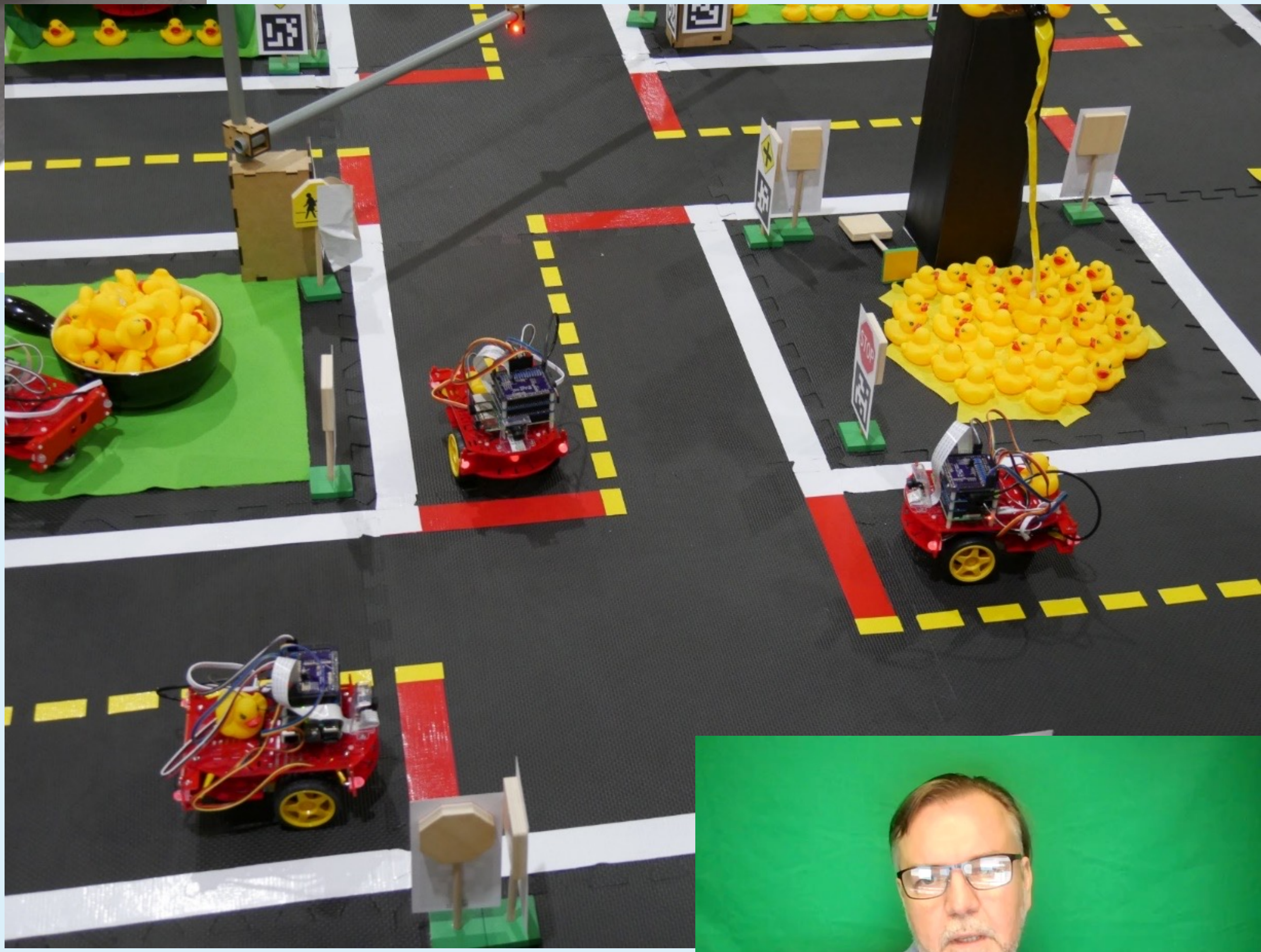
CS 3630



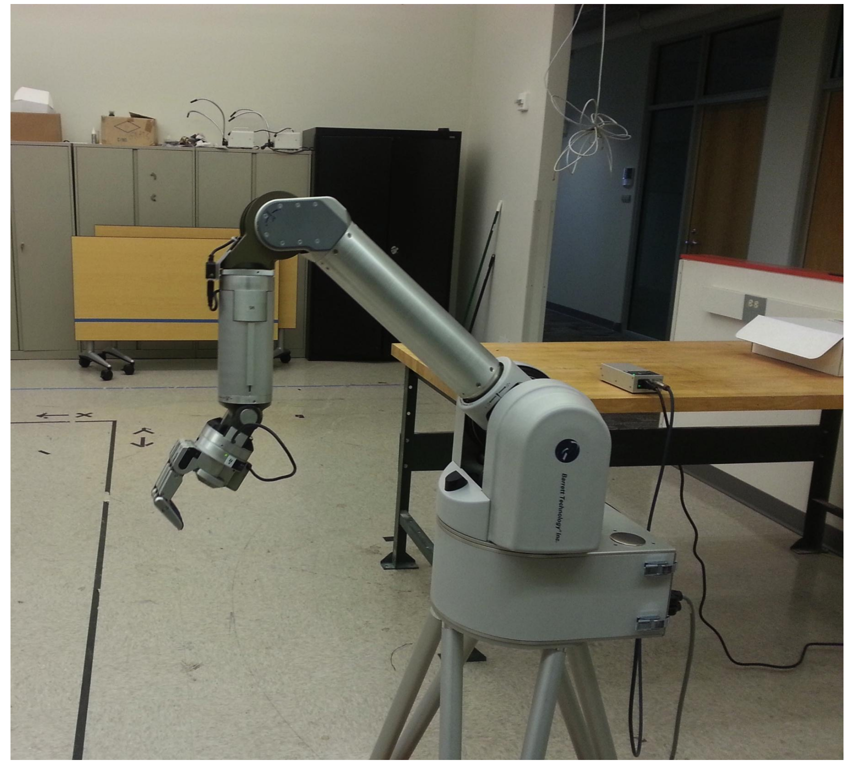
Lecture 25:

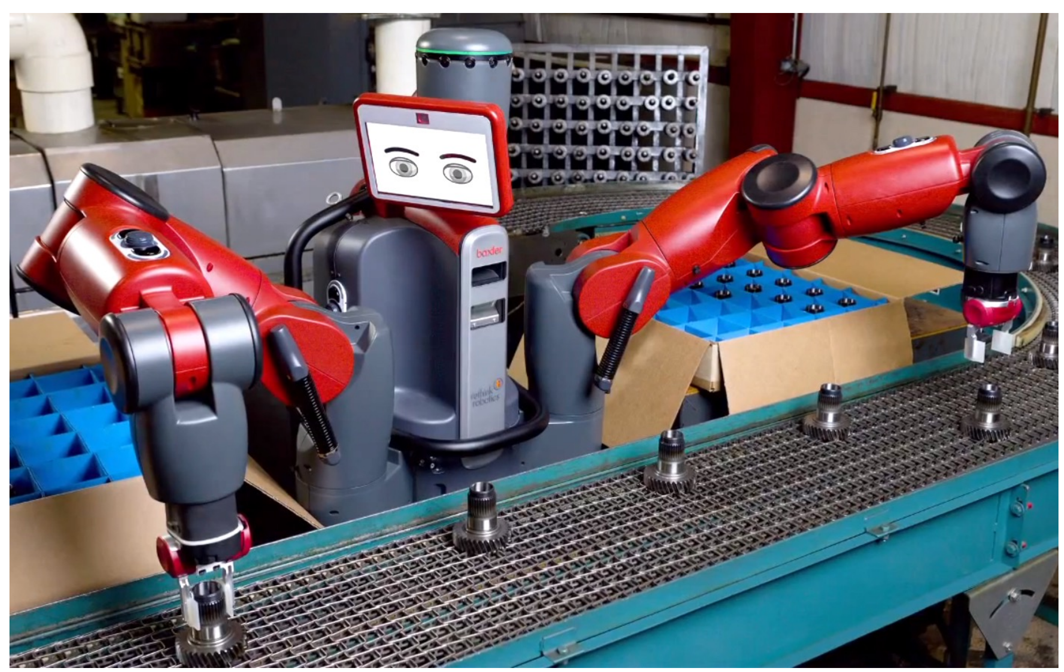
Trajectory Optimization for Motion Planning

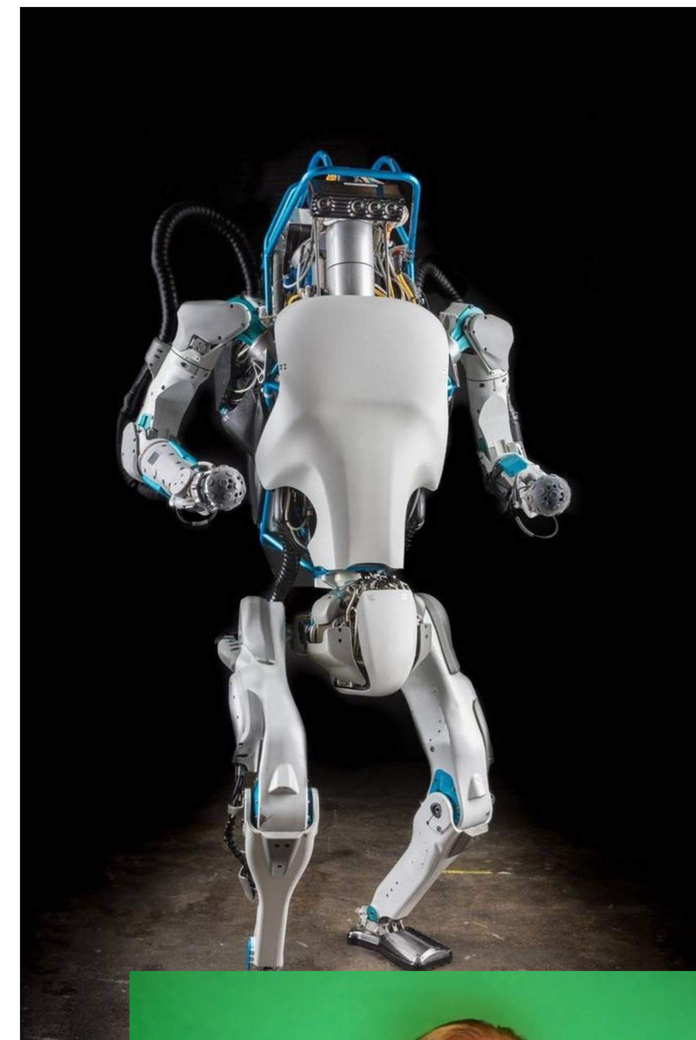
More research, all Georgia Tech!
Some cool applications in Art

1. Motion Planning w Factor Graphs
2. Calligraphy and Graffiti
3. STEAP: Simultaneous Trajectory Estimation and Planning

Motion Planning

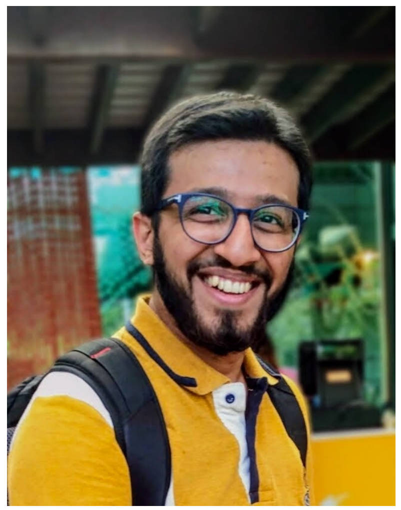






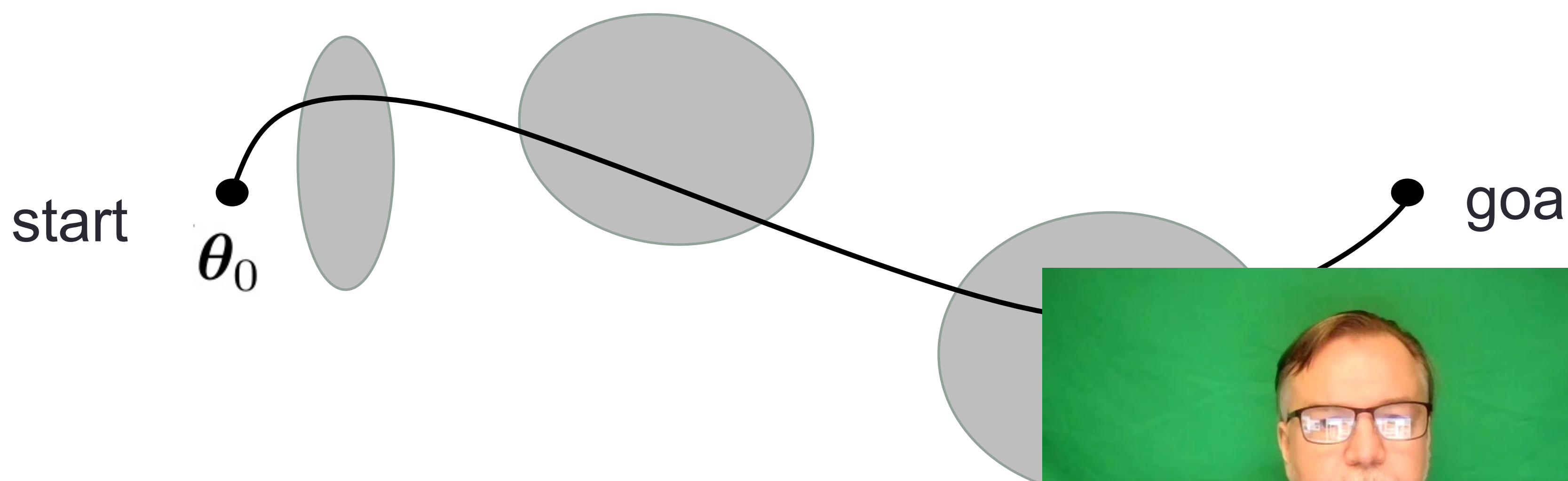
Motion Planning as Probabilistic Inference

