Aerial Mobility in Unknown Environments

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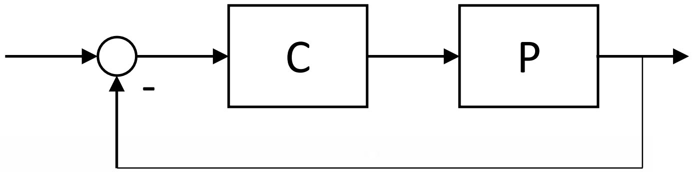
Motivation: human baseline

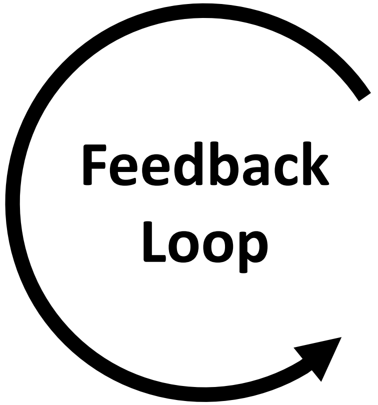
https://www.youtube.com/watch?v=NsxyV-kgfio&t=4s

Human feedback loop

Prediction



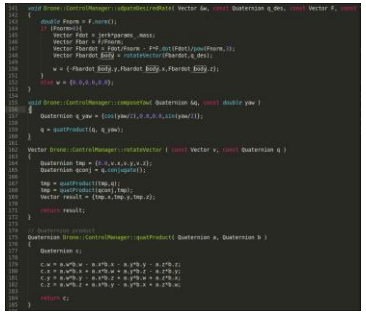
Video Feed



RC Commands

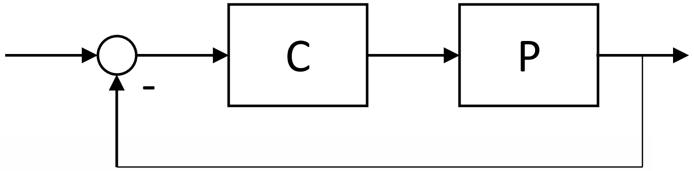
Autonomous feedback loop

Prediction



Video Feed

Feedback Loop



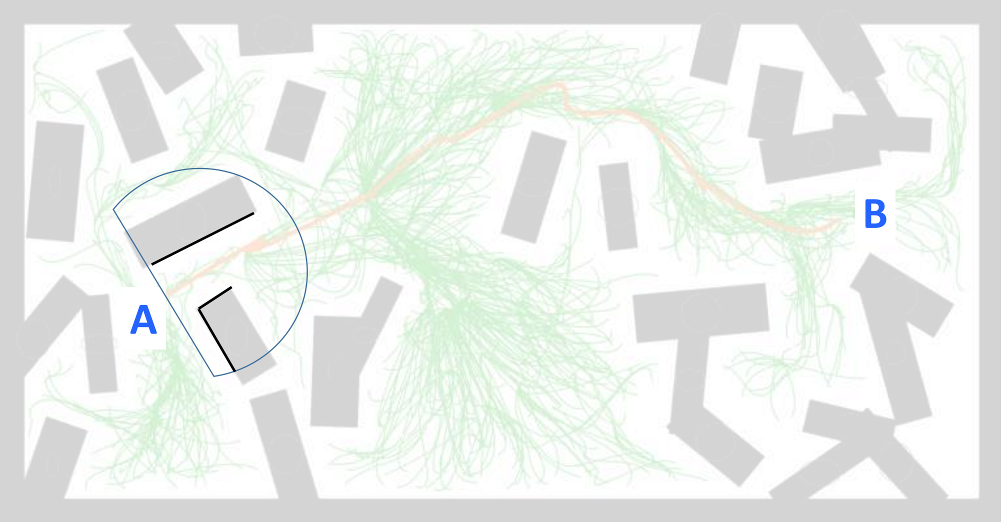
RC Commands

Overview

- Background on planning
- World representation & planning strategy
- Collision avoidance with instantaneous pointclouds
- Adding history to world representation
- Model predictive control & robustness

Background - planning

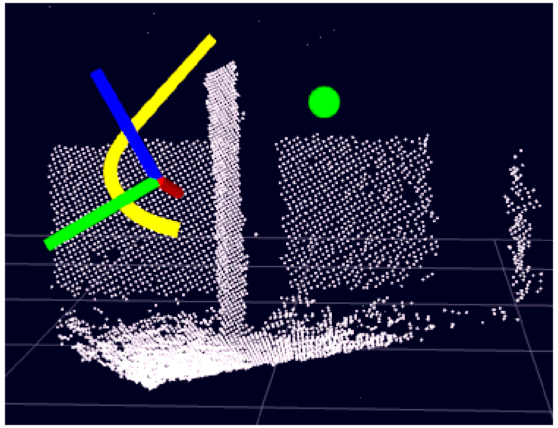
- Classical planning problem (A→B) focused on new algorithms and reduced computation time
- Unrealistic expectation of perception quality
    - **Assumes:** Infinite horizon, no uncertainty, sensor data easily transformed into useful form
    - **Reality:** Finite horizon, state/measurement uncertainty
- Difficult to extend existing planner into receding horizon framework
- **Issue:** Which world representation and planning technique?
    - Need techniques to integrate real-world perception into planners of varying complexity/timescales



Planning in Unknown Environments

- **Problem:** Navigate through unknown environment as fast as possible

Lopez '17

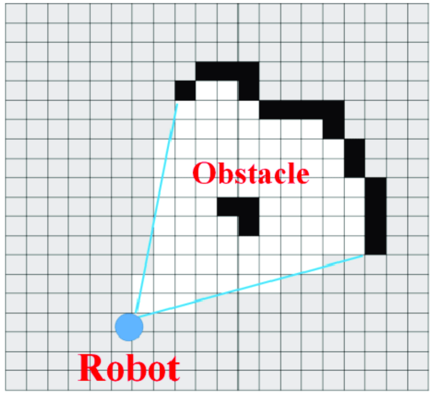


- **Challenge:** World only partially known due to limited perception
- **Two Tasks:**
  1. Transform sensor data into usable world model
  2. Use world model to find path
- **Constraint:** Emphasize fast perception and planning ⇒ **minimize reaction time**
- **Issue:** Planning & perception designed **independently** ⇒ slow reaction time

