, Mark Yim, and Vijay Kumar, “ModQuad: The Flying Modular Structure that Self-Assembles in Midair,” 2018.



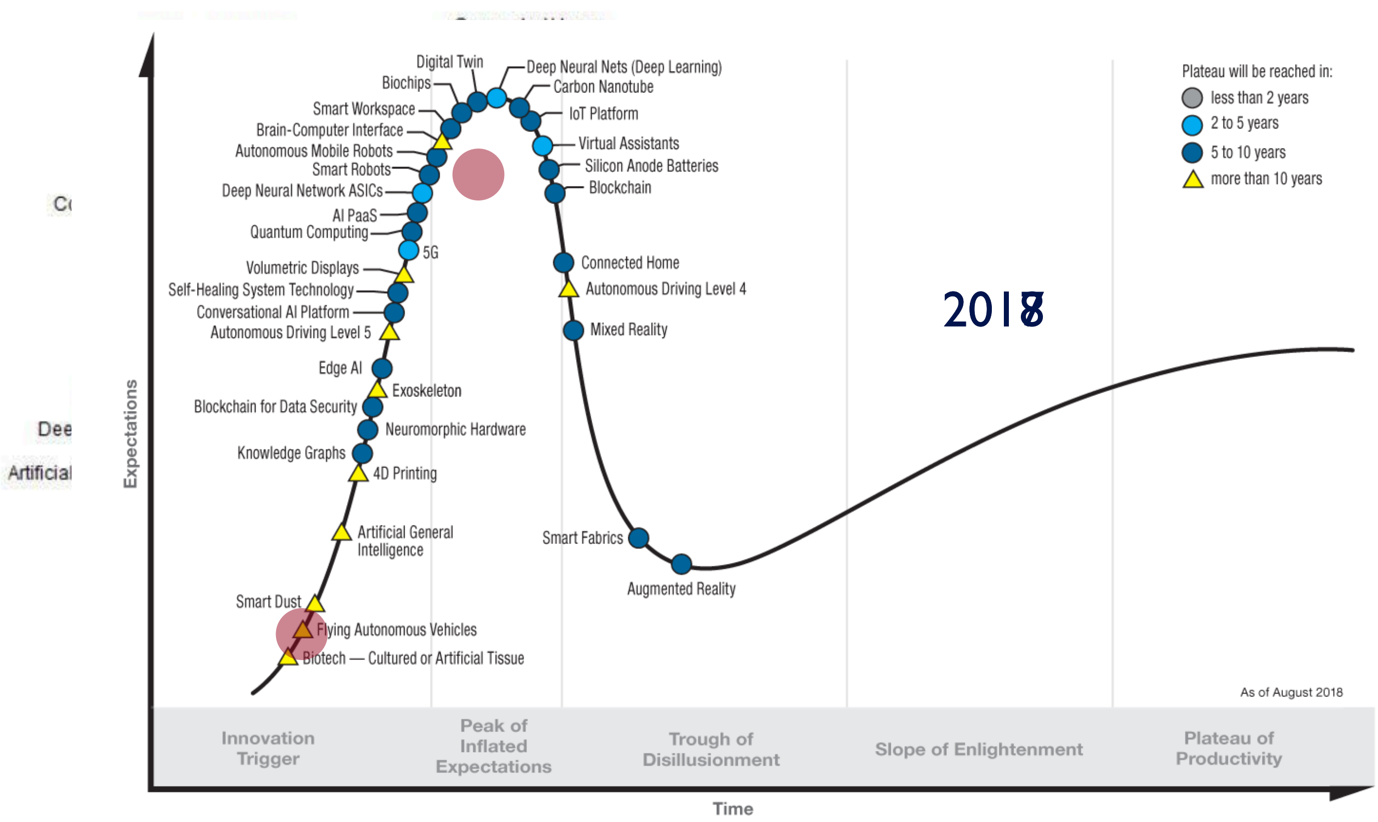
David Saldana




S. Driessens and P. Pounds, “The triangular quadrotor: a more efficient quadrotor configuration,” 2015.

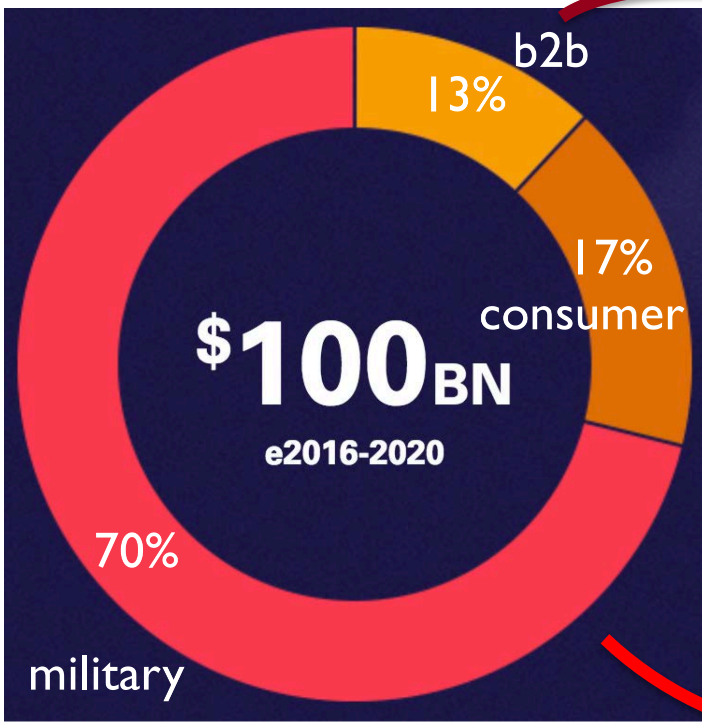
Dario Brescianini and Raffaello D’Andrea, “An omni-directional multirotor vehicle,” 2018.

# Gartner Hype Cycle



# 2019 (10 years later)

## Market

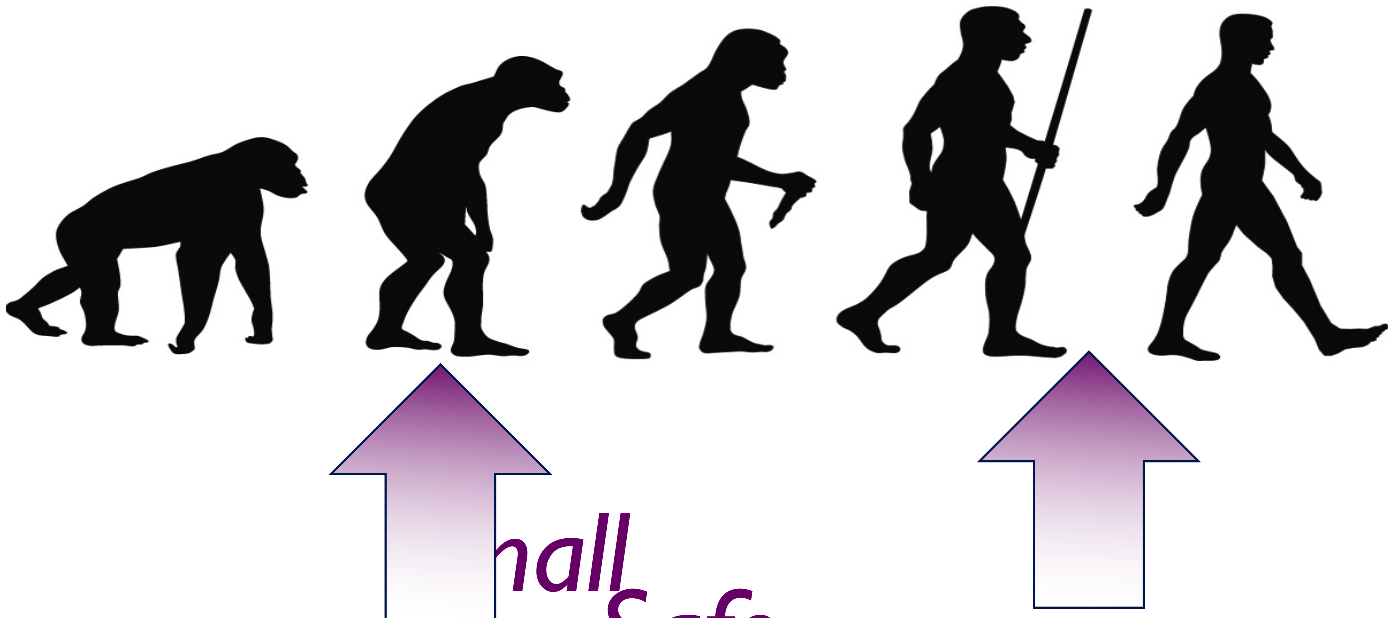



Goldman Sachs Research

Agriculture, Mining, Health


Penn Engineering

# Aerial Robotics Research (and Commercialization)



hall

Safe

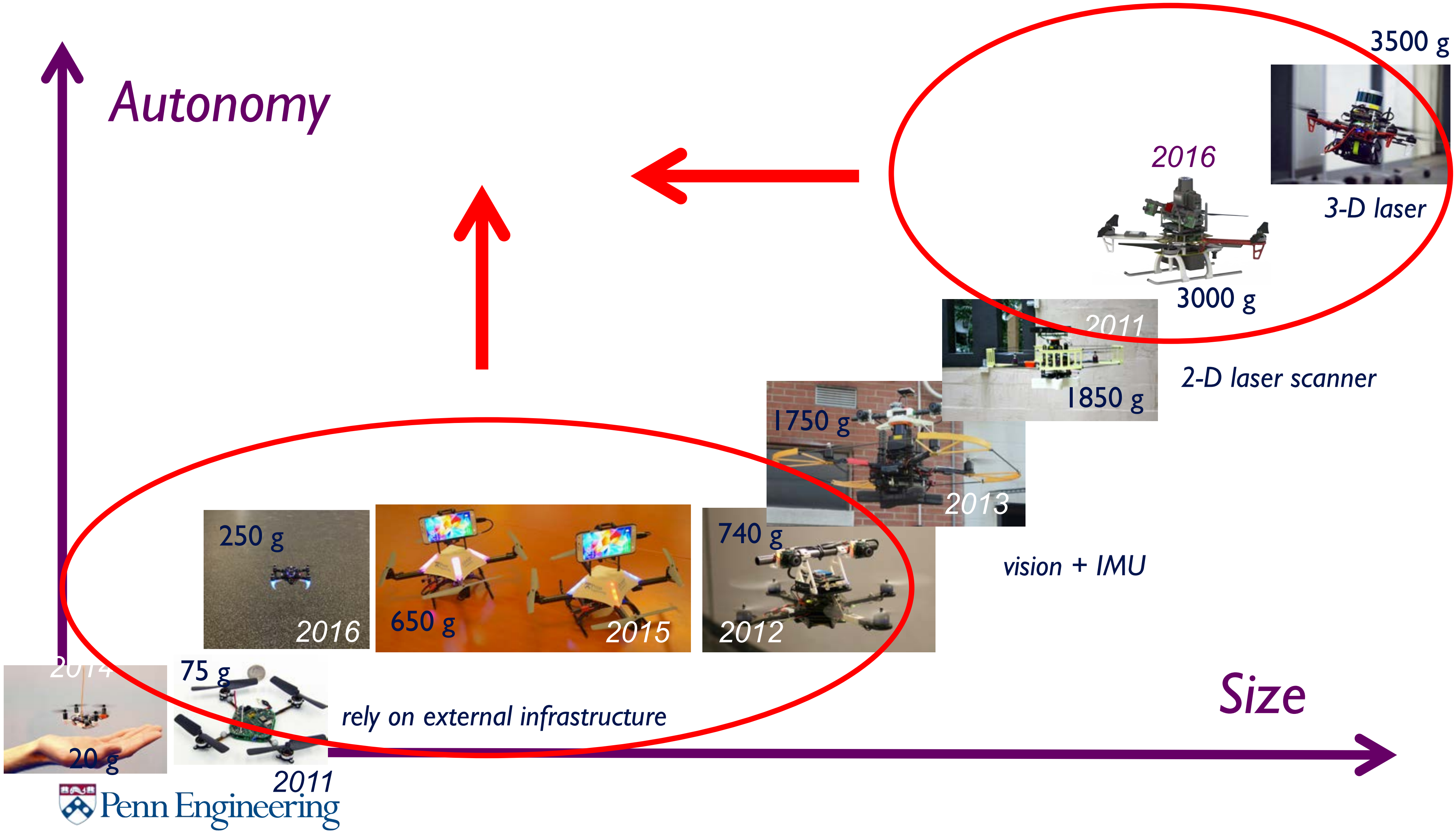
We are here!