Jing Dong, Mustafa Mukadam, Frank Dellaert & Byron Boots
Robotics: Science and Systems, 2016



Trajectory Prior **Collision-free Likelihood**

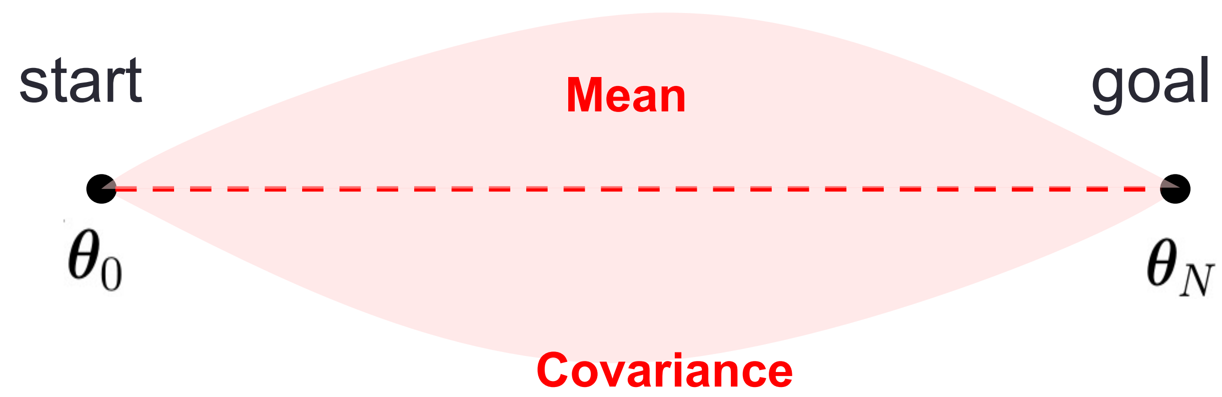
$$\boldsymbol{\theta}^* = \underset{\boldsymbol{\theta}}{\operatorname{argmax}} \left\{ P(\boldsymbol{\theta}) \prod_i P(c_i|\boldsymbol{\theta}_i) \right\}$$

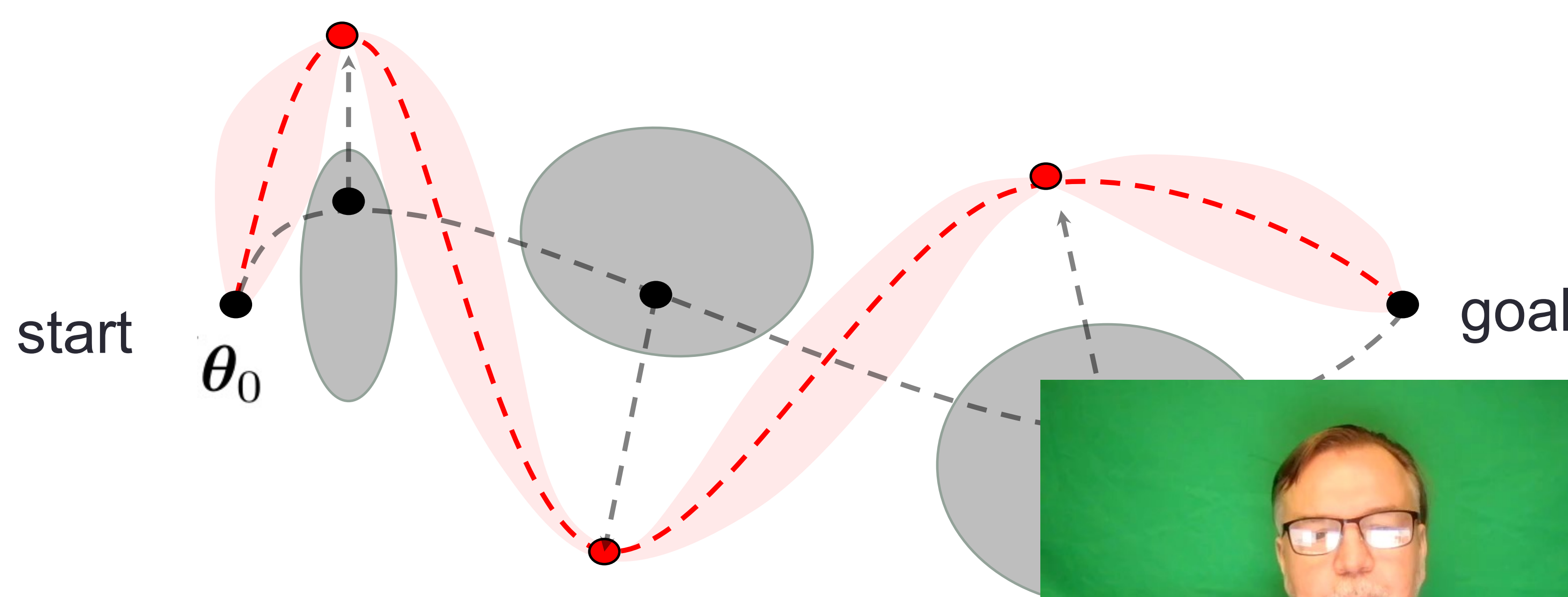


Trajectory as Gaussian Process (GP)

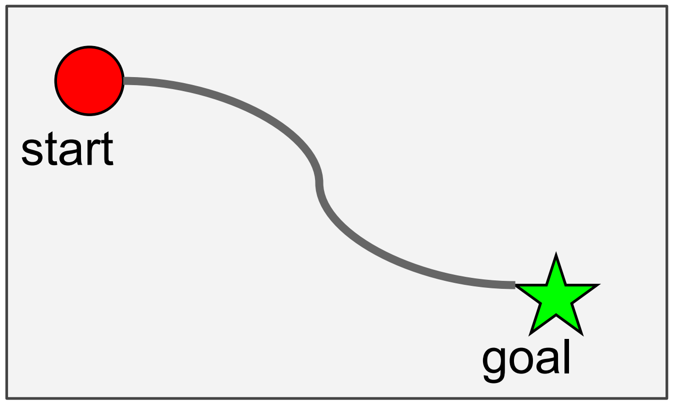
- Trajectory is represented by a few states
- Trajectory is interpolated

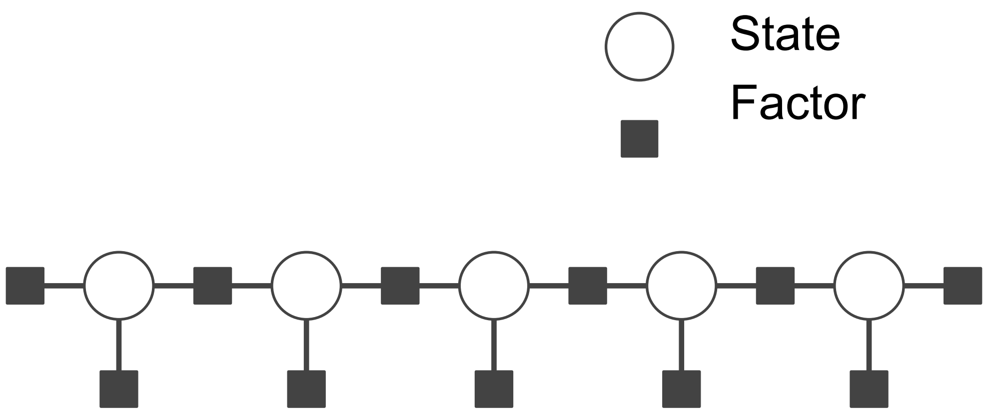
$$\boldsymbol{\theta}(t) \sim \mathcal{GP}(\boldsymbol{\mu}(t), \boldsymbol{\mathcal{K}}(t,t'))$$

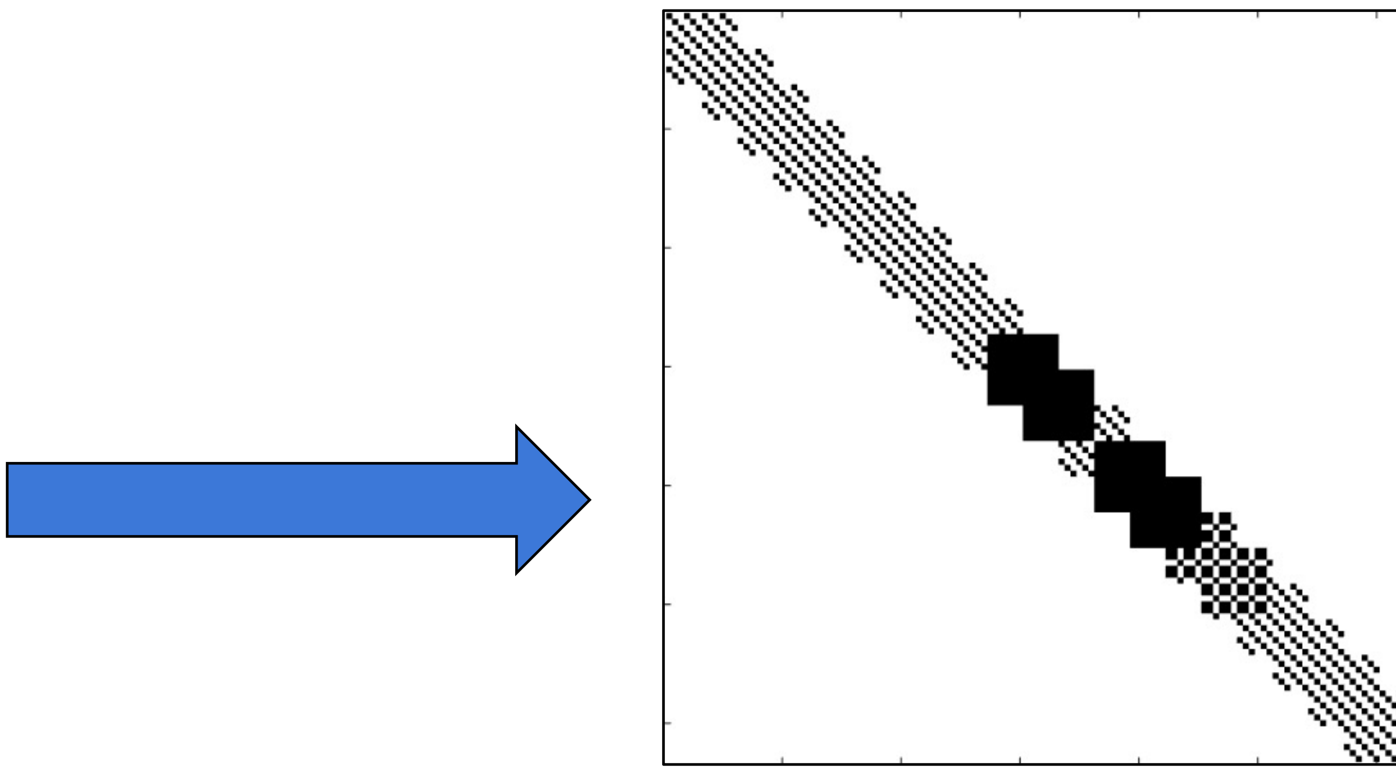




GPMP2: Efficient Least-Square Solution



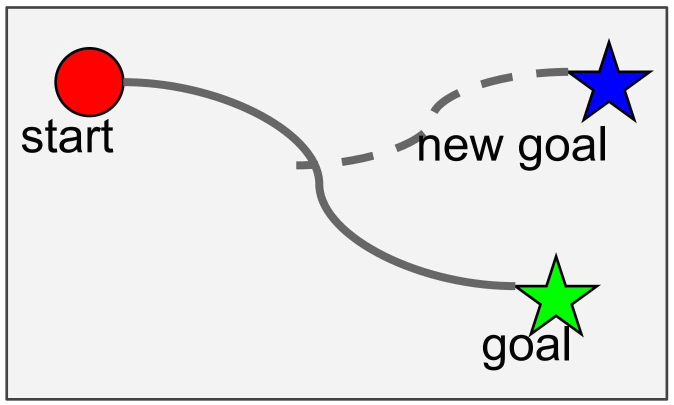


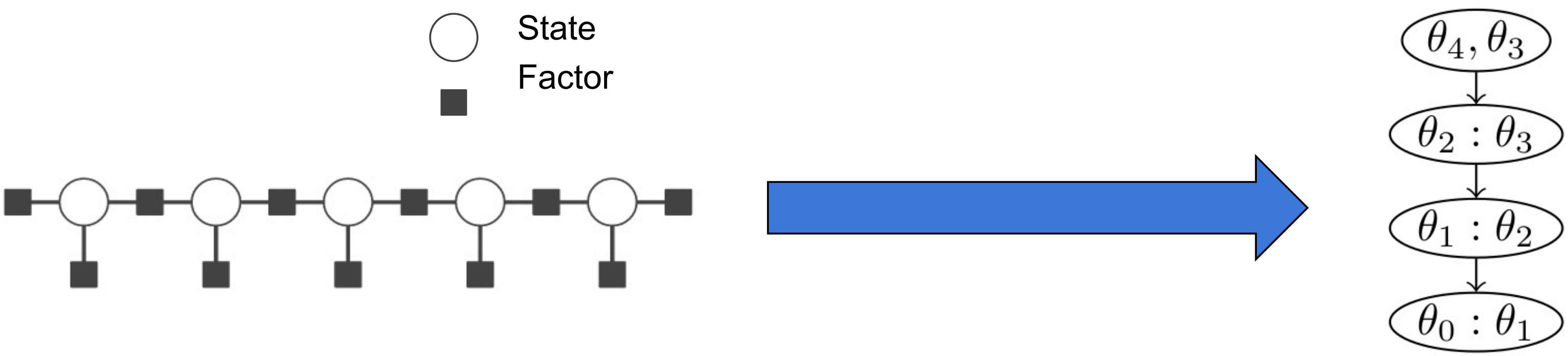


- Efficient inference in factor graphs by solving least-squares optimization problems
- Sparse linear algebra solver is used[1]