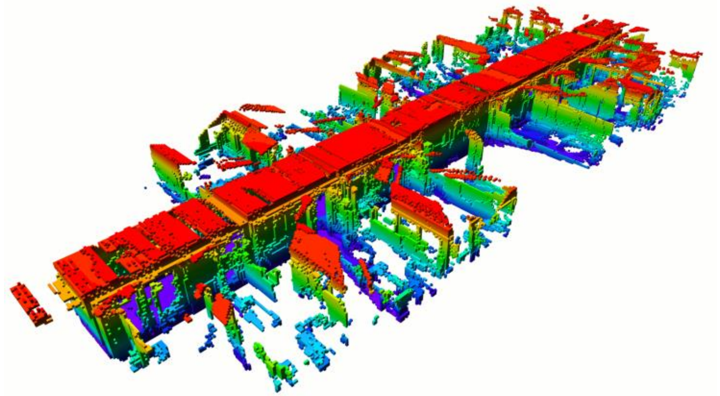
World representations

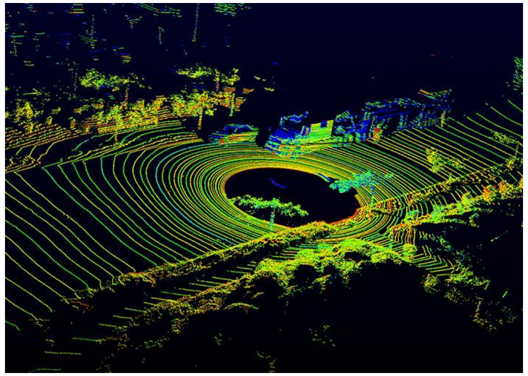
- Occupancy grid map
- Raw sensor measurements
- Other

