Report on:

Fast, Autonomous Flight in GPS-Denied and Cluttered Environments

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Autonomous Exploration Systems
SES 494/598 Spring 2019
Jnaneshwar Das

Fast, Autonomous
Flight in
GPS-Denied and
Cluttered Environments

Bounds of subject

Subject/Task

Additional
Bounds of subject

Fast, Autonomous
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Trajectory Optimization given problem parameters

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Trajectory Optimization given problem parameters

Hardware, Software selection + development
Experimental, real-world testing
(quantitative evidence of successful method for solving problem)

Background for Quadcopters

Quadcopters are becoming increasingly popular in

- Intelligence
- Surveillance
- Reconnaissance
- Photography
- Structure Inspection
- First Response
- Cooperative Construction
- Aerial Manipulation

due to their unique characteristic of

- Mechanical & Control Simplicity
- Maneuverability
- Low Cost

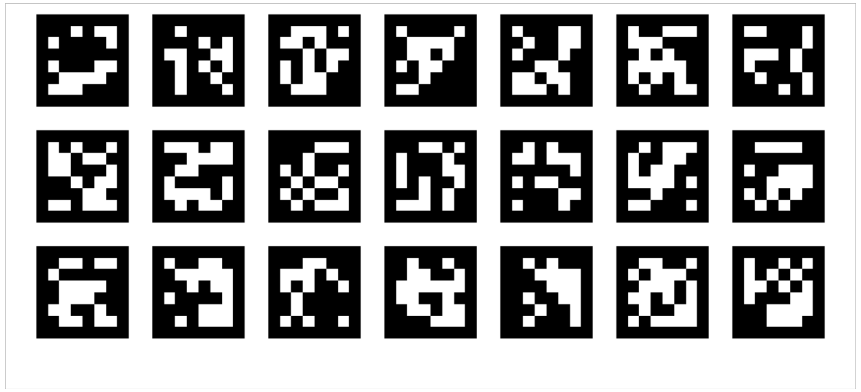
Motivation for lack of Ground Truth

Ground Truth:

A sanity check/feedback for autonomous system to show where it is to better perform what its doing

- Motion capture (lab setting)
- GPS (outdoor)
- Visual Fiducial (indoor/outdoor)

Rely on manipulation of environment



Motivation for lack of Ground Truth

Real world problems are:

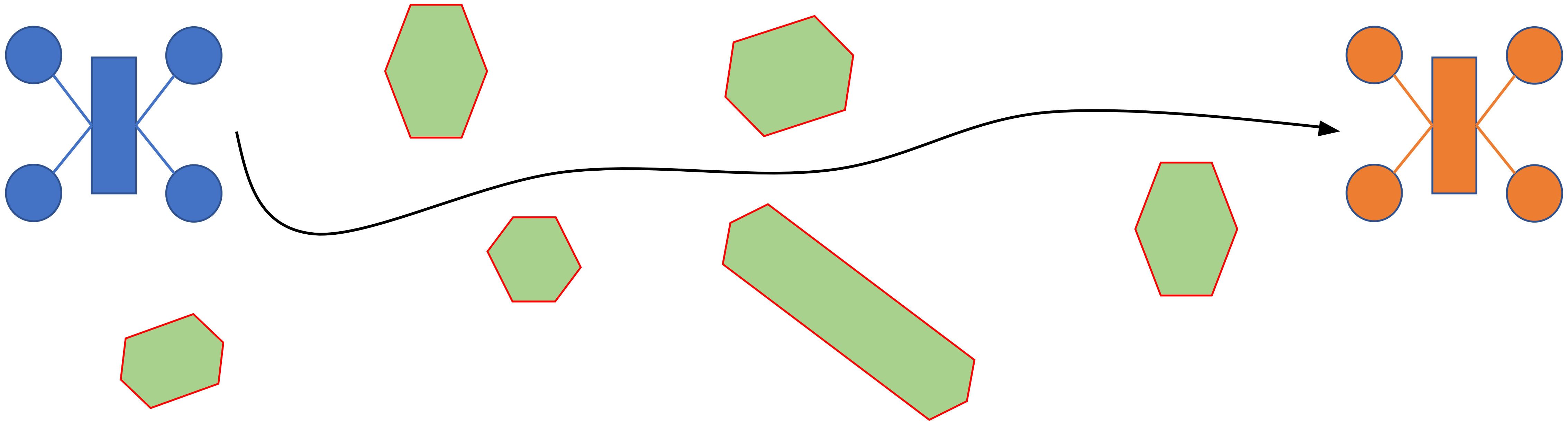
- Dynamic
- Partially known
- GPS-denied

Introduces reliance on only onboard sensing

This Paper Specifically: task specs

Describe a quadrotor system can

- navigate at high speed from start to end pose
- within cluttered environment



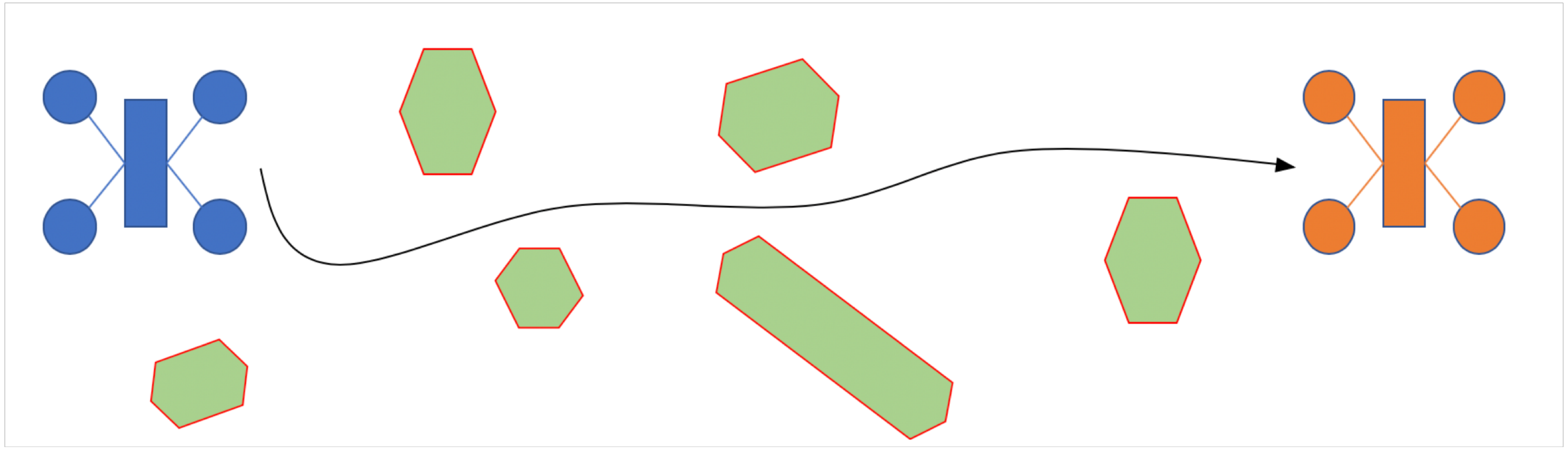
This Paper Specifically: task specs

Describe a quadrotor system can

- navigate at high speed from start to end pose
- within cluttered environment

Using only

- Onboard sensing
- Computation



This Paper Specifically: motivation

- Address DARPA Fast Lightweight Autonomy Program
  - Create small, autonomous micro-aerial vehicle (MAV)

- Difficulty introduced by challenge related to size, weight
  - Bounds *sensor* and *compute hardware*
  - Enables *speed* and *maneuverability*

https://www.darpa.mil/program/fast-lightweight-autonomy

Platform Design

- Required Specs:
  - Max Speed: 20m/s
  - Max acceleration: 10 m/s^2
- Platform: DJI F450 Frame + E600 Motors (P:W ratio 2.4)
- 36 6S LiPo Battery (6s for motor, weight constraint)
  - 5 minutes of flight time
- PDB w/ 12V & 5V regulated power supplies at 120 W each

Platform Design

- Sensors
  - State estimation
  - Mapping

- Cameras for 3D unstructured environment
- Downward pointing lidar
- IMU

- 2D lidar w/ 1 degree of freedom (~ 3D)