Smart

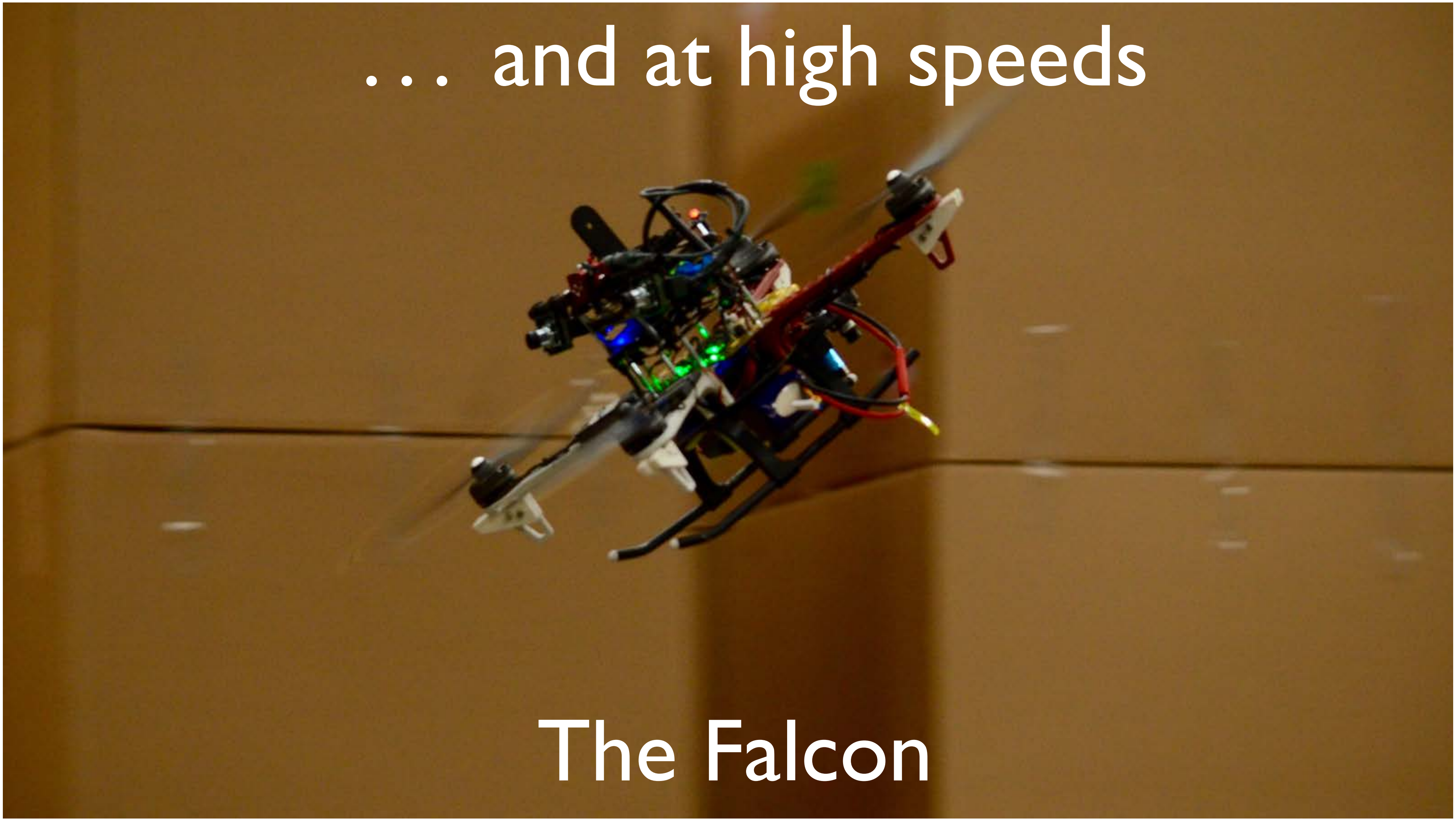
Speed

Swarms

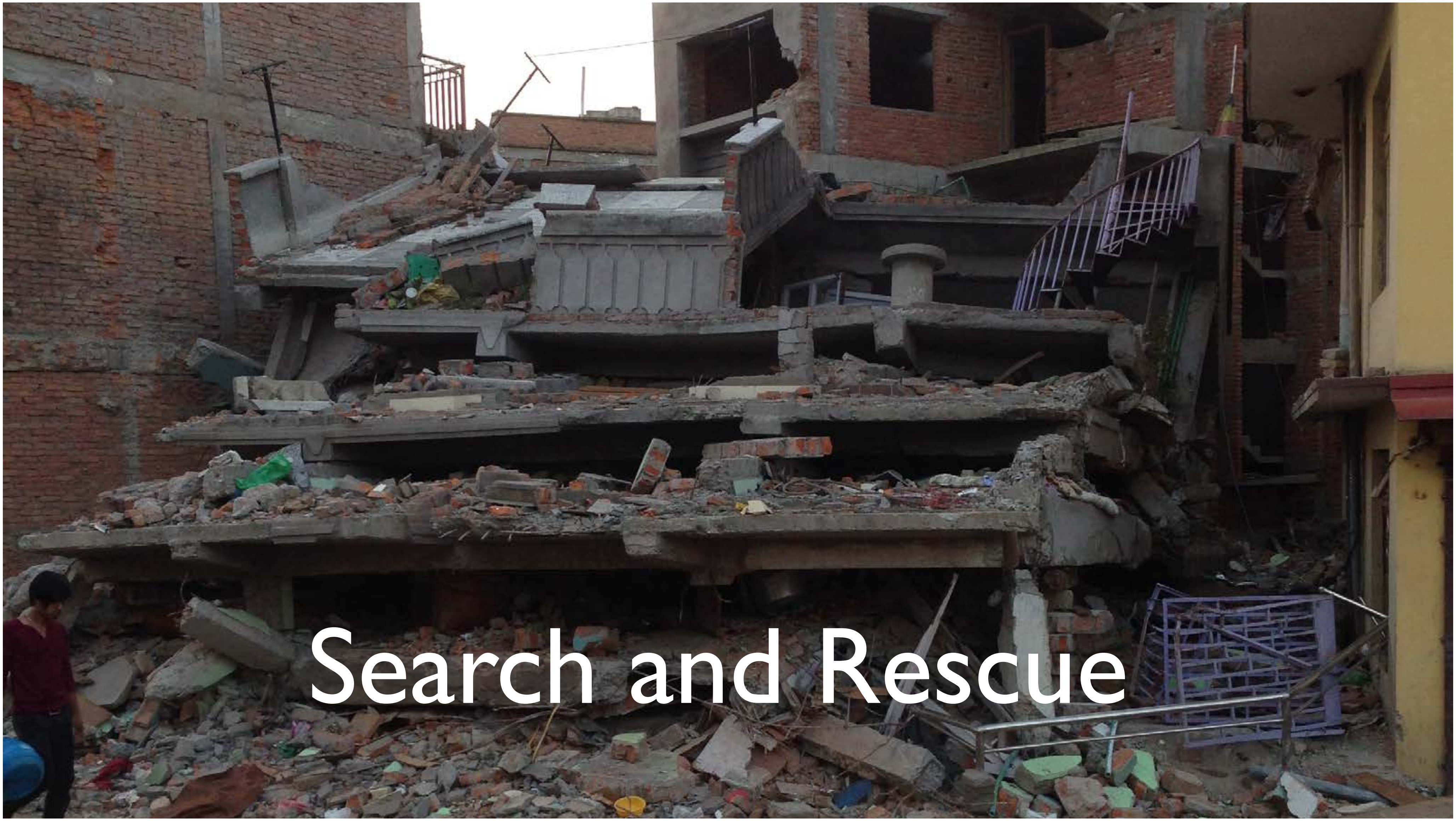
Penn Engineering



Autonomy
Size
3500 g
3-D laser
2016
3000 g
2011
1850 g
2-D laser scanner
1750 g
2013
vision + IMU
250 g
2016
650 g
2015
740 g
2012
2014
20 g
75 g
2011
rely on external infrastructure
Penn Engineering


. . . and at high speeds
The Falcon

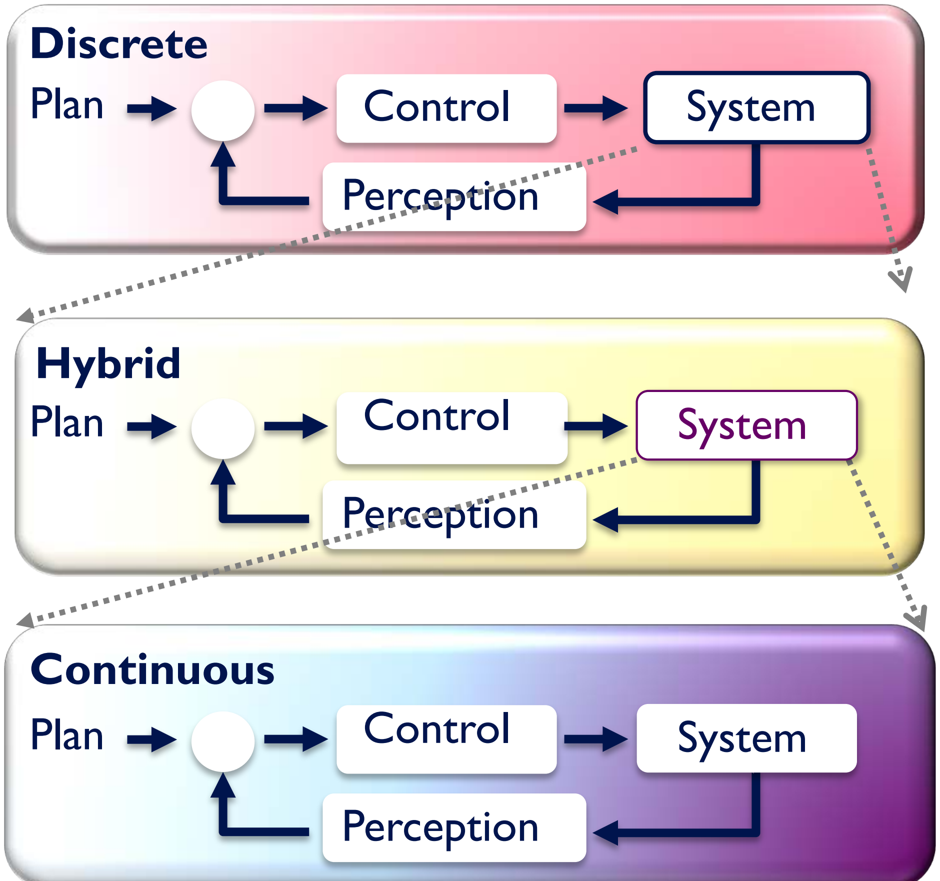
# Search and Rescue



# Five Challenges

- Perception Action Loops for Autonomy
- State Estimation
- Navigation in Cluttered Environments
- Scaling Down in Size, Weight
- Perception Action Communication Loops for Swarms

# 1. Nested Perception/Action Loops




Nonlinear controllers on SO(3)/SE(3)

JTY Wen and K Kreutz-Delgado, The attitude control problem, IEEE Transactions on Automatic control, 1991.