[1] Dellaert, et al. Square Root SAM: Simultaneous localization and mapping via square root information smoothing. *International Journal of Robotics Research*

iGPMP2: Efficient *Updated* Solution



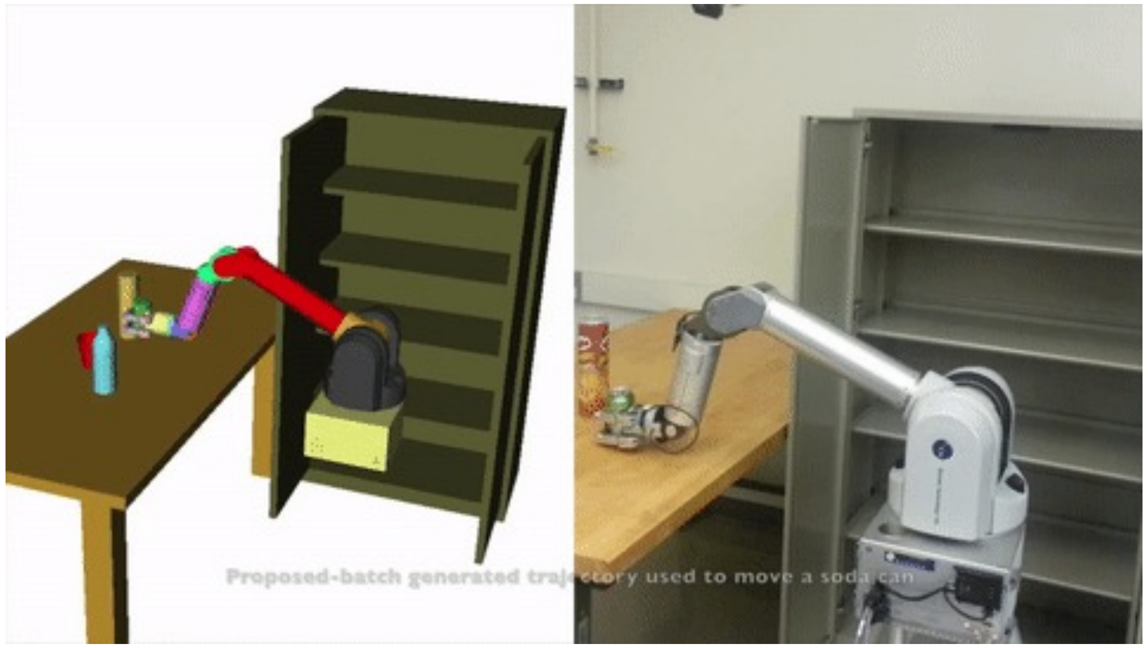


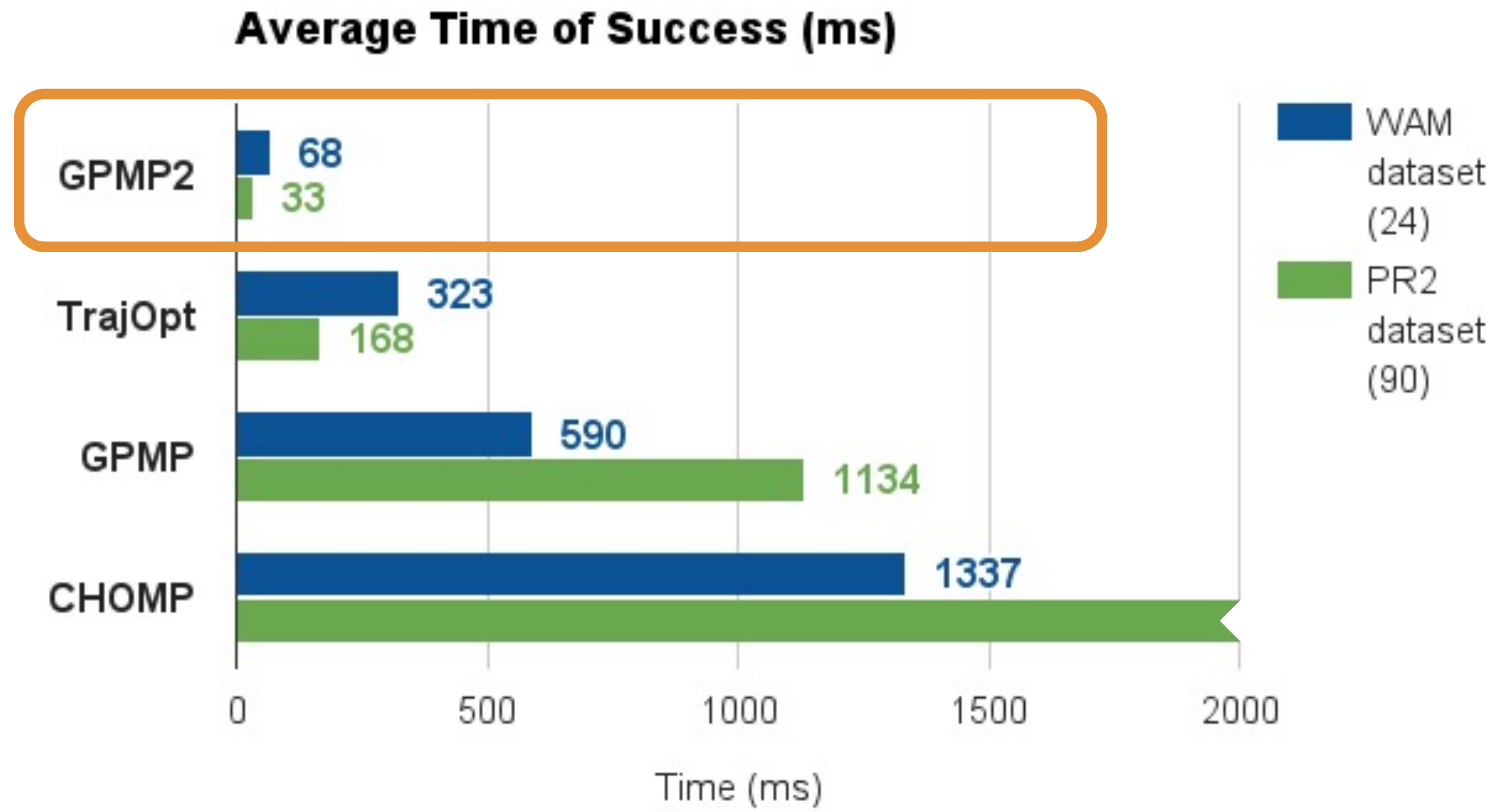
- *Re-planning*: change part of the original problem:
  - Change parts of the factor graph
  - Efficiently update solution via Bayes Tree[2]

[2] Kaess et al. iSAM2: Incremental Smoothing and Mapping Using the Bayes Tree, The *International Journal of Robotics Research* (2011)

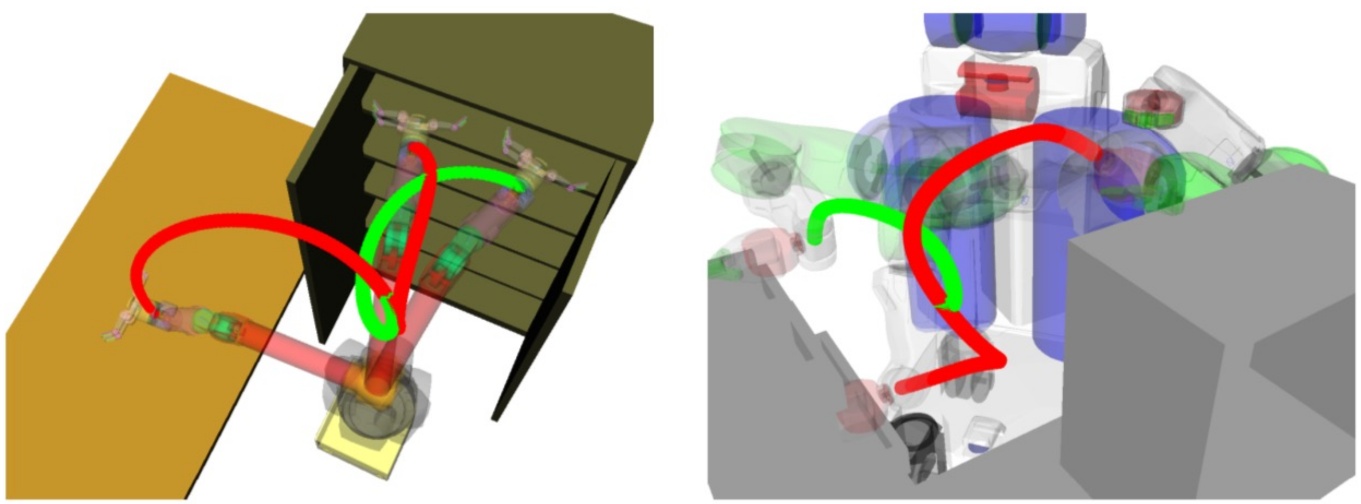
Results

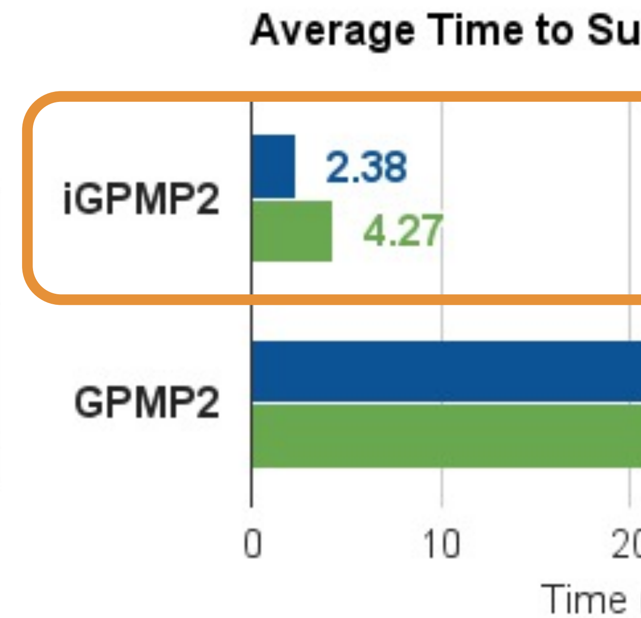
Planning Experiments





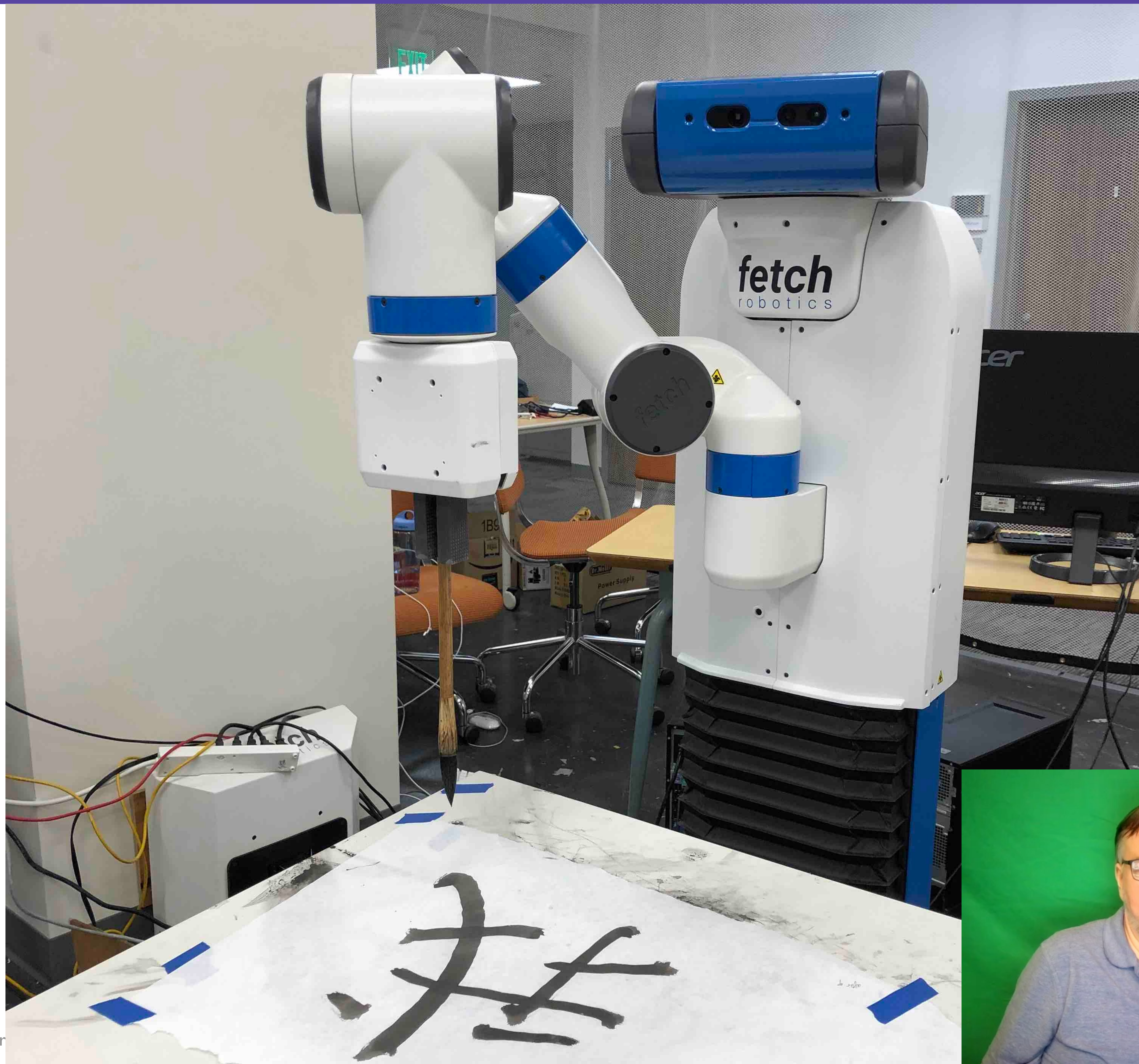
Re-planning Experiments





Application: Robot Calligraphy!