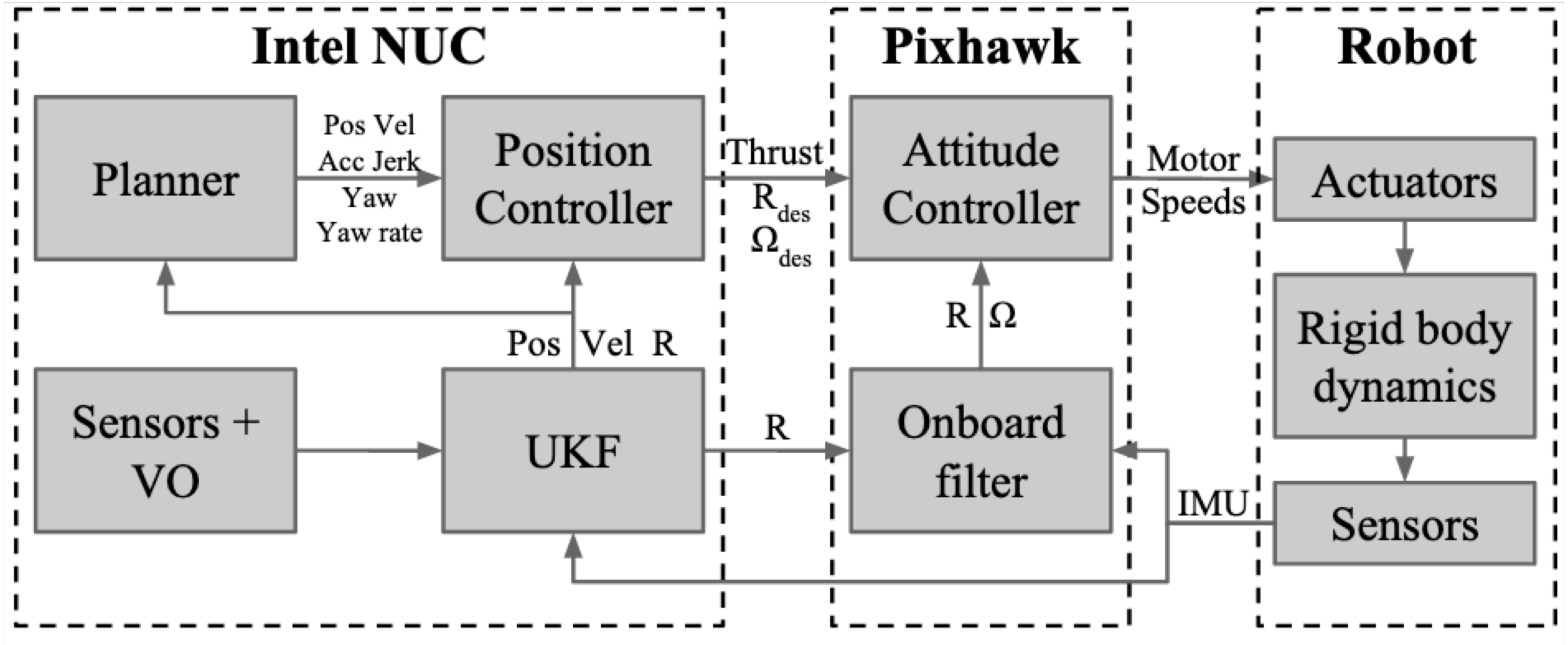
Platform Design

- Compute
  - Estimation
  - Control
  - Mapping
  - Planning
- Intel NUC i7
  - 16GB Ram
  - M.2 SSD

- Communication
- High Power Wireless Radios
  - Ubiquity Networks Picostation M2
  - Nanostation M2

Platform Design

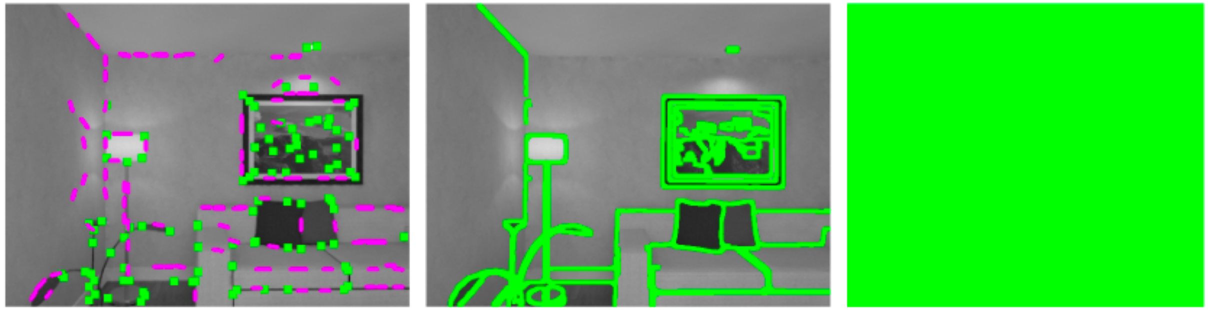
- Software Architecture



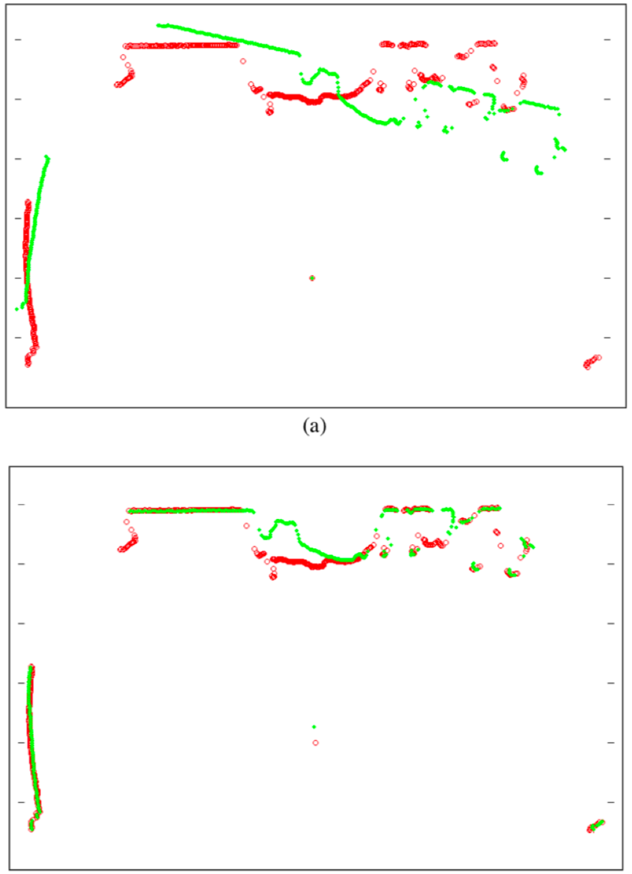
Navigation System

Historically:

- Laser rangefinder
  - Limited computational capability
  - Distance measured in single plane
    - Simplifying assumptions



(a) Sparse (b) Semi-Dense (c) Dense



(a)

(b)

Planning

Mapping

Control

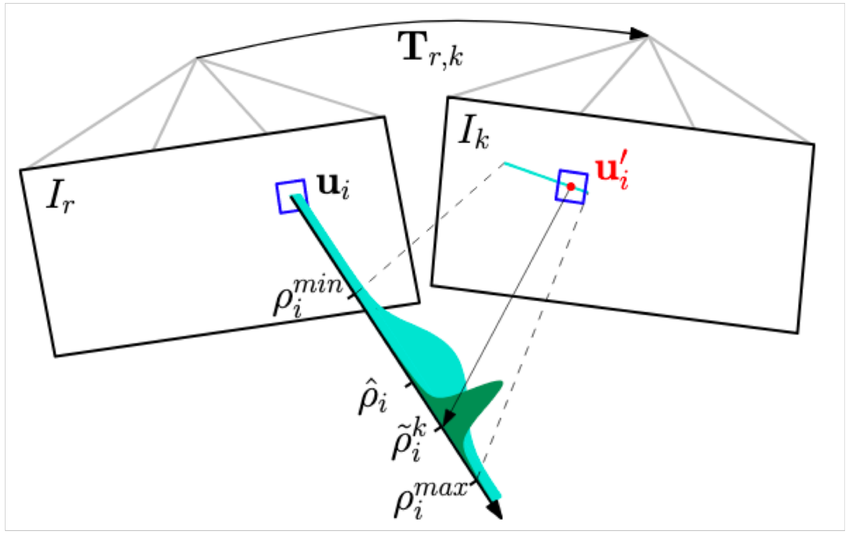
State Estimation

Bachrach, A., He, R., and Roy, N. (2009). Autonomous flight in unknown indoor environments. International Journal of Micro Air Vehicles, 1(4):217–228

Navigation System

Presently:

- Visual Odometry
  - Multi-camera
  - Wide angle lenses
  - Identify point features and edgedlet features



Planning

Mapping

Control

State Estimation

Forster, C., Zhang, Z., Gassner, M., Werlberger, M., and ***Scaramuzza, D****. (To appear, 2017). SVO: Semi-Direct Visual Odometry for Monocular and Multi-Camera Systems. IEEE Transactions on Robotics.*

State Estimation & Control

- RGB-D: not viable outdoors
- Monocular odometry: require initialization process
- Stereo odometry: single frame to initialize, can be re-done online
  - Loss of a lense can use monocular odometry with the remaining camera

Table 2: Advantages and disadvantages of different visual odometry algorithms.

	Monocular	**Stereo**	**Multi-camera**
Mechanical complexity	Low	Medium	Low
Software complexity	Medium	Low-Medium	High
Robustness	Low-Medium	Medium	High
Feature distance	High	Medium-High	High

Navigation System

Historically:

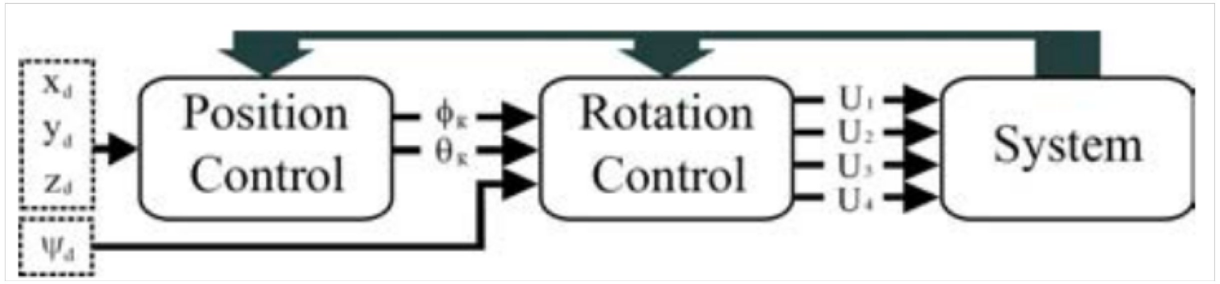
- Quadrotor dynamics are nonlinear
  - Due to rotational degrees of freedom of rotor
- Small angle approximation for horizontal orientation control
- PID and backstepping controllers for stabilization
- Large orientation & tracking error in aggressive trajectories

Planning

Mapping

Control

State Estimation



Bouabdallah, S. and Siegwart, R. (2005). Backstepping and sliding-mode techniques applied to an indoor mi-cro quadrotor. InProceedings of the 2005 IEEE International Conference on Robotics and Automation,pages 2247–2252.

