Autonomous Robotics

Winter 2025

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Recap: Robotics Spans Applications and Industries

- Applicable in a variety of industries and spaces:
  - Industry:
    - Industrial manufacturing
    - Warehouse navigation
  - Outdoor navigation/locomotion:
    - Legged locomotion
    - Outdoor navigation
    - Last mile delivery
    - Self driving cars
  - Home and office manipulation
    - Mobile manipulation
    - Dexterous manipulation

Industrial Robotics

Industrial Robotics Today

Robots in Warehouses (Kiva@Amazon)

Navigation

DARPA Urban Challenge 2007

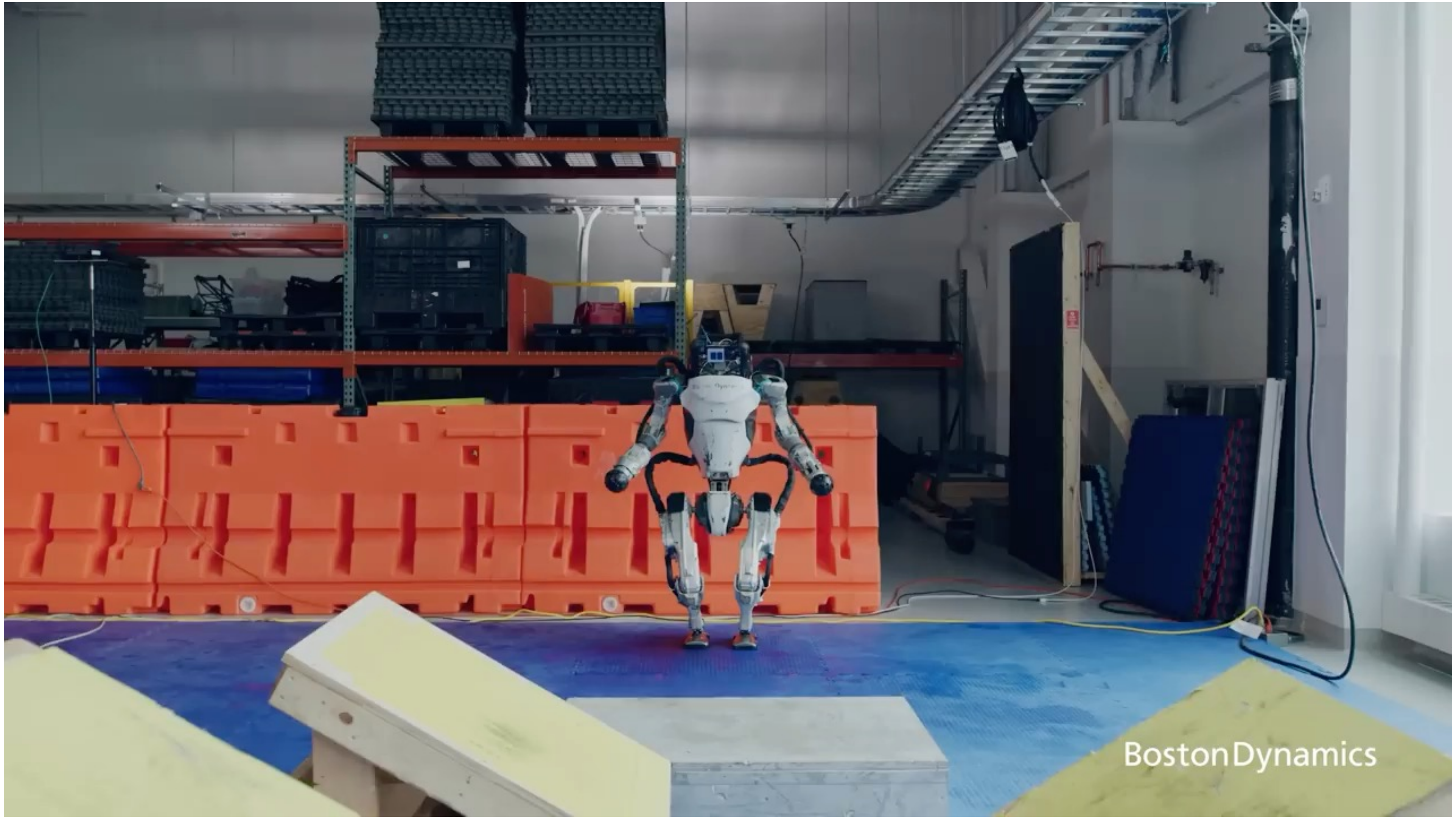
Self-Driving Cars

High-Speed Drone Navigation

Locomotion

Boston Dynamics BigDog (2008)

Humanoid Parkour



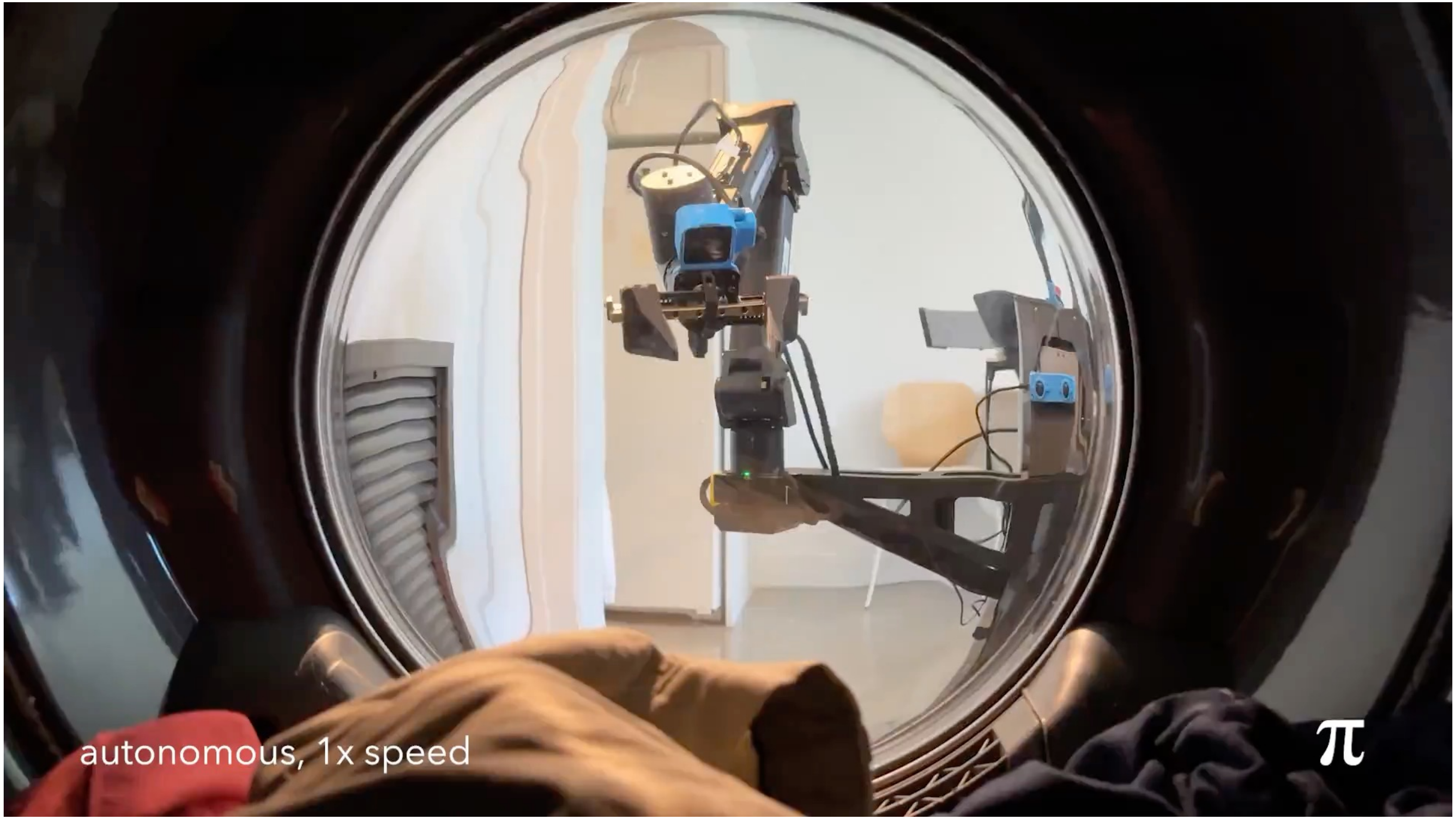
Outdoor Locomotion

Manipulation

Dexterous Manipulation

Mobile Manipulation

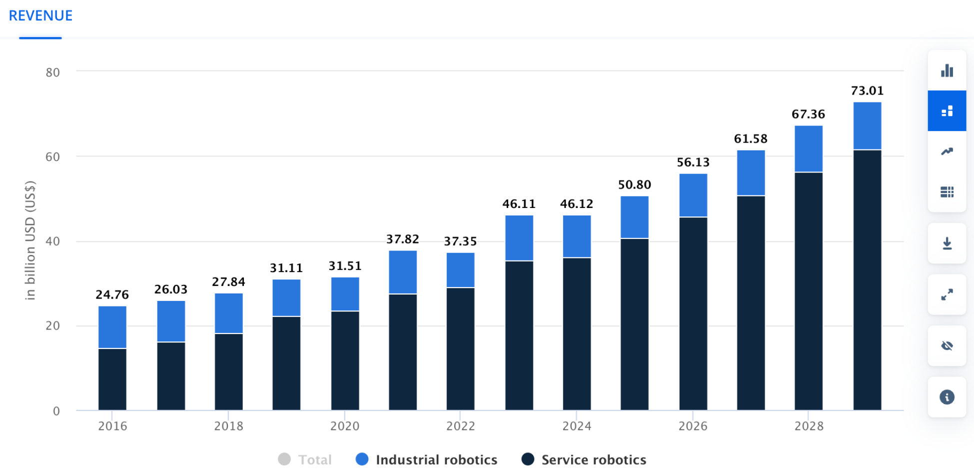
Bimanual Manipulation with Foundation Models



Why should we care about robotics?

Societal Impact

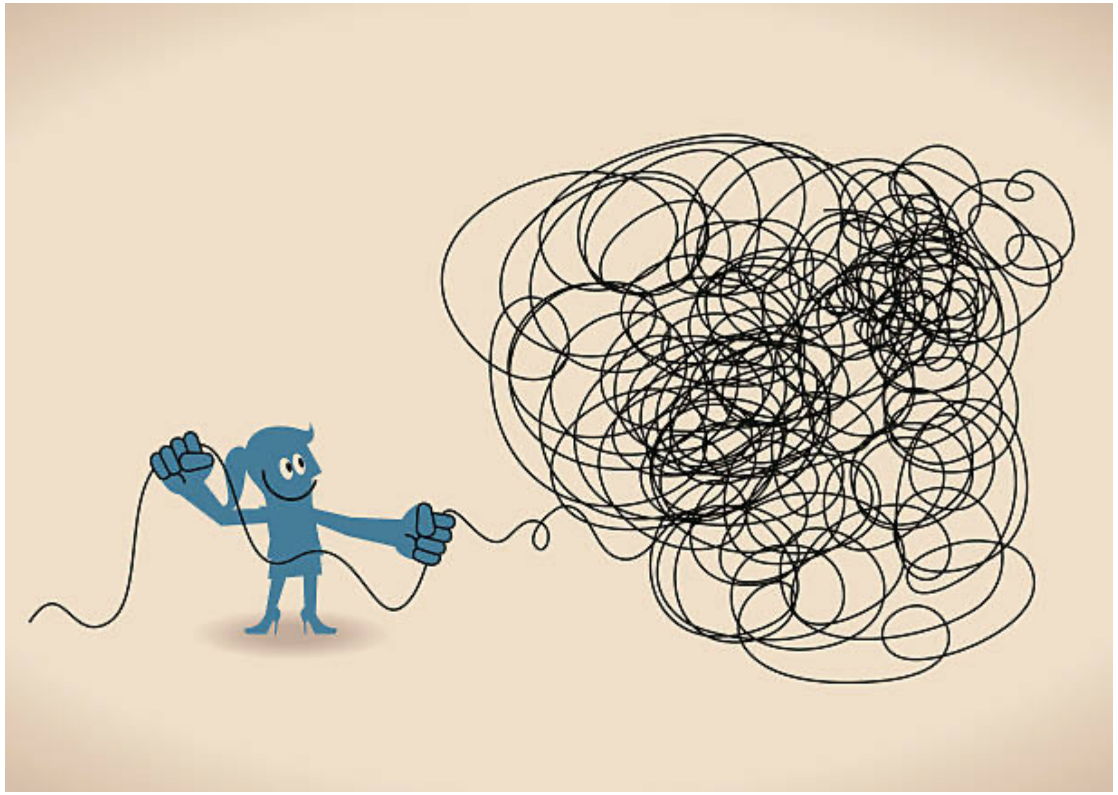
$$



Not solved yet!

Ok this is great – how do we build these robots?

- Need a formal framework for problem definition and a set of tools to solve them



- Sense-plan-act framework with probabilistic inference!