空
乱
思
我



Robot calligraphy

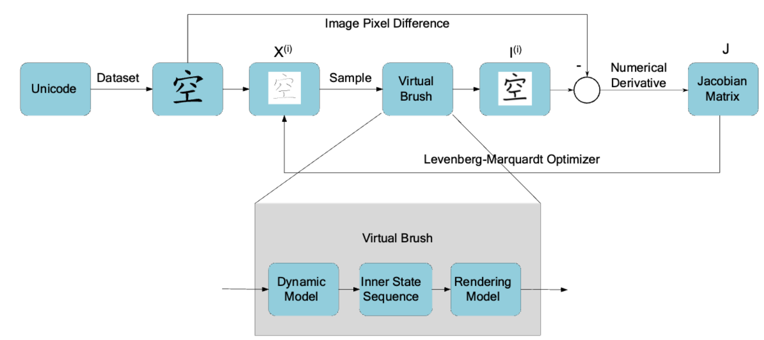
- Calligraphy is beautiful art
- It is also difficult, because it takes human many years of practice to learn
- Controlling the writing brushes successfully would be inspired to many related areas such as robot art and soft robotics

Robot Calligraphy using Pseudospectral Optimal Control in Conjunction with a Novel D
Sen Wang, Jiaqi Chen, Xuanliang Deng, Seth Hutchinson, Frank Dellaert IROS ‘20 https://ar

Methodology

Any character unicode

Input



Trajectory Optimization

Open-loop control

Written results

Dipping Ink

Reasons:

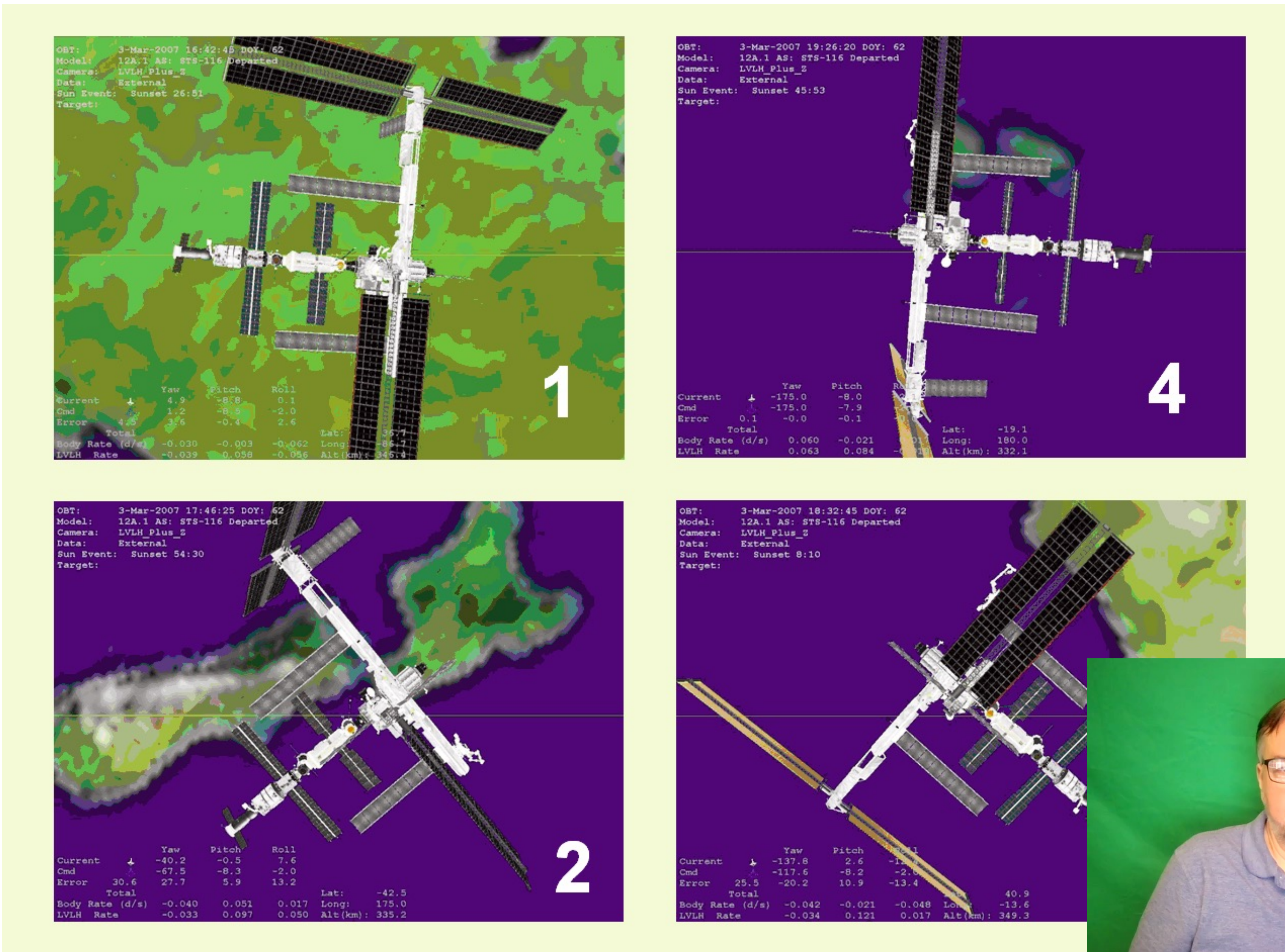
- Supply ink to the brush
- Avoid simulation error accumulate

The basic idea is simple: given a circular ink stone, the brush is pushed down heavily at first to make the tip flat, and we then slowly move it to the edge of the ink stone in different directions with gradually smaller extent.

Dipping ink play speed

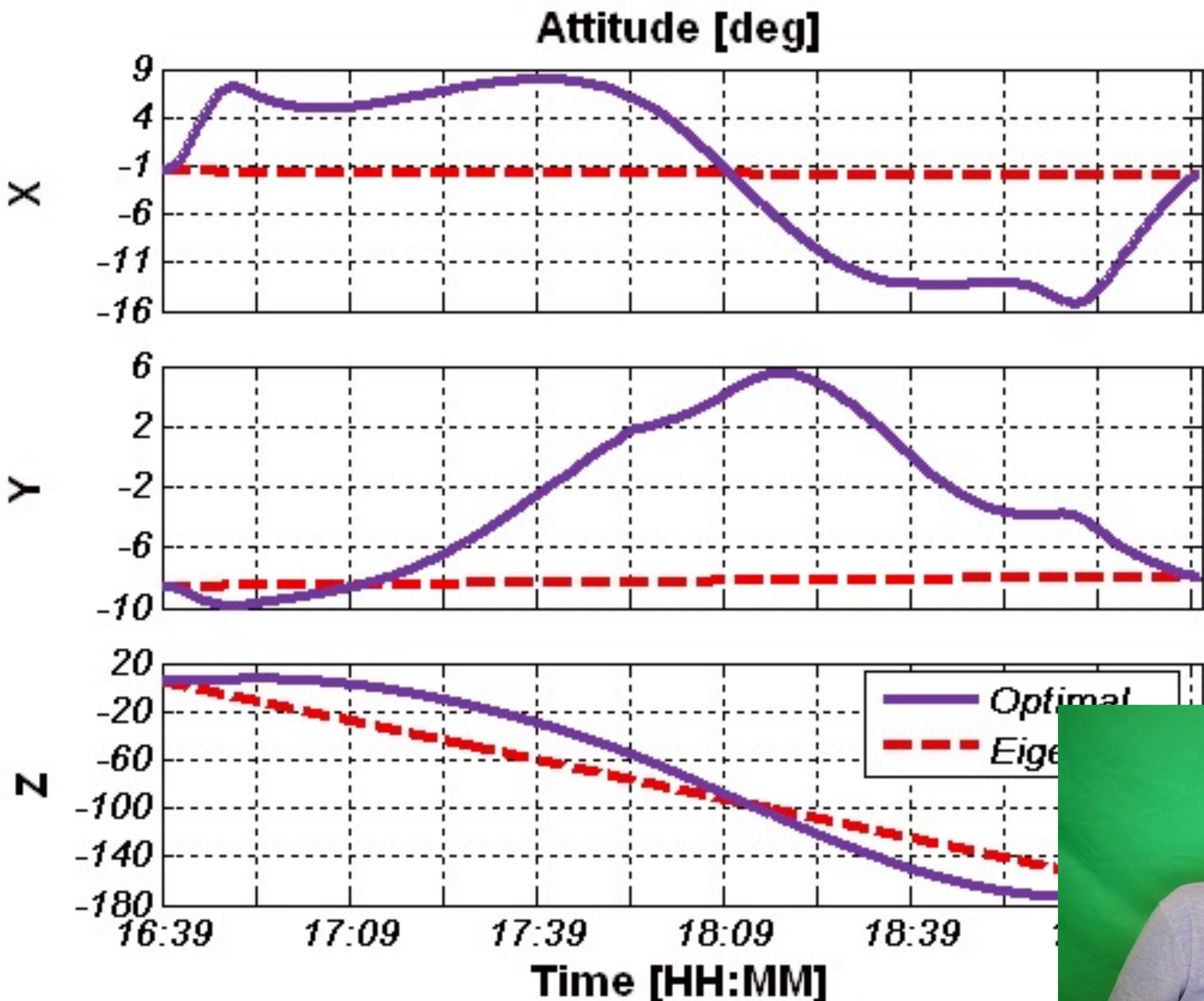
Pseudospectral Optimal Control

- Save NASA $1M !