D Mellinger and V Kumar, "Minimum Snap Trajectory Generation and Control for Quadrotors," *Proc. IEEE International Conference on Robotics and Automation*. Shanghai, China, May, 2011.

T Lee, M Leok, NH McClamroch, "Nonlinear Robust Tracking Control of a Quadrotor UAV on SE(3)," Asian Journal of Control 2012.

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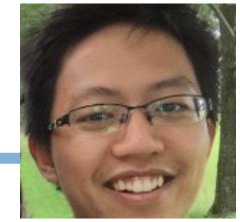
# 2. State Estimation (Stereo + IMU)


Ke Sun


Kartik Mohta

## Model

$$\mathbf{x}_I = \left( {}^I_G\mathbf{q}^\top \quad \mathbf{b}_g^\top \quad {}^G\mathbf{v}_I^\top \quad \mathbf{b}_a^\top \quad {}^G\mathbf{p}_I^\top \quad {}^I_C\mathbf{q}^\top \quad {}^I\mathbf{p}_C^\top \right)^\top$$

Orientation, Gyro bias, Velocity, Acc bias, Position, Cam-IMU extrinsics

$${}^I_G\dot{\mathbf{q}} = \frac{1}{2}\Omega(\omega){}^I_G\mathbf{q}, \quad \dot{\mathbf{b}}_g = \mathbf{n}_{wg}, \quad {}^G\dot{\mathbf{v}} = C\left({}^I_G\mathbf{q}\right)^\top \mathbf{a} + {}^G\mathbf{g},$$

$$\dot{\mathbf{b}}_a = \mathbf{n}_{wa}, \quad {}^G\dot{\mathbf{p}}_I = {}^G\mathbf{v}, \quad {}^I_C\dot{\mathbf{q}} = \mathbf{0}_{3\times1}, \quad {}^I\dot{\mathbf{p}}_C = \mathbf{0}_{3\times1}$$

## Augmented State

$$\mathbf{x}_{C_i} = \left( {}^{C_i}_G\mathbf{q}^\top \ {}^G\mathbf{p}_{C_i}^\top \right)^\top \qquad \mathbf{x} = \left( \mathbf{x}_I^\top \ \mathbf{x}_{C_0}^\top \ \cdots \ \mathbf{x}_{C_{N-1}}^\top \right)^\top$$

## Stereo Camera Measurement

$$\mathbf{z}_i = \begin{pmatrix} u_{i,1} \\ v_{i,1} \\ u_{i,2} \\ v_{i,2} \end{pmatrix} = \begin{pmatrix} \frac{1}{^{C_{i,1}}Z} & \mathbf{0}_{2\times2} \\ \mathbf{0}_{2\times2} & \frac{1}{^{C_{i,2}}Z} \end{pmatrix} \begin{pmatrix} ^{C_{i,1}}X \\ ^{C_{i,1}}Y \\ ^{C_{i,2}}X \\ ^{C_{i,2}}Y \end{pmatrix} + \mathbf{n}_z, \quad {}^{C_{i,j}}\mathbf{p}_f = \begin{pmatrix} ^{C_{i,j}}X \\ ^{C_{i,j}}Y \\ ^{C_{i,j}}Z \end{pmatrix} \quad j \in \{1, 2\}$$

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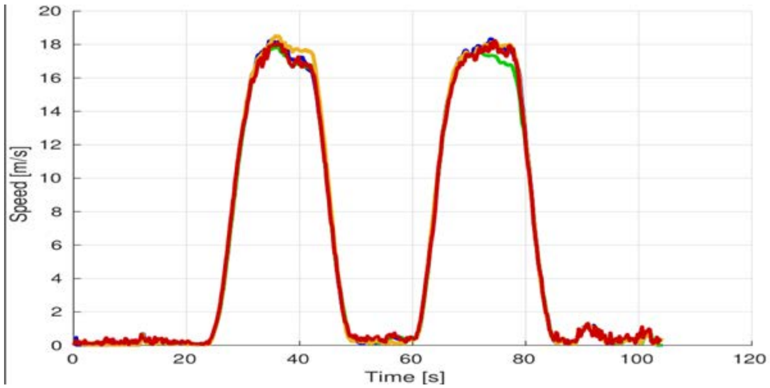
K. Sun, K. Mohta, B. Pfrommer, M. Watterson, S. Liu, Y. Mulgaonkar, C. J. Taylor, and V. Kumar, "Robust Stereo Visual Inertial Odometry for Fast Autonomous Flight", RAL 2018

# Stereo Multistate Constraint Kalman Filter (S-MCKF)

Fast autonomous flight (Top speed at 18m/s)




Autonomous flight in unstructured environment

- Includes various scenes (warehouse, woods, open field, etc).
- Round trip over 700m
- Final drift under 0.5%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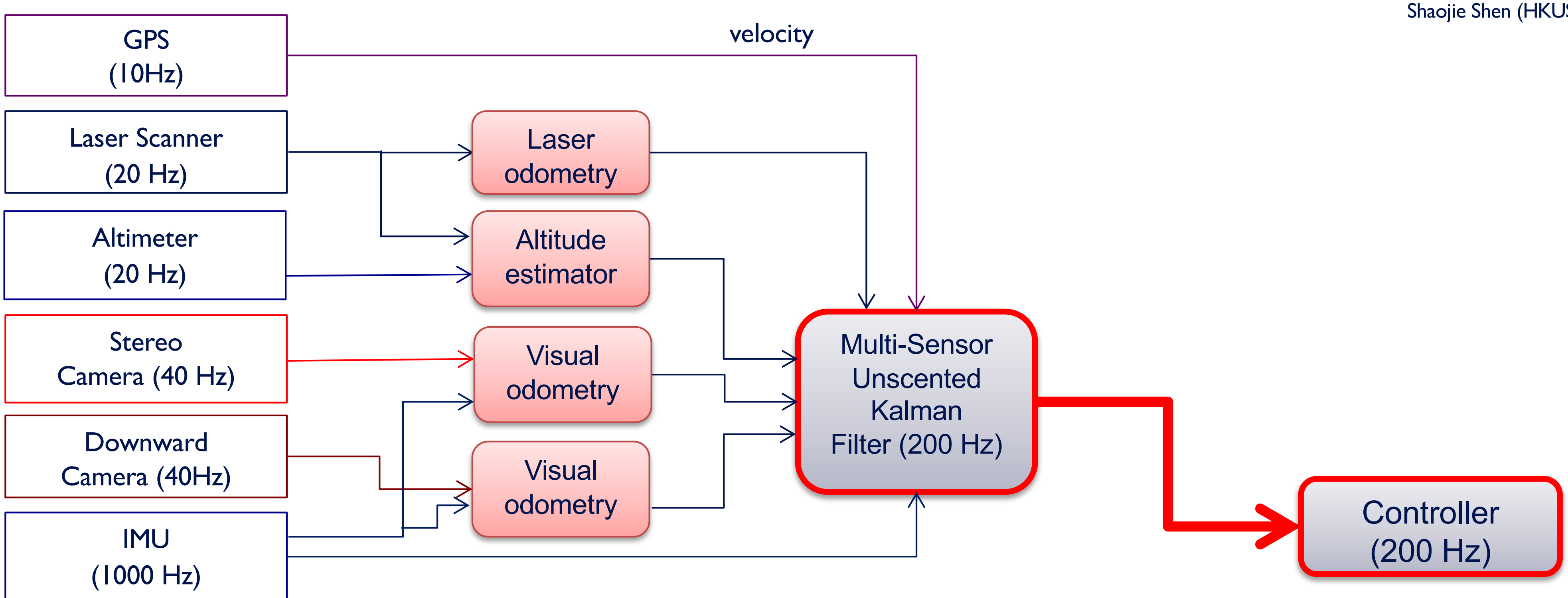
# State Estimation

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.

Shaojie Shen (HKUST)

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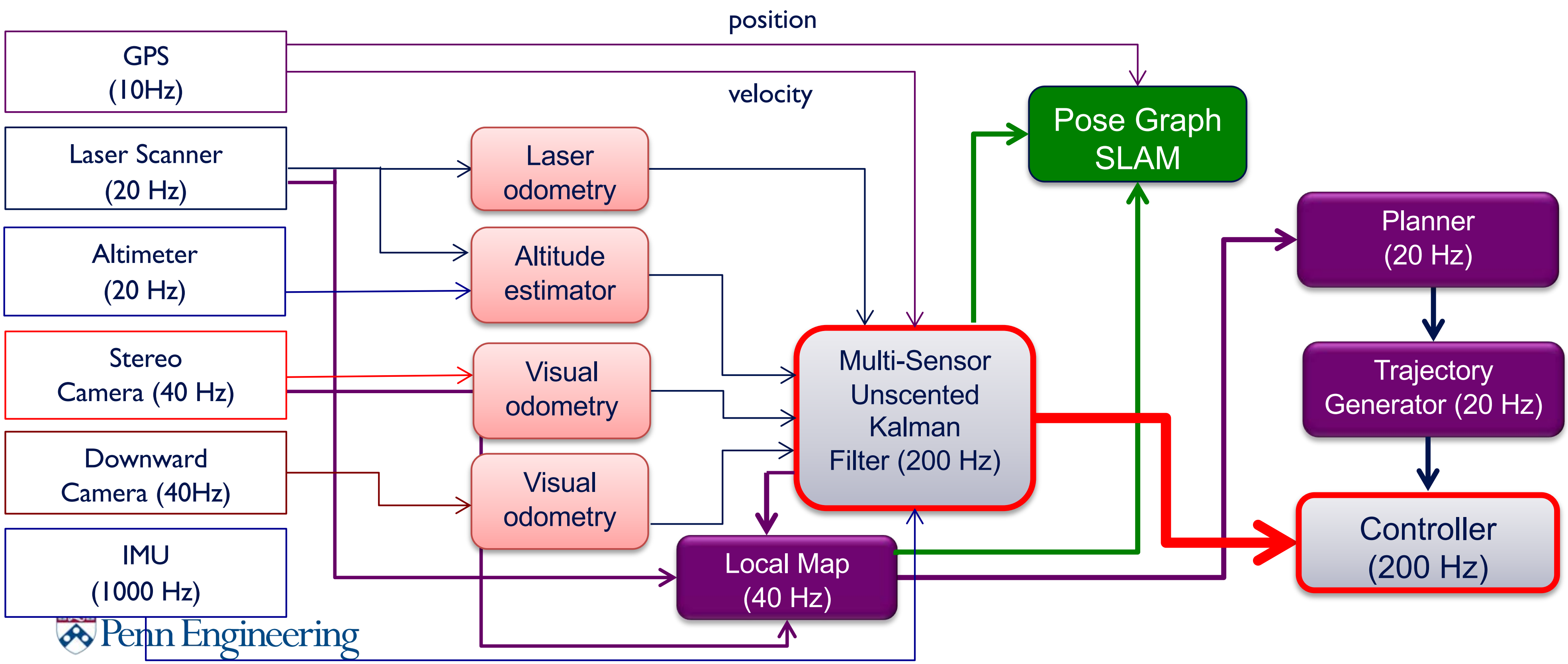
# 3. Autonomy: *Perception and Action for Navigation*