Bouabdallah, S. and Siegwart, R. (2007). Full control of a quadrotor. In2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 153–158

Navigation System

Presently:

- Nonlinear controller using quaternions instead of euler
  - Better orientation control
- Stability controlled via velocity commands
  - Orientation error defined in 3D [SO(3)]
  - Controller that can stabilize large position and orientation error
- Can handle aggressive trajectories well

Planning

Mapping

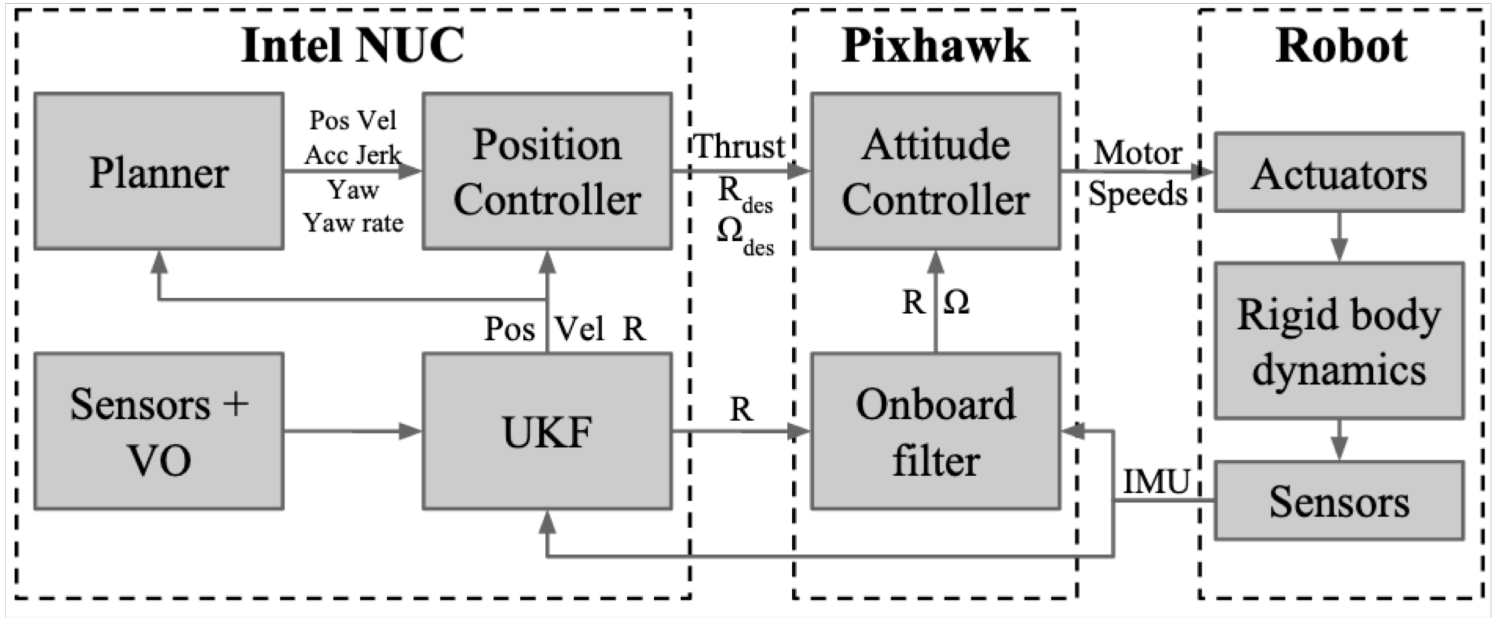
Control

State Estimation

Guenard, N., Hamel, T., and Moreau, V. (2005). Dynamic modeling and intuitive control strategy for an"X4-flyer". In2005 International Conference on Control and Automation, volume 1, pages 141–146.

Lee, T., Leok, M., and McClamroch, N. H. (2010). Geometric Tracking Control of a Quadrotor UAV onSE(3). In2010 49th IEEE Conference on Decision and Control (CDC), pages 5420–5425.

Control



- During a time step, t
  - Planner sends (pos, vel, acc, jerk) to position controller
  - Position controller uses UKF to compute (force, orientation, angular velocity) to orientation (attitude) controller
  - Attitude controller computes thrust and moments, converted to motor speed

Navigation System

Planning

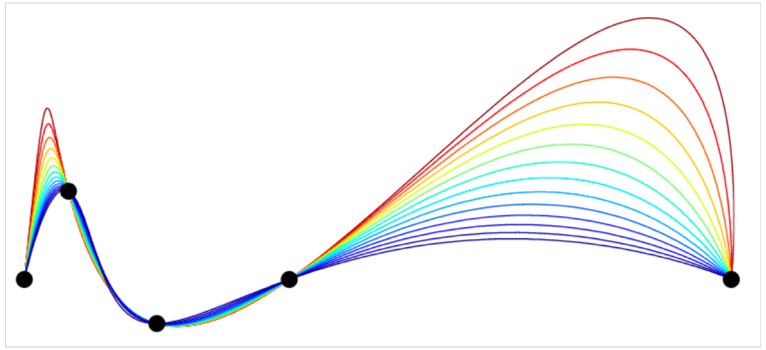
Mapping

Control

State Estimation

Historically:

- Formulating smooth (clear) trajectory generation as QP
  - Dynamics of quadrotor as constraint
- Trajectory generation with obstacles requires additional constraints
  - Add waypoint clear of obstacle, and perform QP again
  - Solve minimum
    snap solution for trajectory



Mellinger, D. and Kumar, V. (2011). Minimum Snap Trajectory Generation and Control for Quadrotors. In2011 IEEE International Conference on Robotics and Automation, pages 2520–2525.

Richter, C., Bry, A., and Roy, N. (2016). Polynomial trajectory planning for aggressive quadrotor flight in dense indoor environments. InRobotics Research, pages 649–666. Springer.

Navigation System

Presently:

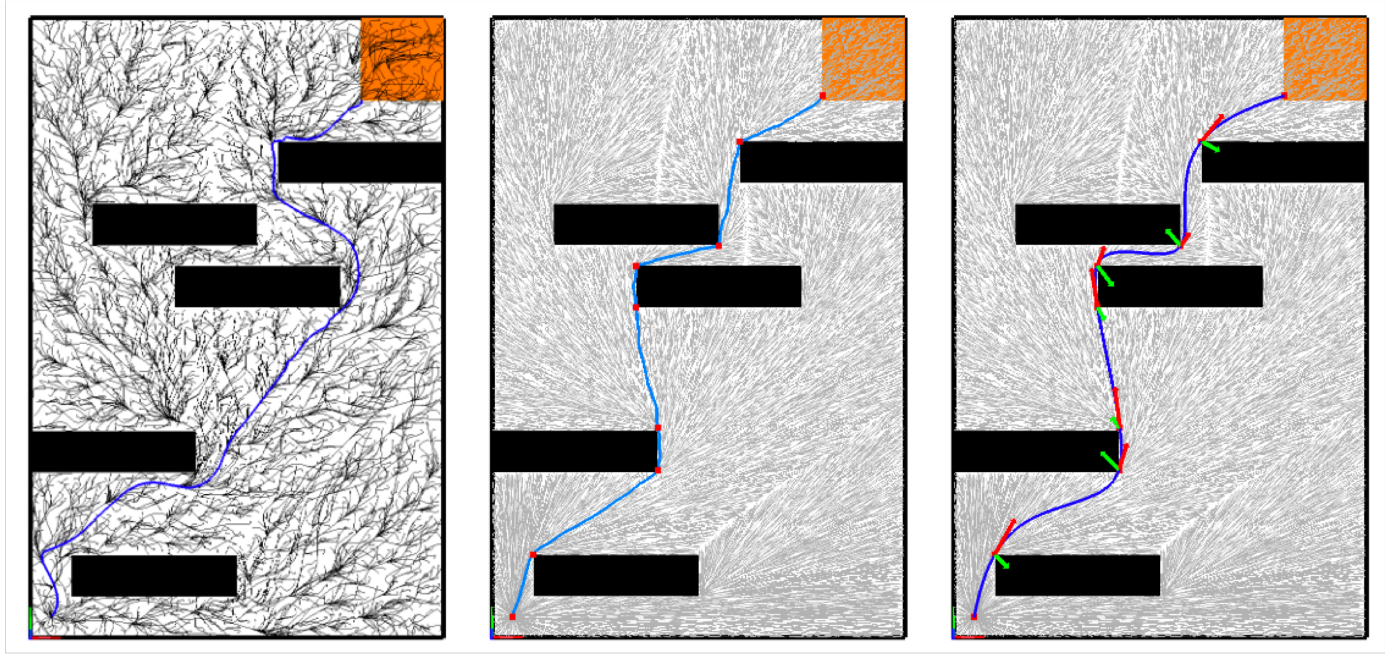
- Identifying safe corridor using trivial solution of map
- Corridor is partially used as constraint of QP for collisions
  - Continue to use dynamics of quadcopter as constraints
  - Use safer definition of safe corridor for increased safety

