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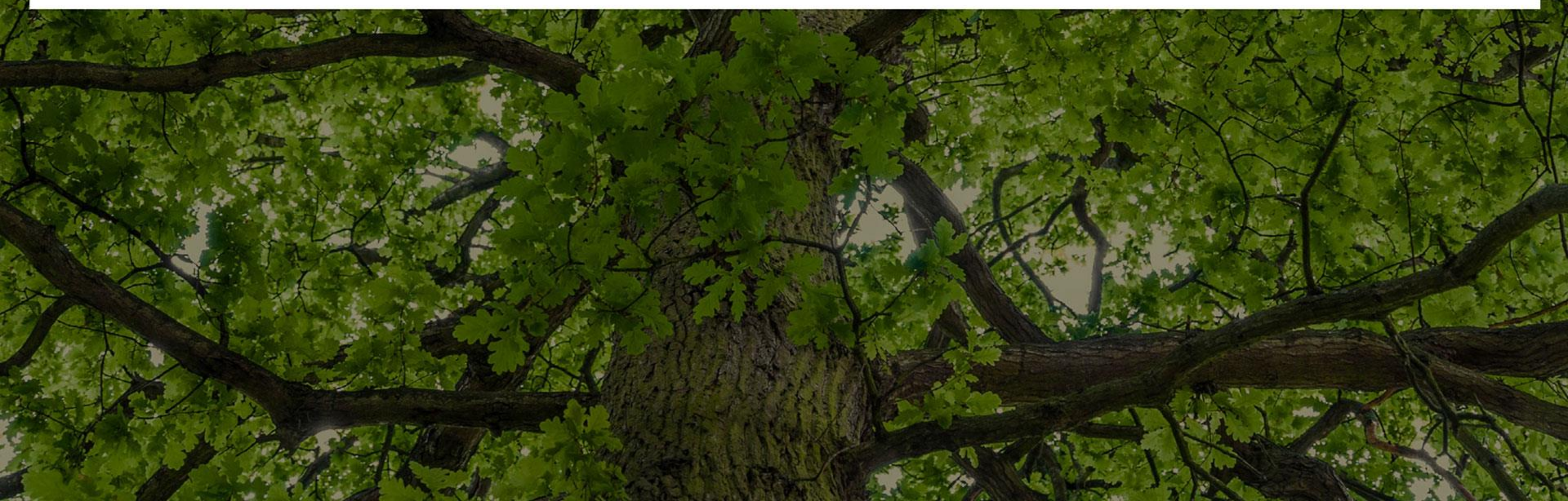
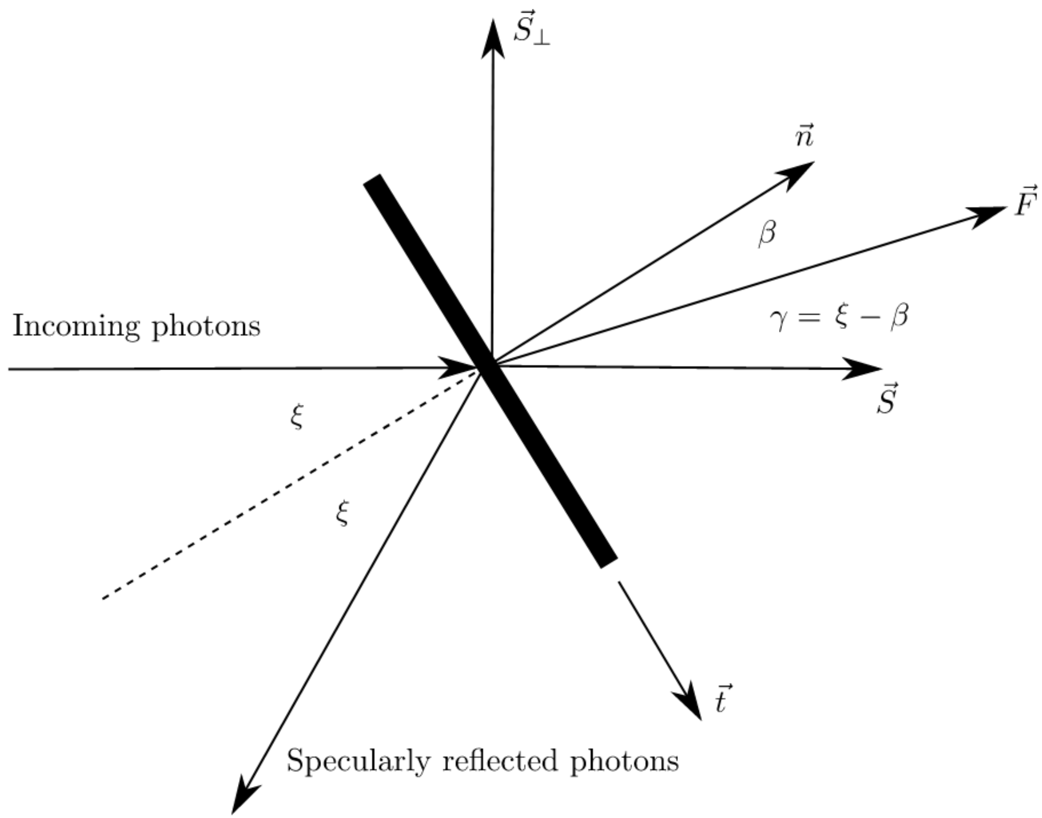
Autonomous Vehicles in a Dynamic World