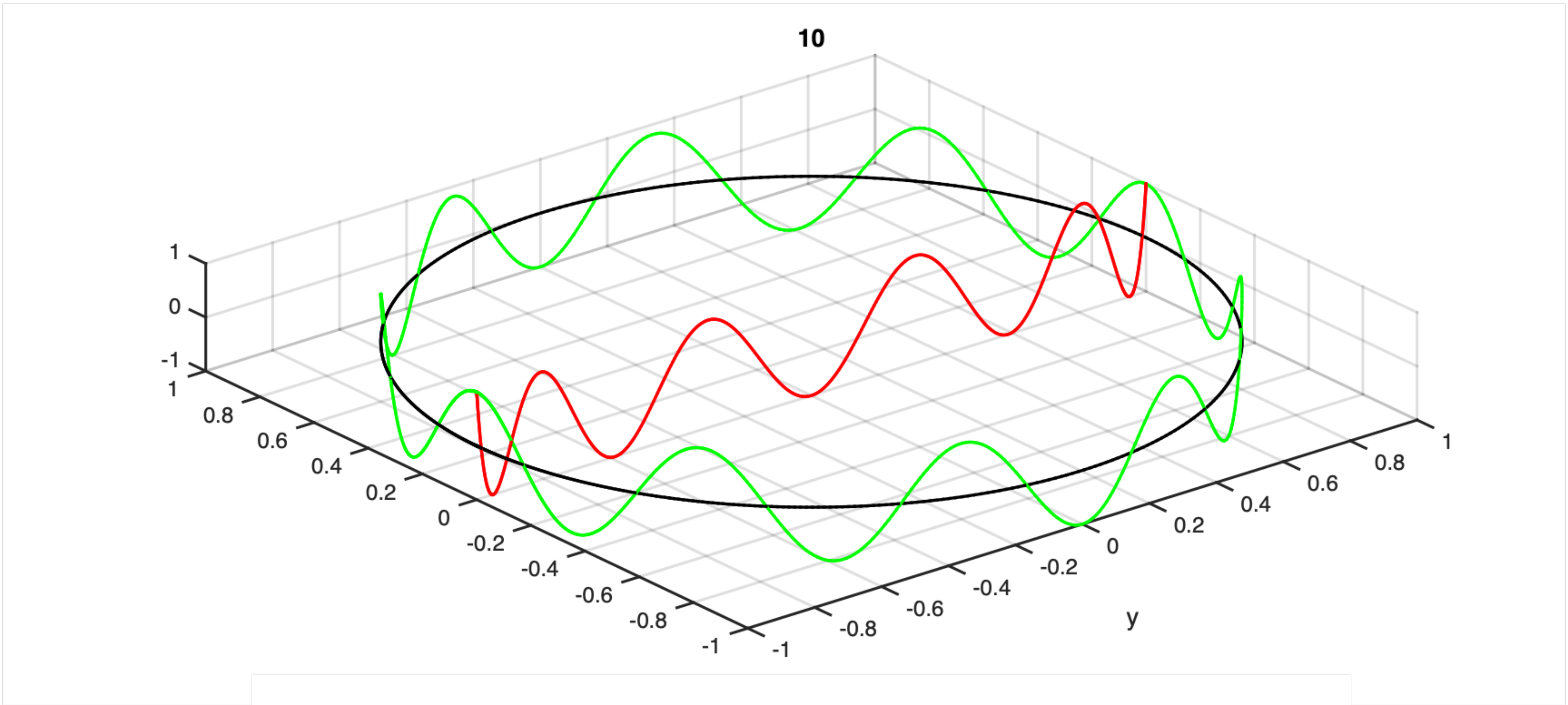


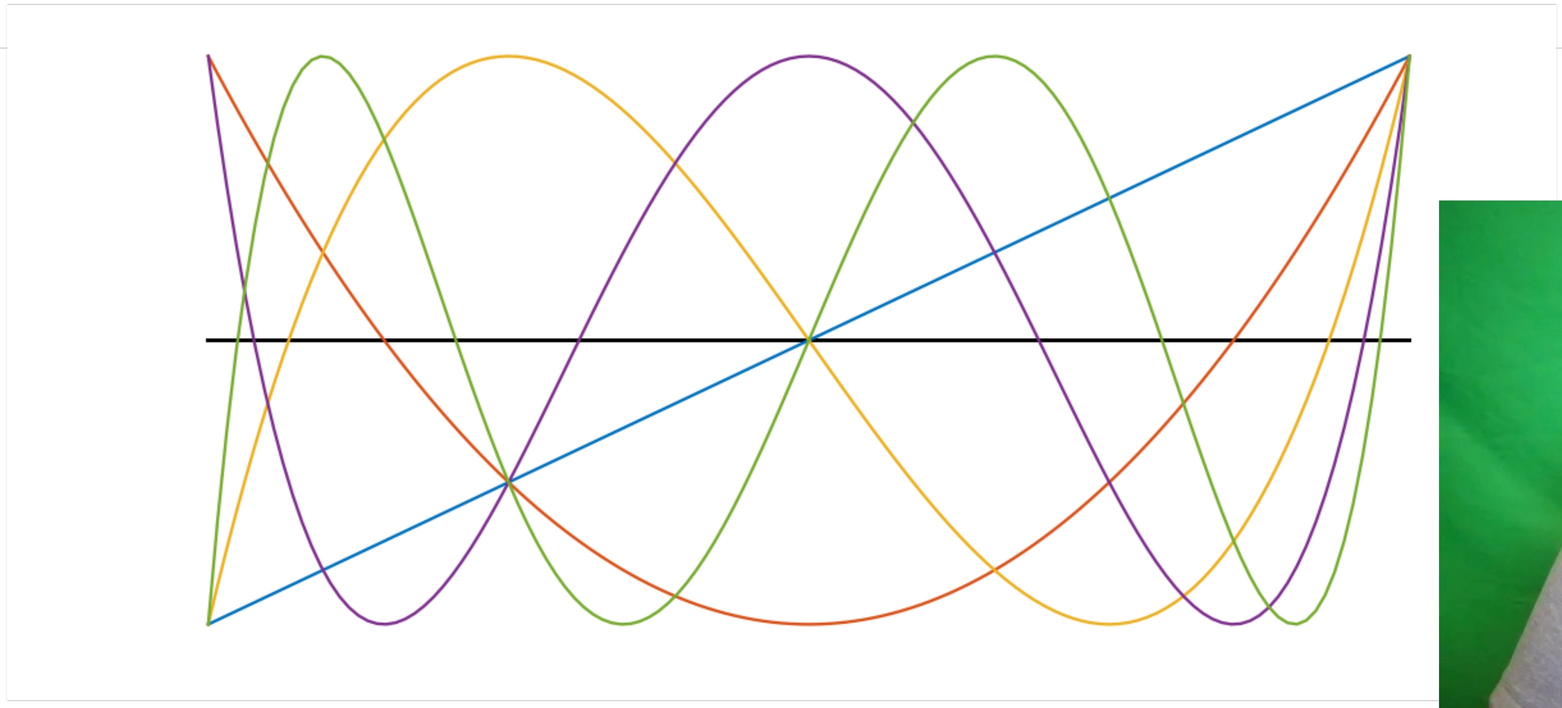
Pseudospectral Optimal Control

- Save NASA $1M !

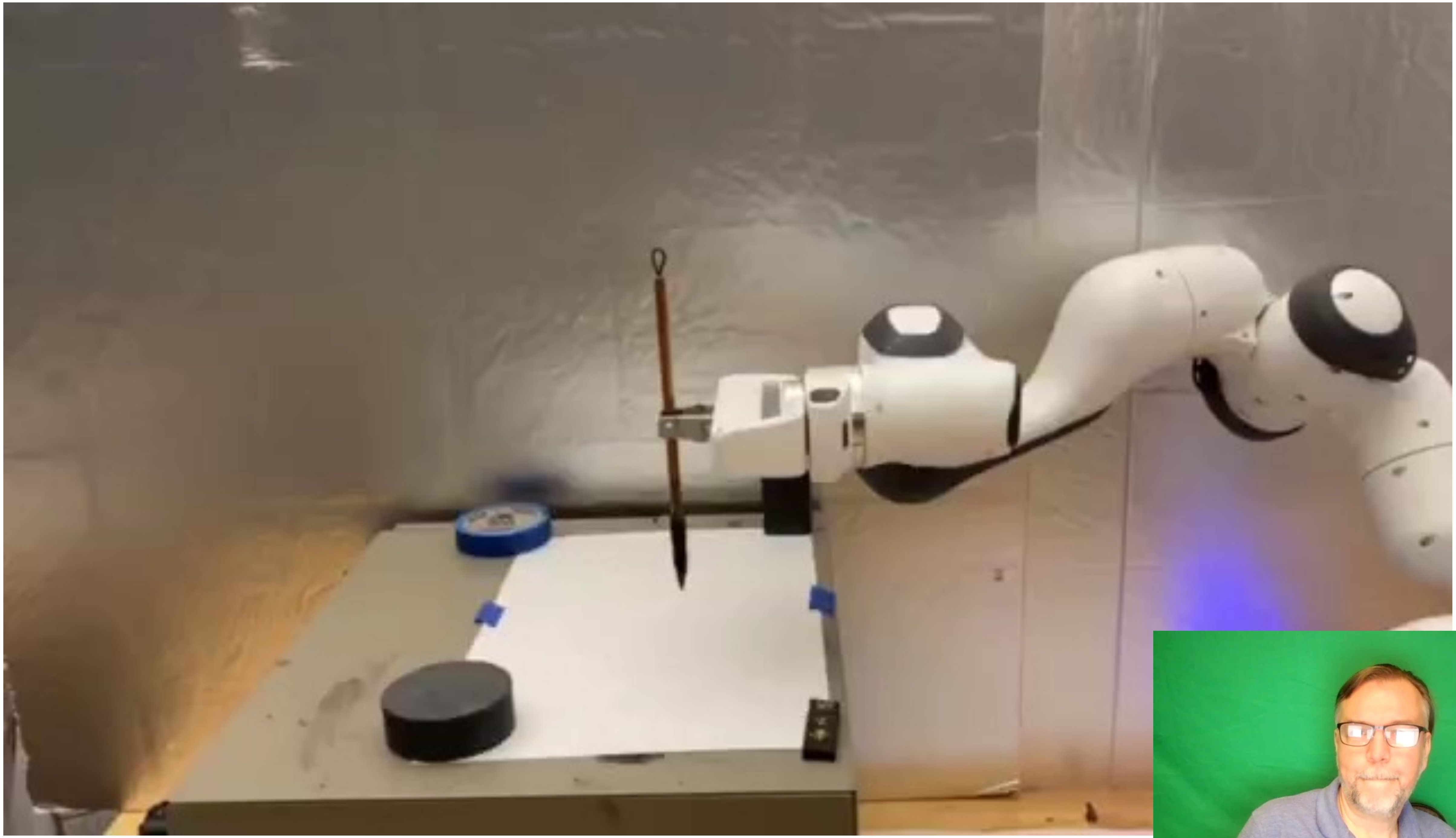


Strokes: Chebyshev polynomials

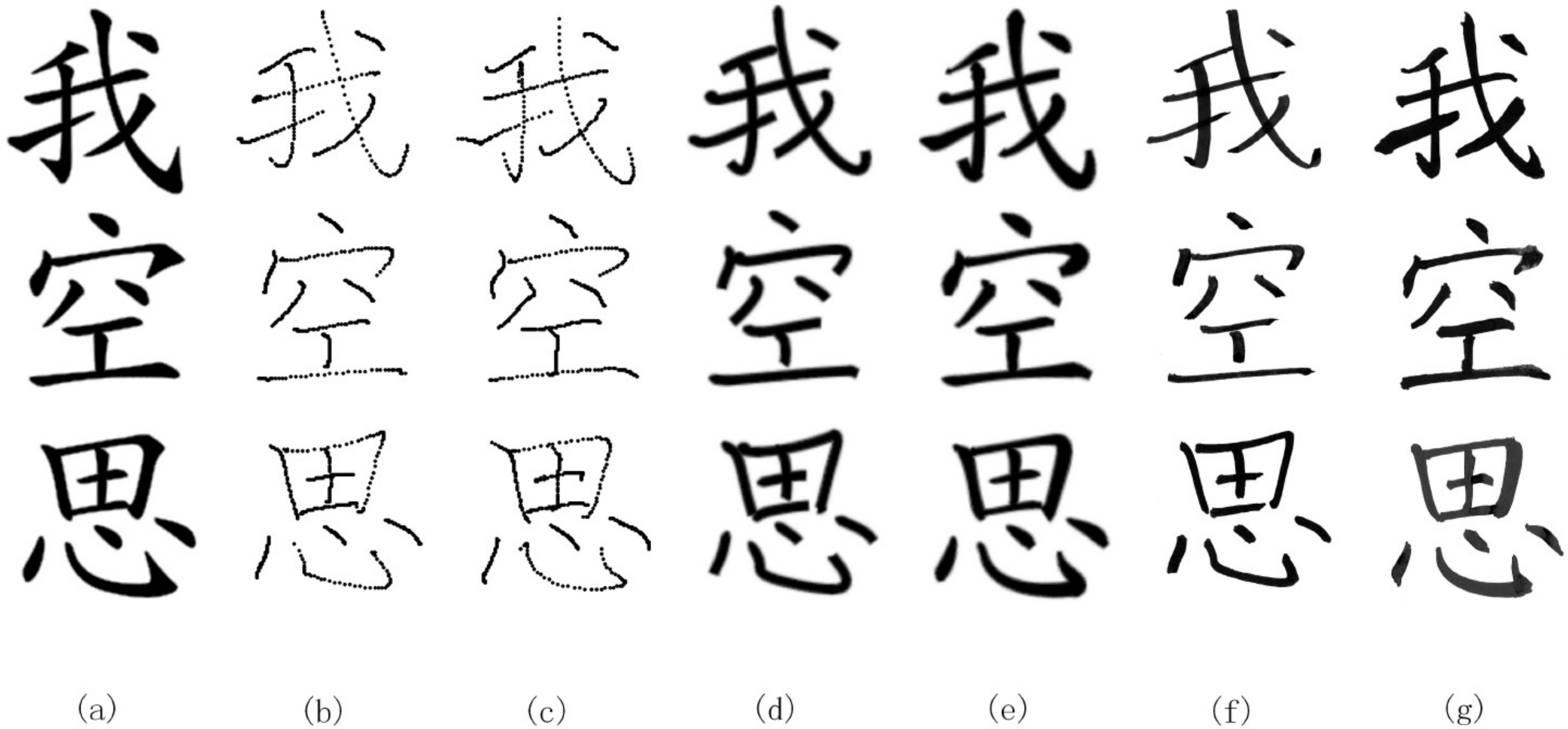




Results



Results



The optimization of different characters: from top down, ‘wo’, ‘kong’, and ‘si’, meaning ‘me’, ‘empty’, and ‘think’. (a) original; (b)
trajectory estimates; (c) Optimized trajectory.

Working on graffiti as well!

