Anatomy of an Autonomous Vehicle

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*Slides based on or adapted from Sanjiban Choudhury
Logistics

• Submit knowledge survey ASAP

• Form a 3 person team by today, Wednesday 1/8 (send a private note to instructors in Piazza).

• Each team will be assigned a car and a computer tomorrow during recitation.

• Come to recitation and start working on Assignment 0.

• Assignment 0 (intro to ROS, due 1/17)
Today’s objective

1. Learn how to architect a mobile robotic system

2. Step through a set of fundamental lessons that shape robot system / algorithm design
Estimate state

Plan a sequence of motions

Control robot to follow plan
Mobile Manipulators
Self-driving Cars
Flying vehicles
Anatomy of a flying vehicle
Mission: Takeoff to Landing
Mission

- **Takeoff**: (Respect power constraints)
- **Enroute**: (Avoid sensed obstacles)
- **Touchdown**: (Plan to multiple sites)

Obstacles in LZ

Map created by sensor

Tree in Approach
**Task:** A contract the robot has 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)
How do we tractably solve the task?
Begin with a blank slate
Robot interacts with environment
Robot interacts with environment
Lesson 0: Look at one piece at a time

Q1: Assume we know everything about the world. What commands should we send to the actuator?

Q2: How do we use raw sensor data to update what we know about the world?
Q1: Assume we know everything about the world.

What commands should we send to the actuator?

Q2: How do we use raw sensor data to update what we know about the world?
Robot interacts with environment

Sensors
- Laser
- Camera
- GPS

Actuators
- Stick
- Lever
- Pedals

World Model
What is the world model?

List of everything we need to know to accomplish the task

- Where is the robot in the world? What is its state?
- What are the obstacles in the world?
- What type are the obstacles (radio towers, trees)?
- What are the no-fly-zones?
- Are there other aircrafts?
- What is the wind, temperature, etc?
Robot interacts with environment
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).
How do we get a model of the helicopter?

Problem: Model is very complicated! Intractable to plan with it.
Insight

“All models are wrong, but some are useful”
-George Box
Lesson 1: Plan with simple models

Use domain knowledge to simplify model

Complex aerodynamical model

Flying unicycle at high speeds!

Different models at different flight regimes
Sensors

Helicopter Models

World Model

Robot interacts with environment

PLAN

Actuators

Sensors

Camera

GPS

Laser

Helicopter Models

World Model

Robot interacts with environment

Actuators

Stick

Lever

Pedals
What **resolution** should we plan at?

Example mission:

Fly from Phoenix to Flagstaff as fast as possible (200 km)

Avoid mountains, no-fly-zones, radio towers, wires, bad weather

Pass through narrow gaps

Problem:

Take forever to plan at high resolution **ALL** the way to goal
Lesson 2: Plan at multiple resolutions

Global planner

Plan at coarse (1km) resolution, compute entire route from start to goal, avoid large obstacles, no-fly-zones etc

(only consider factors that significantly affect mission time)

Local planner

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

\[ \approx 2.5 \text{ km} \]
Robot interacts with environment

Sensors
- Laser
- Camera
- GPS

Helicopter Models

World Model

Global Planning

Local Planning

Actuators
- Stick
- Lever
- Pedals
Lesson 3: Open loop planning is not enough

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
Robot interacts with environment
Q1: Assume we know everything about the world. What commands should we send to the actuator?

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What is the world model?

List of everything we need to know to accomplish the task

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GPS
Laser
Camera
Radio
Radio
Pitot tube, barometer, etc
Can we simply “fuse” laser readings to map the world?

(courtesy Chamberlain et al.)
Flying in a snow storm
Flying in a snow storm
Lesson 4: Use probabilistic models of the sensor

Laser reflected by snow!

Correctly fused laser data using probabilistic models
Sensors

Laser
Camera
GPS

World Model

State Estimation

Global Planning

Local Planning

Control

Actuators

Robot interacts with environment

Helicopter Models

Stick
Lever
Pedals
What is state estimation?

Given raw sensor data, use probabilistic models to estimate world model

\[ P(\text{world model}|\text{data}) \]
Robot interacts with environment
Lesson 5: Guarantee safety

What if the robot encounters unexpected obstacles?

Safety planner that guarantees the robot can stay safe
Robot interacts with environment

Sensors
- Laser
- Camera
- GPS

World Model

State Estimation

Global Planning

Local Planning

Safety Planning

Control

Actuators
- Stick
- Lever
- Pedals

Helicopter Models
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Anatomy of a self-driving car
BOSS: CMU’s winning entry to DARPA challenge (2007)
Tartan Racing: A Multi-Modal Approach to the DARPA Urban Challenge

April 13, 2007

Chris Urmson, Joshua Anhalt, Drew Bagnell, Christopher Baker, Robert Bittner, John Dolan, Dave Duggins, Dave Ferguson, Tugrul Galatali, Chris Geyer, Michele Gittleman, Sam Harbaugh, Martial Hebert, Tom Howard, Alonzo Kelly, David Kohanbash, Maxim Likhachev, Nick Miller, Kevin Peterson, Raj Rajkumar, Paul Rybski, Bryan Salesky, Sebastian Scherer, Young Woo-Seo, Reid Simmons, Sanjiv Singh, Jarrod Snider, Anthony Stentz, William “Red” Whittaker, and Jason Ziglar

Carnegie Mellon University
Hong Bae, Bakhtiar Litkouhi, Jim Nickolaou, Varsha Sadekar, and Shuqing Zeng

General Motors
Joshua Struble and Michael Taylor

Caterpillar
Michael Darms

Continental AG

http://repository.cmu.edu/cgi/viewcontent.cgi?article=1967&context=robotics
BOSS in action!

1. World Model
2. Car Model
3. State Estimation
4. Global Planner
5. Local Planner
6. Safety Planner
7. Control
Additional challenges: Predict human drivers
Looking ahead...
Robot interacts with environment
Next lecture: Introduction to State Estimation

Estimate state

Weeks 2-4
Class Overview

Estimate state

Plan a sequence of motions

Control robot to follow plan

Weeks 2-4

Weeks 7-8

Weeks 5-6