06 November 2020



Solar Sailing

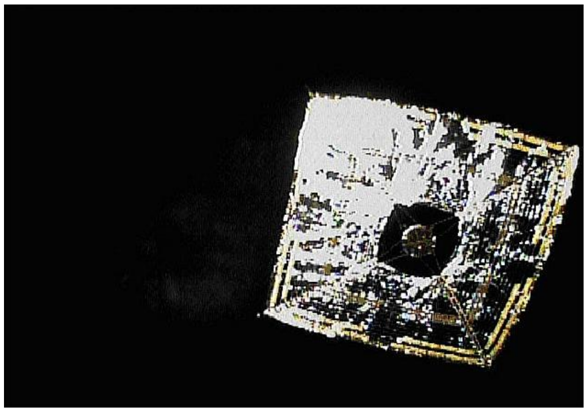
- Satellites that deploy very large reflective surfaces.
- Photons from the sun reflect of the surface, transfer some linear momentum and generate thrust.

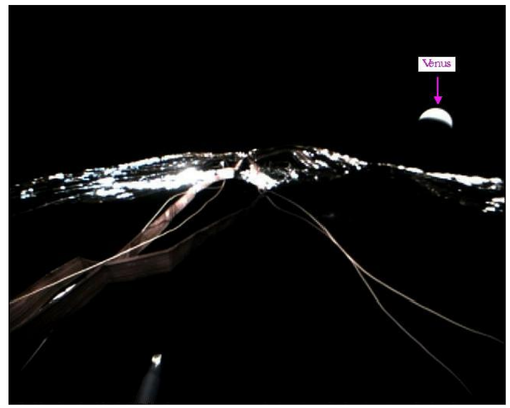


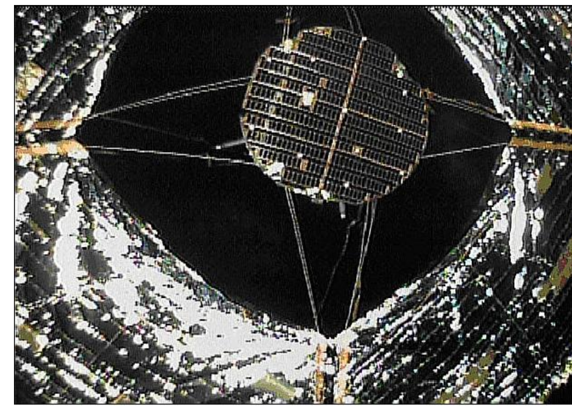
Solar Sailing

IKAROS was a solar sail of 14m x 14m launched in 2010 by JAXA, which performed a fly-by of Venus.