Planning

Mapping

Control

State Estimation



Liu, S., Watterson, M., Tang, S., and Kumar, V. (2016). High speed navigation for quadrotors with limitedonboard sensing. In2016 IEEE International Conference on Robotics and Automation (ICRA), pages1484–1491

Navigation System

Planning

Mapping

Control

State Estimation

Presently:

- Form of receding horizon method (2002) for replanning
  - Mixed integer linear programming
  - Long term constraint (logical) no fly zone
  - Short term constraints (continuous) drone dynamics
- Global update expensive, less accurate w/ open-loop
- Keep local map (3D) & global map (2D)

Bellingham, J., Richards, A., and How, J. P. (2002). Receding horizon control of autonomous aerial vehicles.InProceedings of the 2002 American Control Conference (IEEE Cat. No.CH37301), volume 5, pages3741–3746 vol.5

Navigation System

Planning

Presently:

- Form of receding horizon m
  - Mixed integer linear program
  - Long term constraint (logical)
  - Short term constraints (conti
- Global update expensive, les
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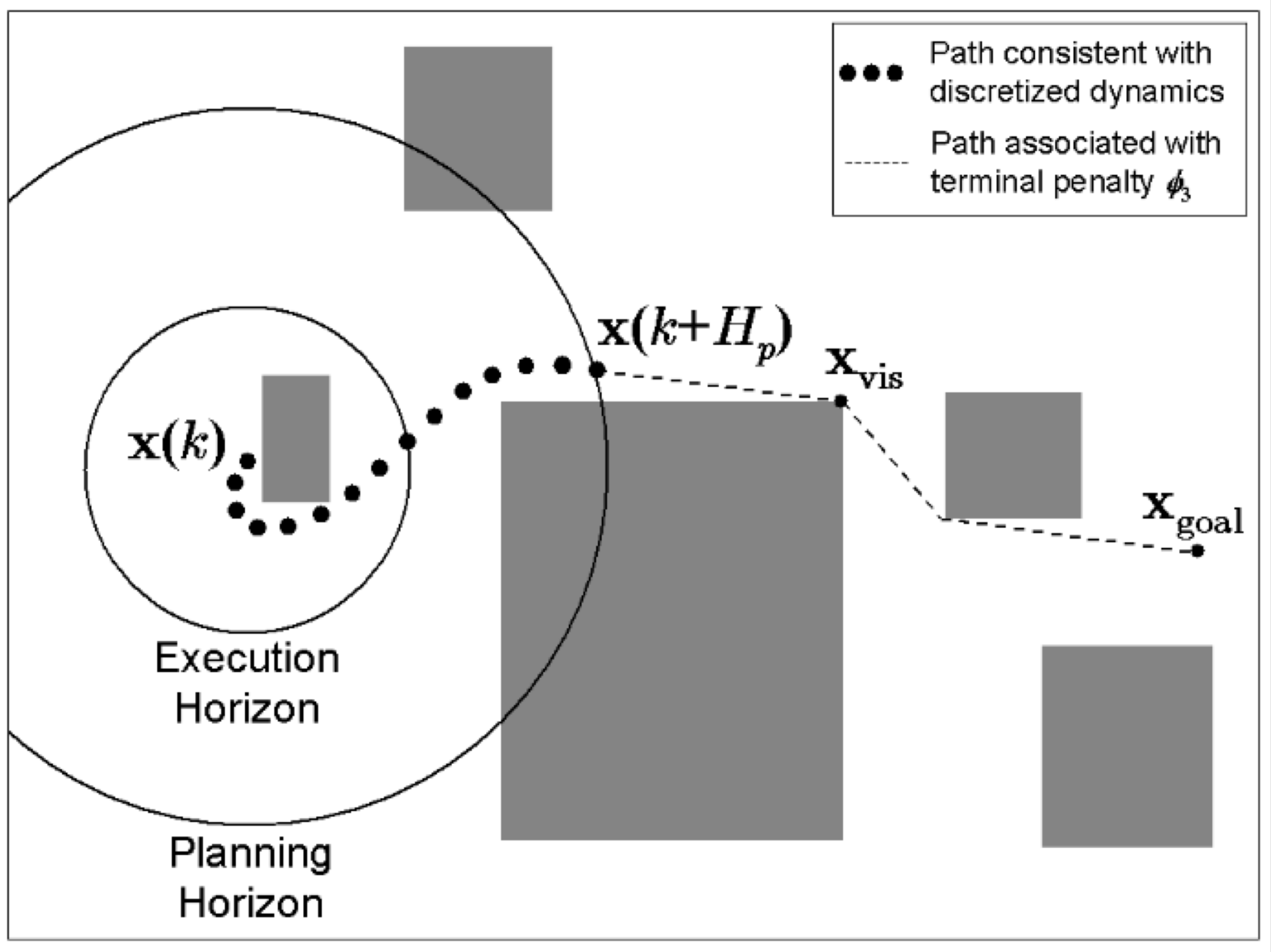
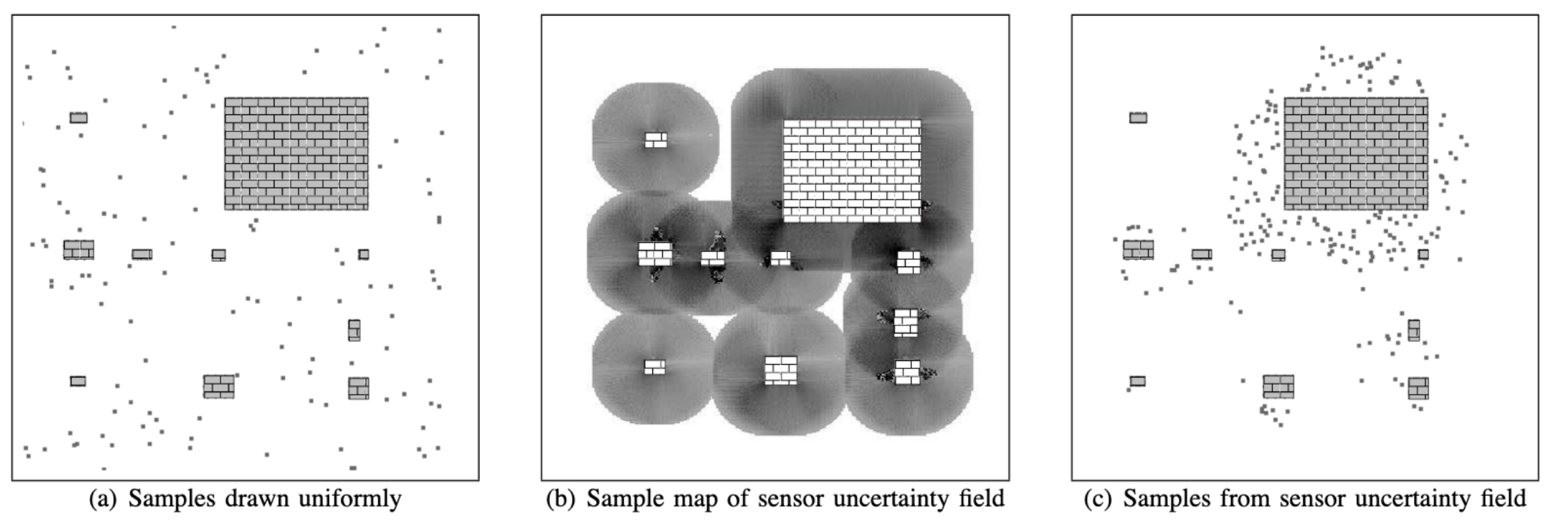


Bellingham, J., Richards, A., and How, J. P. (200
vehicles.InProceedings of the 2002 American C
pages3741–3746 vol.5

Navigation System

Historically:

- Especially difficult
- Used off board compute to generate map
- Navigation within bad localization quality
  - Laser range finders



He, R., Prentice, S., and Roy, N. (2008). Planning in information space for a quadrotor helicopter in a gps-denied environment. In 2008 IEEE International Conference on Robotics and Automation, pages1814–1820