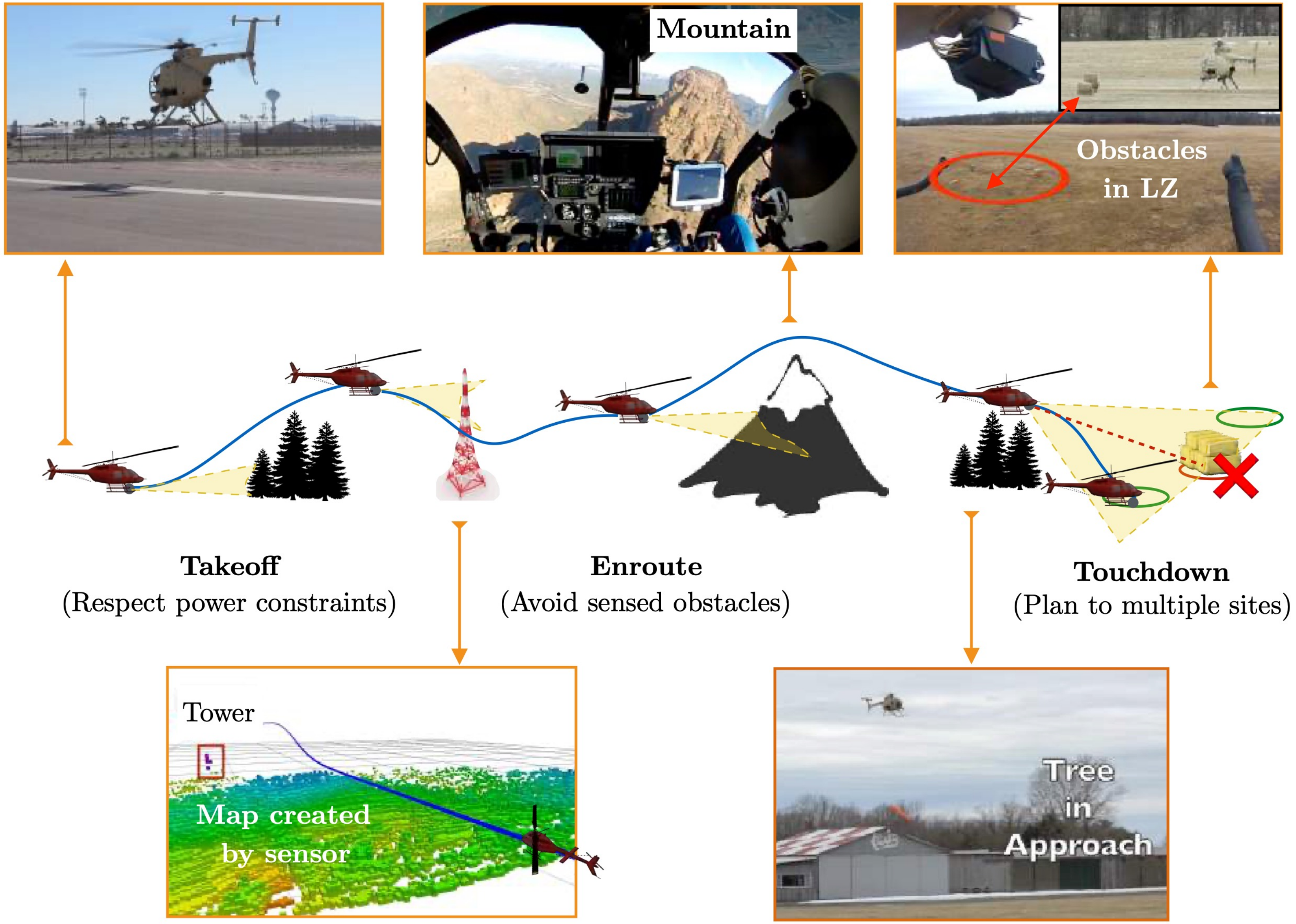
What are we going to talk about today?

- Work through a robotic design process
  - Learn how to think about the design of mobile robot systems
  - Work through the steps for a mobile helicopter
  - Start thinking about how to do this for a car!

Anatomy of a flying vehicle

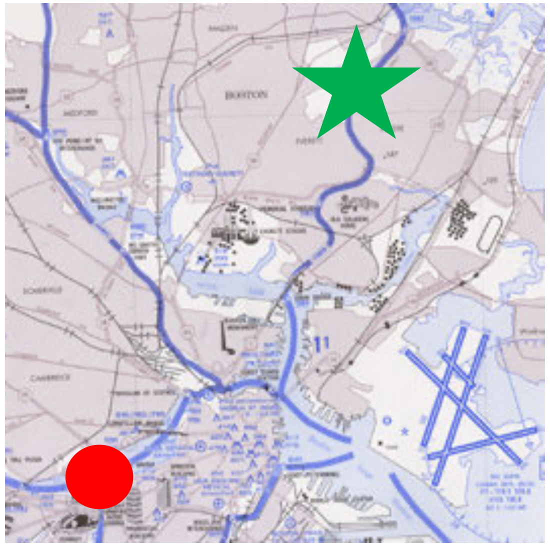
Mission: Takeoff to Landing

Mission


Mountain
Obstacles
in LZ
Takeoff
(Respect power constraints)
Enroute
(Avoid sensed obstacles)
Touchdown
(Plan to multiple sites)
Tower
Map created
by sensor
Tree
in
Approach

Task: Sets of conditions the robot needs to satisfy

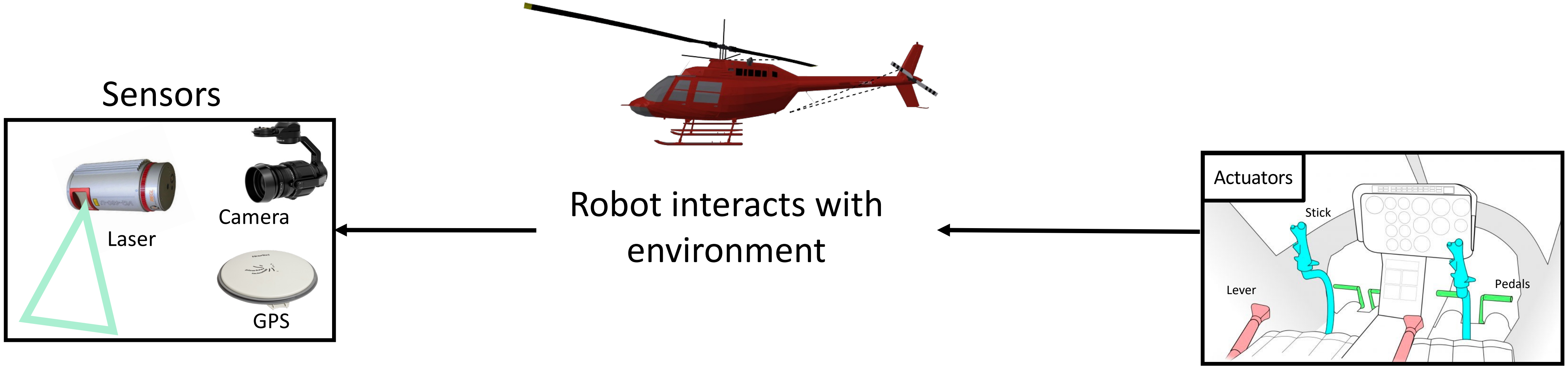
- Given:
  - Start (latitude, longitude), Goal (latitude, longitude)
  - List of no-fly-zones (unsafe air space)
  - Coarse terrain map of continental USA
  - Sensors - GPS, Laser, etc

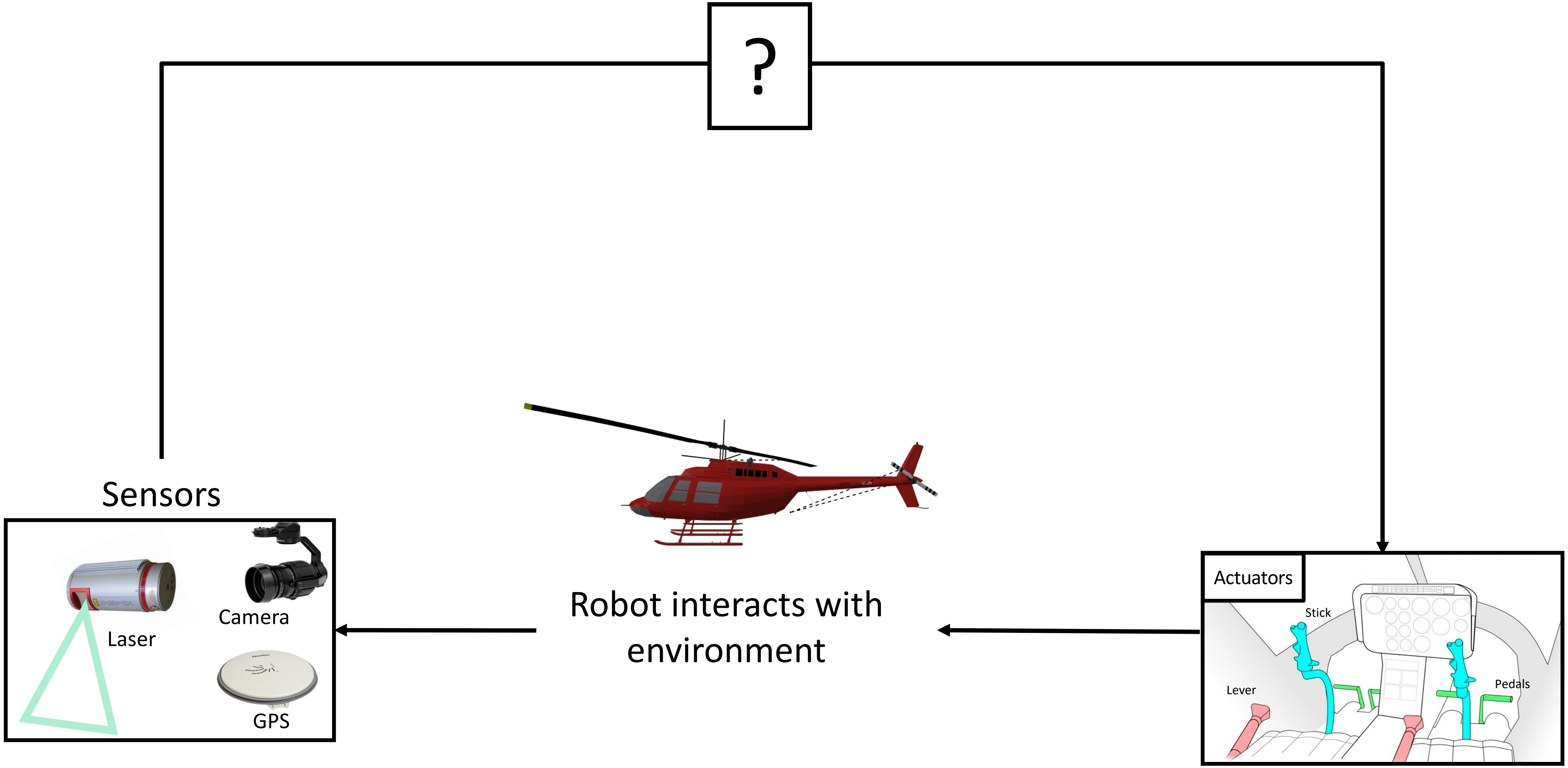


- Objective:
  - **Minimize time** it takes to complete mission
- Constraint:
  - Don’t come close to obstacles / don’t enter no-fly-zones
  - Don’t exceed limits of the vehicle (flying upside down)
  - Don’t run out of fuel!