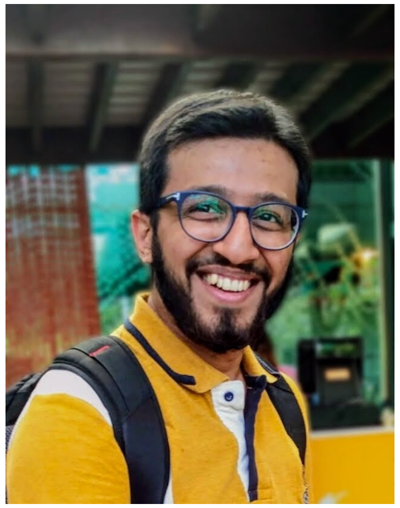
STEAP: Sim. Trajectory Estimation and Planning

Mustafa Mukadam, Jing Dong, Frank Dellaert & Byron Boots

Robotics: Science and Systems, 2017

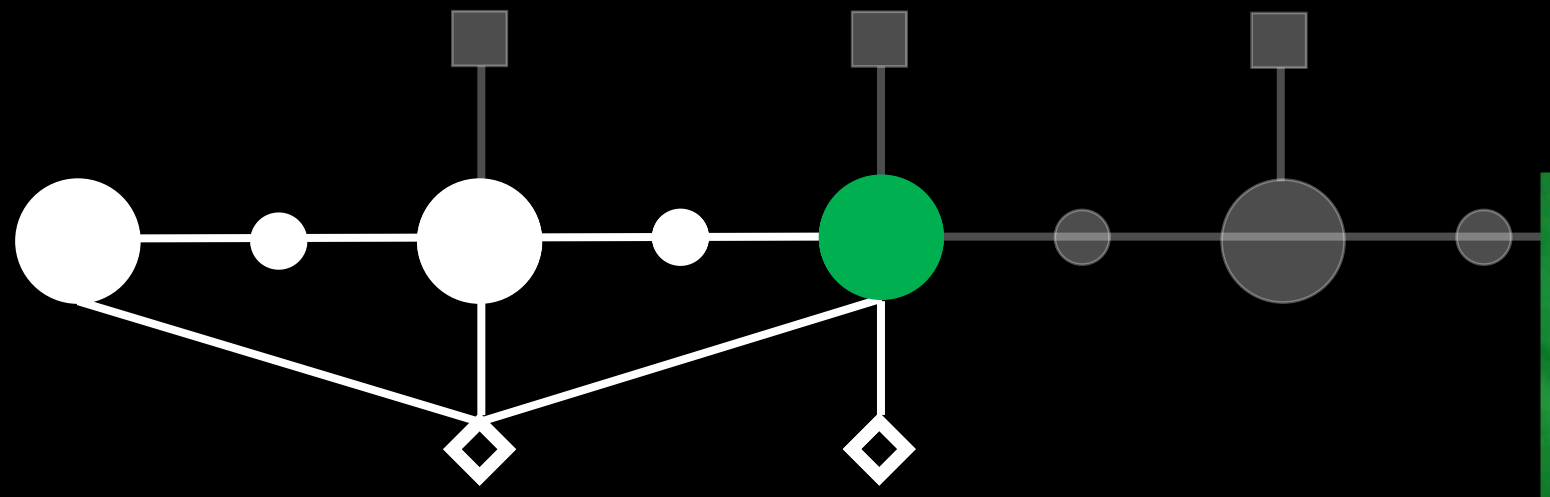
Autonomous Robotics, 2018

SLAM -> STEAP



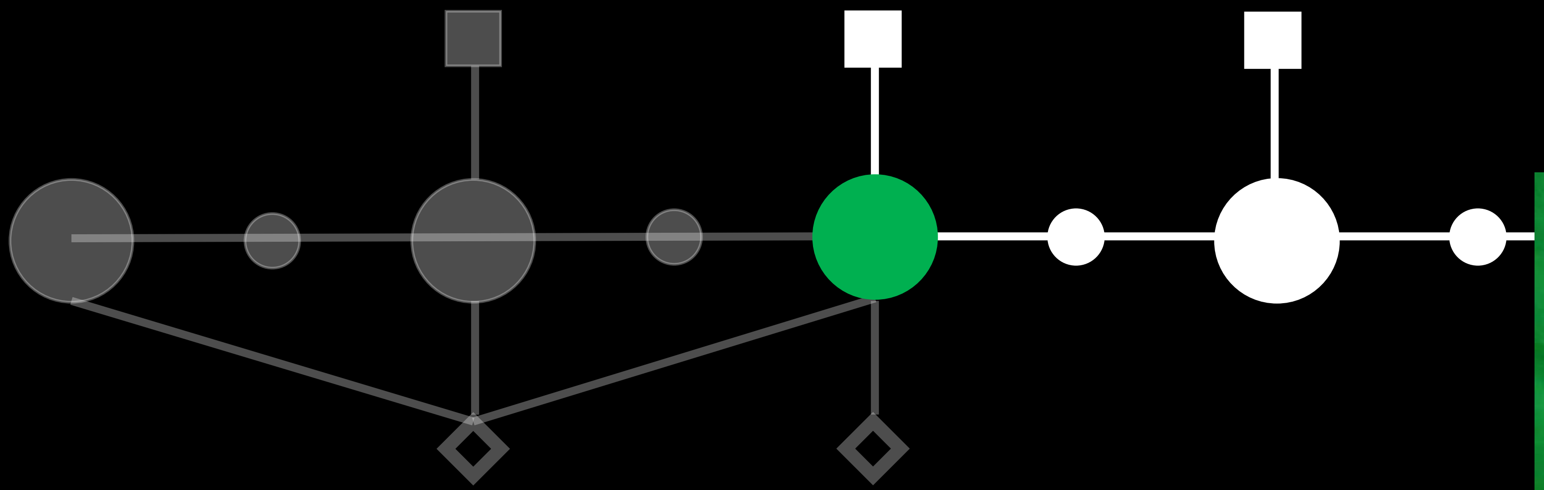
STEAM: Simultaneous Trajectory Estimation and Mapping

Barfoot et al., RSS 2014



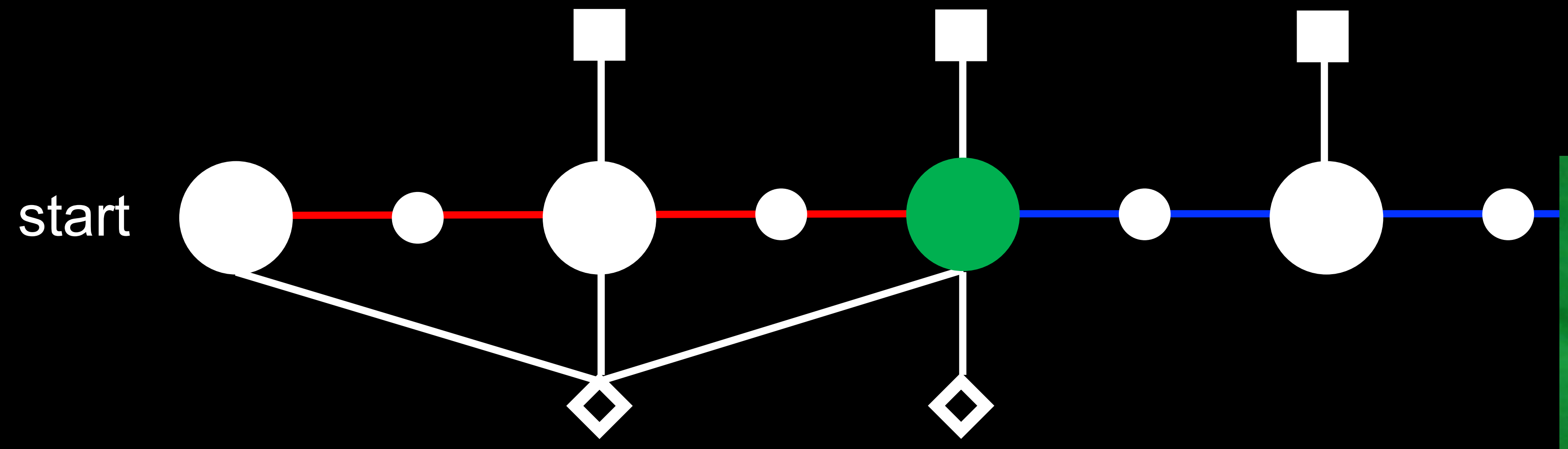
GPMP2: Gaussian Process Motion Planner 2