Nam ‘15

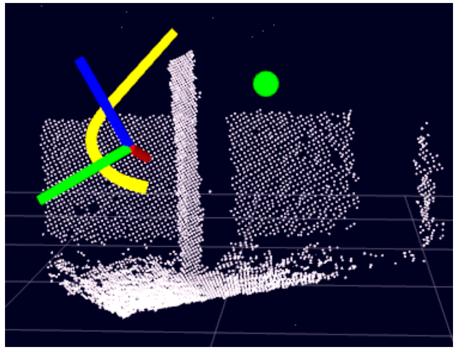


Hornung ‘13

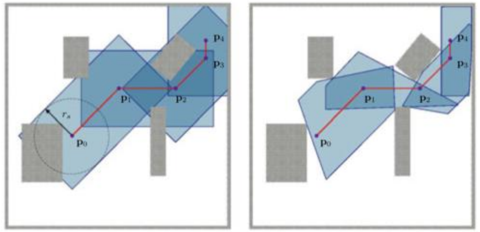




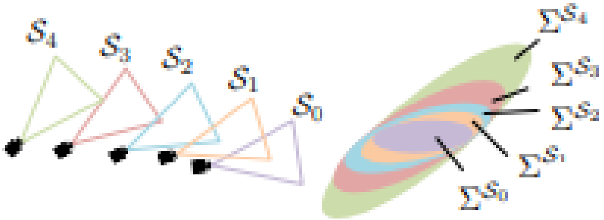
Lopez ‘17



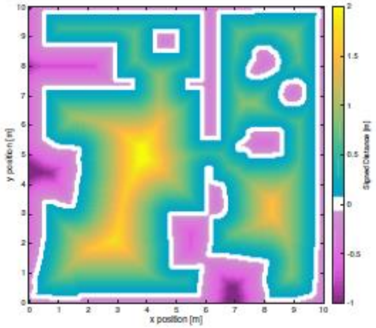
Liu ‘17



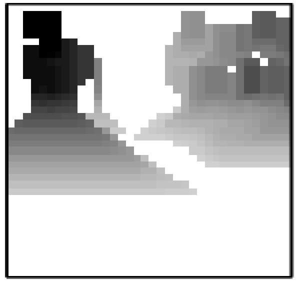
Florence ‘18



Oleynikova ‘16



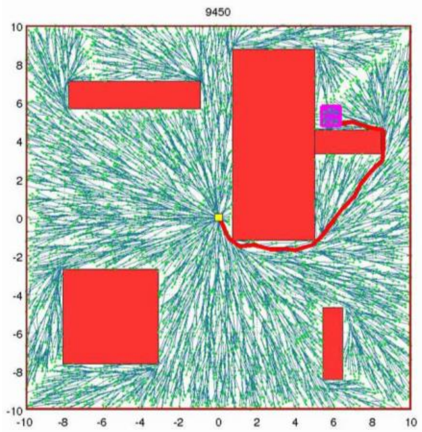
Otte ‘09



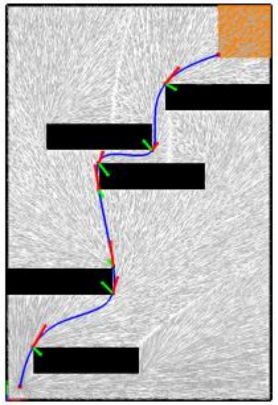
Path planning strategies

- Graph/tree search
- Optimization-based
- Motion primitives
- Hybrid

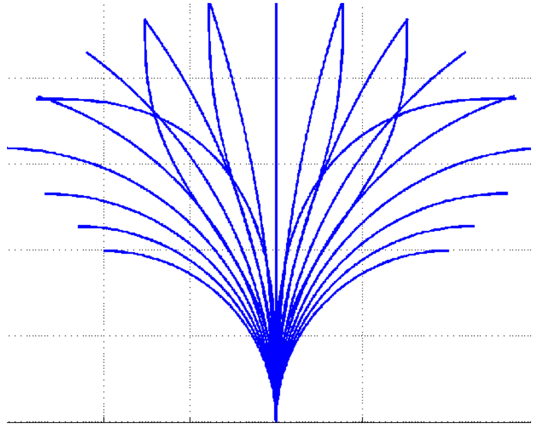
Karaman ‘11



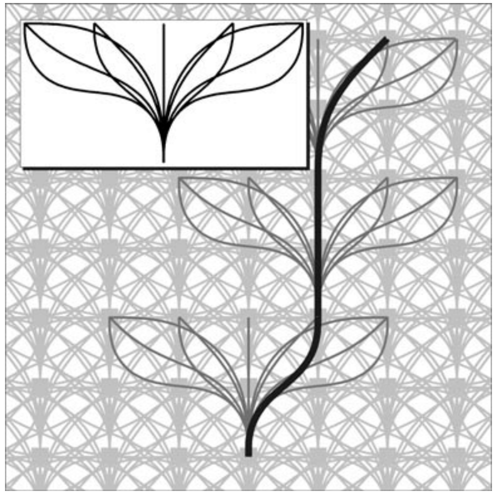
Richter ‘16



Pivtoraiko ‘09

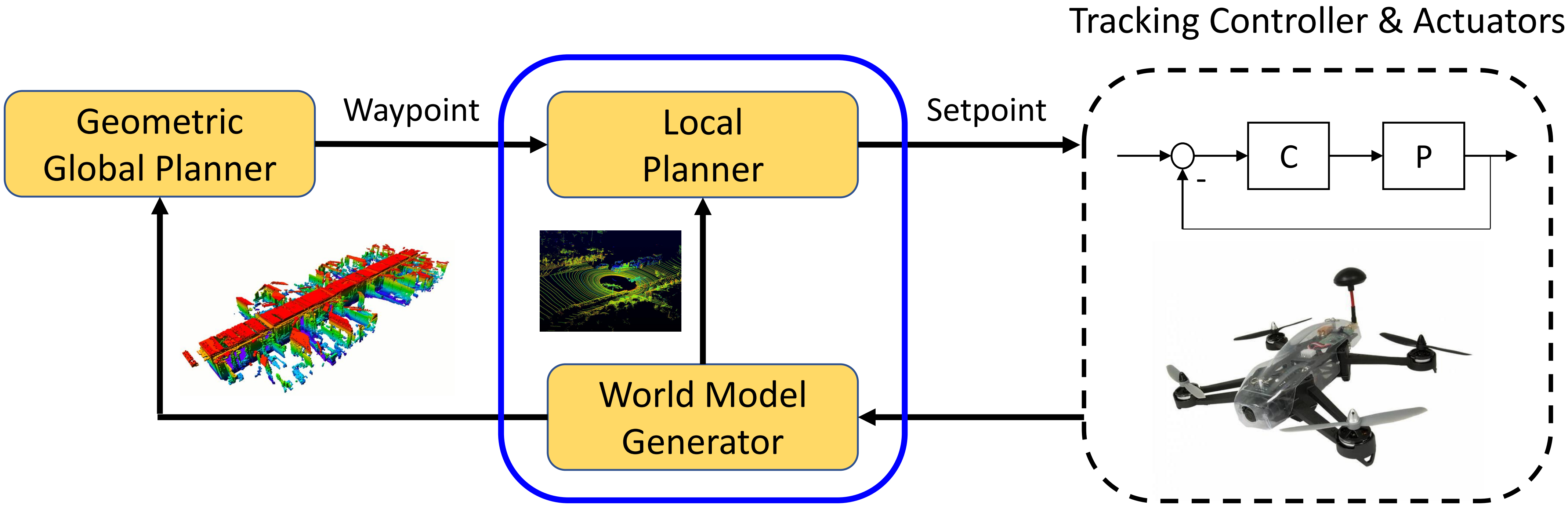


Pivtoraiko ‘09



Hierarchical planning architecture

- **Issue:** Limited computation power ⇒ limit planning horizon **or** reduce model fidelity
- **Solution:** Long horizon, simple model **global planner** + short horizon, complex model **local planner**
  ⇒ **Hierarchical planning**
- **Insight:** Global planner guides local planner



Triple Integrator Planner

- **Goal:** Efficient perception/planning pipeline for aggressive obstacle avoidance

- **Approach**
    1. Use **instantaneous** perception data for collision avoidance
    2. Generate motion primitives **online** with **approximate but accurate** vehicle model
    3. Check for collisions **efficiently**

Lopez ‘17

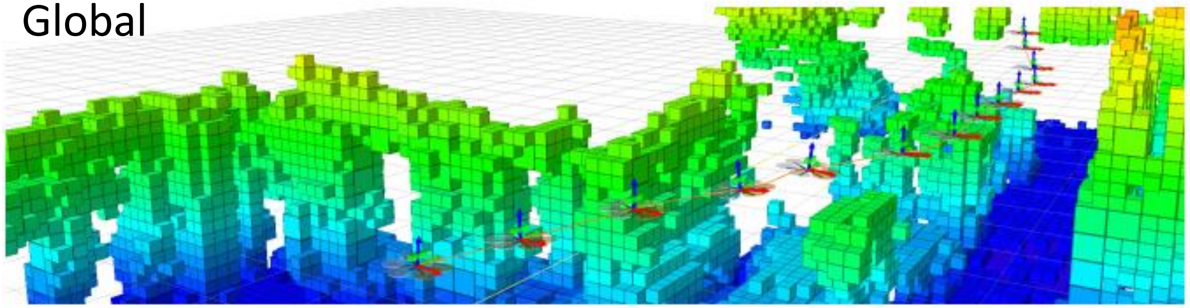
- **Result:** **5ms** computation time is ≈**10x faster** than previous state-of-the-art