How do we tractably solve the task?: The model-based way

Begin with a blank slate


Sensors
Laser
Camera
GPS
Robot interacts with
environment
Actuators
Stick
Lever
Pedals


?
Sensors
Laser
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Robot interacts with environment
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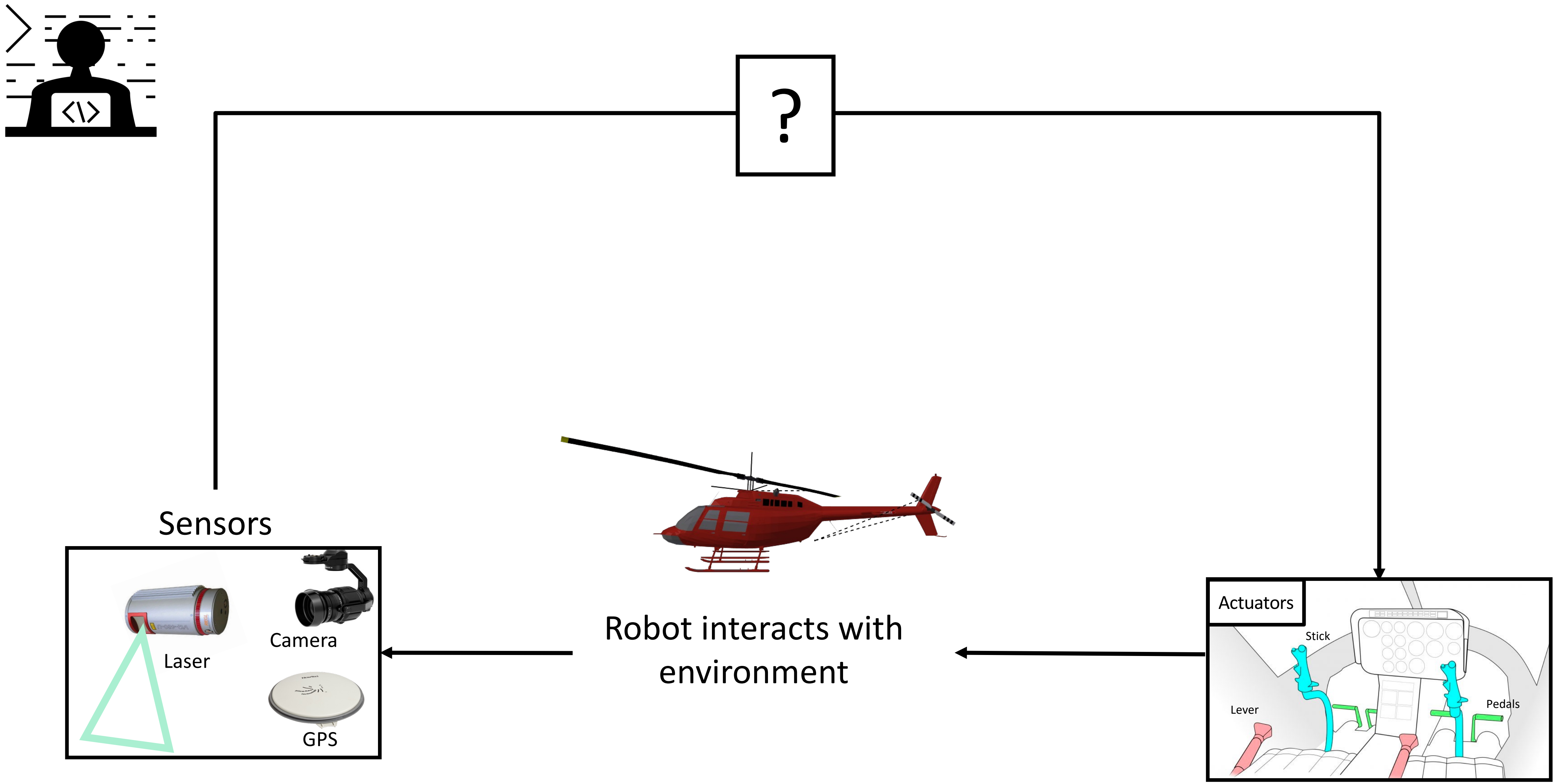
Stick
Lever
Pedals

Let‘s use our knowledge about the world to solve this?



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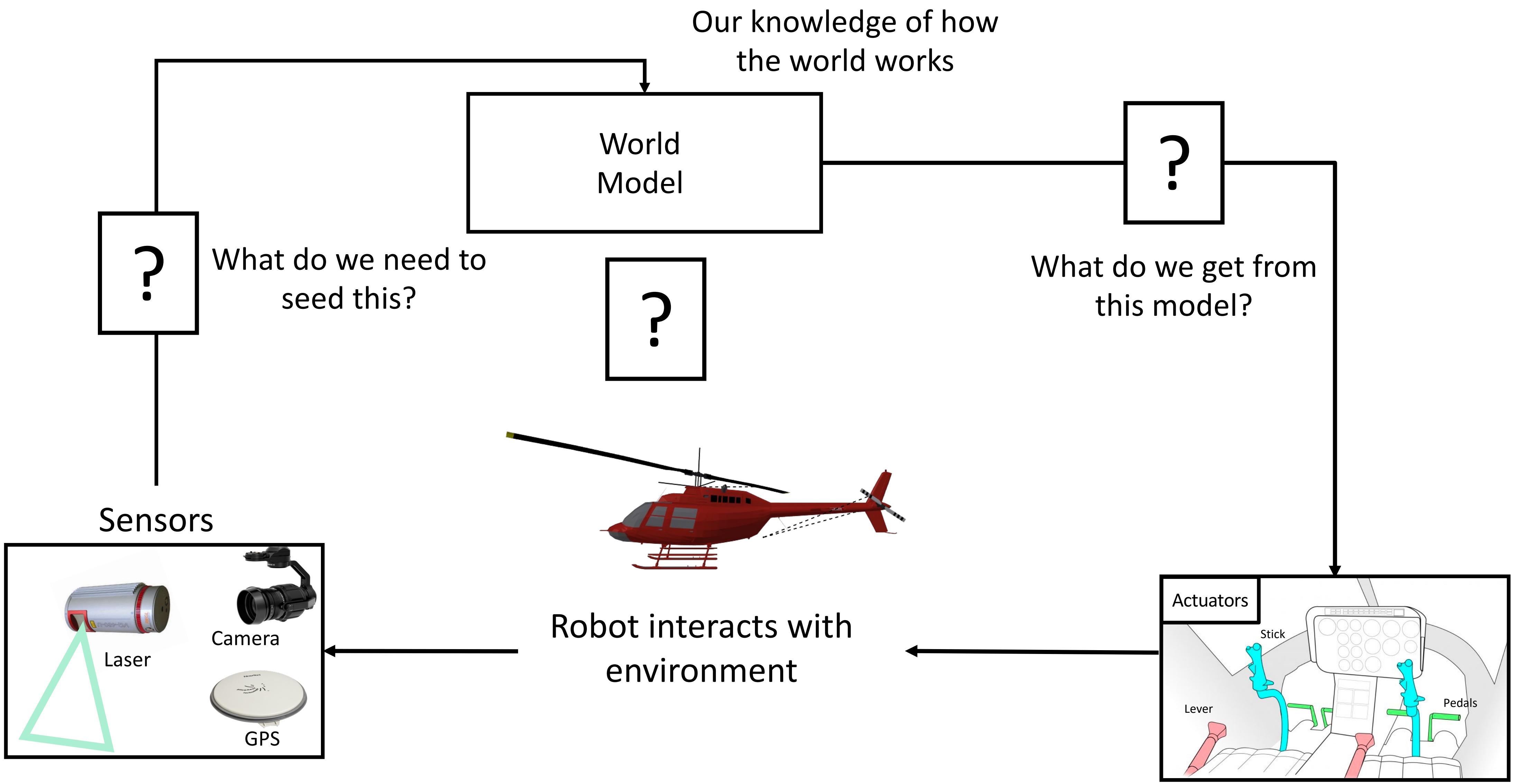

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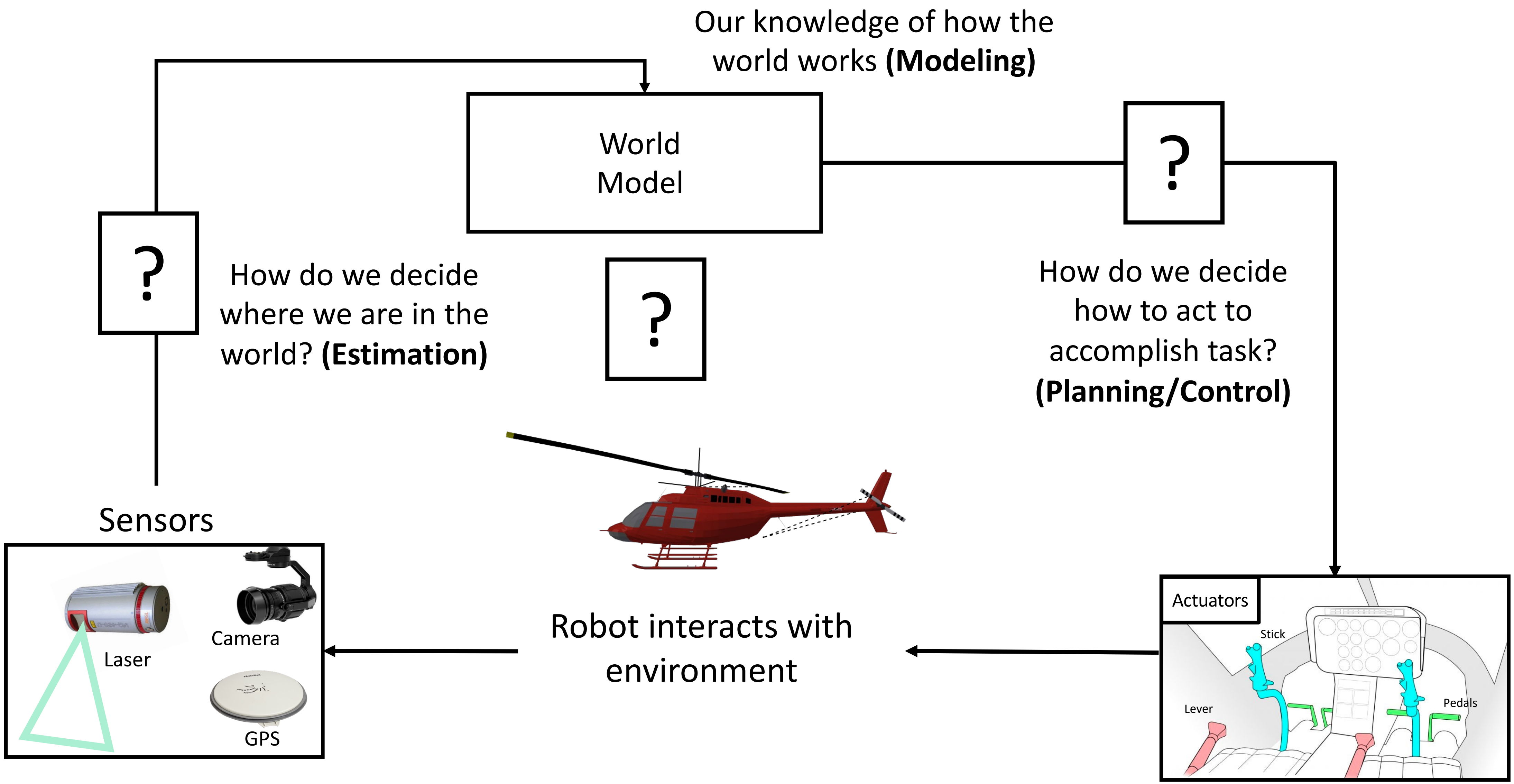
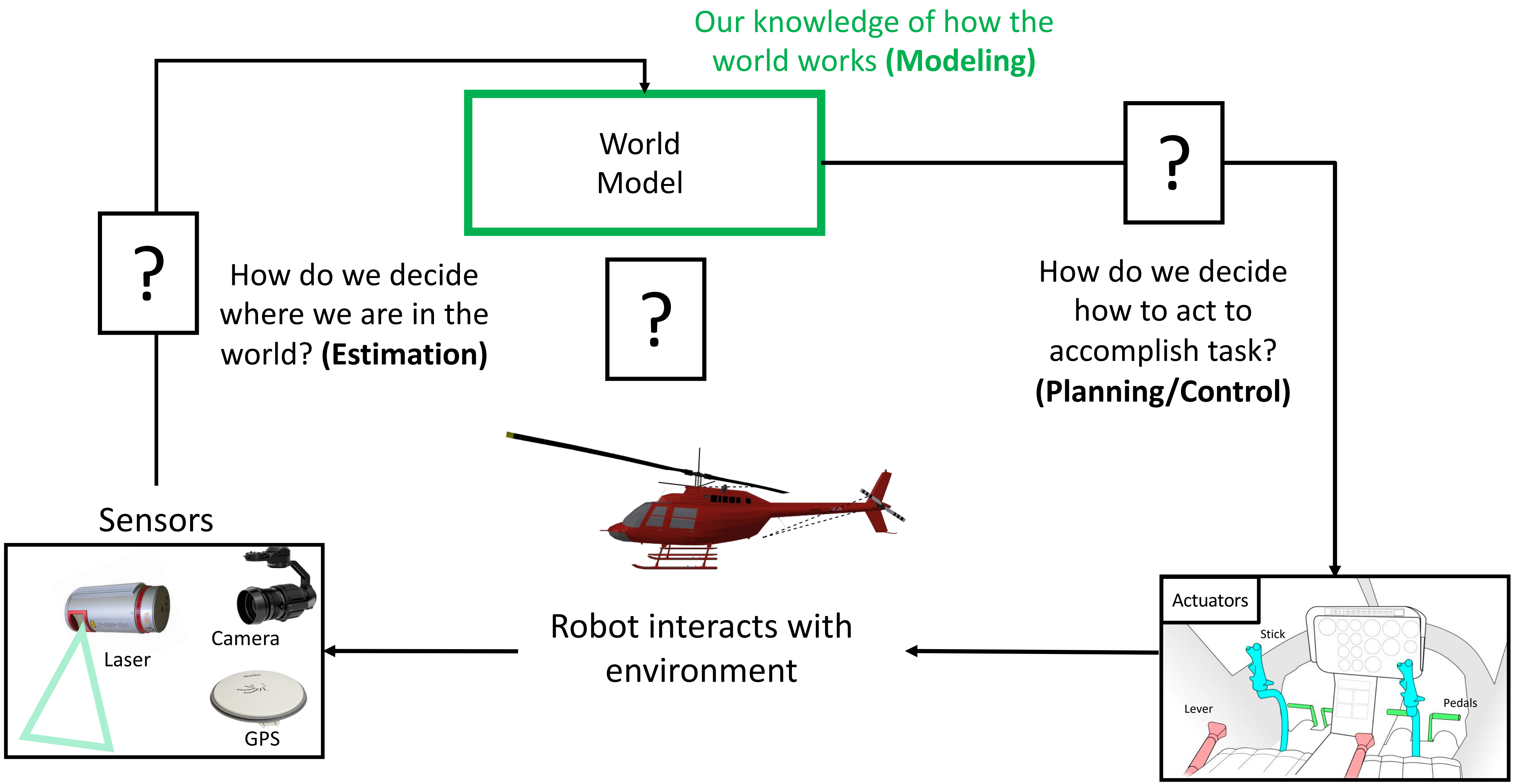
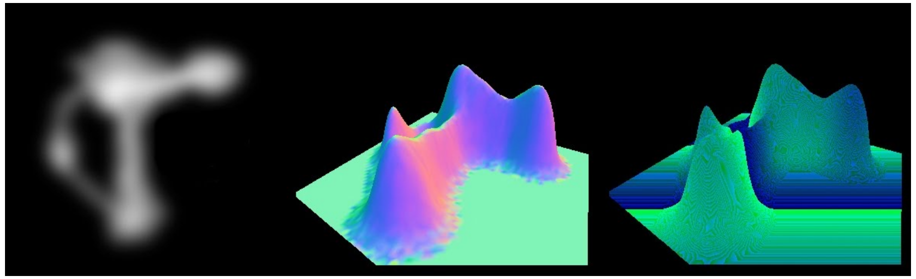