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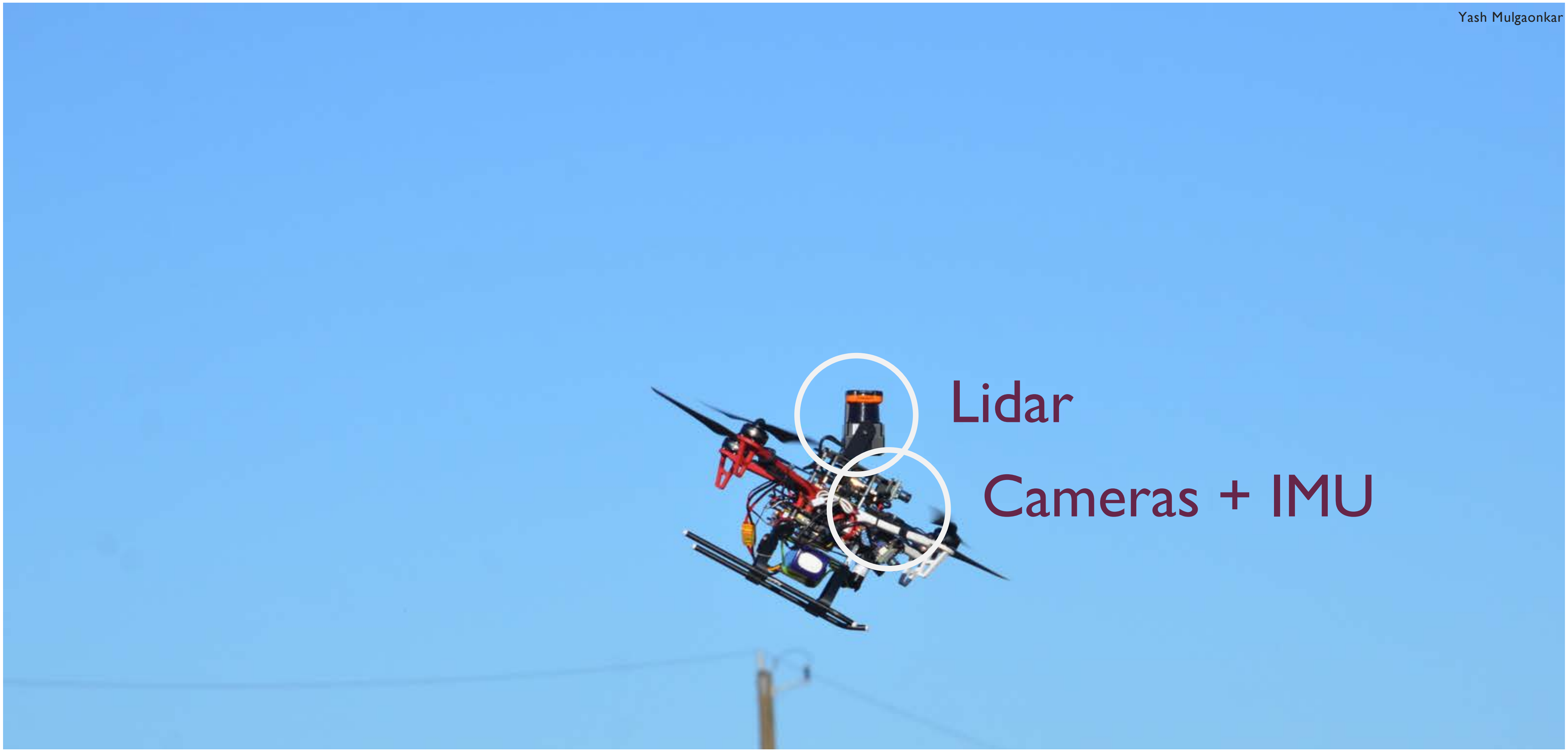
# DARPA Fast Lightweight Autonomy (FLA)

Yash Mulgaonkar



# 3 Planning in Cluttered Environments

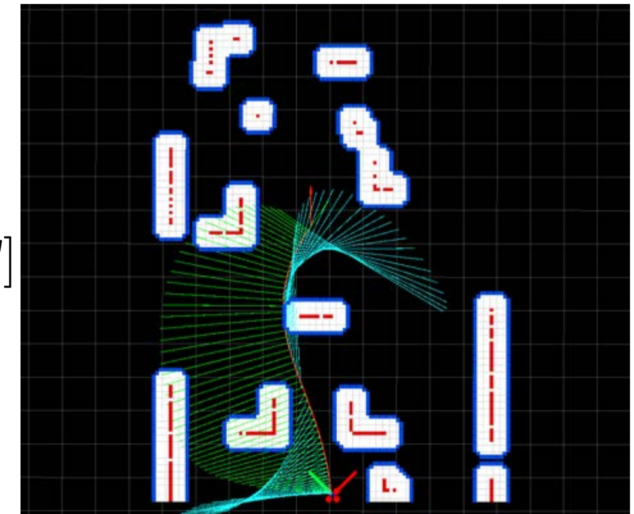
## 1. Optimal Control

$$\min_{u(t),\, T} J(x(t), u(t)) + \rho T$$

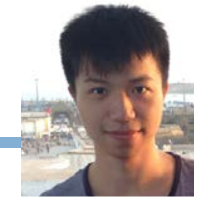
$$\dot{x} = Ax(t) + Bu(t),\; u(t) \in \mathcal{U},\; \forall t \in [0, T]$$

$$x(0) = x_0,\; x(T) \in \mathcal{X}^{\text{goal}},\; x(t) \in \mathcal{X}^{\text{free}}$$

$$\mathcal{X}^{\text{goal}} \subset \mathcal{X}^{\text{free}}$$



- Relative degree 4 (input and state constraints)
- Non convex
- Safe corridors in different homology classes
- Partially known environment (limited field of view sensors)



*Sikang Liu*

*Mike Watterson*

*Sarah Tang*

*Subhrajit Bhattacharya*

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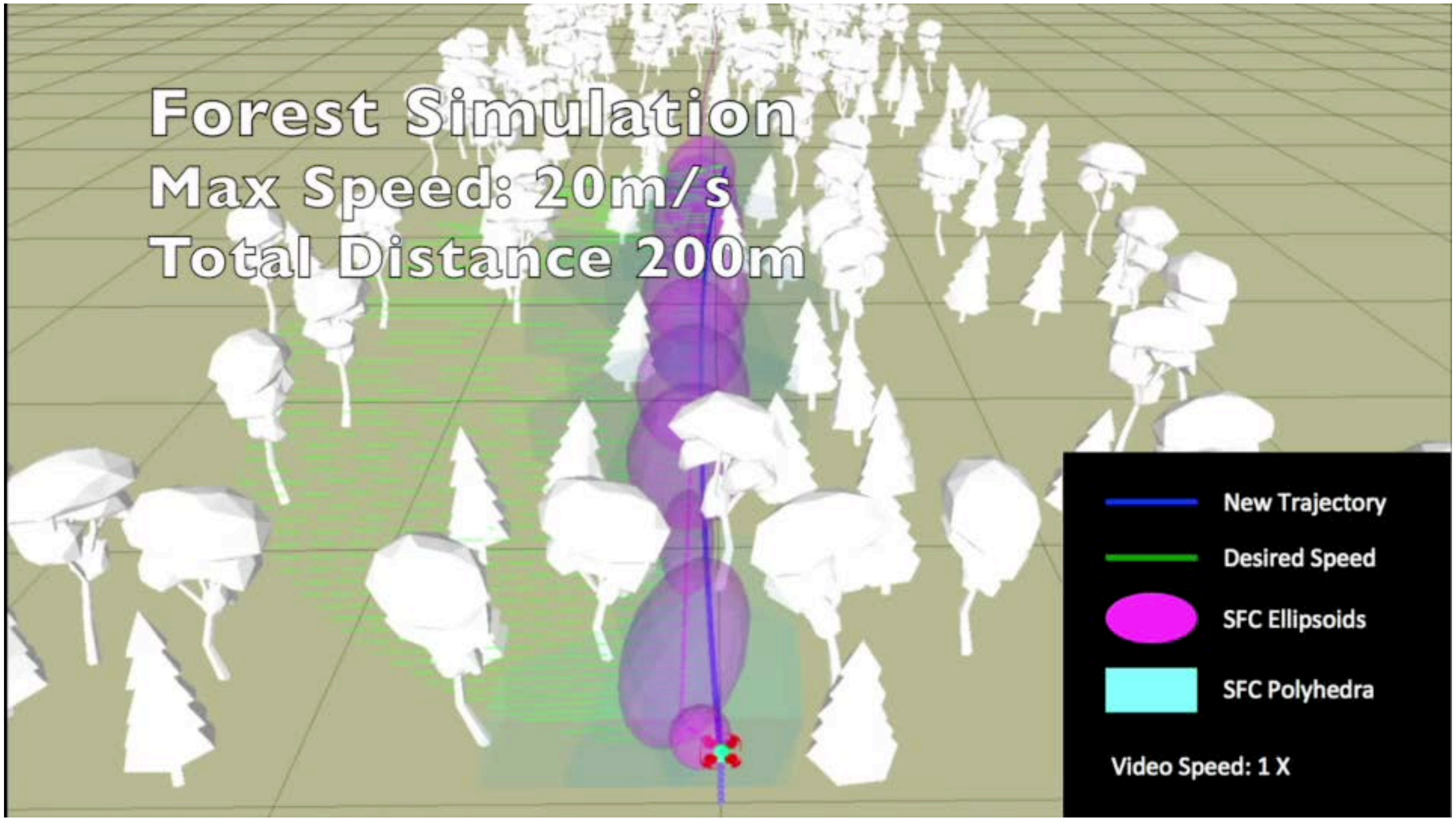
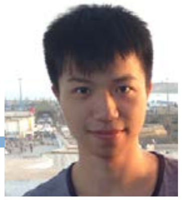
# FLA (5-20 m/s)



*Sikang Liu*

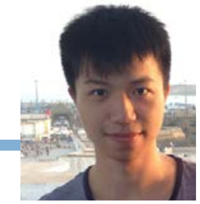
*Mike Watterson*

*Sarah Tang*

*Subhrajit Bhattacharya*


S. Bhattacharya, M. Likhachev and V. Kumar, "Topological Constraints in Search-based Robot Path Planning." *Autonomous Robots*, 33(3):273-290, 2012.
S. Liu, M. Watterson, S. Tang, and V. Kumar, "High speed navigation for quadrotors with limited onboard sensing," *Robotics and Automation Letters*, 2016.
S. Liu, N. Atanasov, K. Mohta, and V. Kumar, "Search-based Motion Planning for Quadrotors using Linear Quadratic Minimum Time Control," IROS 2017.