Planning

Mapping

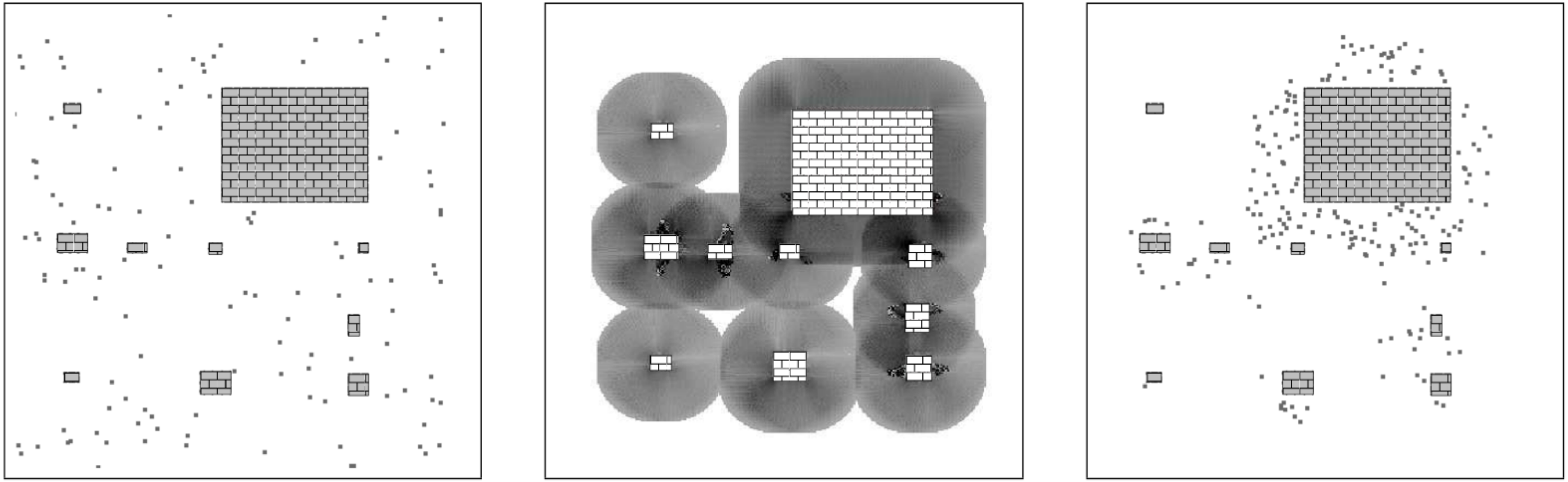
Control

State Estimation

Grzonka, S., Grisetti, G., and Burgard, W. (2009). Towards a navigation system for autonomous indoor flying. In2009 IEEE International Conference on Robotics and Automation, pages 2878–2883.

Navigation System

Planning



(a) Samples drawn uniformly (b) Sample map of sensor uncertainty field (c) Samples from sensor uncertainty field

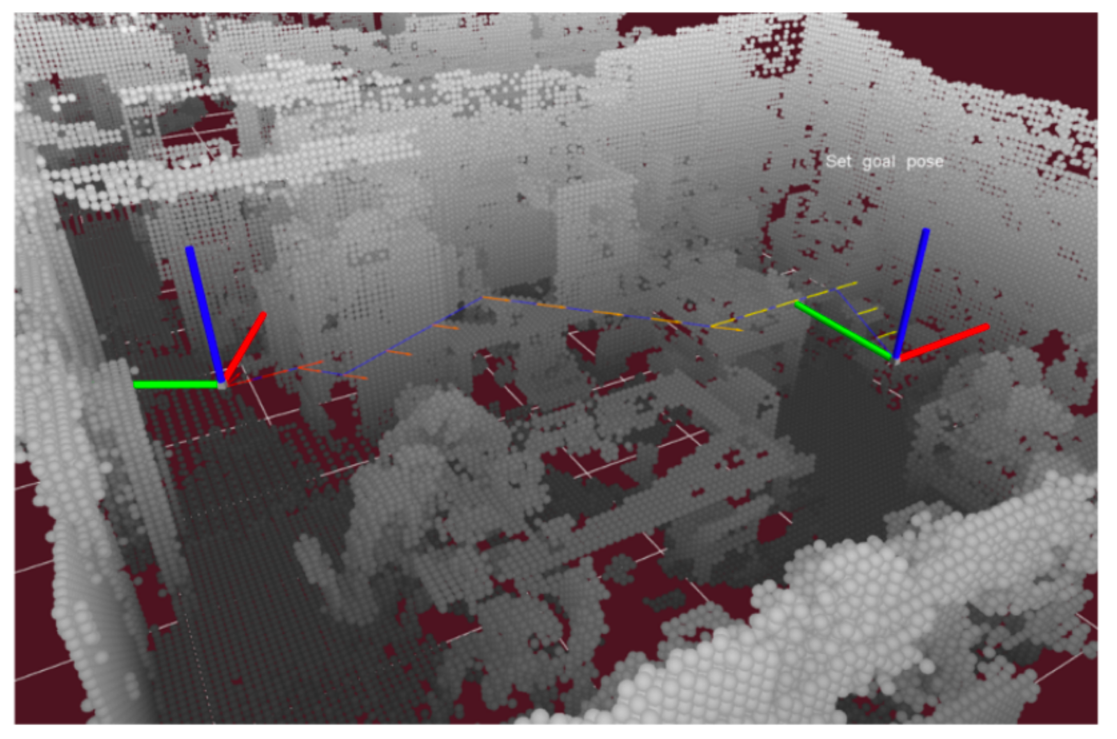
Grzonka, S., Grisetti, G., and Burgard, W. (2009). Towards a navigation system for autonomous indoor flying. In2009 IEEE International Conference on Robotics and Automation, pages 2878–2883.

He, R., Prentice, S., and Roy, N. (2008). Planning in information space for a quadrotor helicopter in a gps-denied environment. In 2008 IEEE International Conference on Robotics and Automation, pages1814–1820

Navigation System

Currently:

- Full navigation system running onboard without map
  - RGB-D (lighter than Lidar)
  - Real-time 3D SLAM
  - Goal of paper is to describe how to do nav. and map while avoiding obstacles



Valenti, R. G., Dryanovski, I., Jaramillo, C., Str¨om, D. P., and Xiao, J. (2014). Autonomous quadrotor flight using onboard rgb-d visual odometry. In2014 IEEE International Conference on Robotics and. Automation (ICRA), pages 5233–5238.

Planning

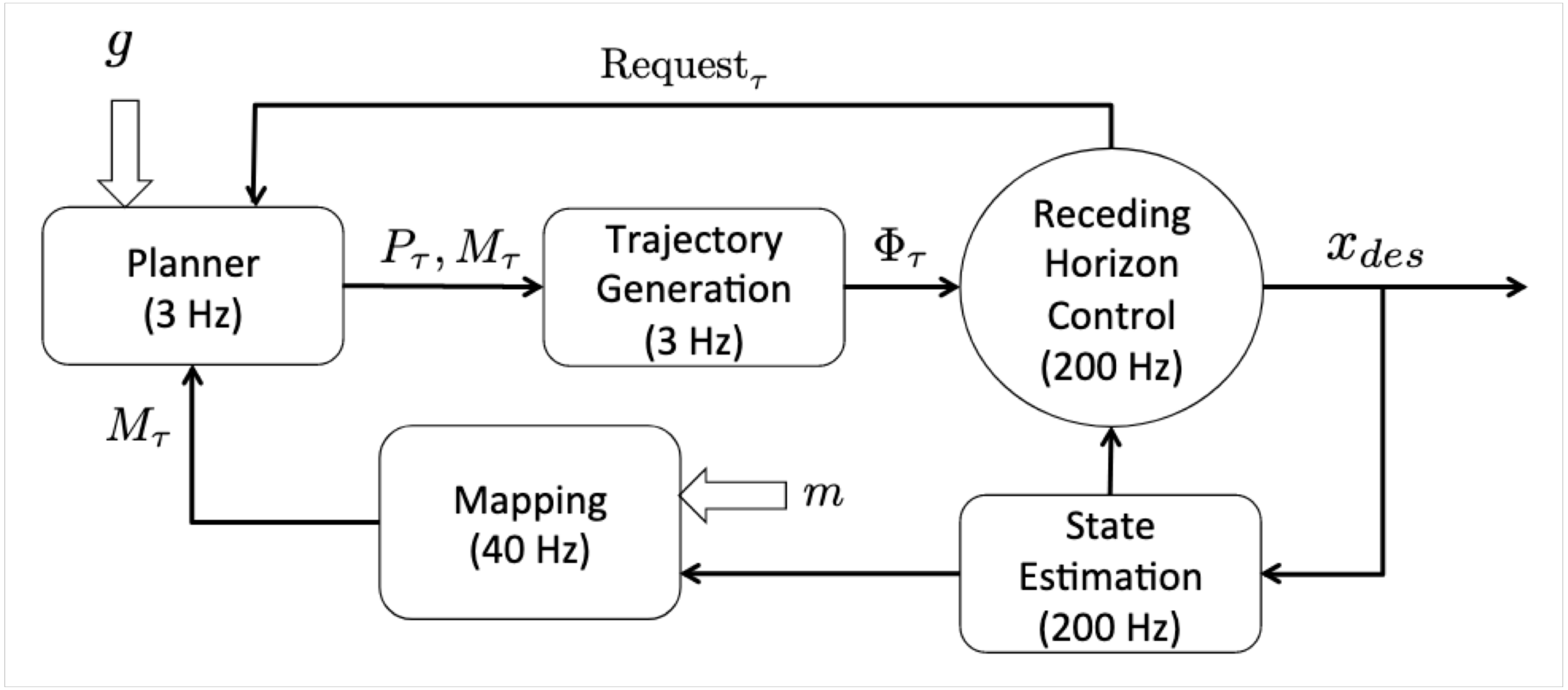
Mapping

Control

State Estimation

Mapping and Planning

- Navigation system:
  - Goal, g
  - Path, P_t
  - Map, M_t
  - Trajectory, ϕ_t
  - Desired State, x_{des}