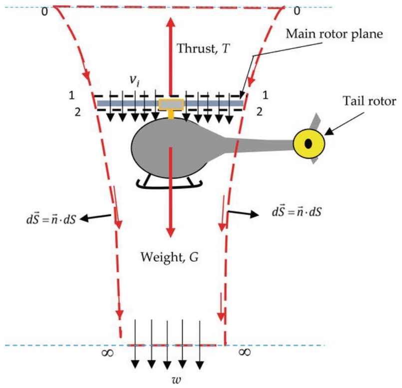
Let‘s start by thinking about how to model the world



How can we model how the world works?

World model



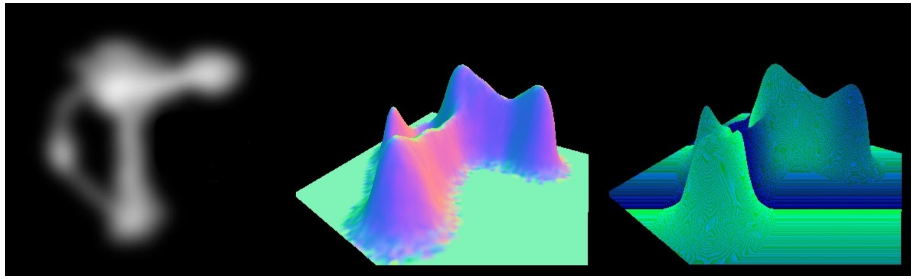


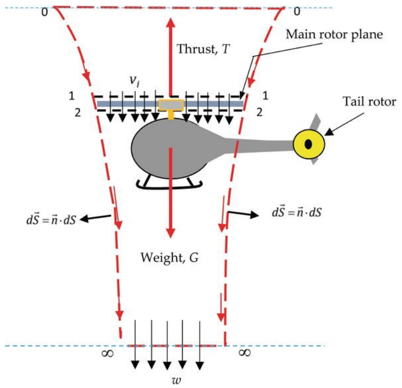
How can we model how the world works?

Model describes our understanding of how the world **works:**

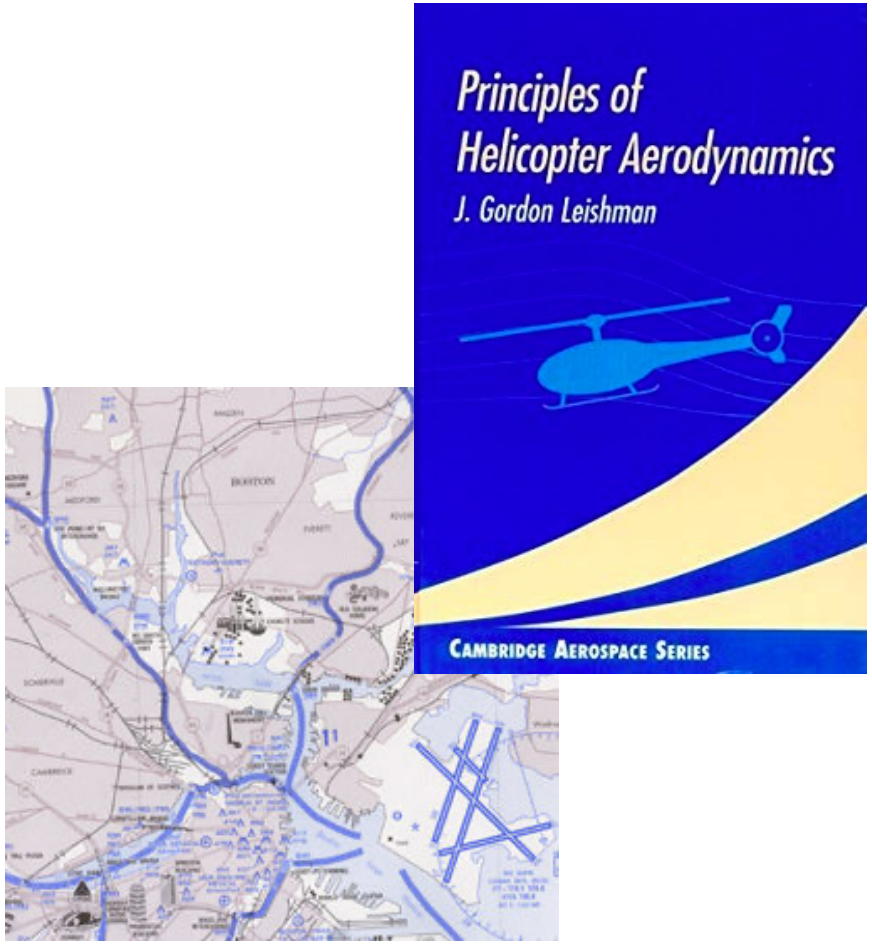
- Variables that are modeled:
  - Position of helicopter
  - Speed of helicopter
  - Payload distribution
  - …
- How they change:
  - Physics (including wind/temperature)
  - Obstacles/maps of the world
  - Other aircrafts
  - …
- Cost / objective of the mission
  - No fly zones
  - Flight preferences
  - …

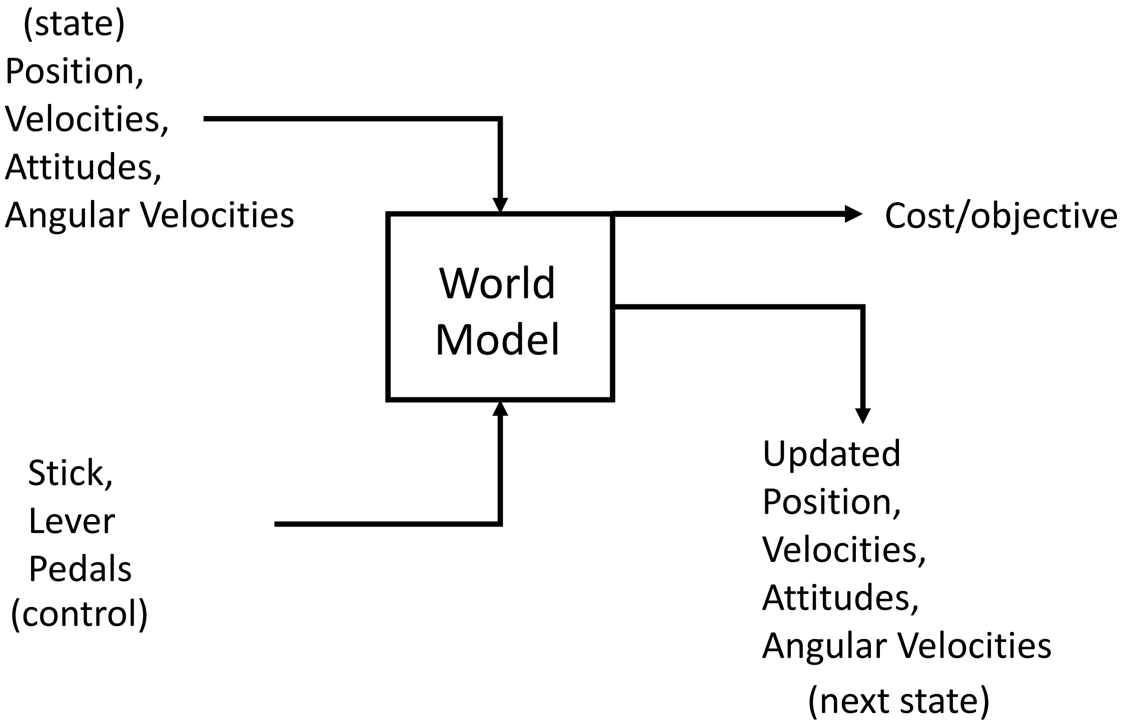
World model





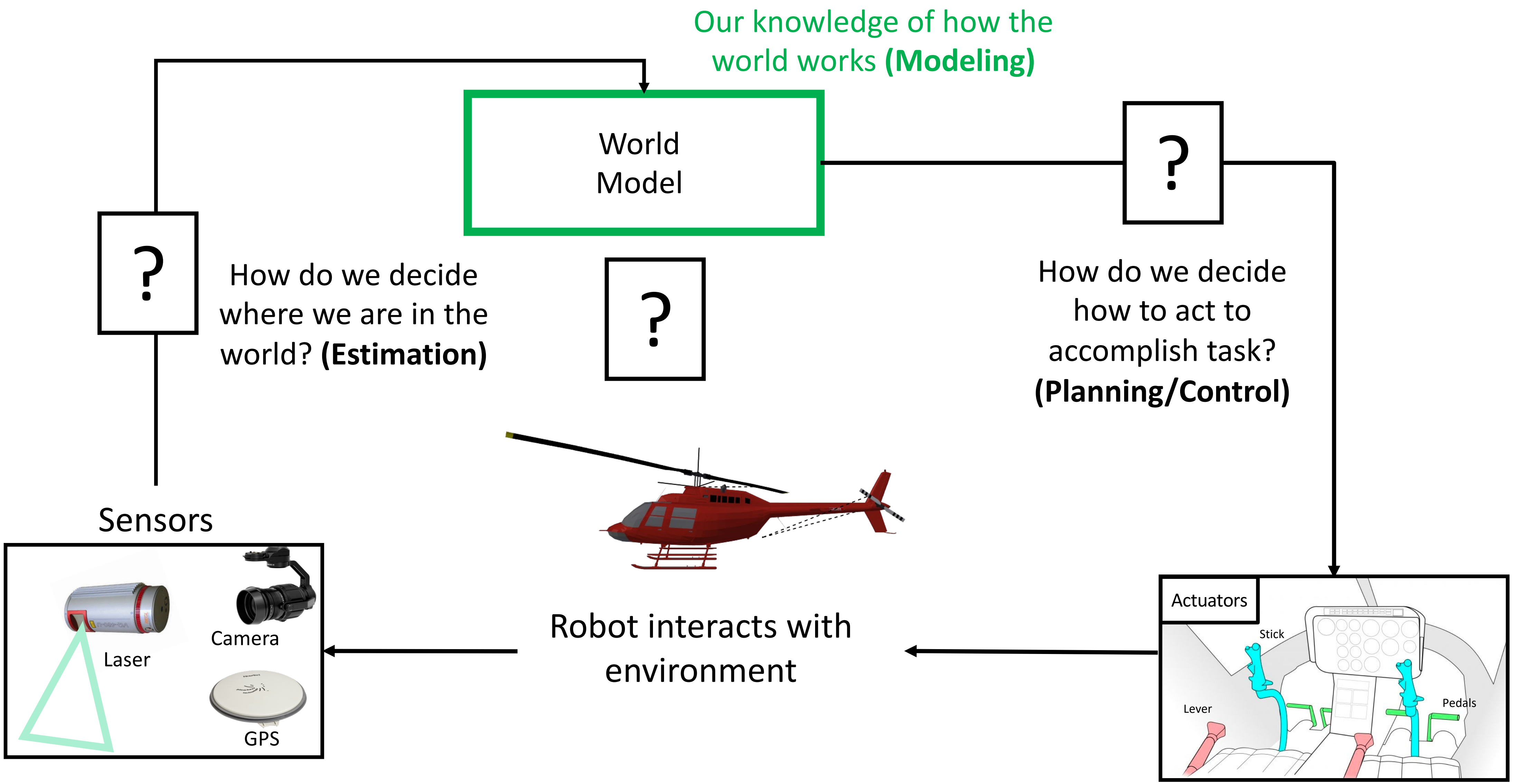
How can we instantiate a helicopter world model?