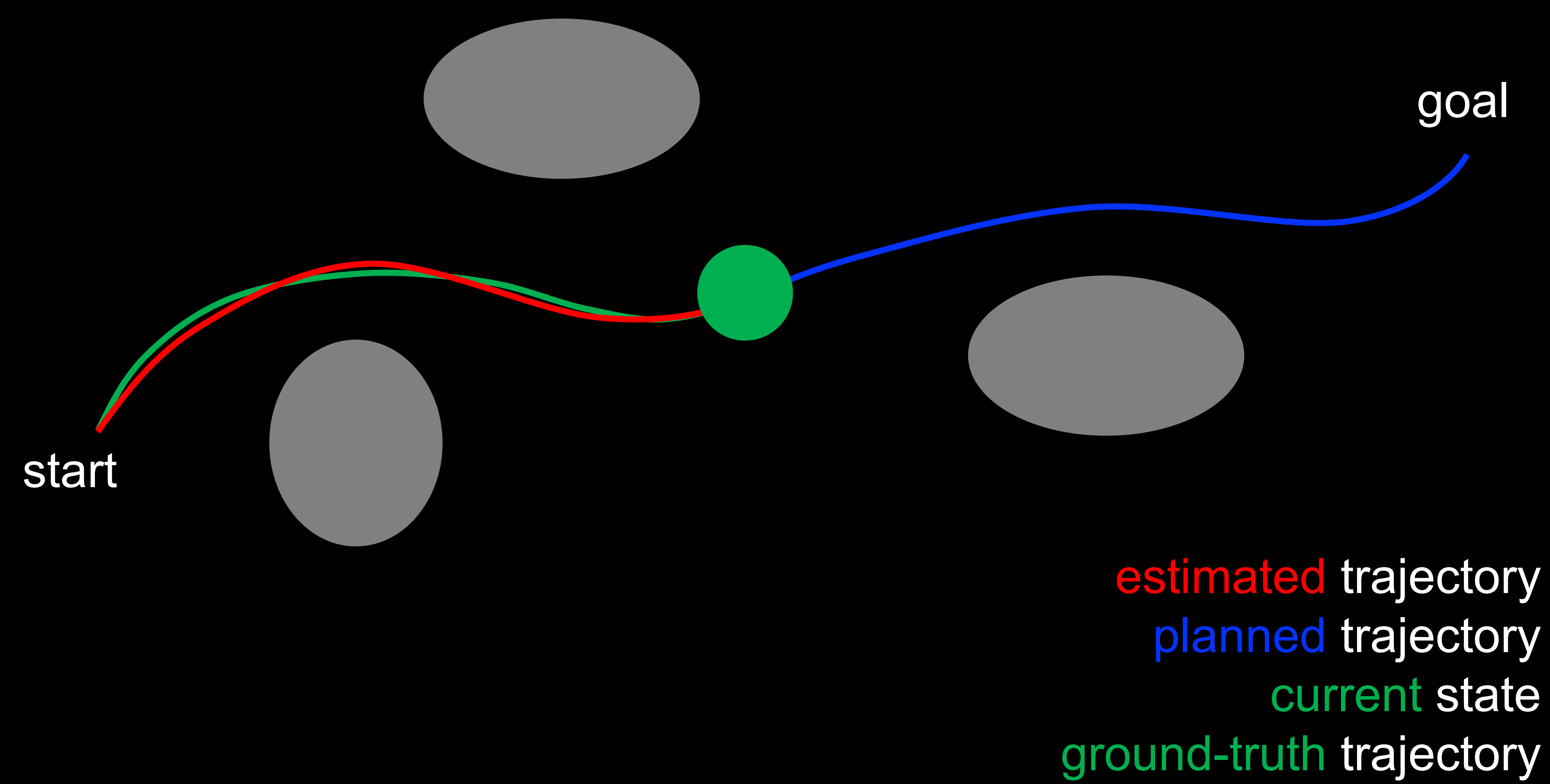
Dong et al., RSS 2016

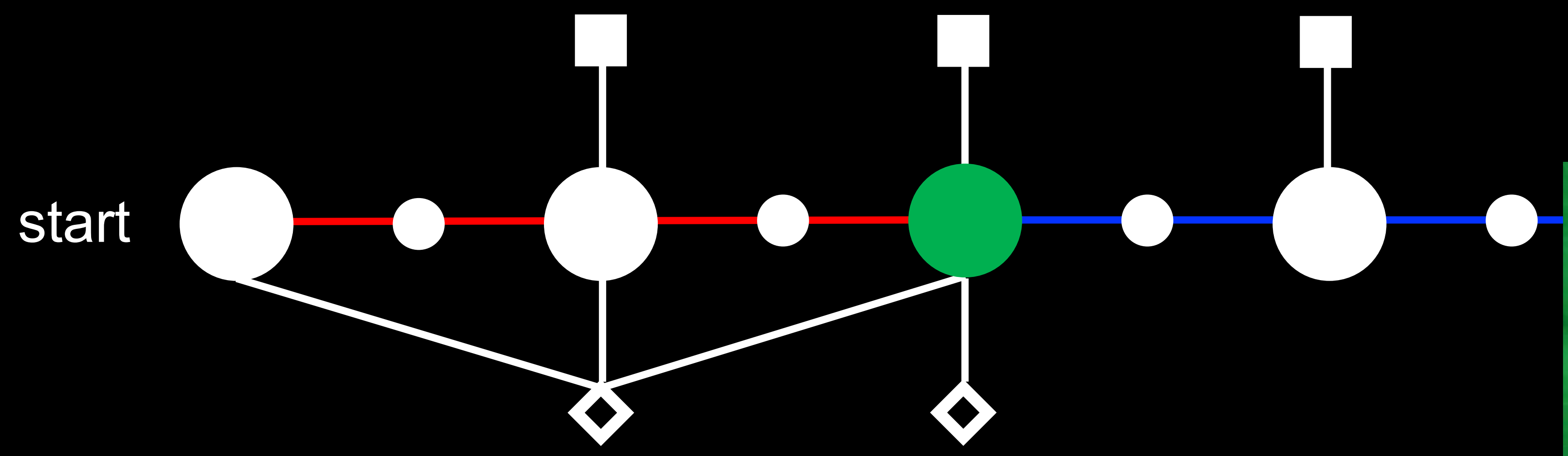


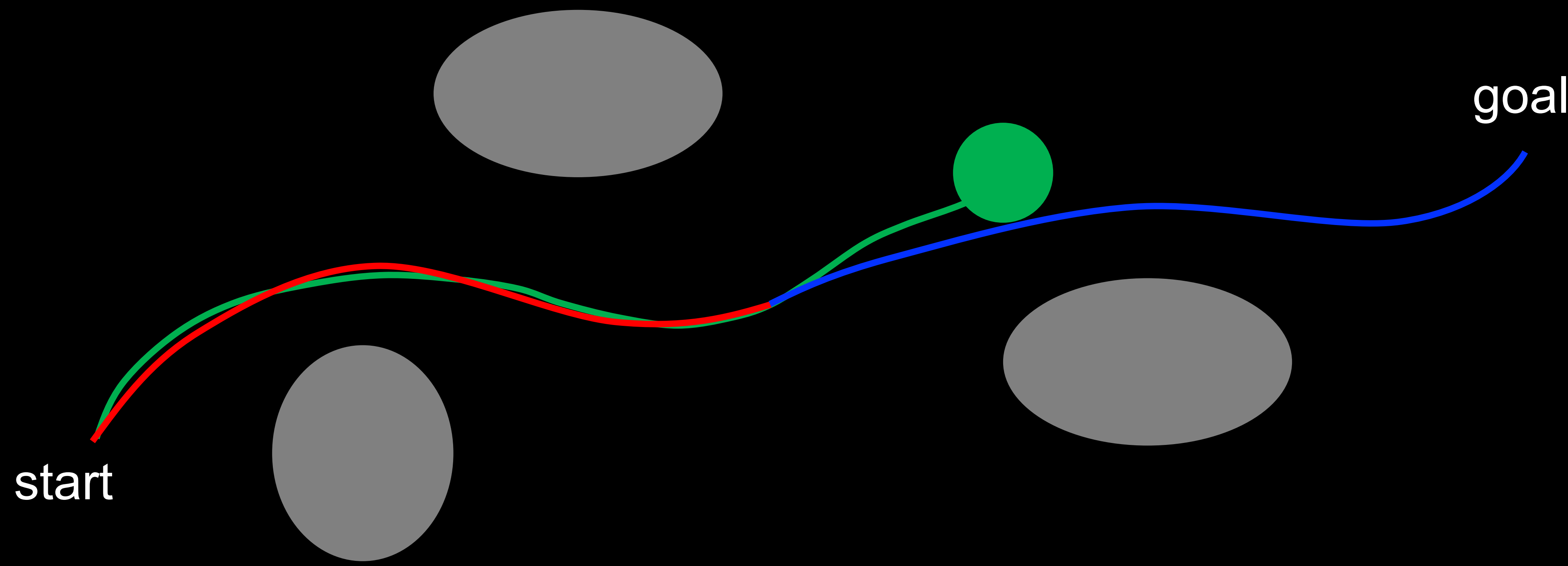
STEAP: Simultaneous Trajectory Estimation and Planning

estimated trajectory
planned trajectory
current state

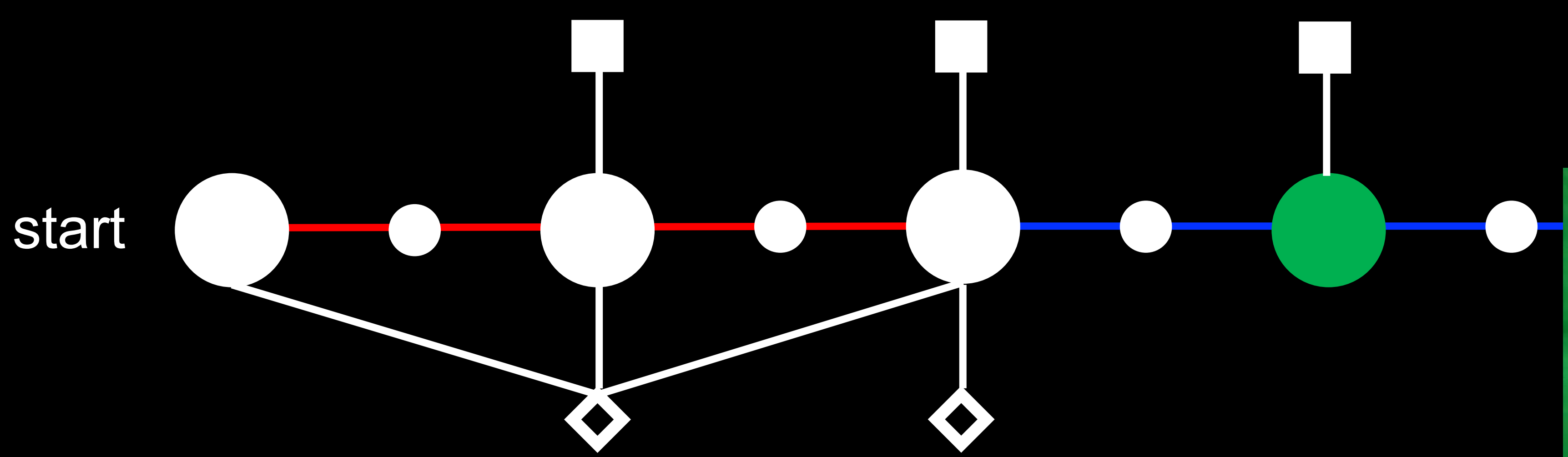


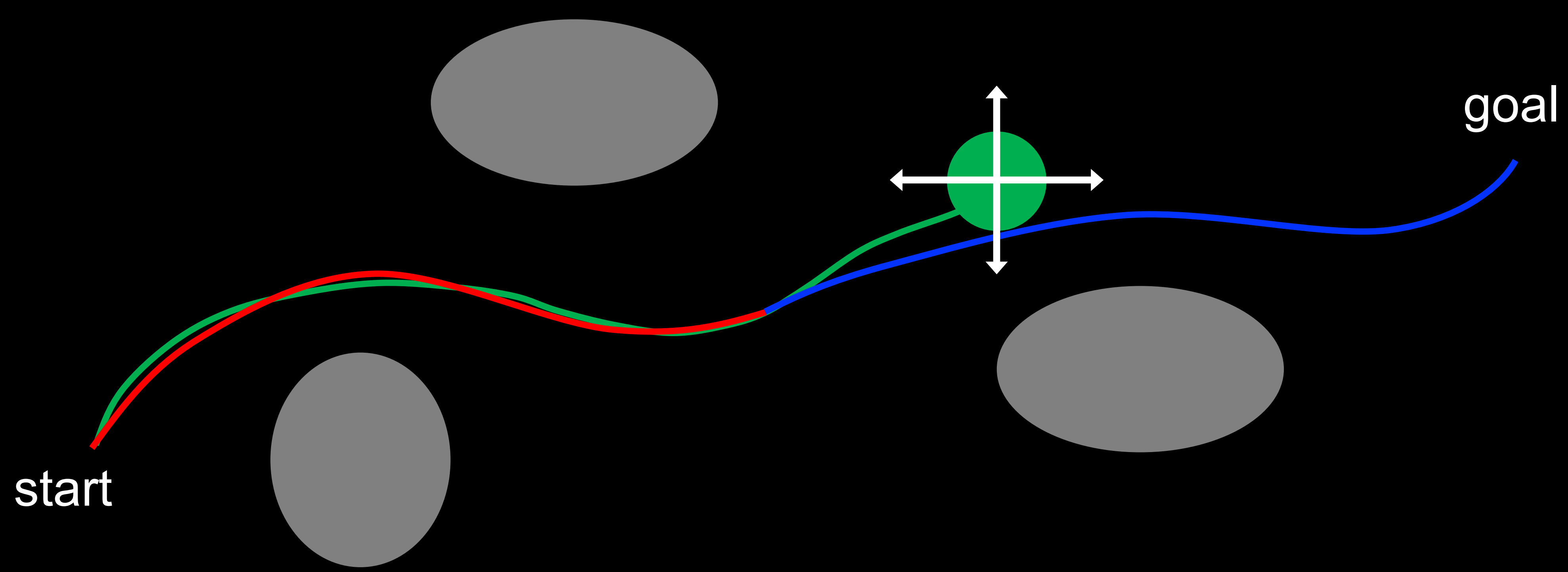

goal
start
estimated trajectory
planned trajectory
current state
ground-truth trajectory


start

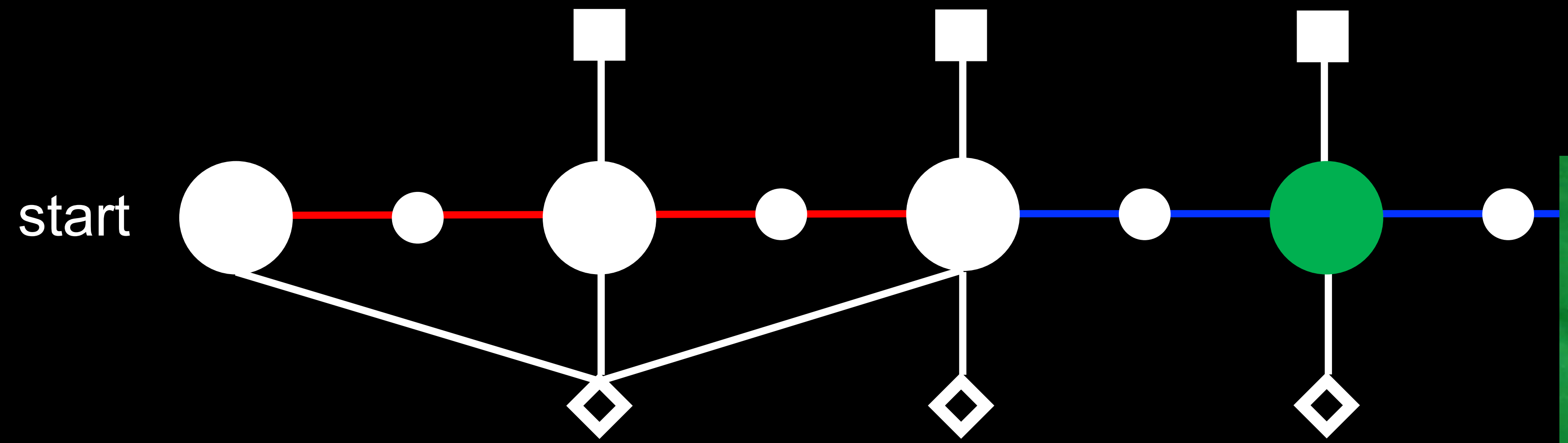


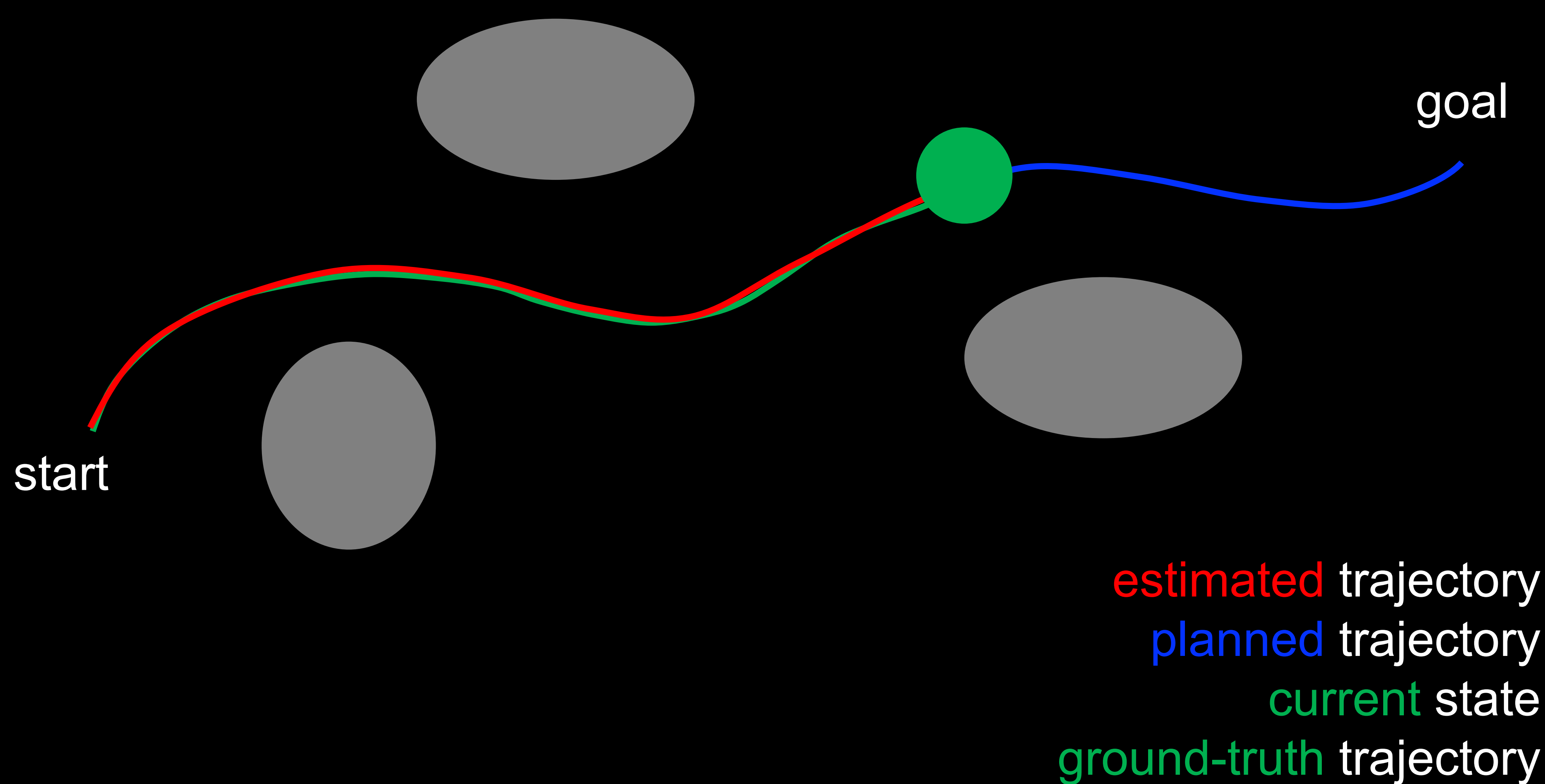
estimated trajectory
planned trajectory
current state
ground-truth trajectory