# Planning in Cluttered Environments

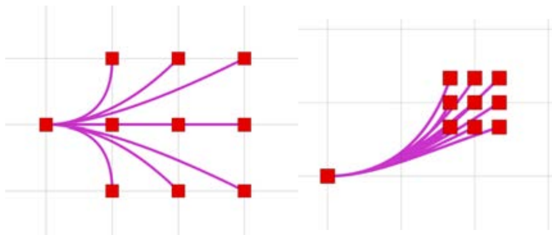


*Sikang Liu*

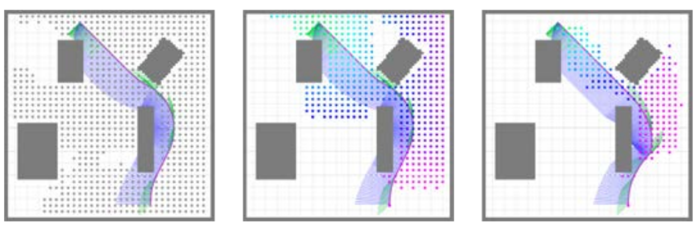
*Nikolay Atanasov*
(UCSD)

## 2. Search-Based Planning with Motion Primitives

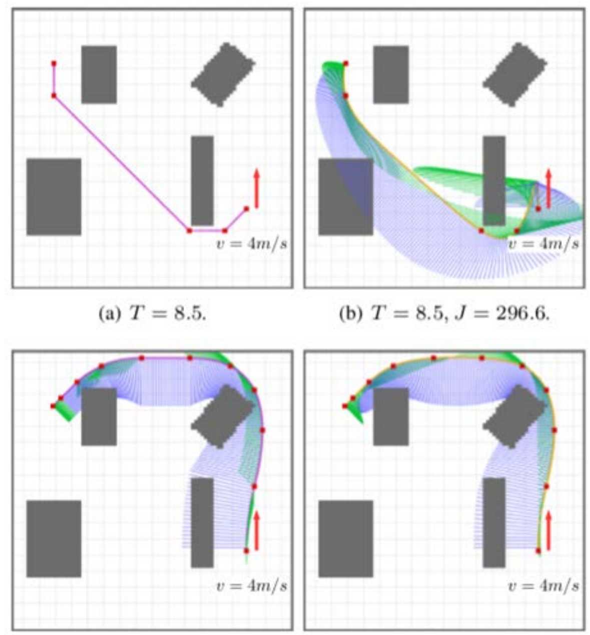
### Minimum snap primitives



### Search over induced discretization on state space



### Results for different functionals




(a) $T = 8.5$. (b) $T = 8.5, J = 296.6$.

(c) $T = 10, J = 14.0$. (d) $T = 10, J = 21.3$.

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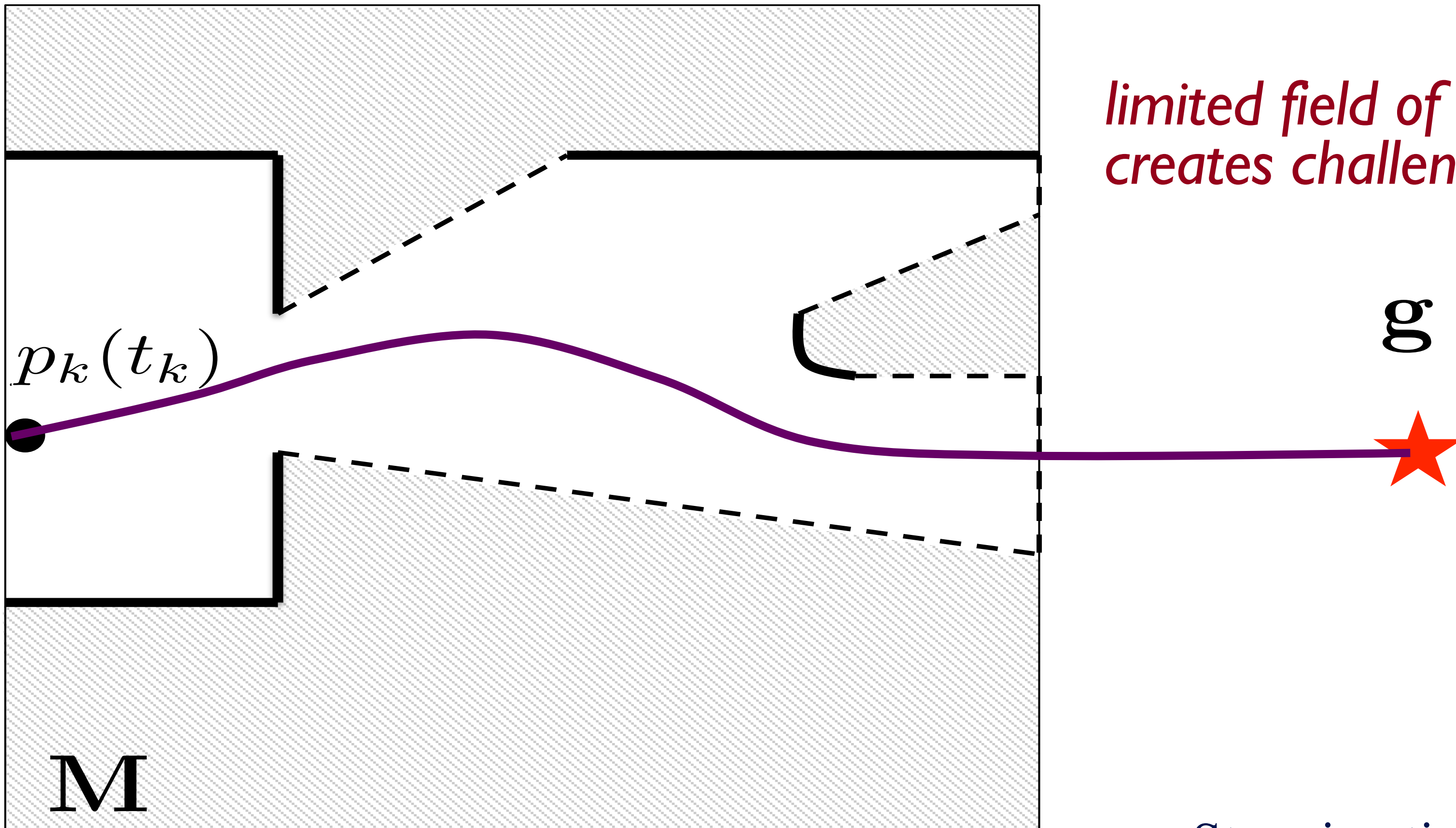
S. Liu, N. Atanasov, K. Mohta, V. Kumar, Search-based motion planning for quadrotors using linear quadratic minimum time control, IROS 2017

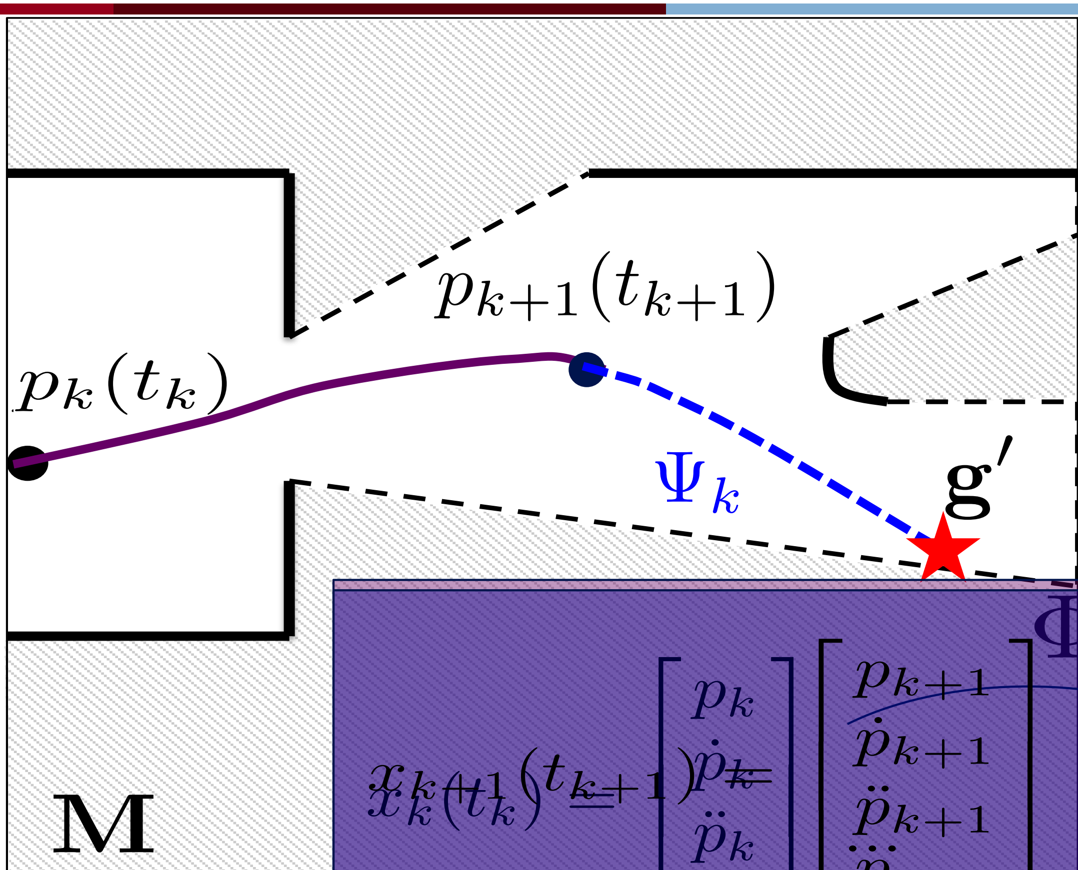
# Resolution complete but …



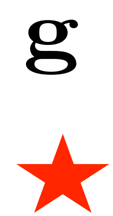

*limited field of view creates challenges*

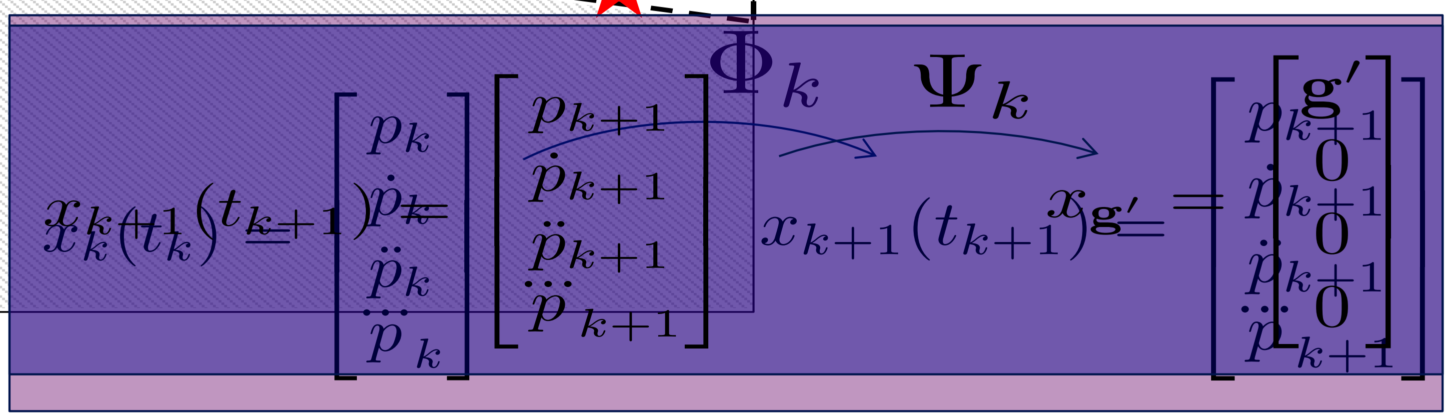
$v$ = 20 m/s, max acceleration 1 $g$ $\Longrightarrow$ Stopping time ~ 2 s
Stopping distance ~ 20 m