World representation revisited

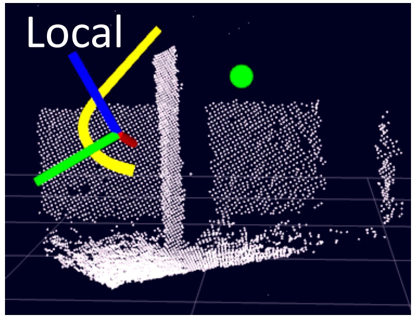
- **Goal:** Low overhead, avoid sensor fusion/costly perception processing
- **Approach:** Construct simple world representation from *instantaneous* point cloud
  - **k-d tree:** convenient data structure for nearest neighbor search
  - 2 transformations: depth image → pointcloud → k-d tree
- **Limitations:**
  - No history of previously seen obstacles ⇒ tradeoff computation time/knowledge
  - Constrained to travel in sensor FOV ⇒ unknown space is occupied space

Burri ‘15

Global



Lopez ‘17

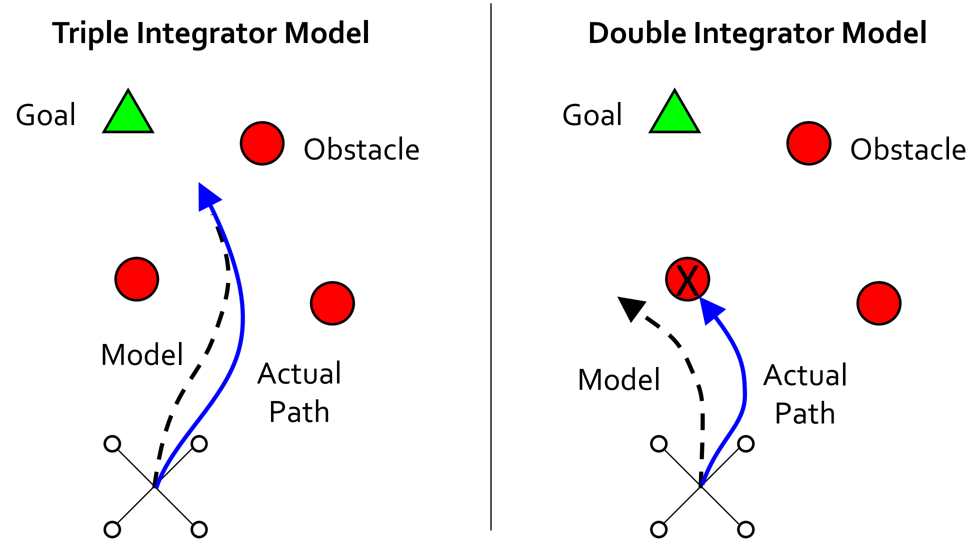


Minimum-time motion primitives

- **Goal:** Generate collision avoidance maneuvers with minimal computation time

  ⇒ **Motion primitives**

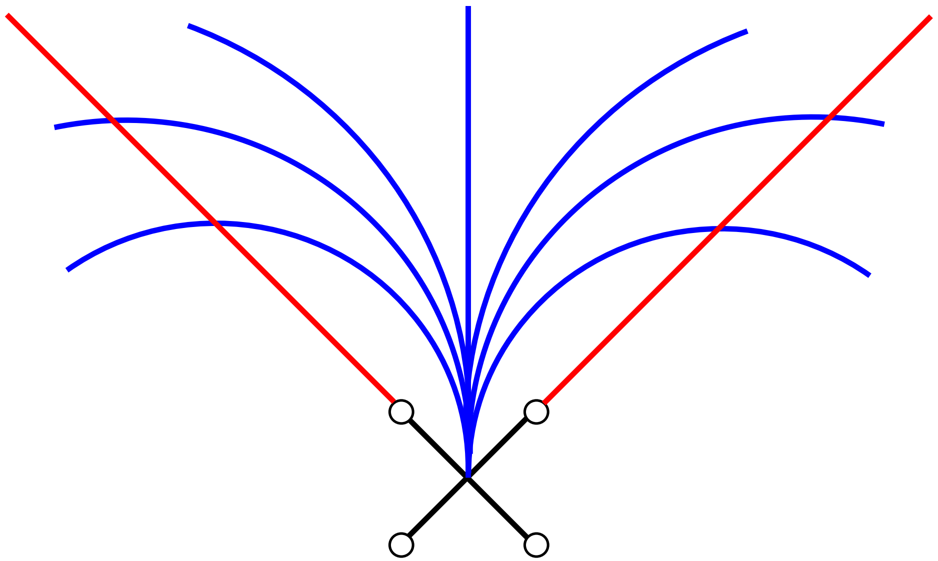
  - **Formulation:**
    - Triple integrator model to approximate vehicle dynamics, **including attitude**
    - Min-time decoupled state/input constrained optimal control problem, with *jerk* as control input