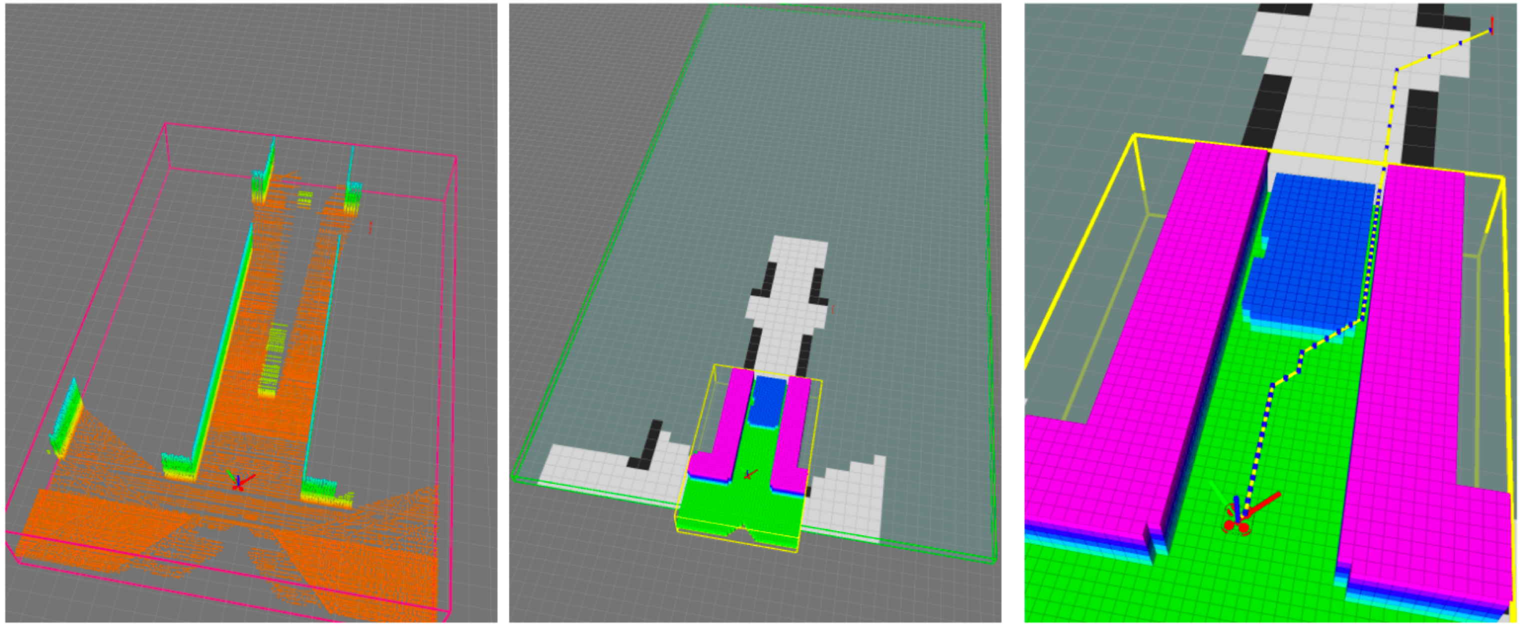


Mapping

- Local Point Cloud around robot location
  - LIDAR on servo generates fine 3D map
  - Global map in this way would be expensive
  - Generate local point cloud around robot
- Use the local point cloud to construct a 2D map in the global frame to solve dead-end problems (due to local planning only)

Planning

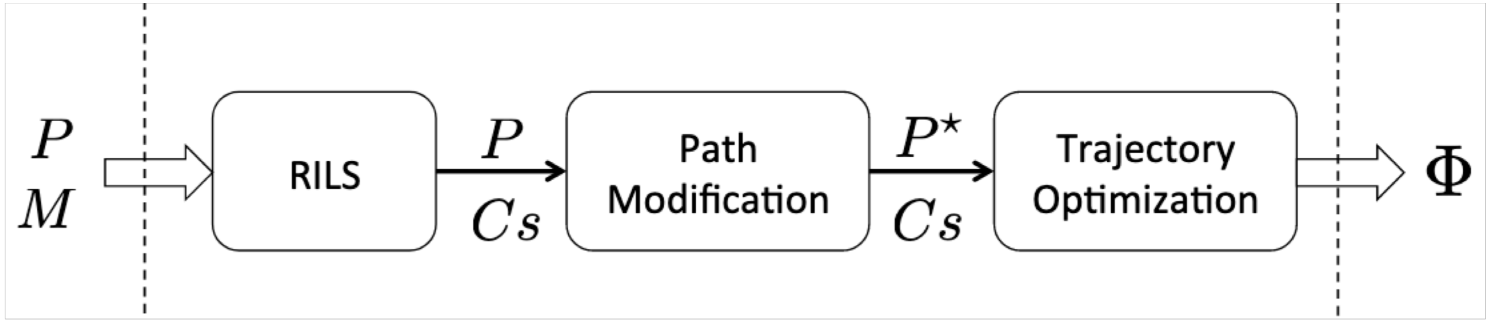
- Use a plan that links the local 3D map to the global information map
- Local point cloud range equal to sensor range
  - Global map is bigger with coarser information



(a) Local point cloud M^c (40 m×20 m× 4 m). (b) Local map M^l (15 m × 10 m × 3 m) and global map M^w(80 m × 40 m). (c) Path planned using both M^l, M^w.

Trajectory Generation

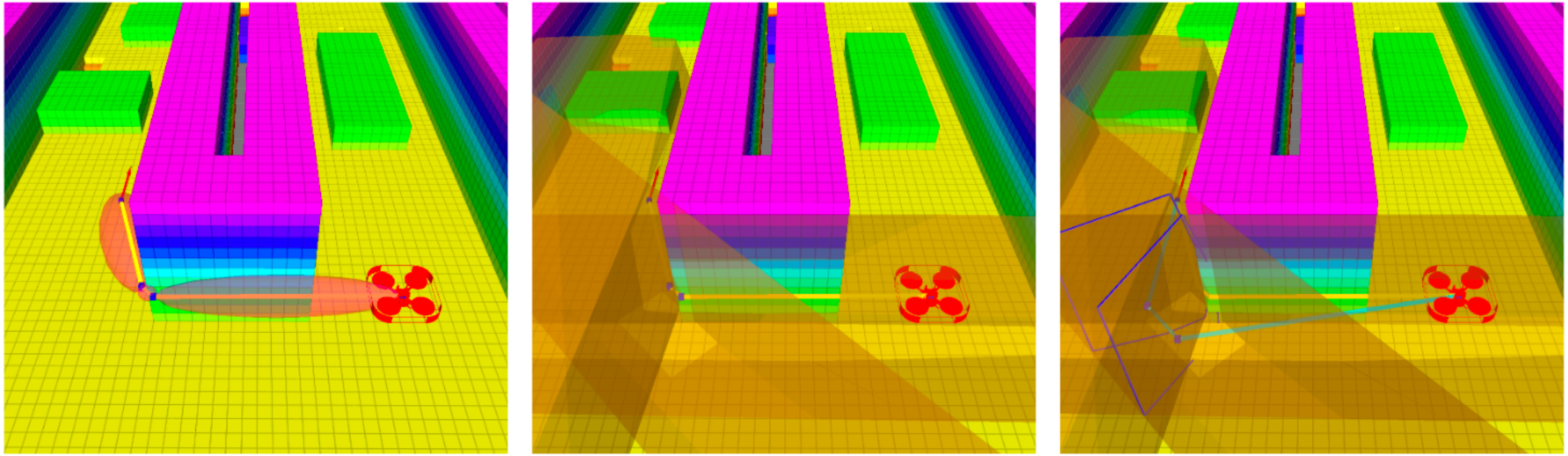
- Given the map M and a prior path P
  - Identify safe corridor in M that excludes obstacle points
  - Shift immediate waypoints to center of corridor, P @ centroid of corridor
  - New path P and safe corridor are used to produce new trajectory



  - C: related to corridor shape
  - RILS:

Trajectory Generation

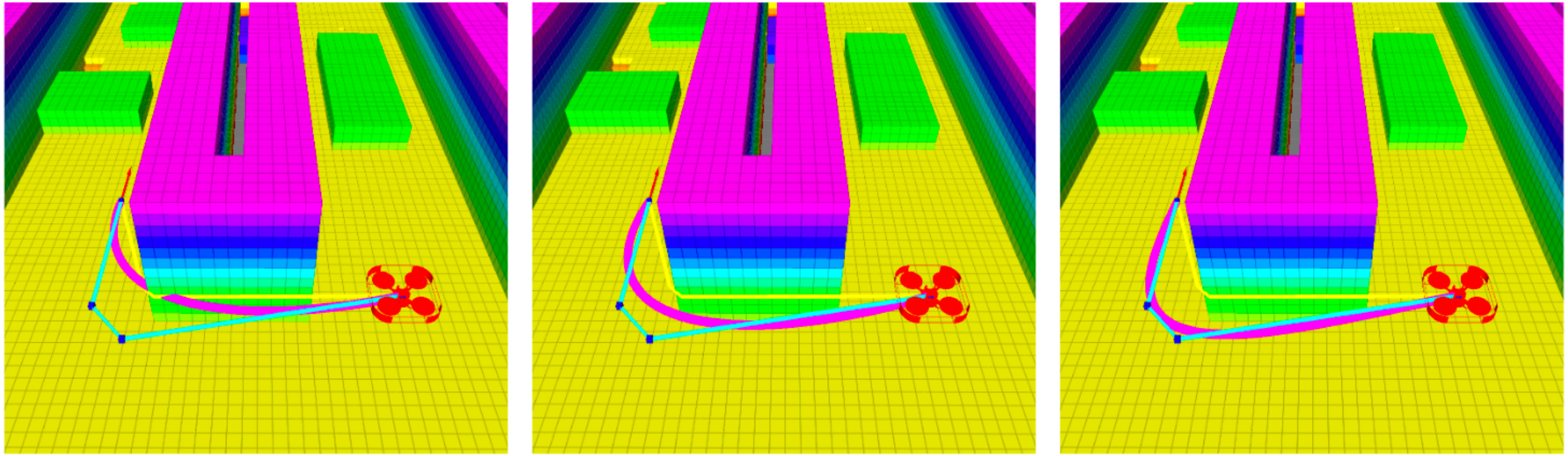
- Safe Path (image)



(a) Grow ellipsoid for each line segment. (b) Inflate the ellipsoid to generate the convex polyhedra. (c) Modified path $P^{\star}$.