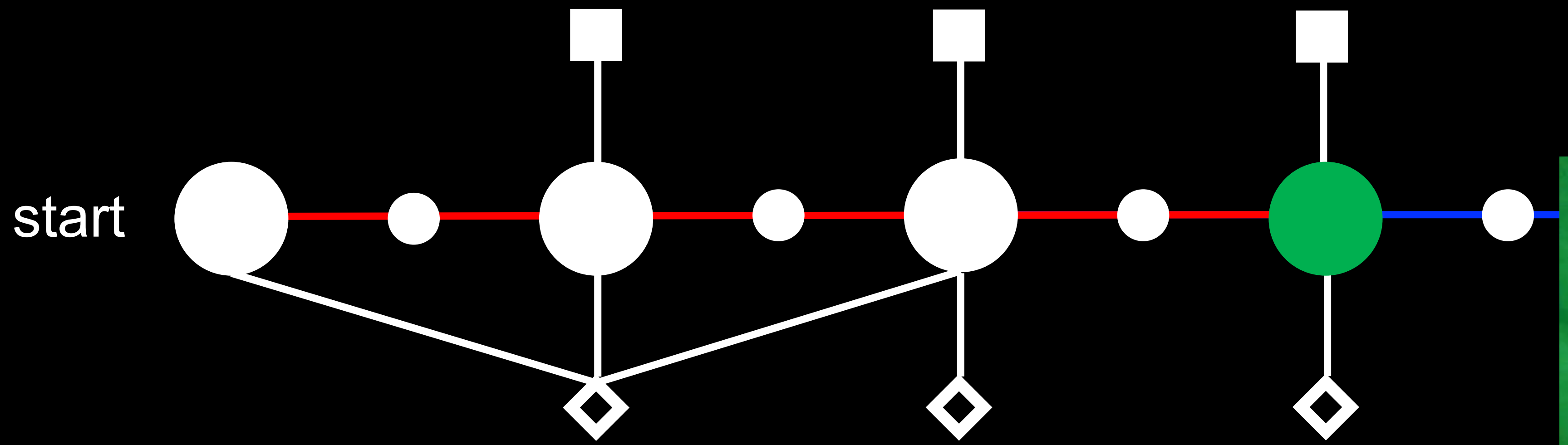


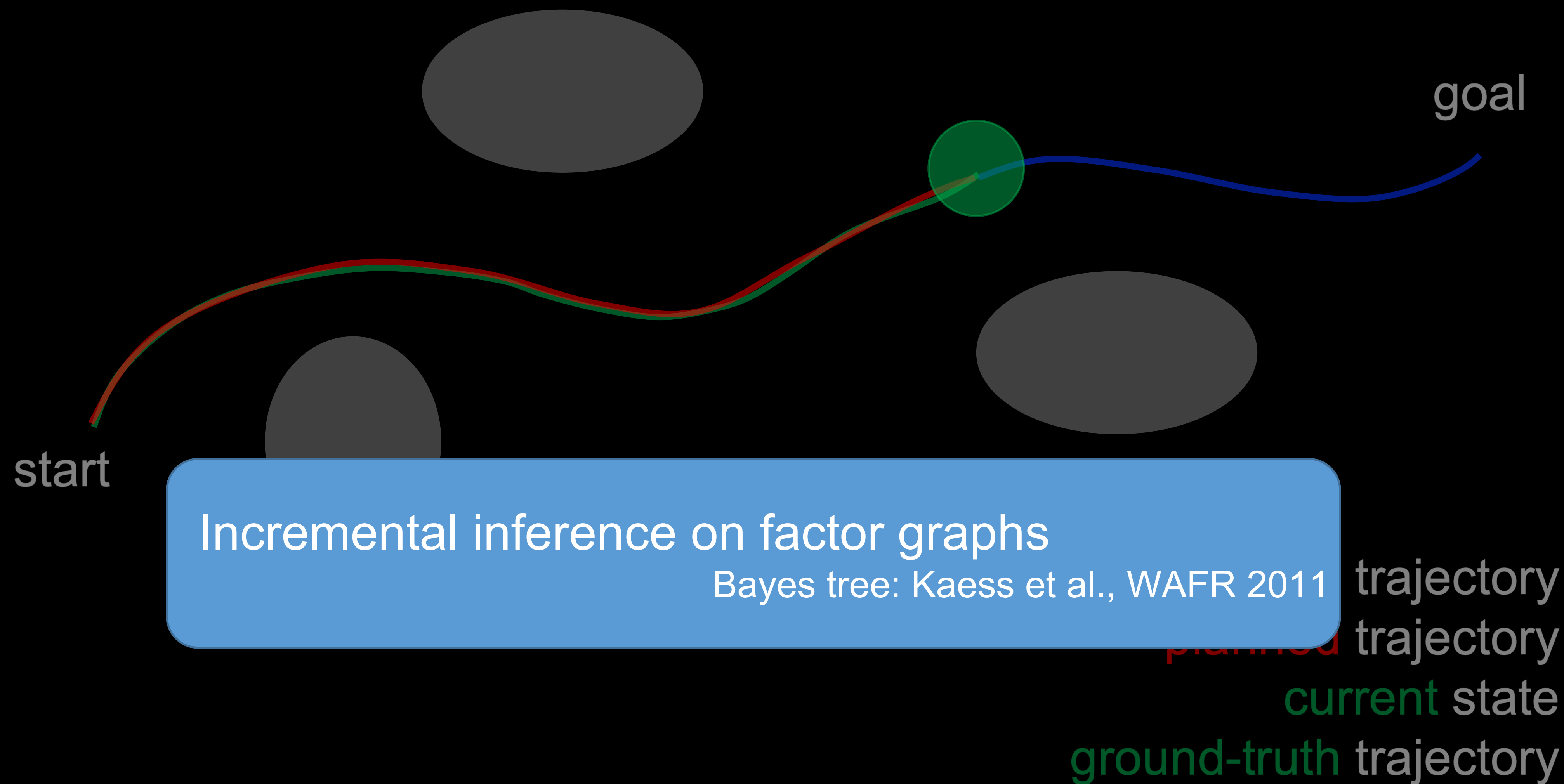


estimated trajectory
planned trajectory
current state
ground-truth trajectory



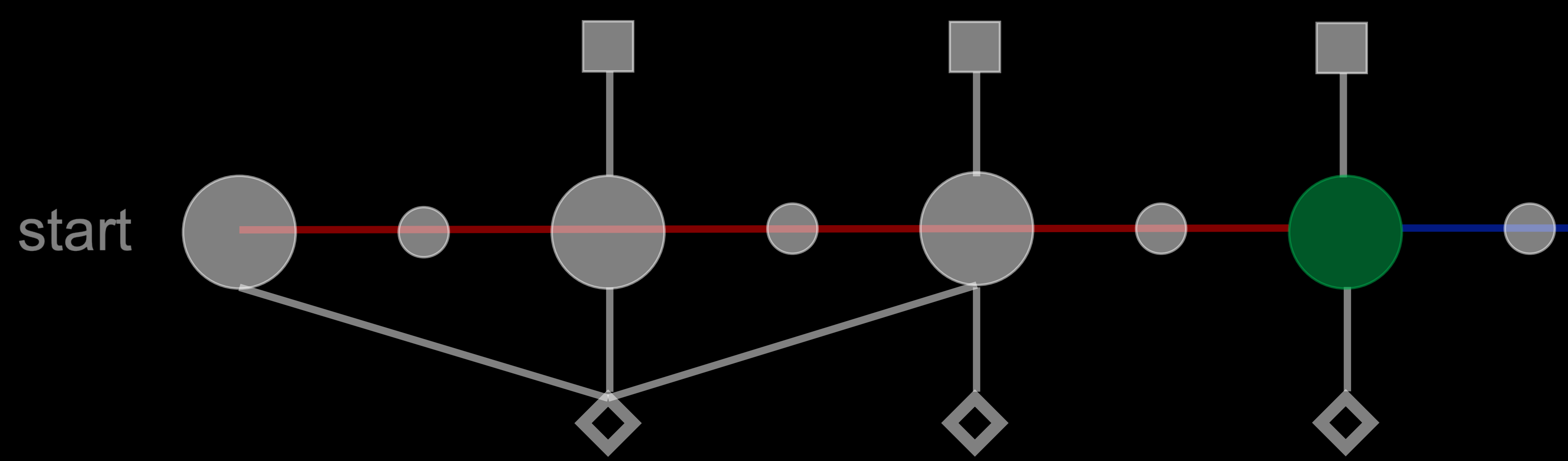

goal
start
estimated trajectory
planned trajectory
current state
ground-truth trajectory

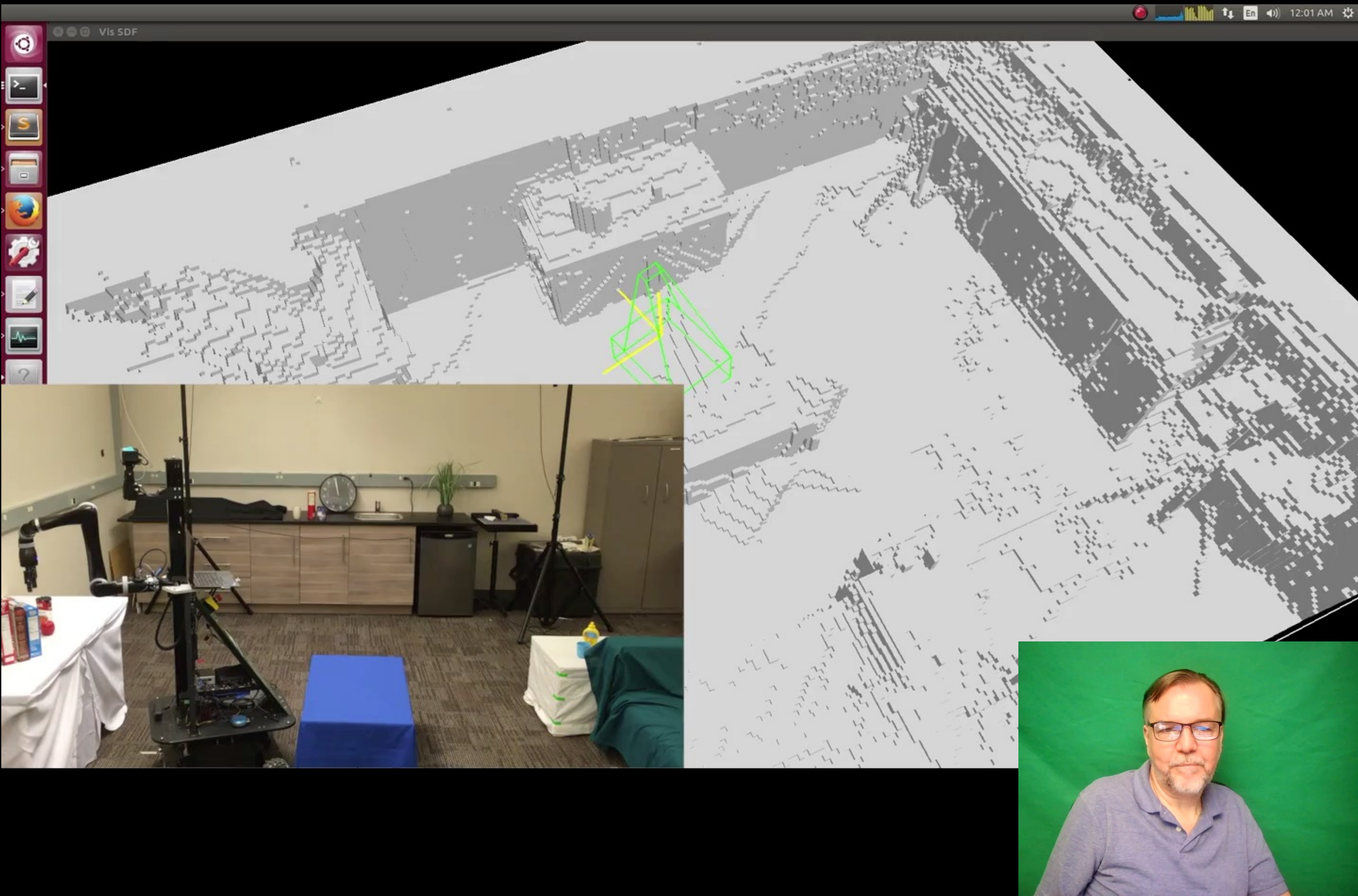

start



Incremental inference on factor graphs

Bayes tree: Kaess et al., WAFR 2011




Vis SDF
En
12:01 AM