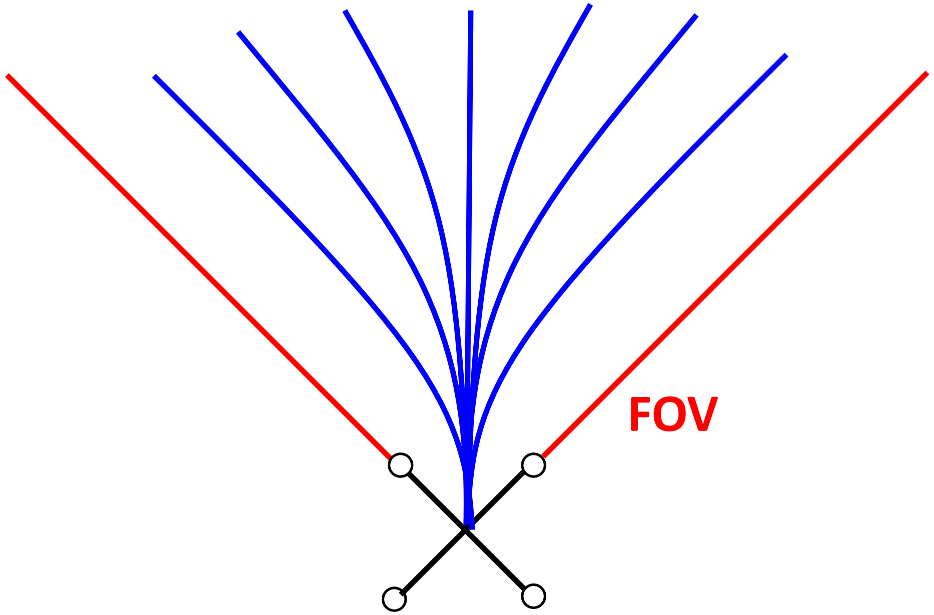
- **Key idea:** Plan in **velocity space** to reduce comp. complexity
  - **Closed-form** solution ⇒ 3-D primitives generated online in **4.7μs**
  - Primitive generated from current state to desired *speed* and *direction*
- **Result:** Bang-(off)-bang solution in jerk ⇒ highly agile maneuvers

State- vs. control-based motion primitives

- **Control-based: Satisfy control constraints** but **violate state constraints**
- **Sate-based: Satisfy state constraints** but require **solving TPBVP ⇒** time consuming
- **Key Insight:** Planning in velocity space allows TPBVP to be solved with minimal comp. time ⇒ state/control input constraints guaranteed satisfied
  - Sample over speed and direction



Control-based primitives violate FOV constraint

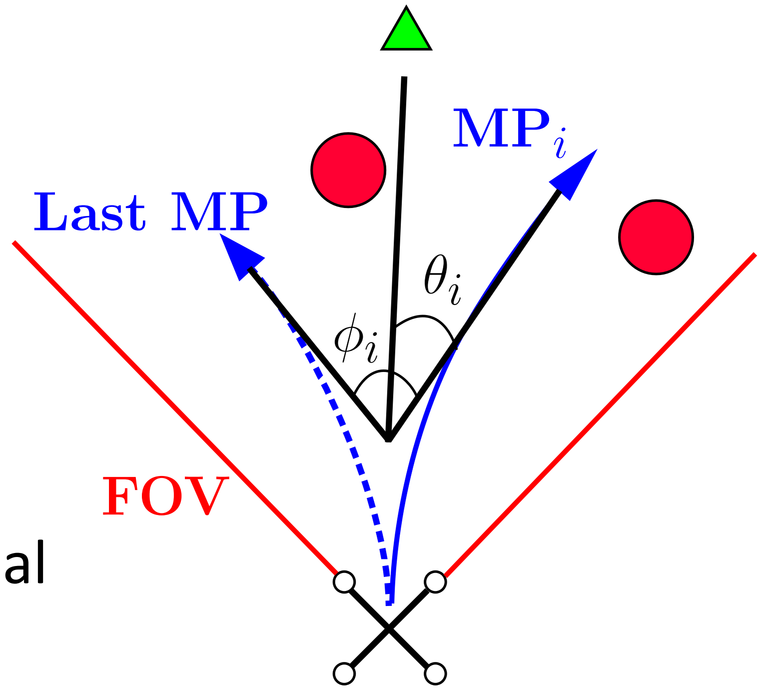


State-based primitives trivially satisfy FOV constraint

Primitive sorting

- **Goal:** Construct cost function *independent* of world model
- **Idea:** Calculate primitive cost using *heading* information and primitive *length*
- **Cost of primitive MP*$_i$*:**

$$J_i = \underbrace{\phi_i}_{\text{Stage Cost}} + \underbrace{c_1\theta_i + c_2\left(d_{\text{perception}} - d_i\right)^2}_{\text{Terminal Cost}}$$



- **Stage cost:** Prioritize "similar" primitives
- **Terminal cost:** Prioritize "long" primitives in direction of goal