# Safety Certificate

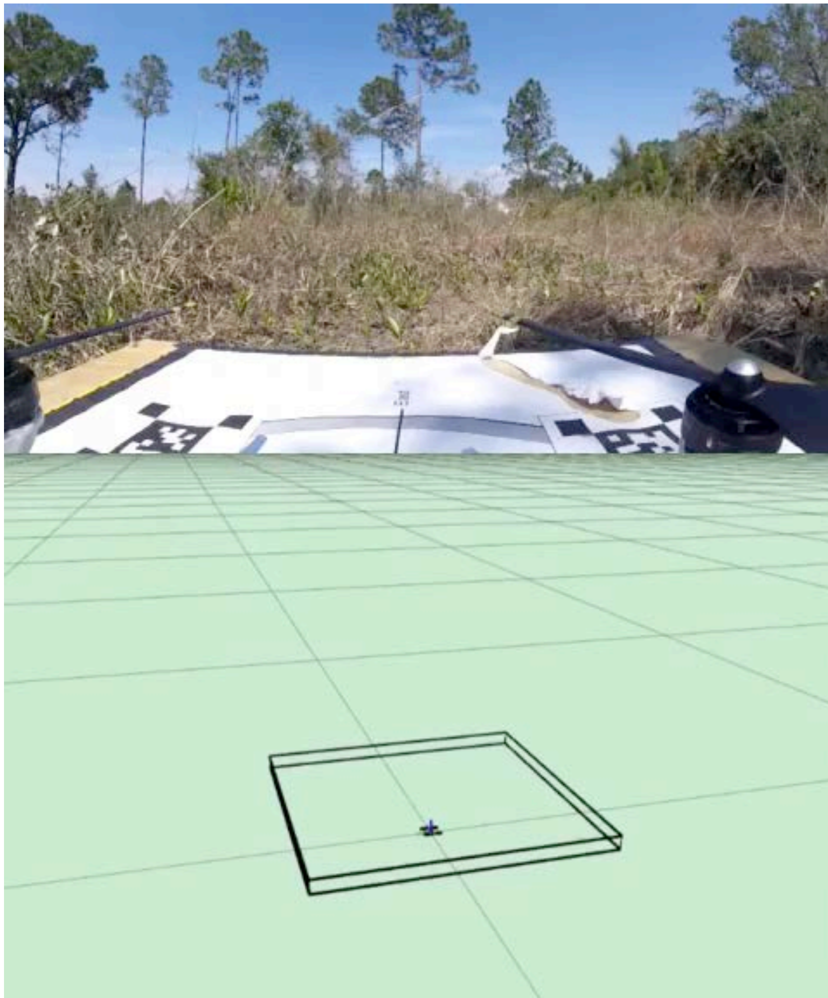


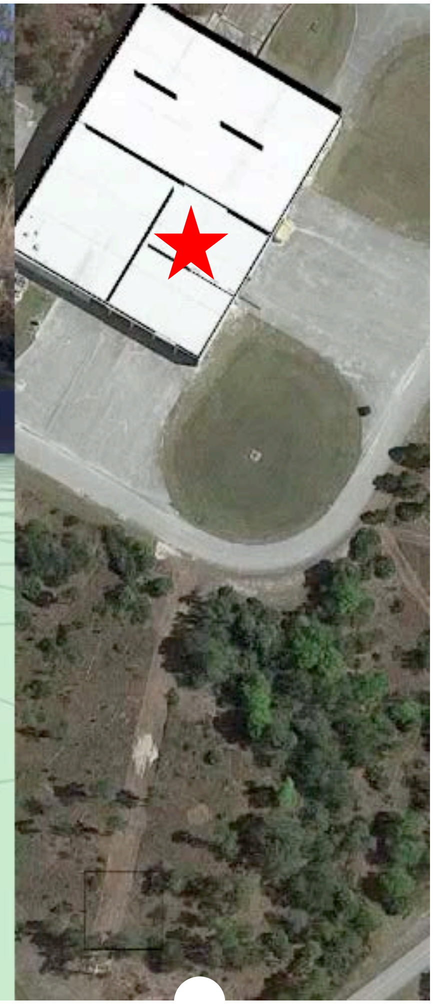

- Safety
- Completeness
- Suboptimality

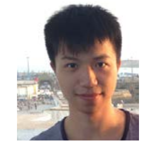


# Autonomous Flight in Unknown GPS-Denied Environment (5 m/s)







Sikang Liu

Mike Watterson

Kartik Mohta

Ke Sun

Yash Mulgaonkar

CJ Taylor

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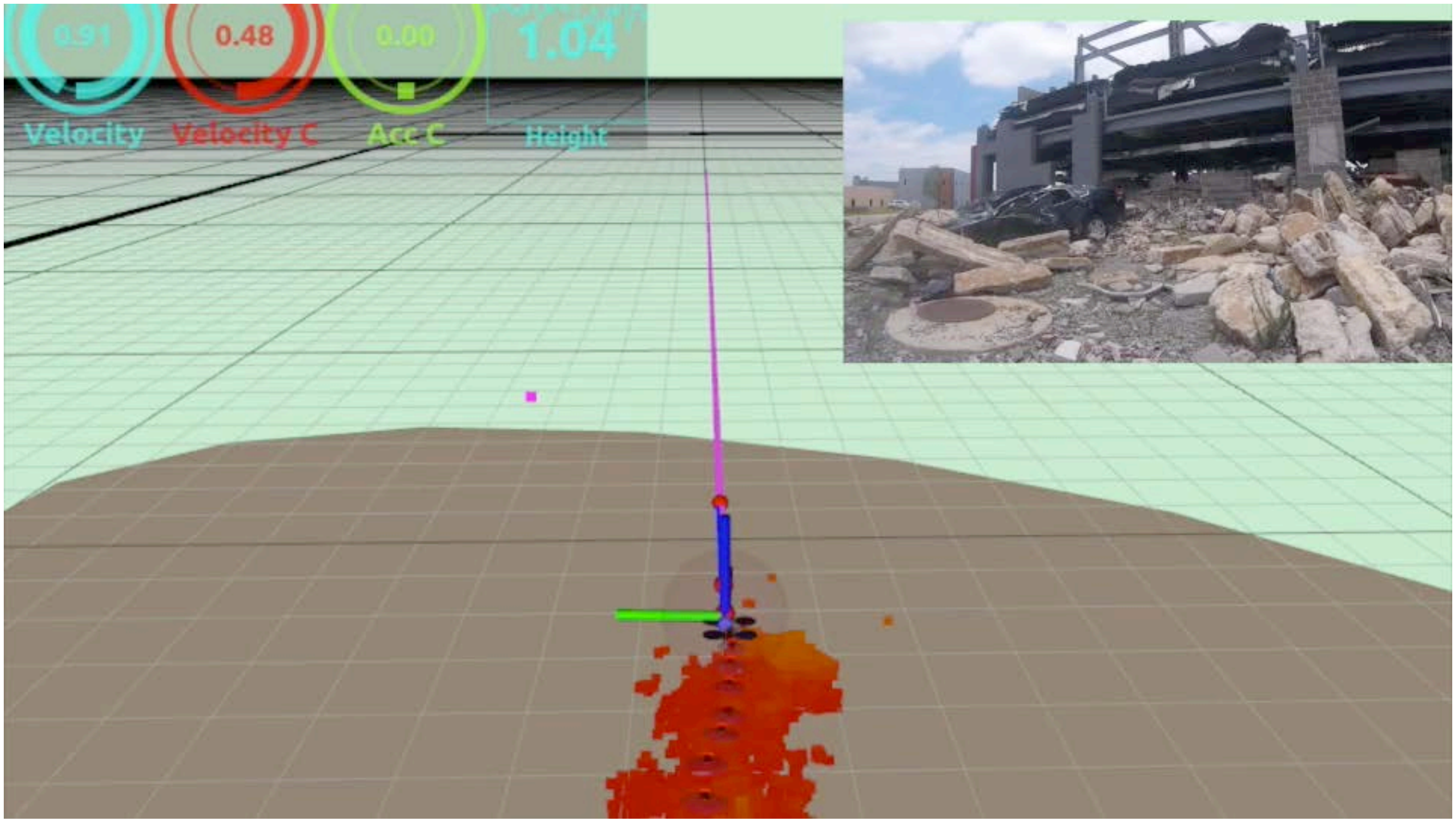
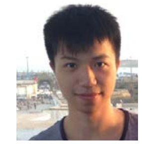
# Search of Collapsed Buildings





Shreyas Shivakumar


Sikang Liu


Mike Wattersor


Kartik Mohta


Ke Sun


CJ Taylor

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S. S. Shivakumar, K. Mohta, B. Pfrommer, V. Kumar and C. J. Taylor, Guided Semi Global Optimization for Real Time Dense Depth Estimation, ICRA 2019.


Raghu Balasa


Alex Burka


Amilcar Cipriano


Monica DeGuzman


Jason Derenick


Xuchu (Dennis) Ding


Brandon Duick


Nader Elm


Pete Furlong


Gray Greene


Vinutha Kallem


Nick Lynch


Billy Sisson


James Sui


Justin Thomas


Denise Wong

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exyn technologies

www.exyn.ai


Fully Autonomous Aerial Robot for Mine Inspection and Mapping
Stope Flight: Beyond Visual Line-of-Sight and Communications Range

# 4. Light Weight Autonomy

2.5 kg quadrotor (2017)

Stereo camera synced with Vector NAV IMU, LiDar, Intel i7

1 kg quadrotor (2018)

Stereo camera synced with Vector NAV IMU, NVDIA Jetson TX2 + FPGA (low-level pixel-wise operations) – OSRF

TOF 3-D camera, 6m range, 100x65 deg, 60 Hz – PMD technologies

250 gram quadrotor (2018)

Qualcomm® Snapdragon Flight™ development board running Snapdragon Navigator™ flight controller and Machine Vision (MV) SDK

S. S. Shivakumar, K. Mohta, B. Pfrommer, V. Kumar and C. J. Taylor, Guided Semi Global Optimization for Real Time Dense Depth Estimation, ICRA 2019.