Trajectory Generation

- Safe Path (image)

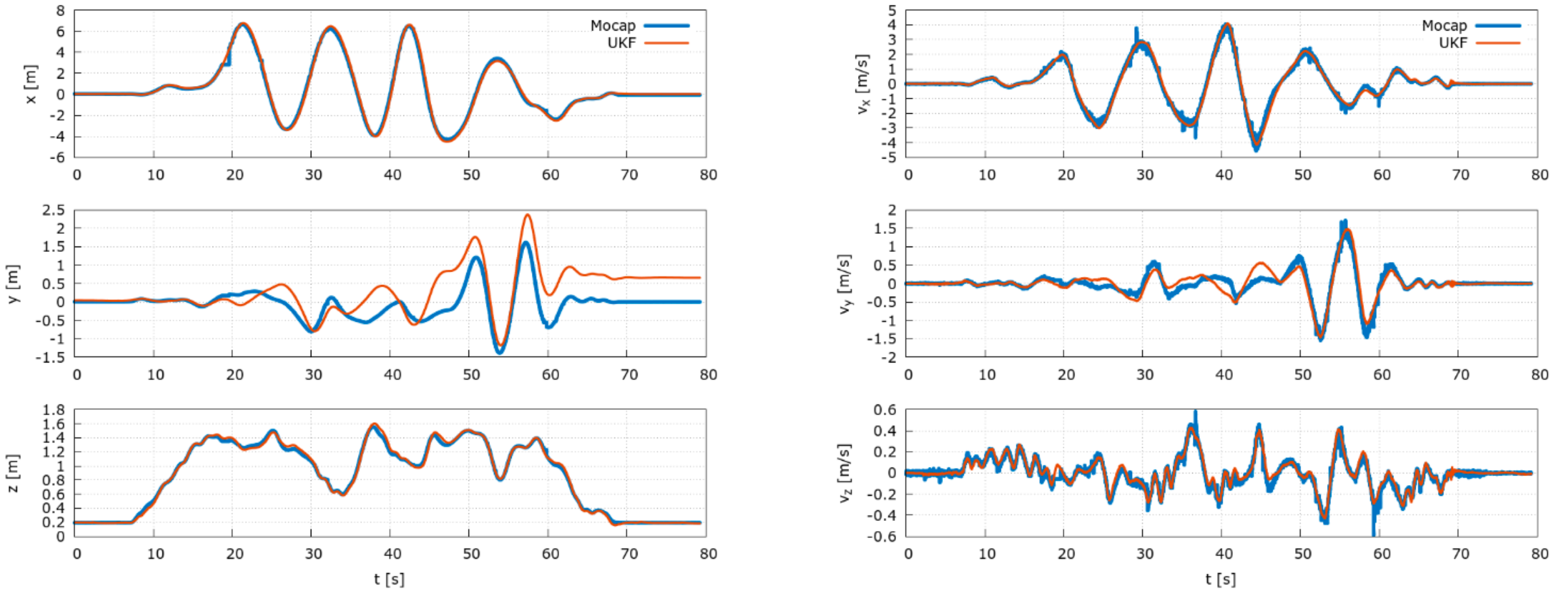


(a) $\epsilon = 0$ (b) $\epsilon = 20$ (c) $\epsilon = 100$

Figure 16: The generated trajectories (purple) for different values of the weight ϵ. As we increase the weight, the trajectory gets closer to the given path (cyan).

Results

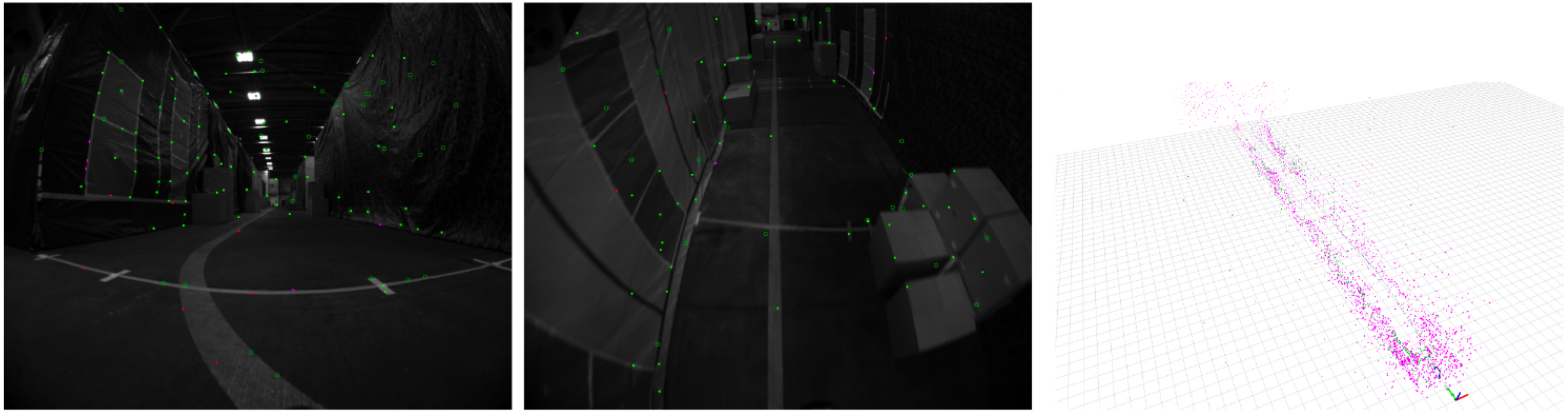
- Objective: long distances to goal point
  - Estimation accuracy valuable
- 1% drift indoors of UKF vs. Motion Capture (60 m flight, 0.6m drift)



(a) Position (b) Velocity

Results

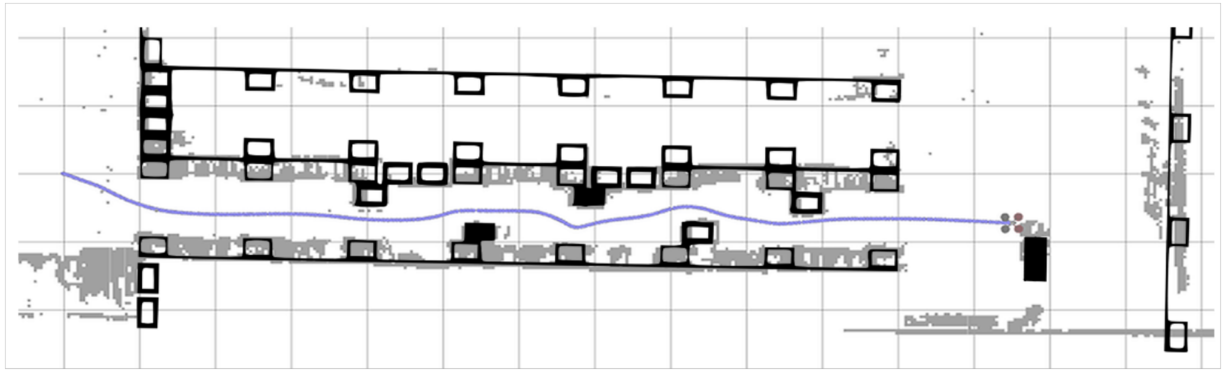
- Objective: long distances to goal point
  - Estimation accuracy valuable
- 2% drift in aggressive fight of SVO after aggressive flight
- Features still detected well on global map