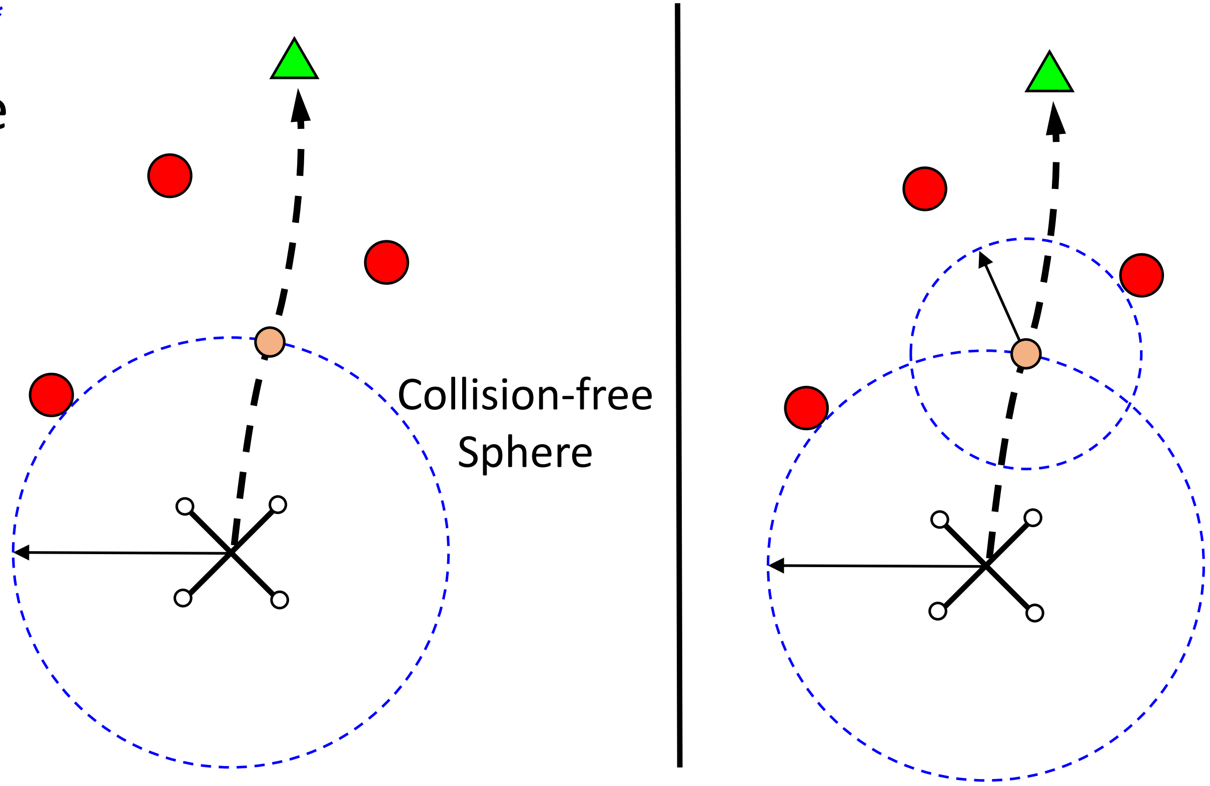
Efficient collision checking

- **Issue:** Collision checking typically expensive
  - Existing methods finely sample path or further process sensor data ⇒ **slow**

- **Key idea:** Estimate **next possible time t^*** based on top speed and closest obstacle

- **Procedure:**
  1. Estimate t^*
  2. Evaluate primitive at t^*
  3. Repeat until collision or sensing horizon reached

- Check small # of points along primitive
  ⇒ **Low computation time**

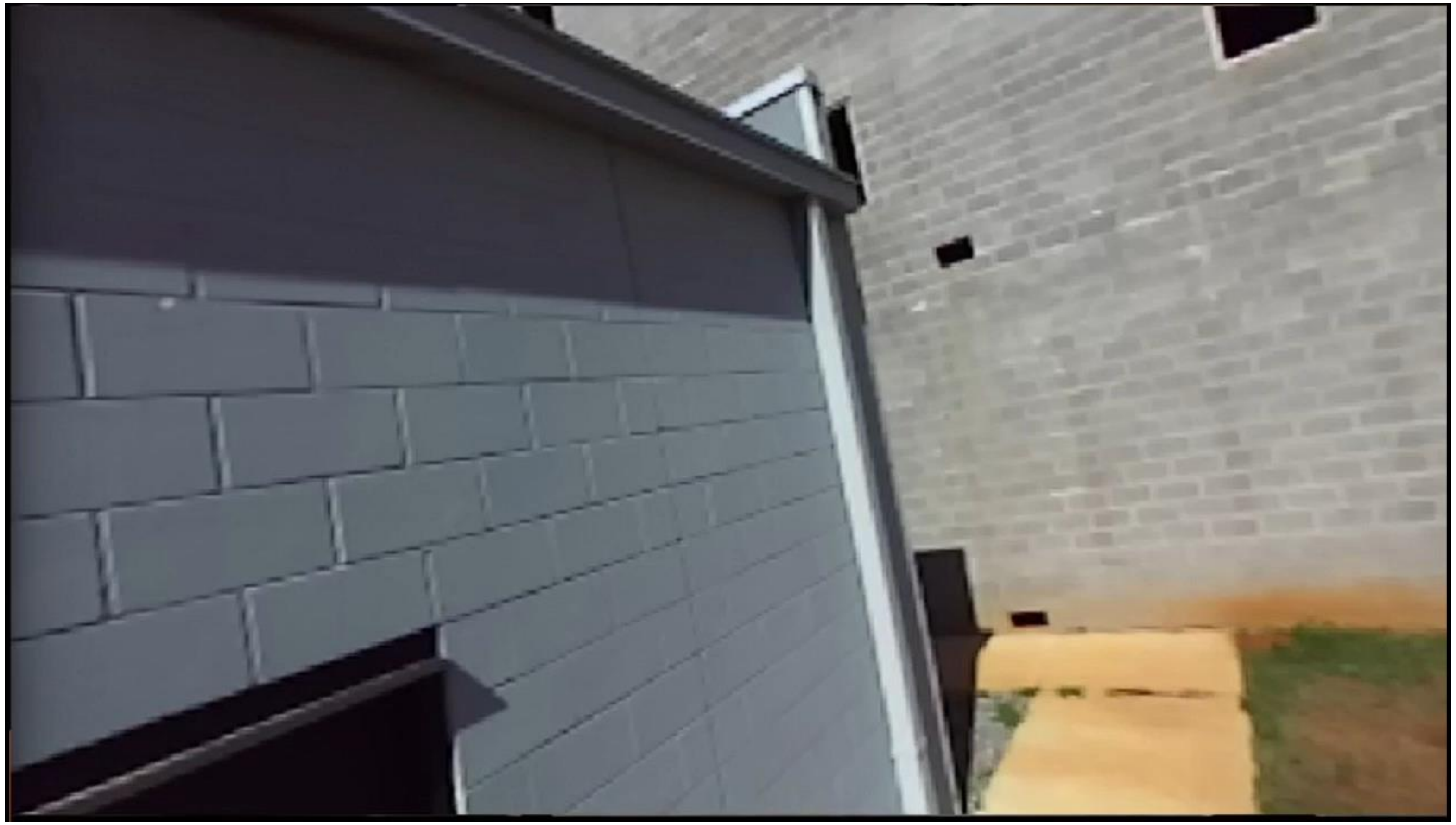


Indoor Flight Experiments [Lopez '17]