"All models are wrong, but some are useful" –
George Box

How do we actually use the model?



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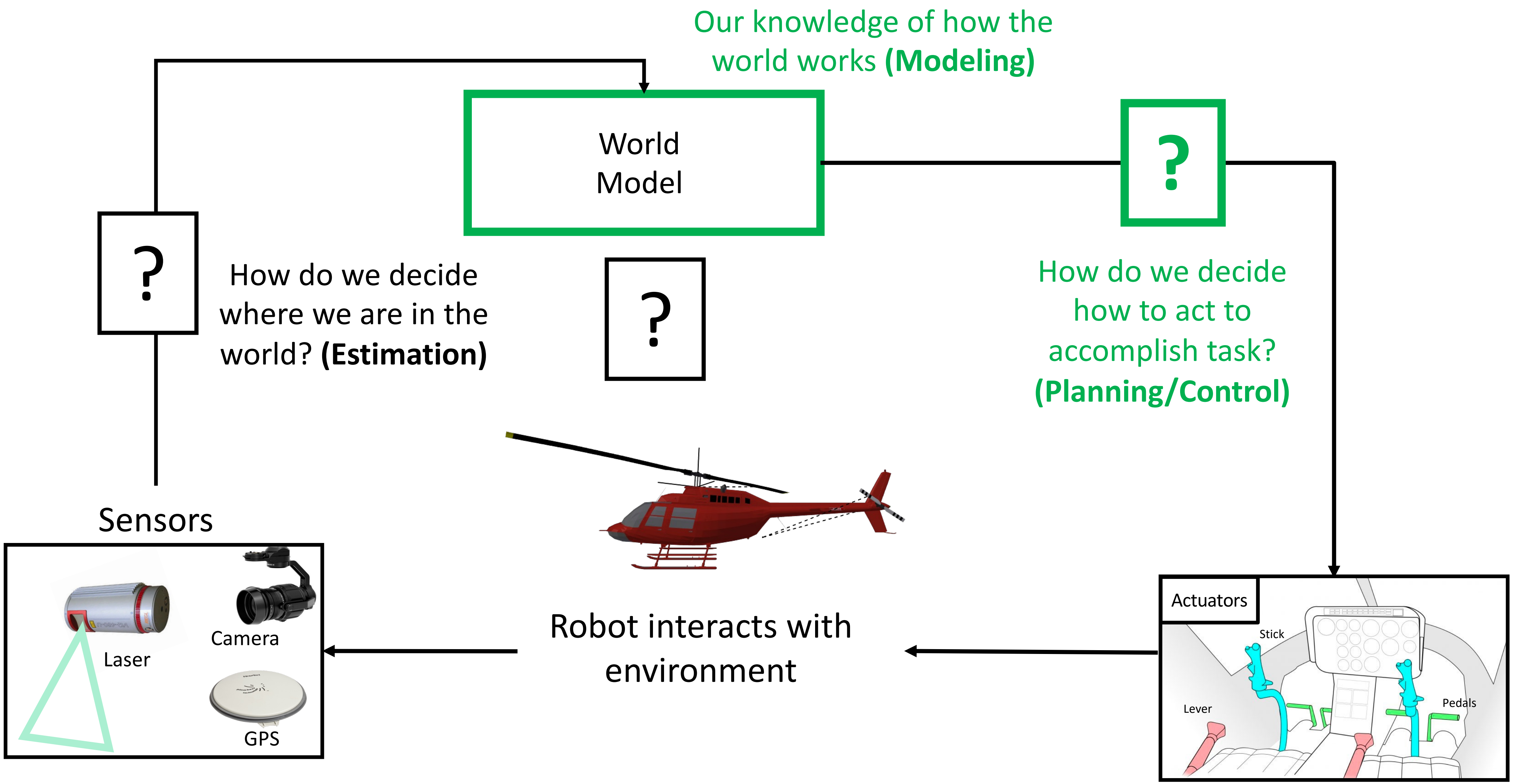
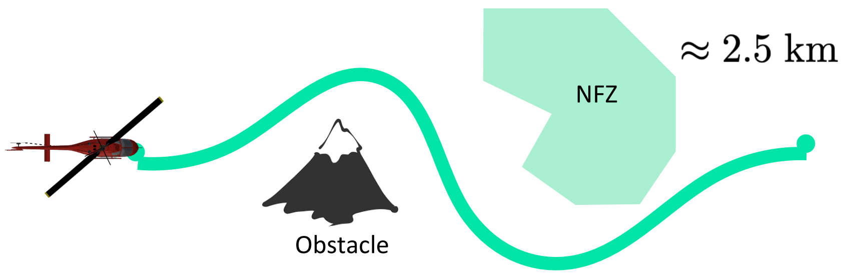


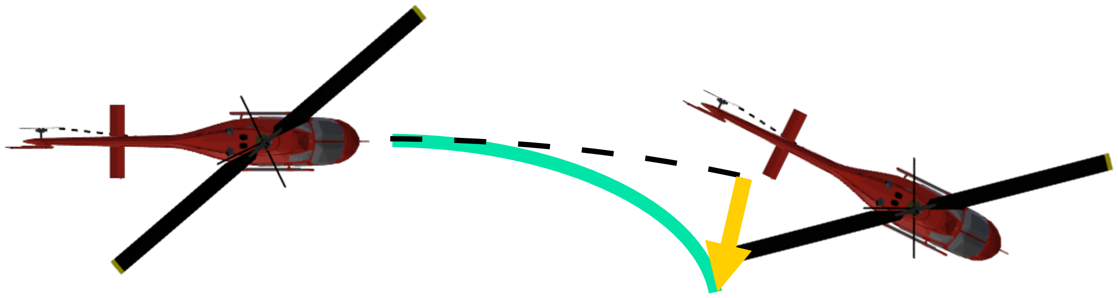
Using world models to decide behavior

Planning (coarse/global)



“Plan" at coarse (10 m) resolution,
follow the global route,
avoid all obstacles, produce
smooth
dynamically feasible paths

Control (fine/local)



“Control” at fine (10cm) resolution
to follow designated path,
rejecting disturbances and model
errors

What is planning?

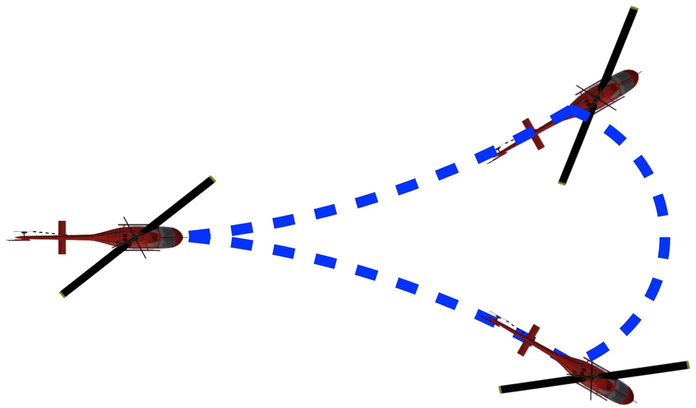
Planning is an optimization problem in which …

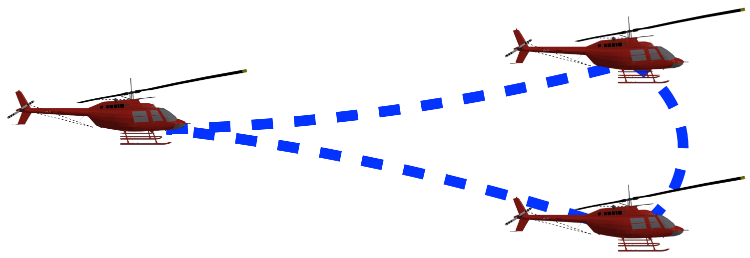
we search over a sequence of actions…

towards minimizing a cost function (e.g., time)…

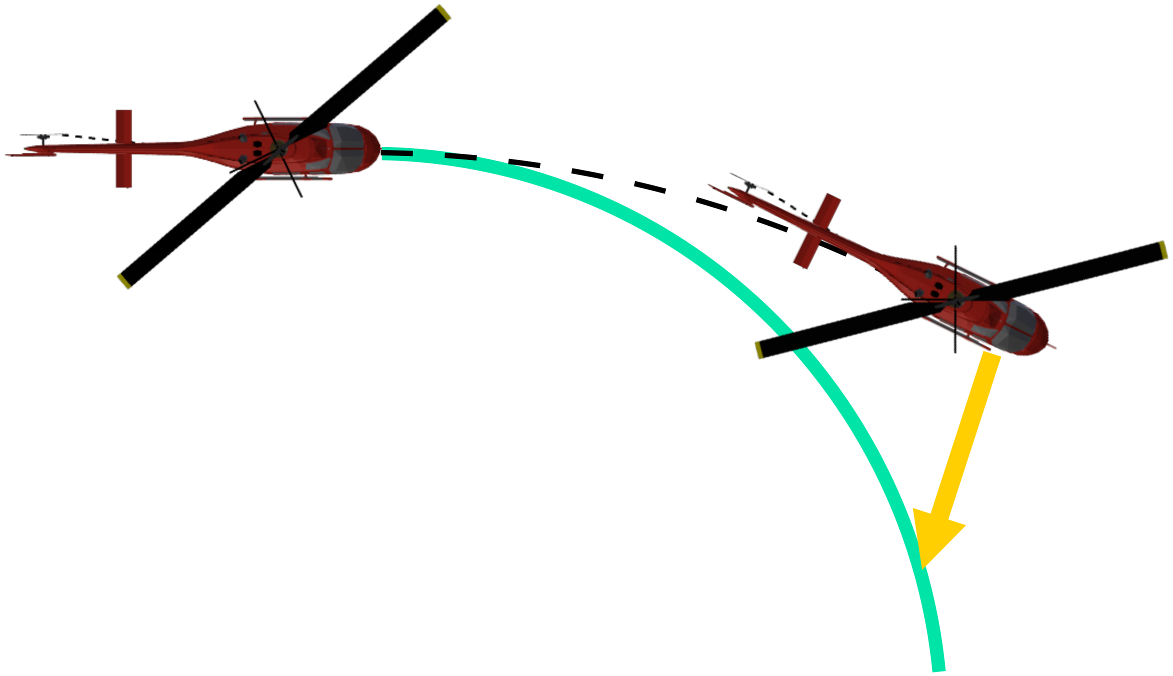
using a model of the robot to predict where it will go…

while making sure we are not violating constraints (e.g. crash).





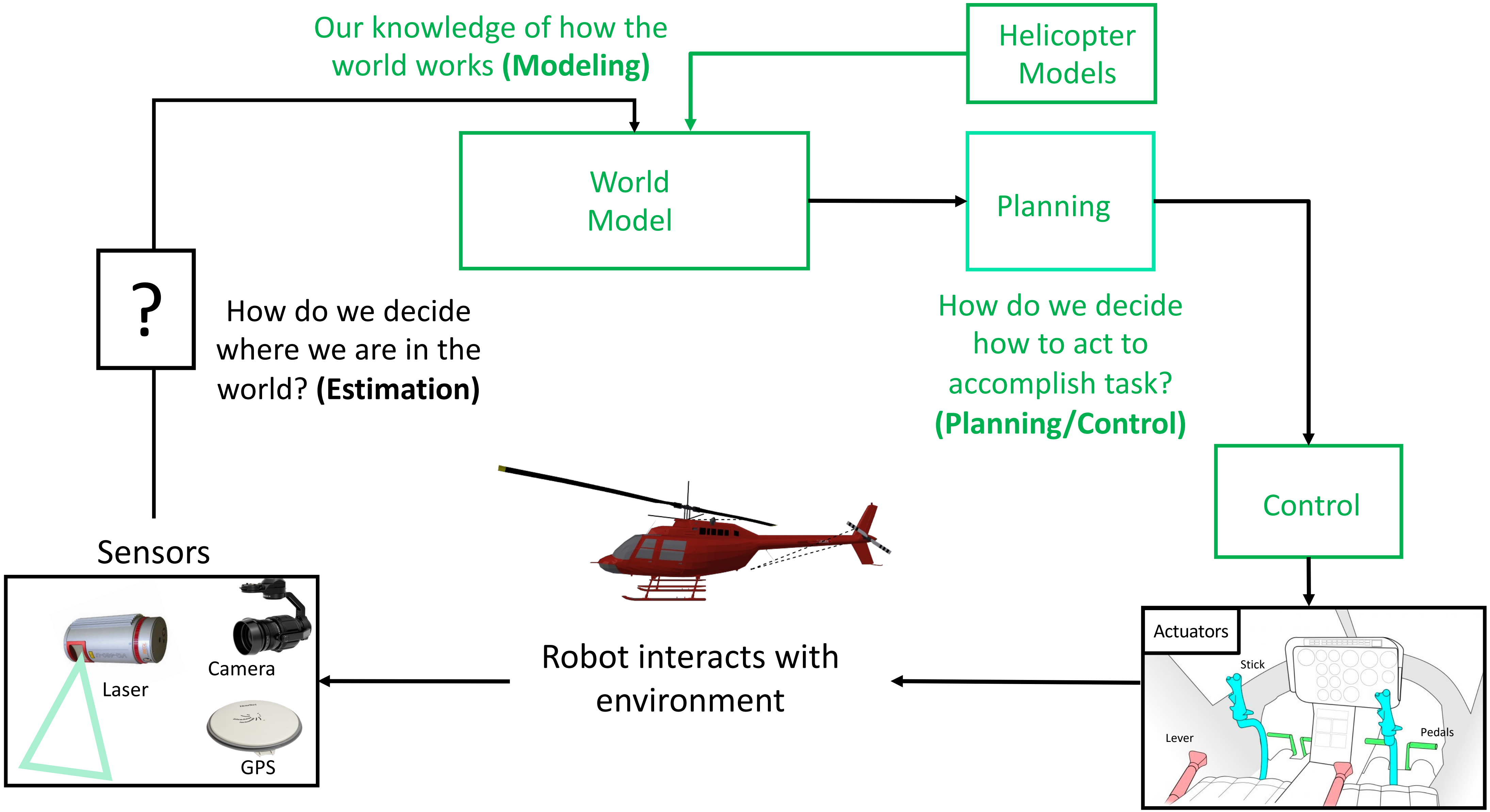
What is control?