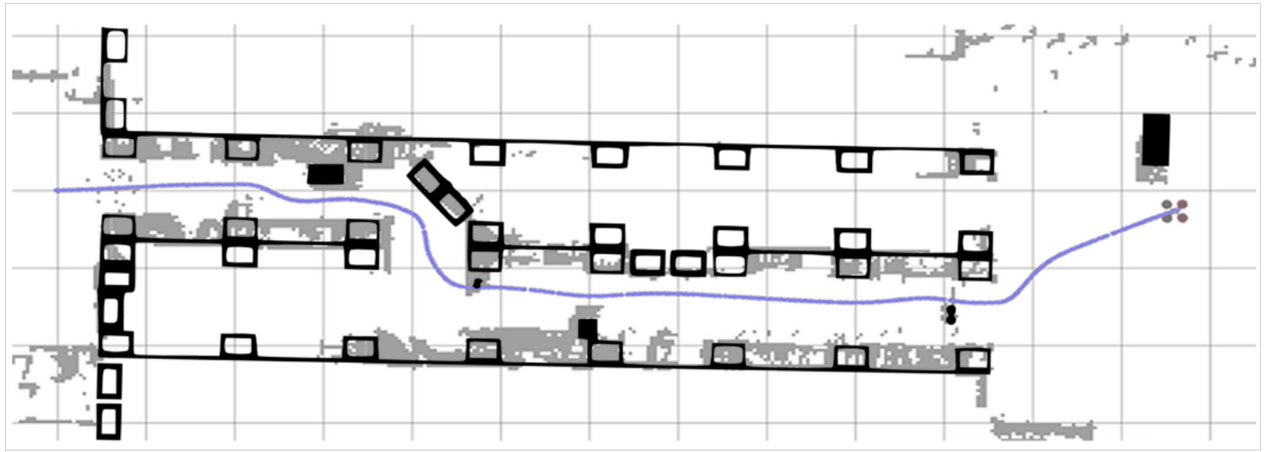


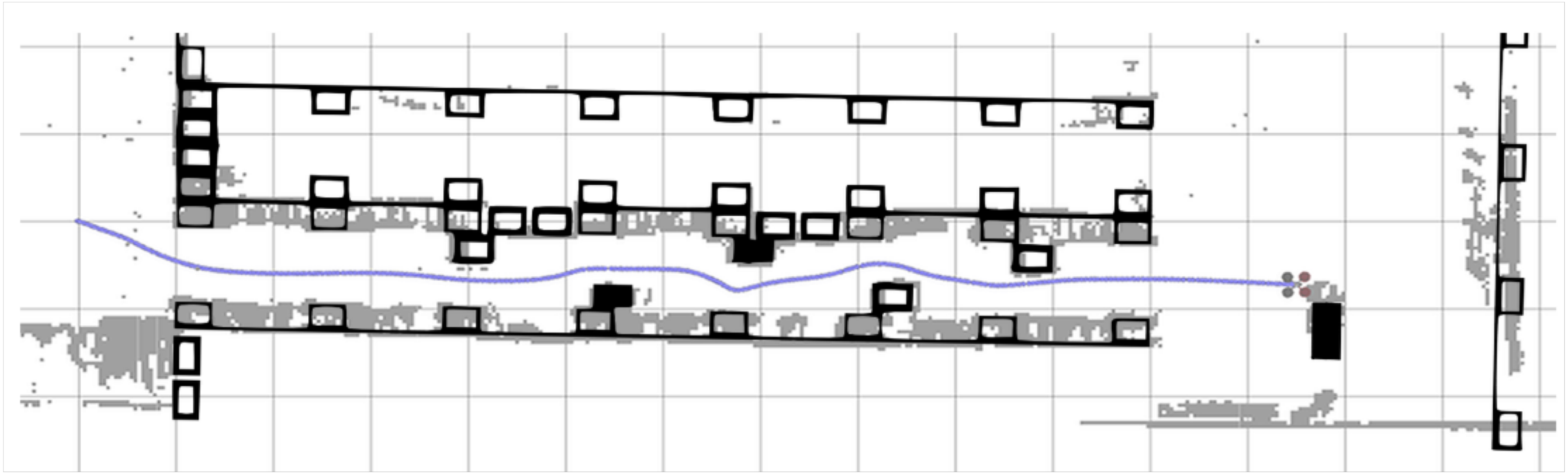
(a) Onboard image with features during hover (b) Onboard image with features during aggressive flight (c) Map of sparse 3D points

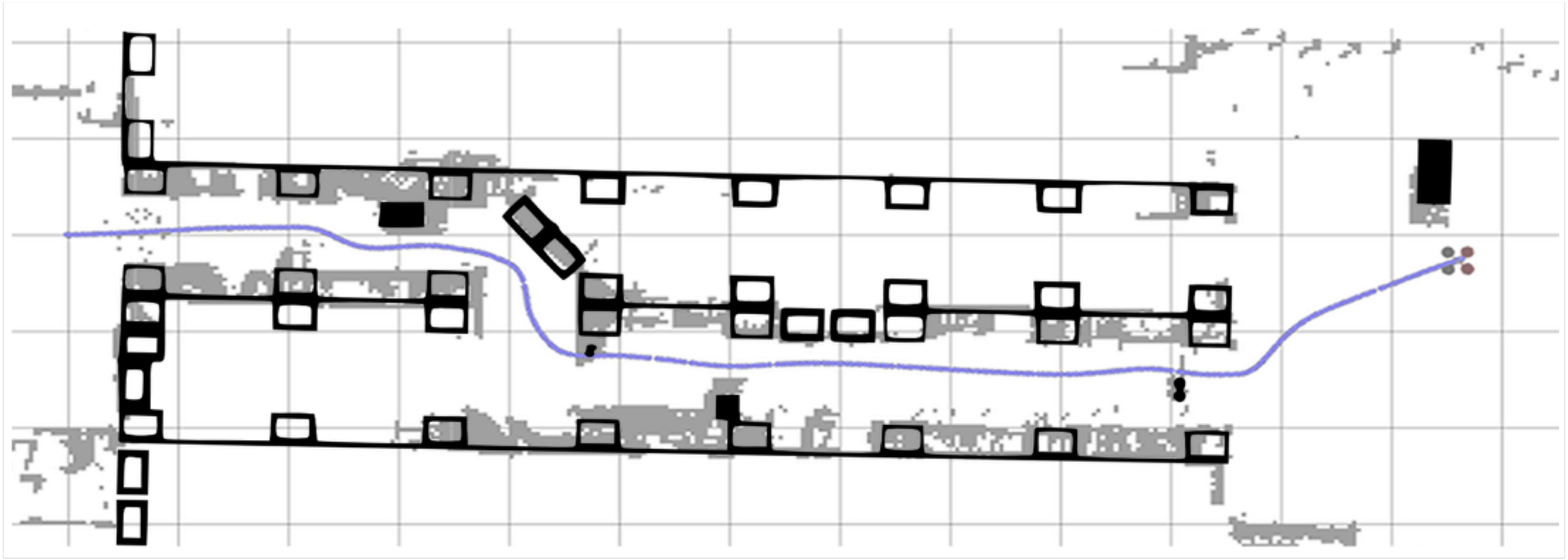
Results

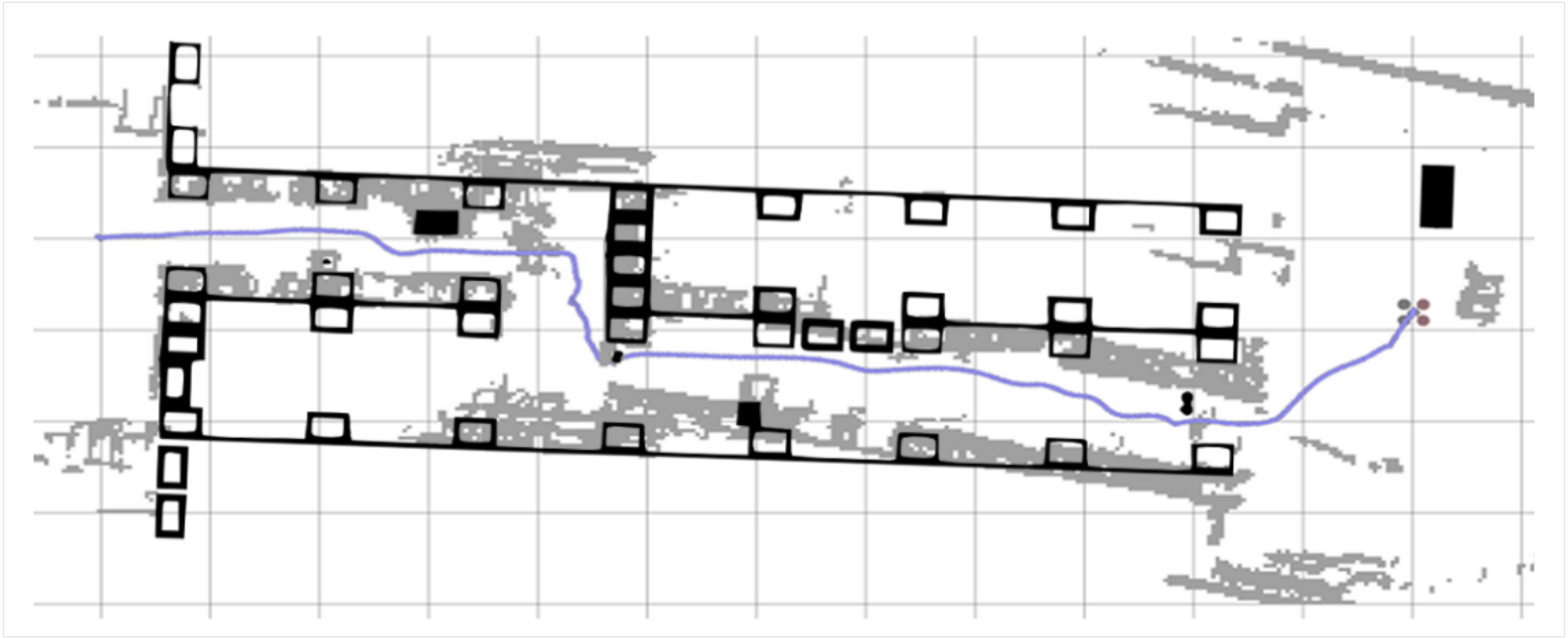
- Real world point to point tasks suffer from drift











Overview of Errors

- Visual odometry requires salient features, warehouse floor is smooth
- Mapping requires compute, and is the limitation for the speed of the quadcopter
  - Dynamically feasible trajectories are eclipsed by small map size, especially first pass