Outdoor tests: good day

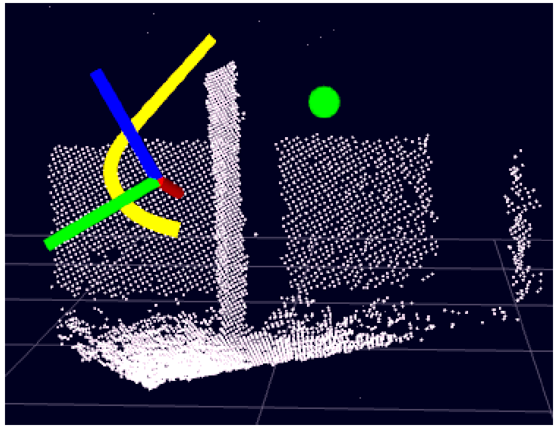
Wall seen ~3.5m away

Outdoor tests: good day

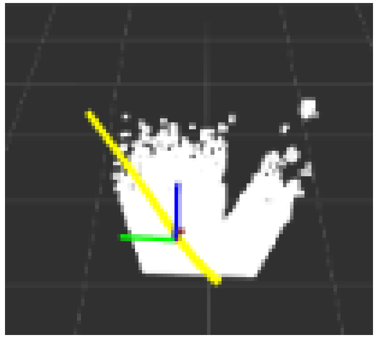


Adding history to world model

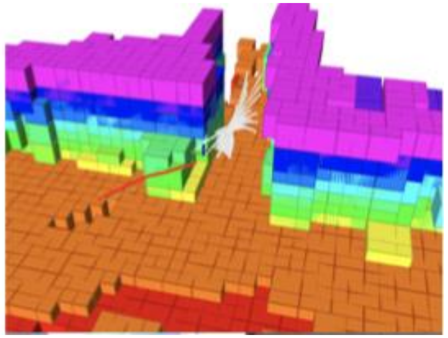
- Advantages of instantaneous pointclouds:
  - Robust to state estimation uncertainty
  - No temporal fusion ⇒ little required computation
- **Issue:** No history of previously observed obstacles ⇒ **myopic**
- **Possible solutions:**
  - Primitive/trajectory history
  - Pointcloud history without fusion
  - **Sliding occupancy map**



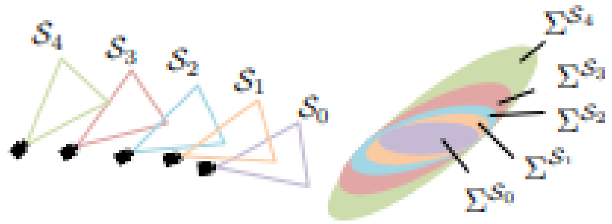
Lopez ‘17



Ryll ‘19



Florence ‘18



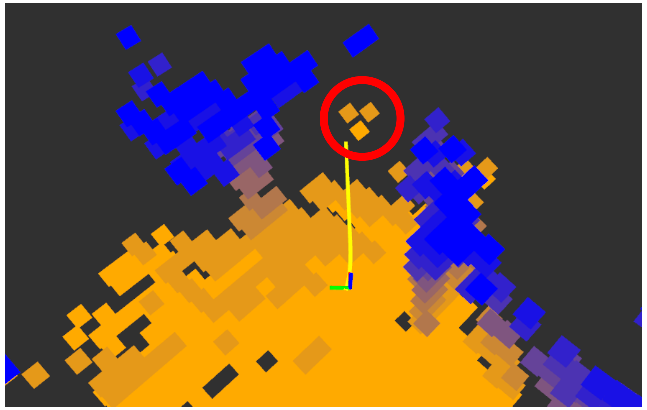
More outdoor test: good day

- **World model:** Instantaneous pointcloud + local map

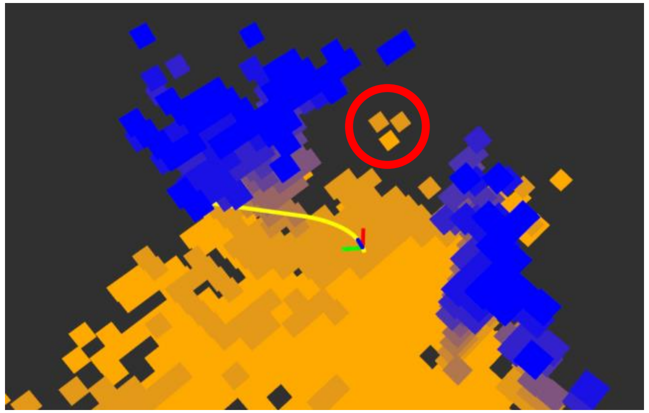
More outdoor test: good day

- **World model:** Instantaneous pointcloud + local map

Pole enters sensing range



Initial Primitive

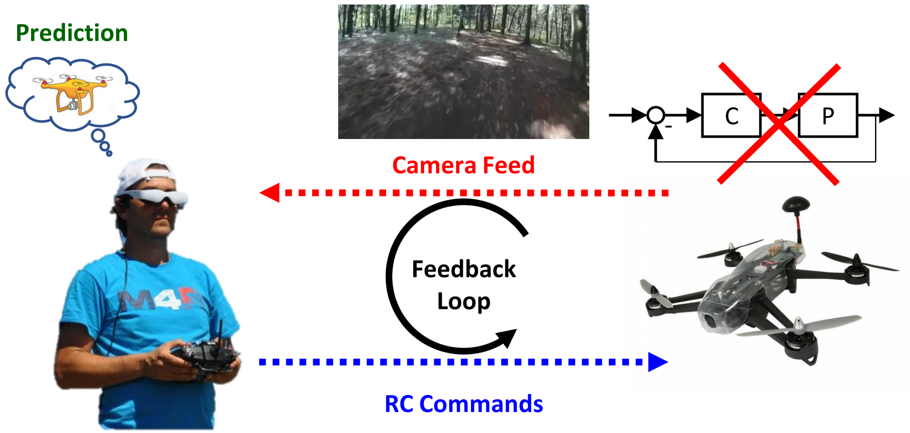


Next Selected Primitive

Outdoor tests: bad day

Ad-hoc design of planning/control architecture ⇒ **no performance guarantees**

Model Predictive Control



- **MPC:** Repeatedly solve constrained, multivariable optimal control problem

Prediction

Optimizer

$$
\begin{aligned}
u^* = \ & \underset{\bar{u}}{\text{argmin}} && J \\
& \text{subject to} && \dot{\bar{x}} = \hat{f}(\bar{x}) + \hat{b}(\bar{x})\bar{u} \\
& && \bar{x} \in \mathbb{X}, \ \bar{u} \in \mathbb{U}, \\
& && \bar{x}(t_0) = x(t_0), \ \bar{x}(t_f) \in \mathbb{X}_f
\end{aligned}
$$