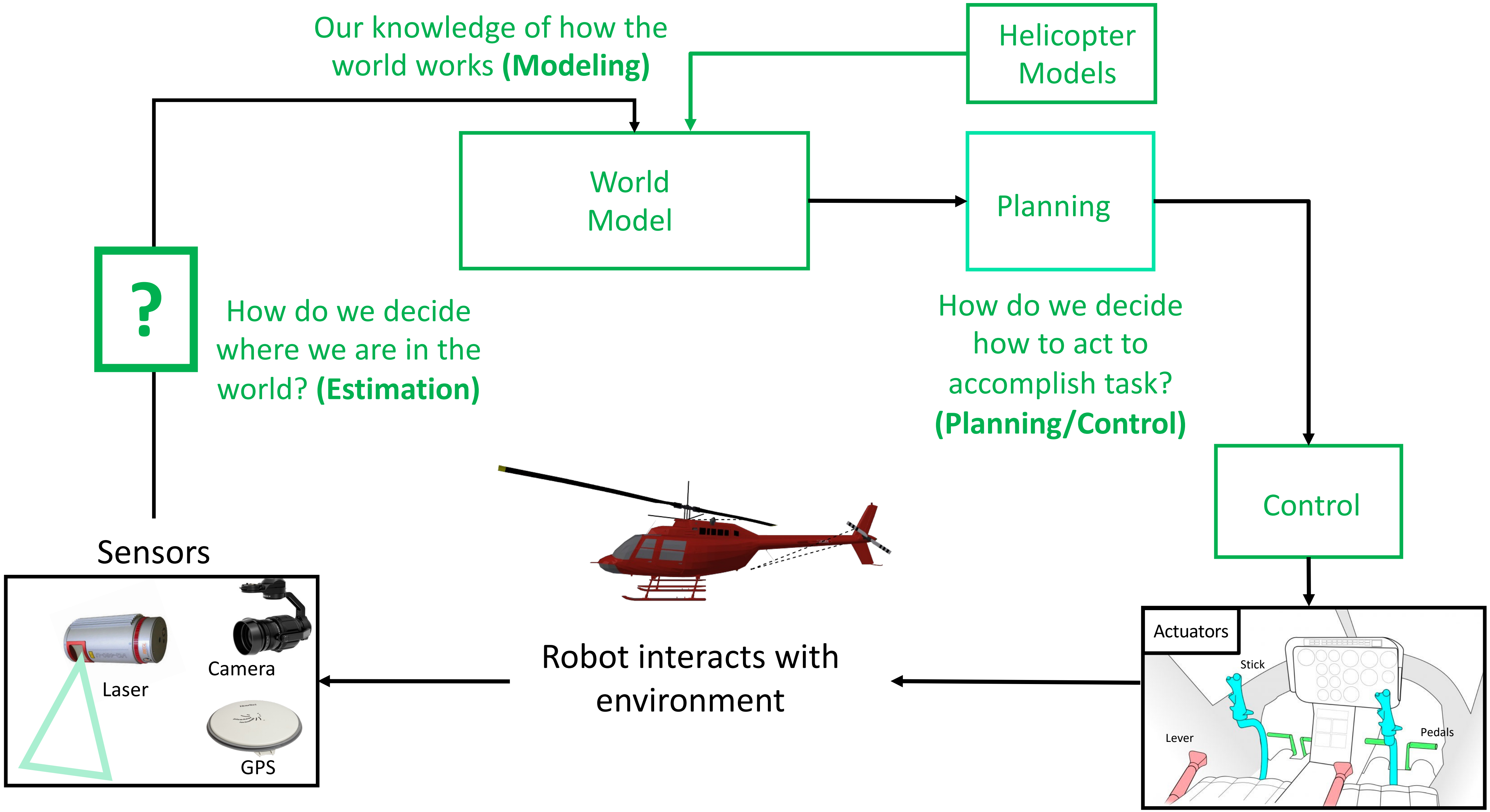
Robot will go “off” the plan for many reasons
(disturbance, model errors, actuation errors, …)

A **controller** immediately corrects for any tracking error and gets the robot back on the path

Let’s zoom out



Let’s zoom out



How do we estimate “state” for the world model?

So far: Assume we know everything about the world.

What commands should we send to the actuator?

Now: How do we use raw sensor data to update what we know about the world?

How can we use the sensor readings to update the world model?

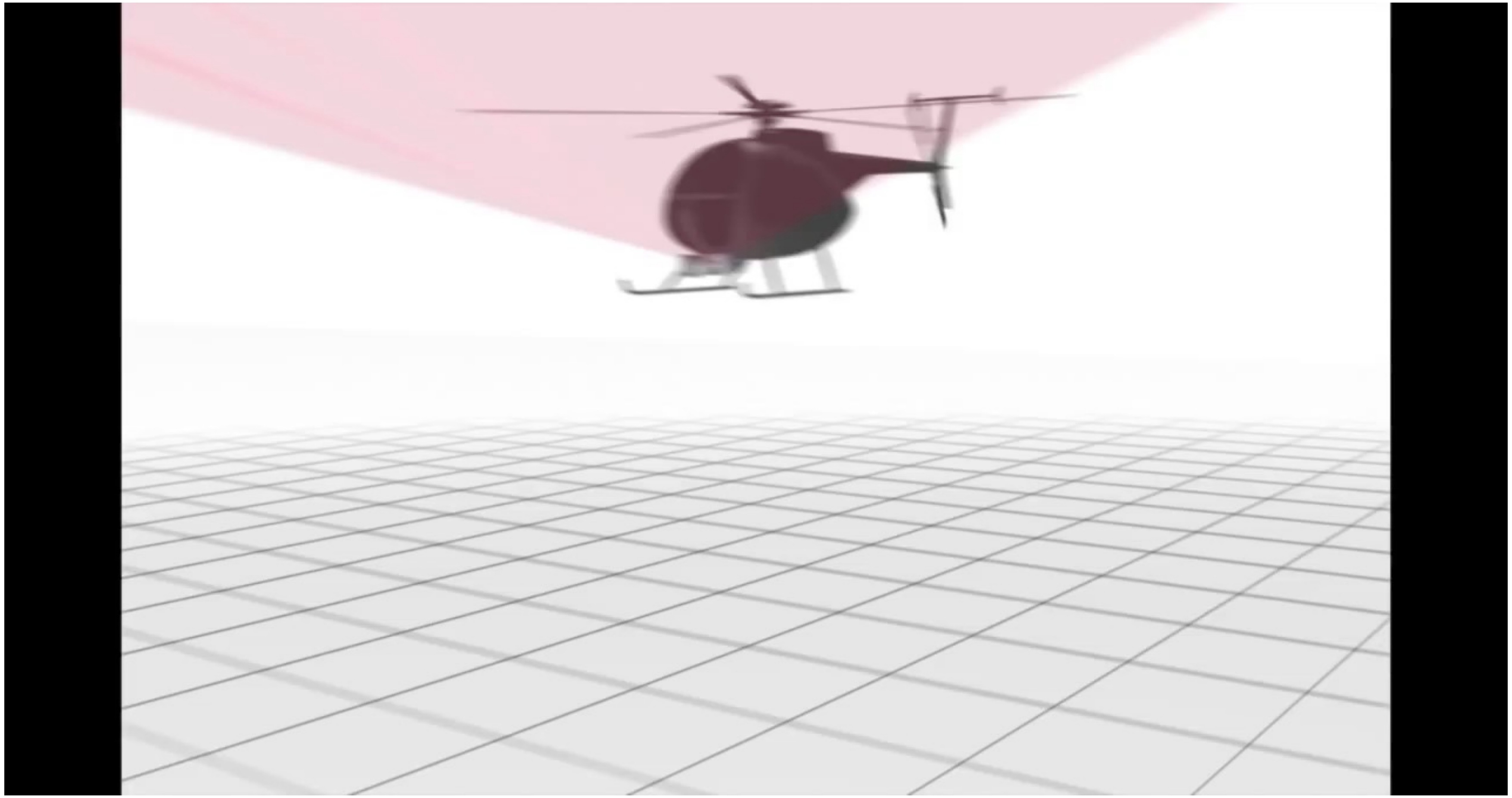
World models need to be grounded in the "state" of the world

- Where is the robot in the world? What is it's state? — GPS
- What are the obstacles in the world? — Laser
- What type are the obstacles (radio towers, trees)? — Camera
- What are the no-fly-zones? — Radio
- Are there other aircrafts? — Radio
- What is the wind, temperature, etc? — Pitot tube, barometer,

Why is this difficult?

Why is estimating the state of the world model difficult?

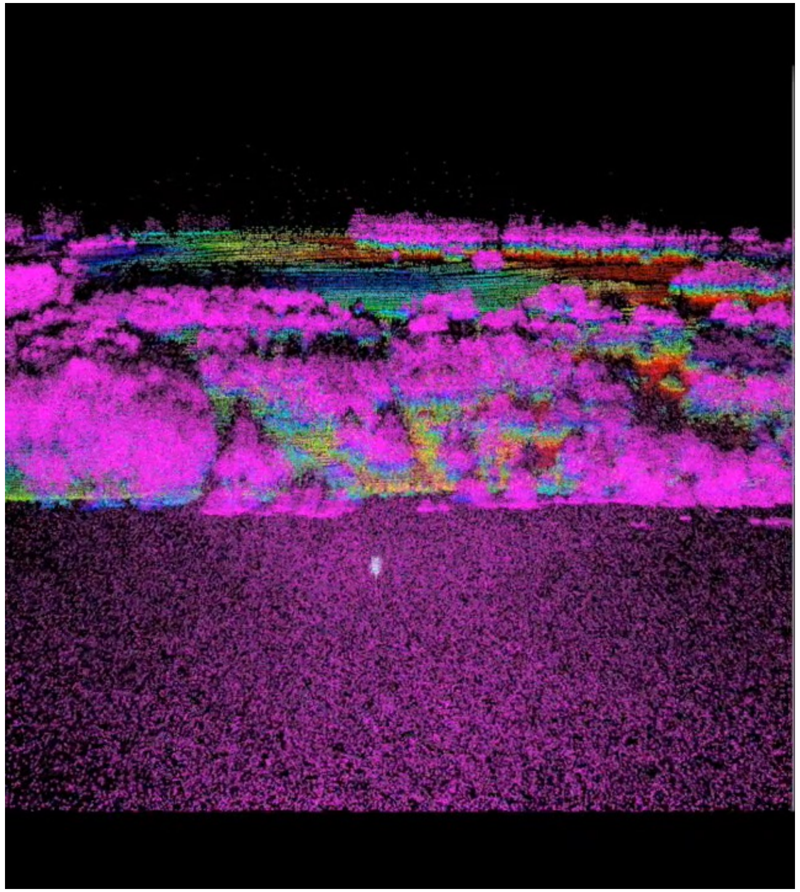
Large amounts of information



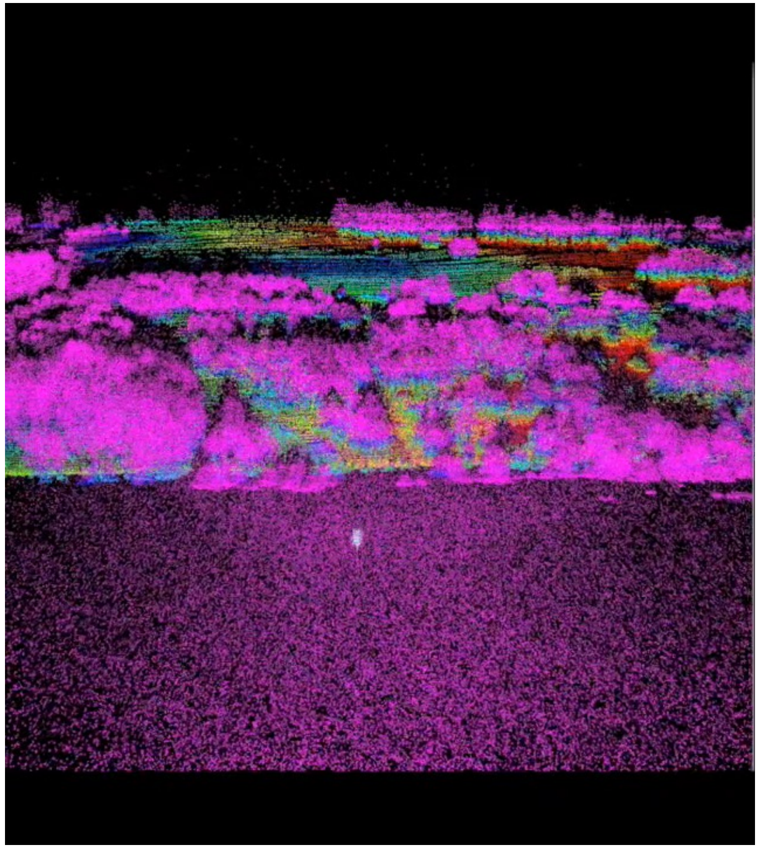
(courtesy Chamberlain et al.)