A. Weinstein, A. Cho, and G. Loianno, and V. Kumar, “VIO-Swarm: A Swarm of 250 gram autonomous

Giuseppe Loianno

Shreyas Shivakumar

Kartik Mohta

Ke Sun

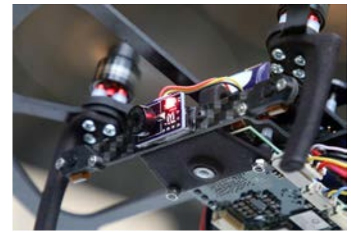
CJ Taylor

Penn Engineering

# Robustness to Collisions


250 gram quadrotor

Qualcomm® Snapdragon Flight™ board with Snapdragon Navigator™ flight controller

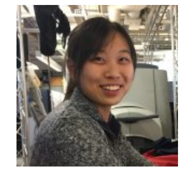



***Tiercel***

133 gram quadrotor capable of sustaining collisions

Qualcomm® Snapdragon Flight™ board with forward-facing stereo cameras, a downward facing camera for VIO, onboard WiFi and GPS


Yash Mulgaonkar


Wenxin Liu


Giuseppe Loianno


Dinesh Thakur

Yash Mulgaonkar, Wenxin Liu, Dinesh Thakur, Kostas Daniilidis, Vijay Kumar, The Tiercel: A novel autonomous micro aerial vehicle that can map the environment by flying into obstacles, IEEE Robotics and Automation Letters, submitted (2020)

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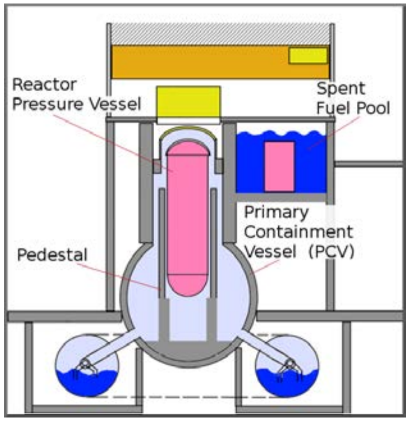
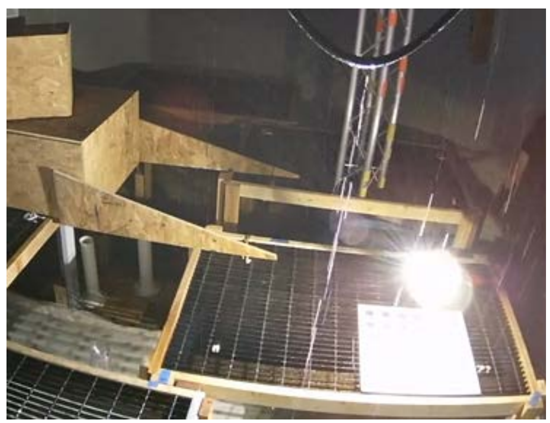
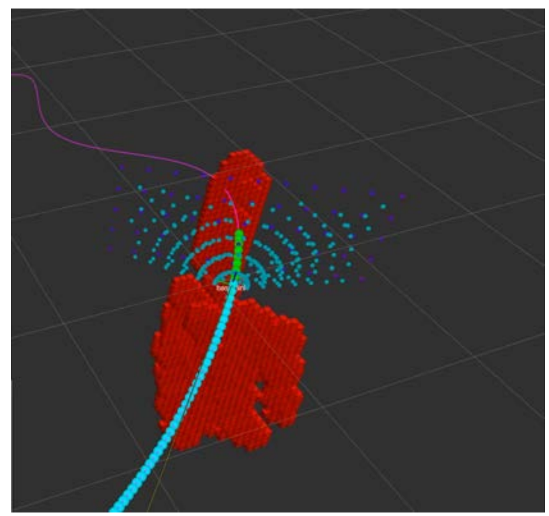
# Autonomous Flight in Fukushima Daiichi Reactor Unit 1



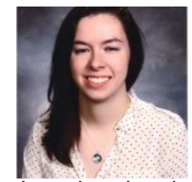


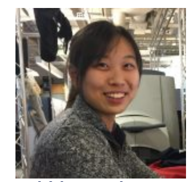



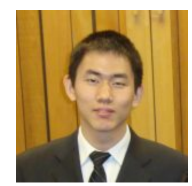



Dinesh Thakur


Giuseppe Loianno


Laura Jarin-Lipschitz


Wenxin Liu


Elijah Lee

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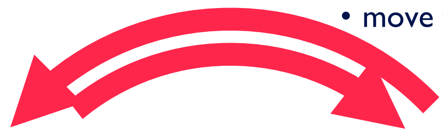
Monica Garcia (SWRI), Richard Garcia (SWRI), Wataru Sato (TEPCO)

# 5. Aerial Robot Swarms

- observations inform actions
- move for better observations



**Perception** **Action**

***Perception—Action Loops***

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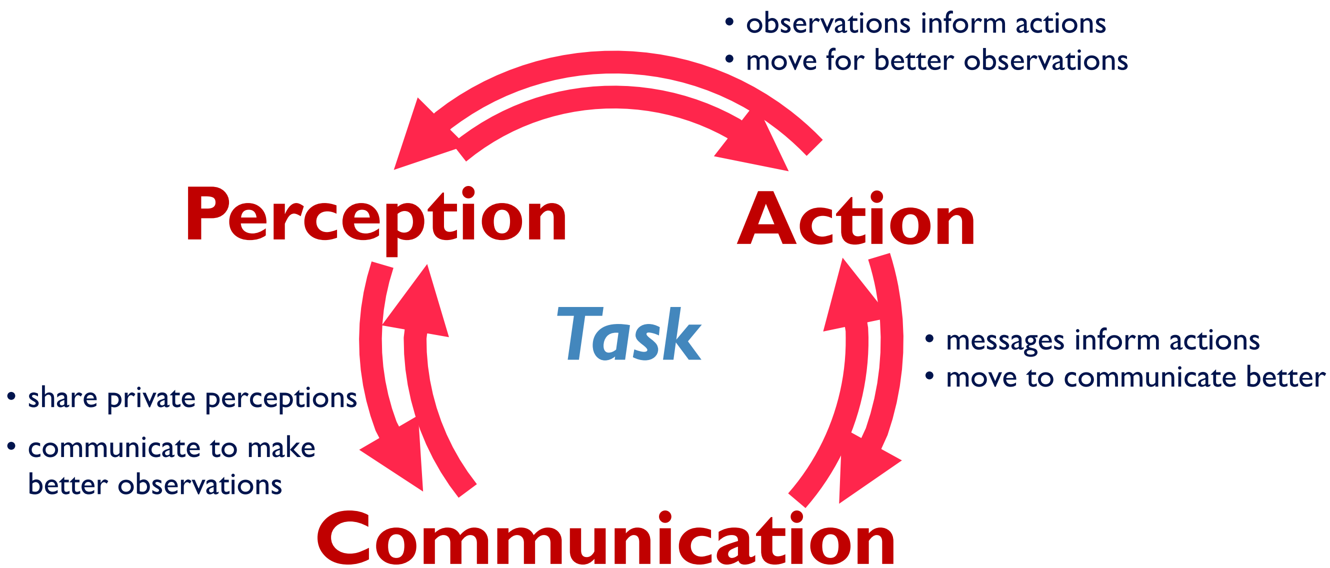
# 5. Aerial Robot Swarms



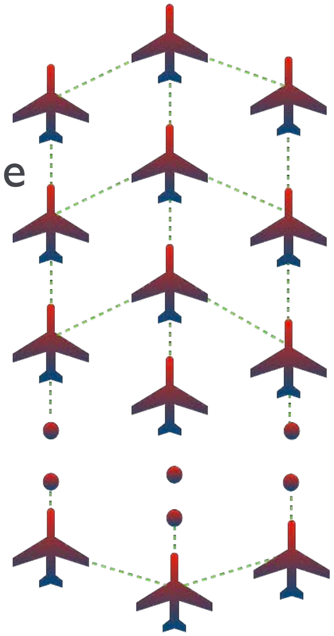

***Perception—Action—Communication Loops***

# Decentralized Multi-Robot Teams

Aaron Weinstein

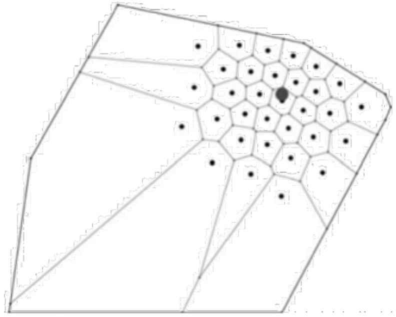
Giuseppe Loianno

- Centralized methods are not practical for real-world robot deployments (Turpin, '14)
  - Partial observability by individual agents
  - Limited communication
- Decentralized, correct-by-construction policies available only for very simple cases
  - simple communication and sensing models
  - edge or cloud computation
  - point robots



Tanner, Pappas and Jadbabaie, 2004


A. Weinstein, A. Cho, and G. Loianno, and V. Kumar, "VIO-Swarm: A Swarm of 250 gram autonomous quadrotors " ICRA 2018.



Sensor Coverage
Cortes, 2004

Belta and Kumar, 2005

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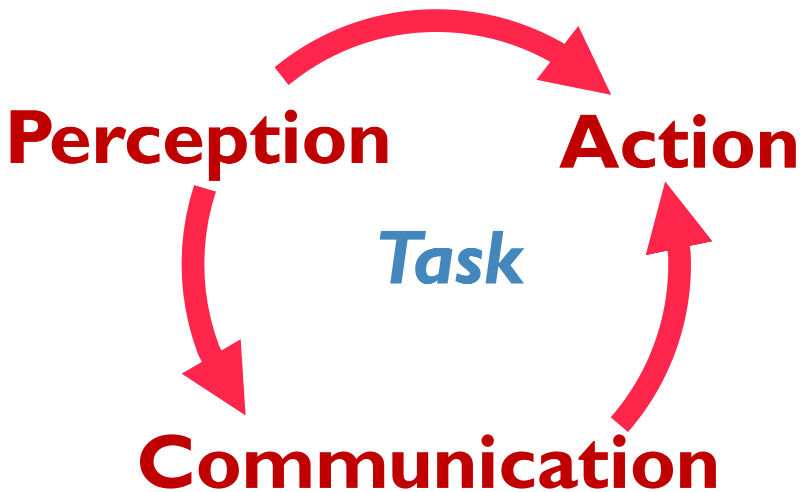
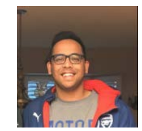
# Distributed Learning: PAC Loops




- Key Ideas:
  - Learn **communication policies**
  - Learn **action policies**
  - Learn **planning policies**


Jimmy Paulos


Ekaterina Tolstaya


Arbaaz Khan


Steven Chen


Dinesh Thakur


Laura Jarin-Lipschitz

(with Professor Alejandro Ribeiro)