Command

u^*

Plant

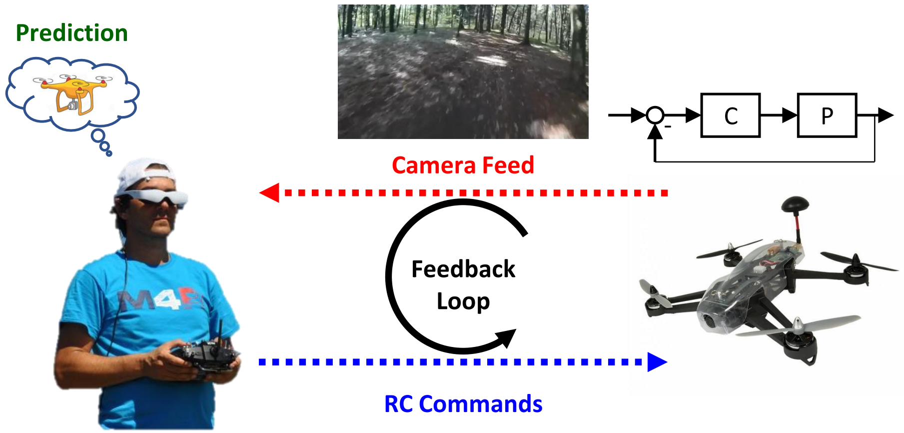
$$\dot{x} = f(x) + b(x)u^* + d$$

$x(t_0)$

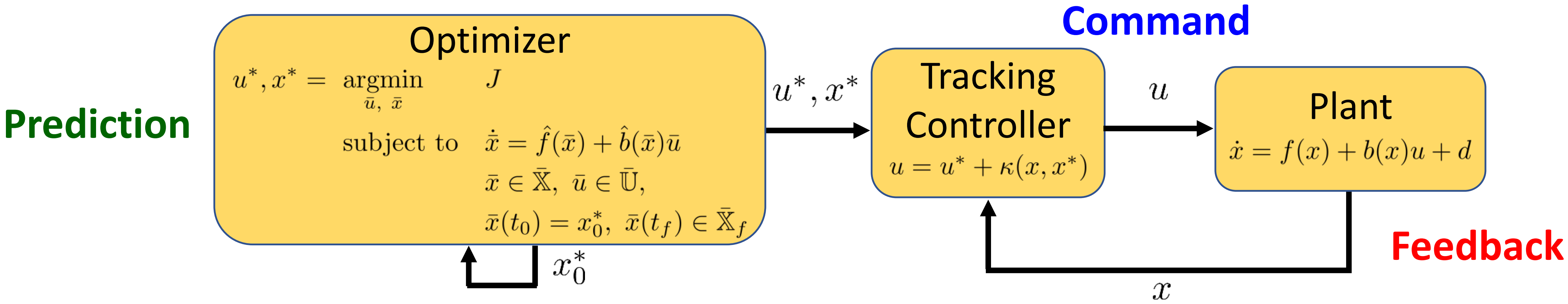
Feedback

- **Insight:** Works well with accurate model of dynamics ⇒ **robustness issues**

MPC with tracking controller

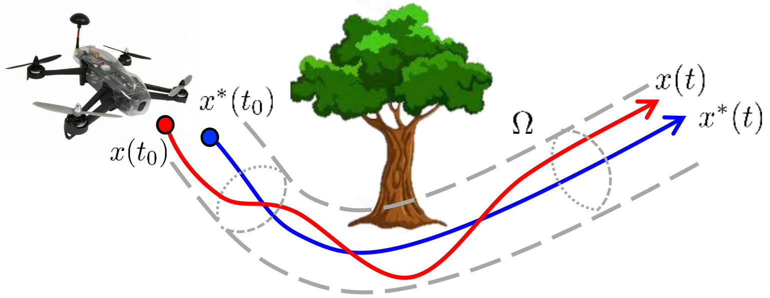


- MPC + tracking controller ⇒ **compensate** for model error & disturbance



- **Standard architecture** in many fields (e.g., robotics, aerospace, etc.)
- **Issue:** Ad-hoc feedback controller design ⇒ **no performance guarantees**
  - **Tube MPC** ⇒ performance guarantees

Tube MPC



- **MPC:** Open-loop execution of optimal control solution
  - **Little robustness** to unmodeled dynamics/disturbances

- **Tube MPC:** Generate open-loop reference that is tracked by **ancillary controller**
  - Controller bounds tracking error ⇒ **tube** around desired trajectory

- **Issue:** Constructing controller/tube non-trivial for nonlinear systems

- Existing methods **overly conservative**, **expensive to compute**, & **not generalizable**

- Very active area of research for nonlinear systems

Planning needs for subterranean challenge

- Less emphasis on speed, more emphasis on autonomy
    - Frontier exploration
    - Active search
- Perception-degraded environment
    - Planning needs resiliency to state estimation errors/failures
- Accurate SLAM
    - Return to previously visited areas to improve SLAM accuracy
- Multi-robot coordination

Summary

- Plethora of planning approaches
  - Select based on available sensors, computation, & domain

- Coupled perception & planning design for max performance
  - Perception/localization-aware planning

- Resiliency to perception/localization errors & failures

- Testing in the wild crucial!

Questions?

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