Why is estimating the state of the world model difficult?

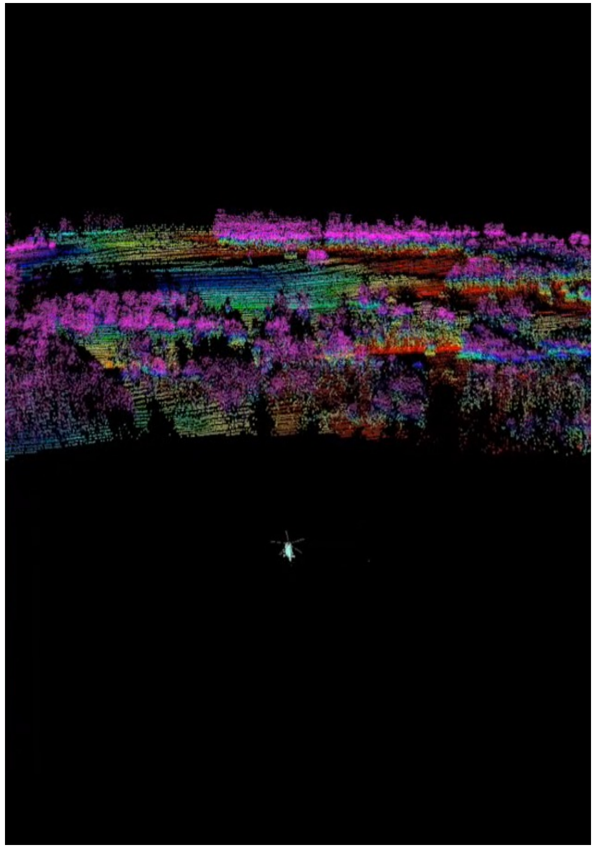
Noisy sensor readings – e.g., flying in a snowstorm



Estimate a "belief" over the state of the system in the world model



Laser reflected by snow!



Correctly fused laser data using probabilistic models

- Obtain probabilistic estimates of state

$$P(\text{world model}|\text{data})$$

- Use the probabilistic estimates of state for robust "planning" under uncertainty

Yay! We have most of the elements of a system

Our knowledge of how the world works **(Modeling)**

Helicopter Models

World Model

Planning

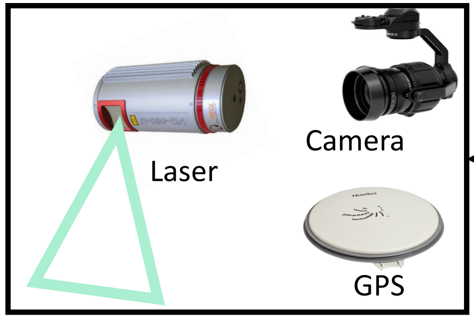
State estimation

How do we decide where we are in the world? **(Estimation)**

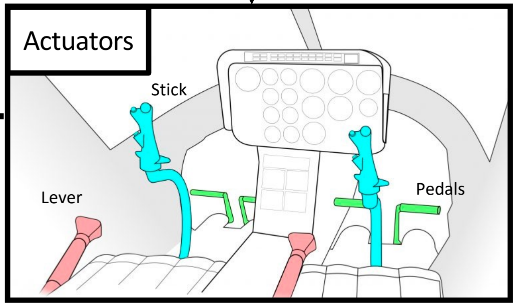
How do we decide how to act to accomplish task? **(Planning/Control)**

Control

Sensors



Robot interacts with environment



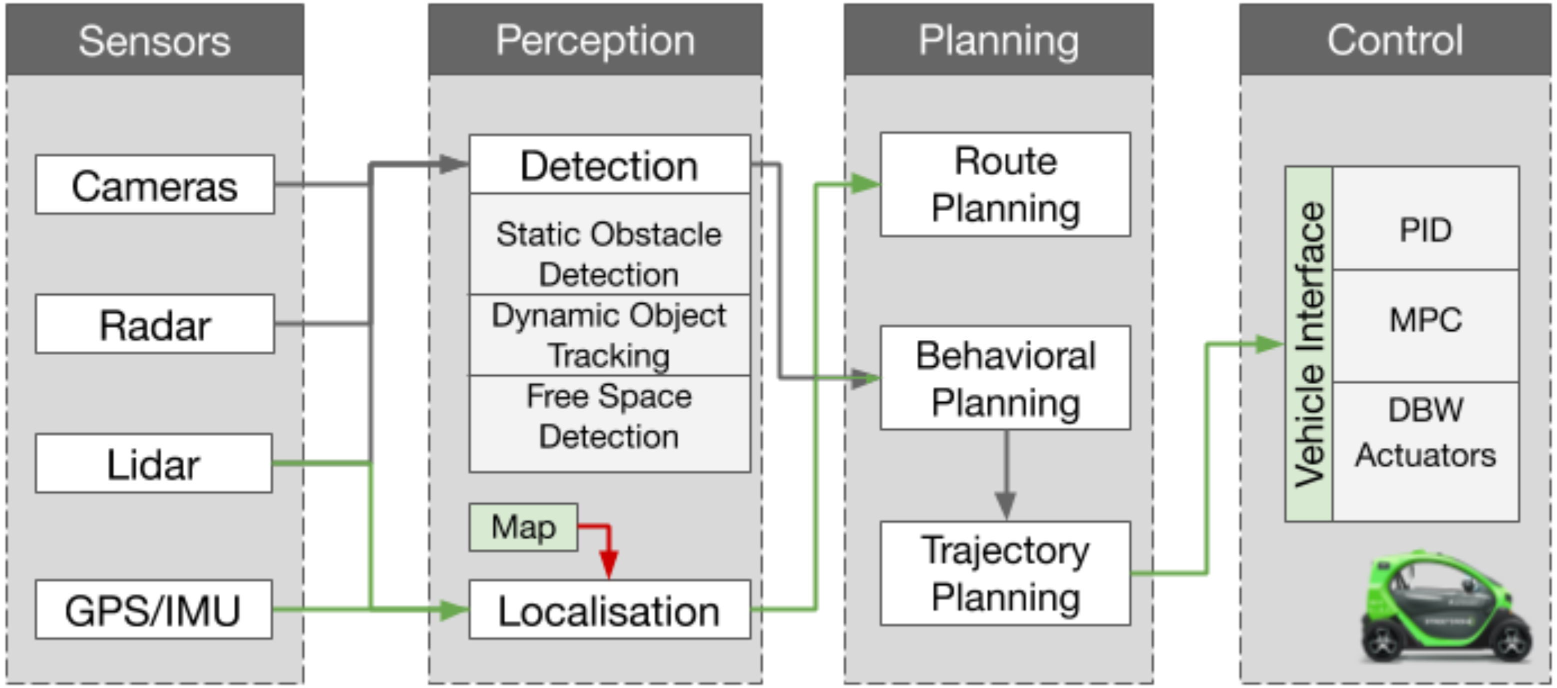
But we have no helicopters, only cars! Do the same lessons apply?

We’ll figure that out this quarter!

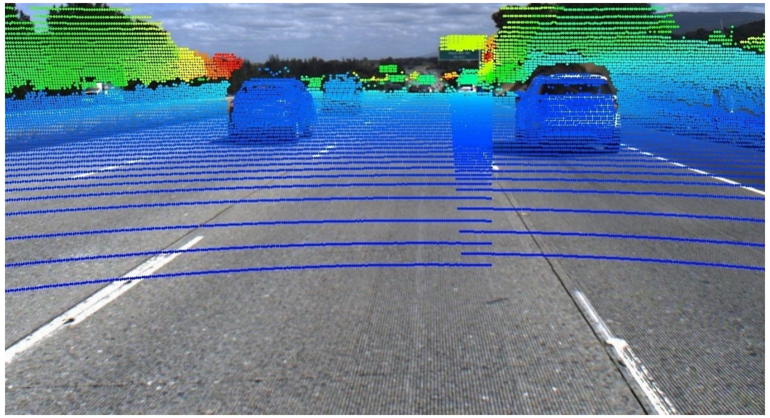
Sense-Plan-Act Framework

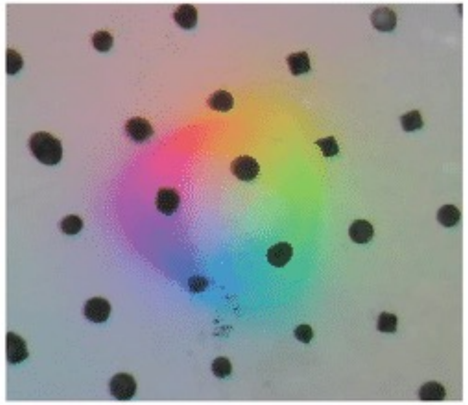
Robotics has three primary subpieces:

1. Sensing → from measurements
2. Planning → from models
3. Acting → control in the world



Sensing: Why is it nontrivial?



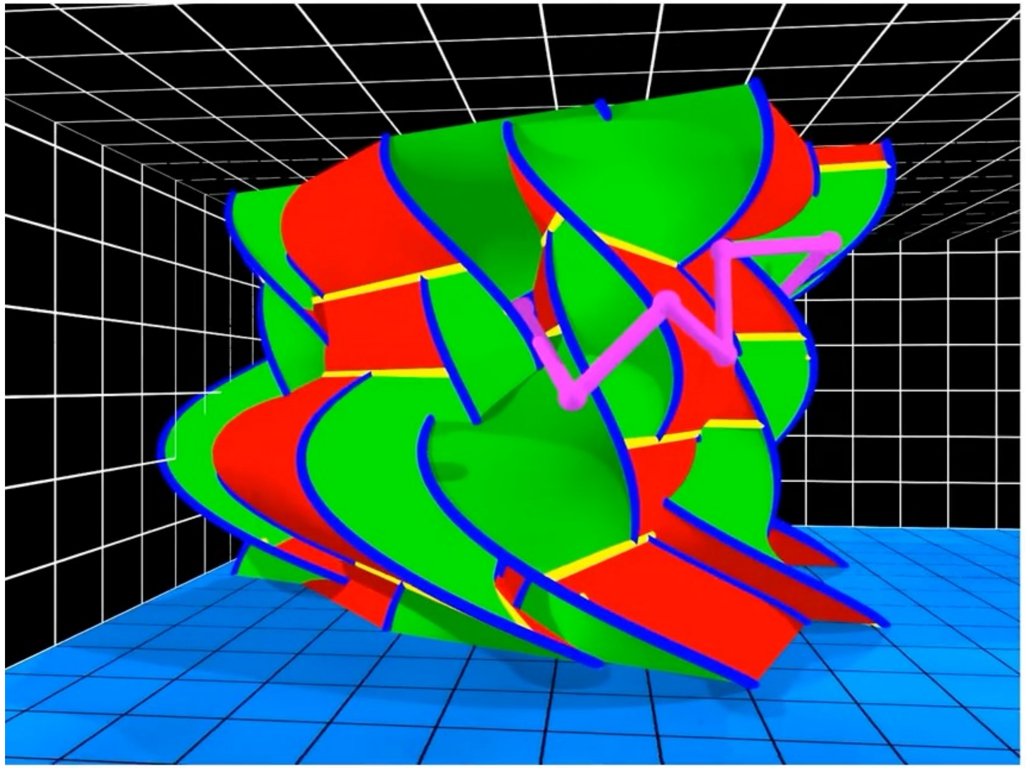
- Sensors have overwhelming amounts of information
- Partially observed
- Noisy and prone to drift

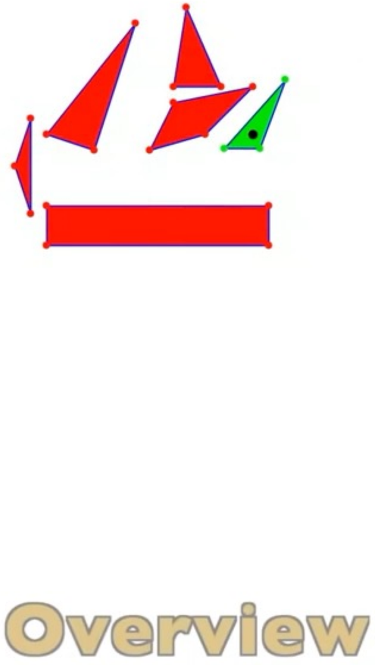
Acting: Why is it nontrivial?