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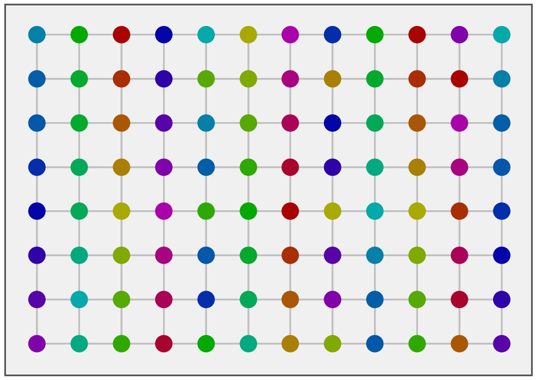
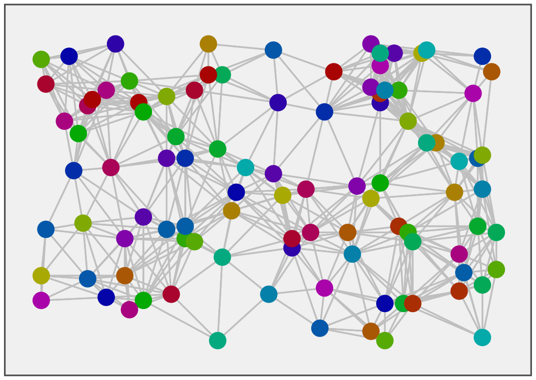
# Graph Neural Networks



CNNs

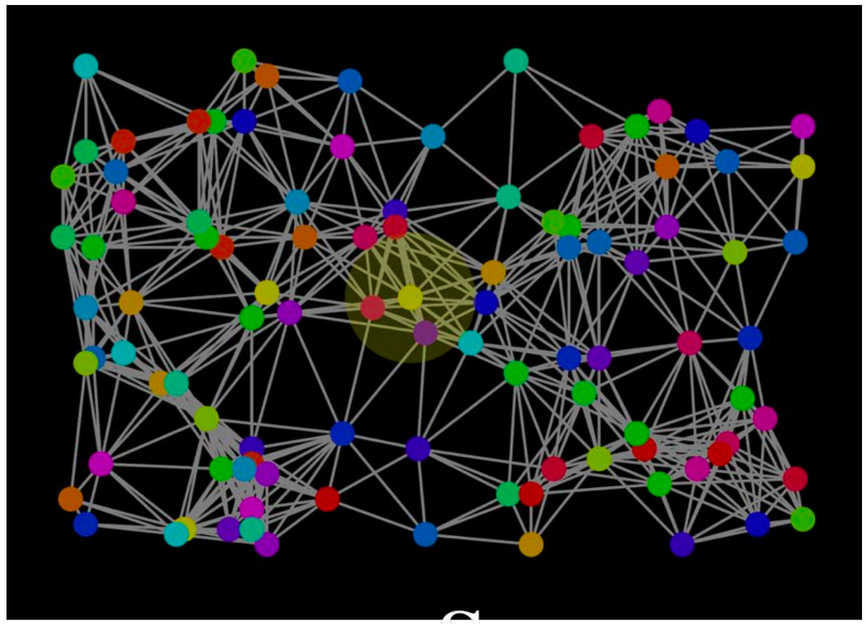


GNNs

*Aggregate information at each node from neighboring node using graph adjacency properties*

- Robots act on relative position and velocity information
  - Must stay close to each other
  - Must avoid collisions
  - Must "align" themselves

# Aggregate over belief states of neighbors



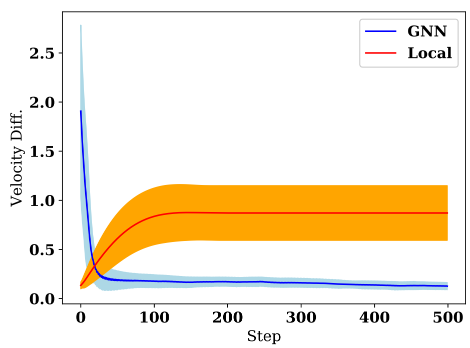
$$\mathbf{z} = \sum_{k=0}^{K} h_k \mathbf{S}^k \mathbf{x}^{(k)} = \mathbf{H}(\mathbf{S})\mathbf{x}$$

# Flocking

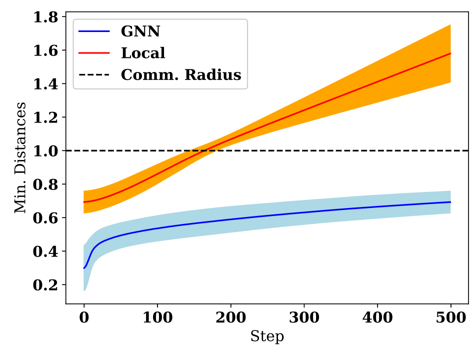
GNN-learned control policy (K=3)

$$\mathbf{u}_i^{\dagger} = -\sum_{j \in \mathcal{N}_i} (\mathbf{v}_i - \mathbf{v}_j) - \sum_{j \in \mathcal{N}_i} \nabla_{\mathbf{r}_i} U(\mathbf{r}_i, \mathbf{r}_j).$$

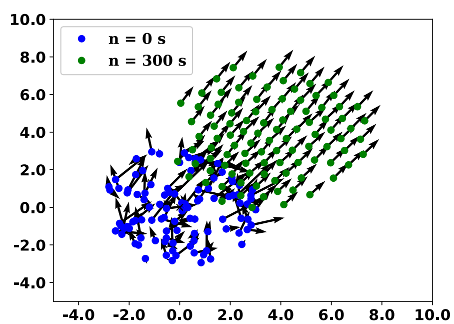
Tanner, Pappas and Jadbabaie, 2004



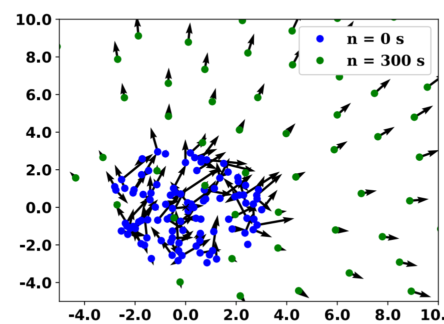
(a) Average difference in velocities



(b) Average minimum distance to a neighbor



(c) Flock positions using the GNN



(d) Flock positions using the local controller

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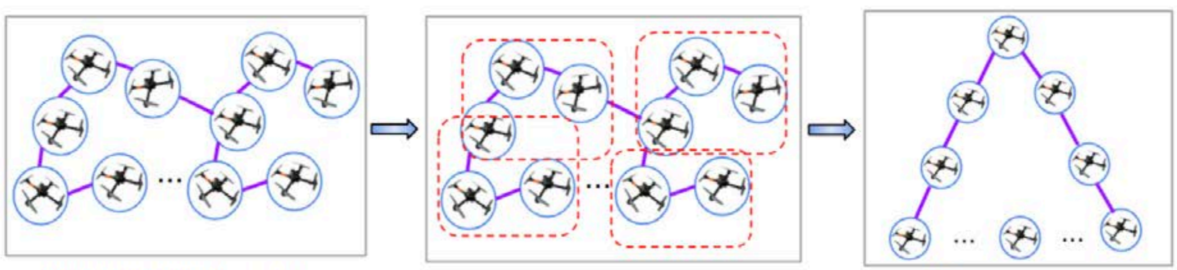
# Graph Policy Gradients

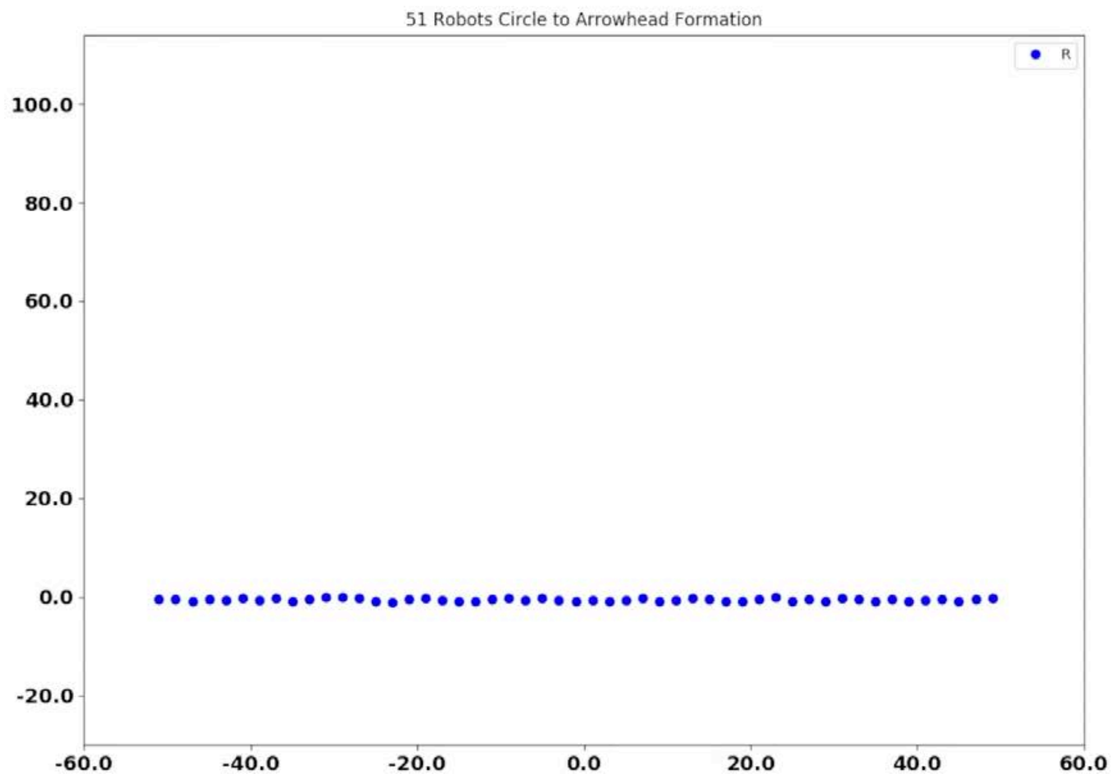
Arbaaz Khan

- Train GNNs on a small number of robots
  - Information from k-hop neighbors is aggregated by each robot
  - Local controllers are learned by each robot
  - Centralized reward used to train the robots
- Extend to swarms with larger numbers
  - Transfer of policies to larger groups with similar "local" graph properties



Arbaaz Khan, Vijay Kumar, and Alejandro Ribeiro, Graph Policy Gradients for Large Scale Unlabeled Motion Planning with Constraints , IEEE International Conference on Robotics and Automation, submitted (2020)

# Graph Policy Gradients for Large Scale Formation Control



# Conclusion

- Autonomy using smartphone grade processors/sensors
- 10x improvement in performance/price
- Applications to search and rescue and precision agriculture
- Integration of model-based and data-driven methods

AI 1.0 ➡ AI 2.0 ➡ AI 3.0


Elizabeth Beattie


Steven Chen


Avi Cohen


Sambeeta Das


Jnaneshwar Das


Luis Guerrero


Laura Jarin-Lipschitz


Jimmy Paulos

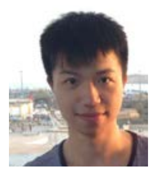

Jim Keller

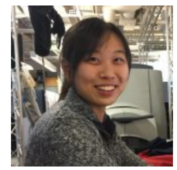

Arbaaz Khan


Monroe Kennedy


Elijah Lee


Rebecca Li

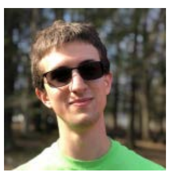

Sikang Liu


Wenxin Liu


Giuseppe Loianno


Kartik Mohta


Dan Mox


Ian Miller


Yash Mulgaonkar


Ty Nguyen


Tolga Özaslan


Chao Qu


Rattanachai Ramaithitima


Kelsey Saulnier


Ke Sun


James Svacha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