- Robot systems in the real world are subject to significant perturbations/noise → need to be stable in the face of these perturbations

Planning: Why is it nontrivial?

- Searching/Optimization through a complex non-convex space
- Combination of discrete/continuous optimization

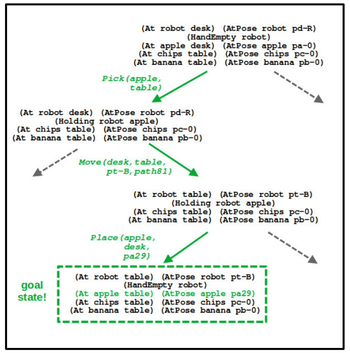


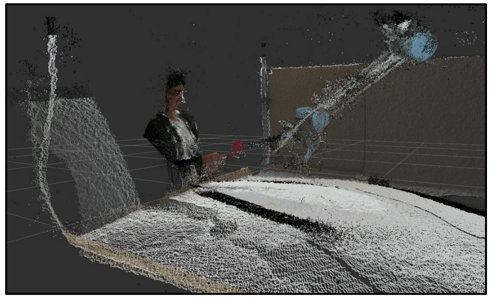


Robotics: Integrated System Research

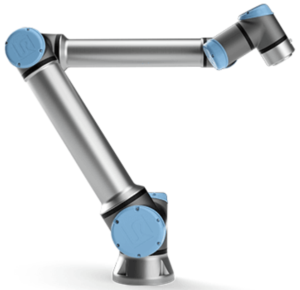
Focus on addressing all problems at once

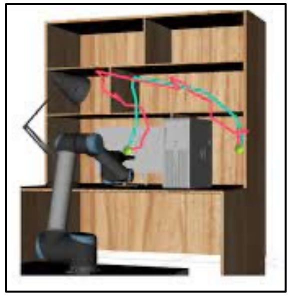
$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} = \tau_g(\mathbf{q}) + \mathbf{B}\mathbf{u},$$

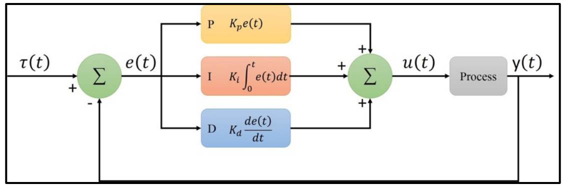




State Estimation → Modeling and Prediction → Planning → Low-level control →

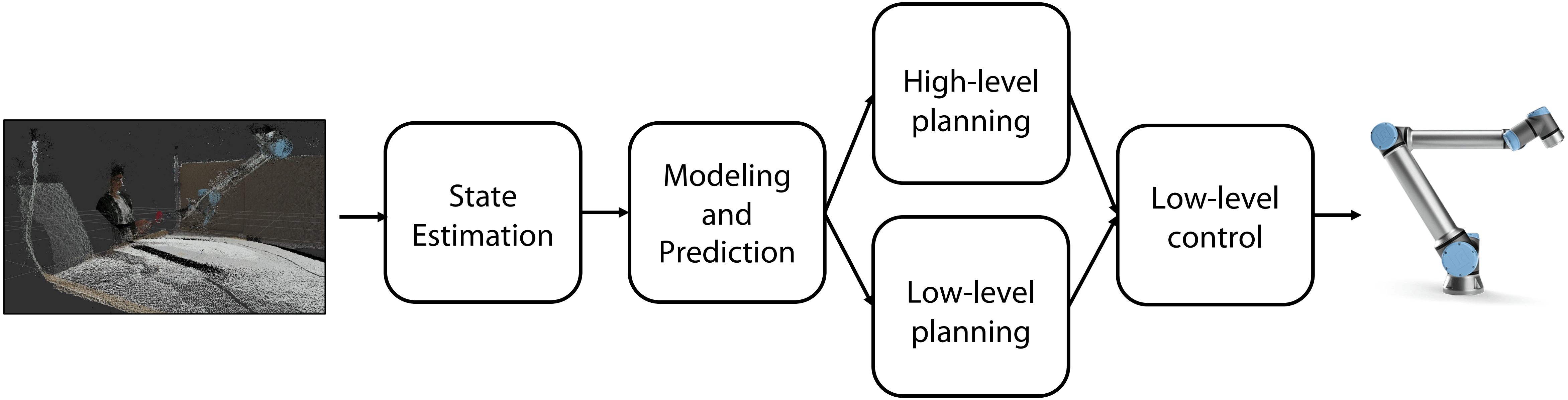




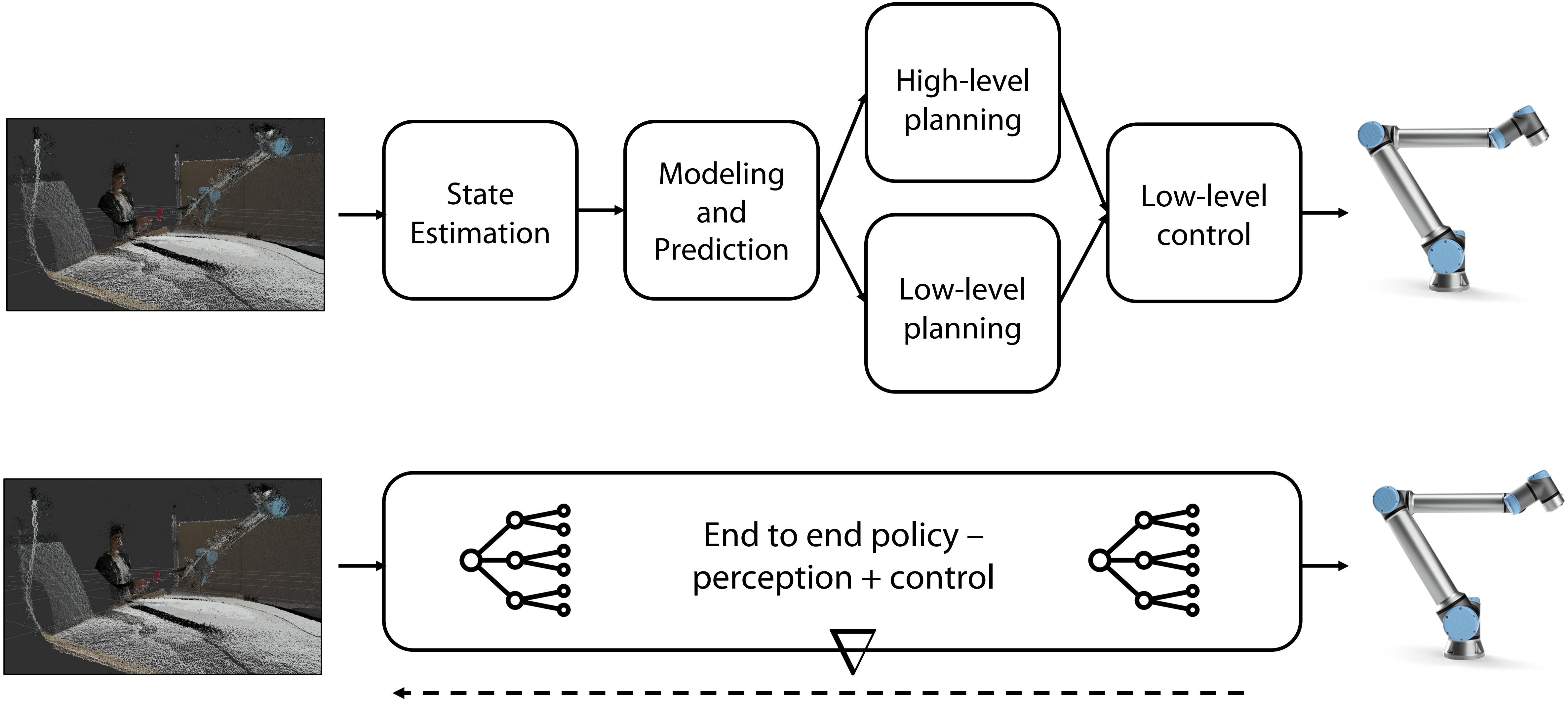


How do we tractably solve the task?: The model-free way

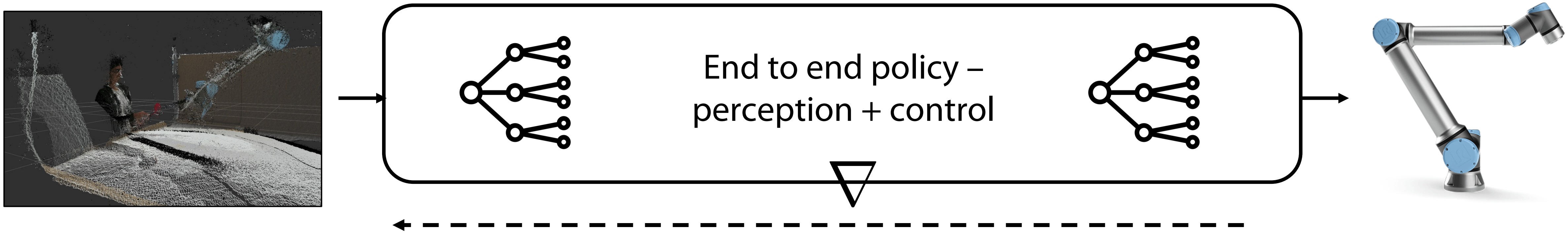
What does a typical model based look like?



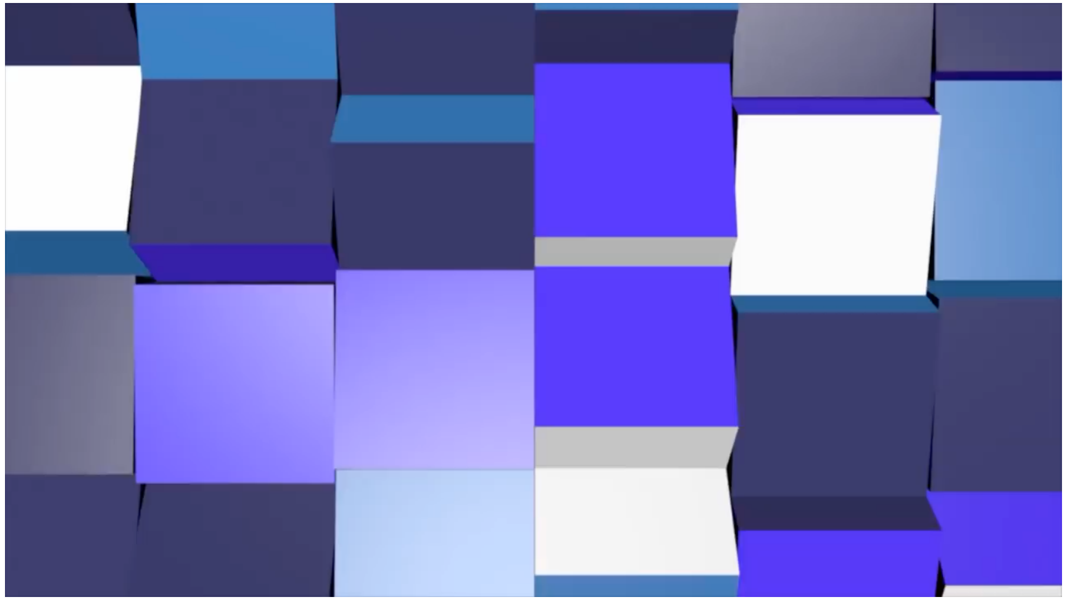
End-to-End Learning Based Control for Robots



End-to-End Learning Based Control for Robots



Option 1: Imitation Learning



Learning by copying an expert

Option 2: Reinforcement Learning

Learning through trial and error

Why might we want/not want to do this?

- Modules compensate for each other
- Avoids hand-designing and supervising interfaces
- Often more performant/less biased

- Lack of Interpretability
- Lack of Reusability
- Often data inefficient

Class Outline

State Estimation
- Robotic System Design
- Filtering
- Localization
- SLAM

Control
- Feedback Control
- PID Control
- MPC
- LQR

Planning
- Search
- Heuristic Search
- Motion Planning
- Lazy Search

Learning
- Imitation Learning
- Policy Gradient
- Actor-Critic
- Model-Based RL