Image credit JAXA

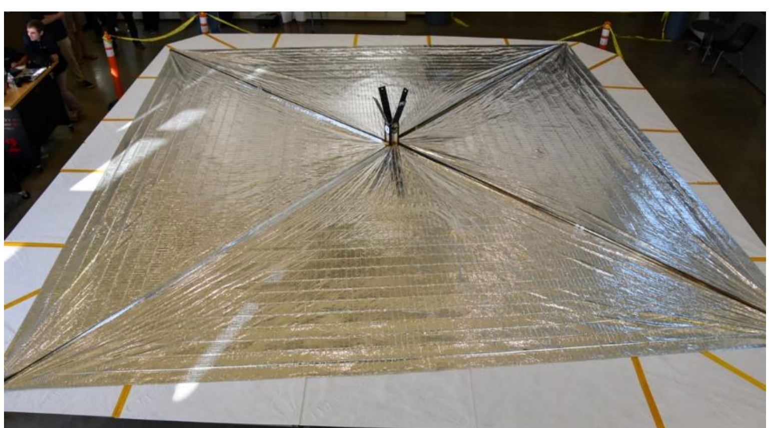




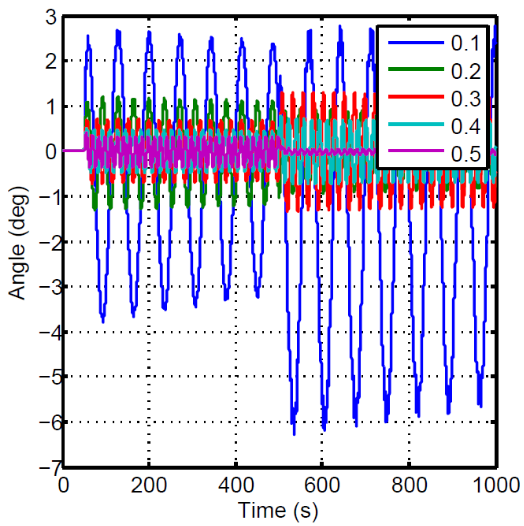


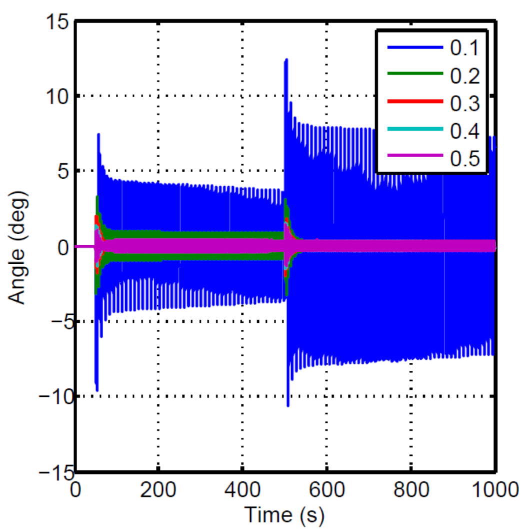
Lightsail-1 and -2 were both 3U CubeSats (10cm x 10cm x 30cm), which deployed a 32m2 solar sail and were launched in 2015 and 2019.

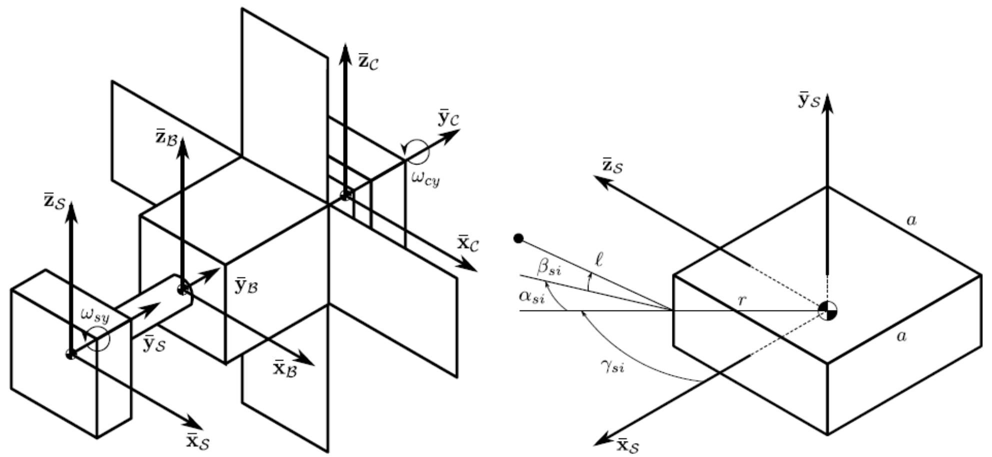
Image credit Planetary Society



Solar Sailing







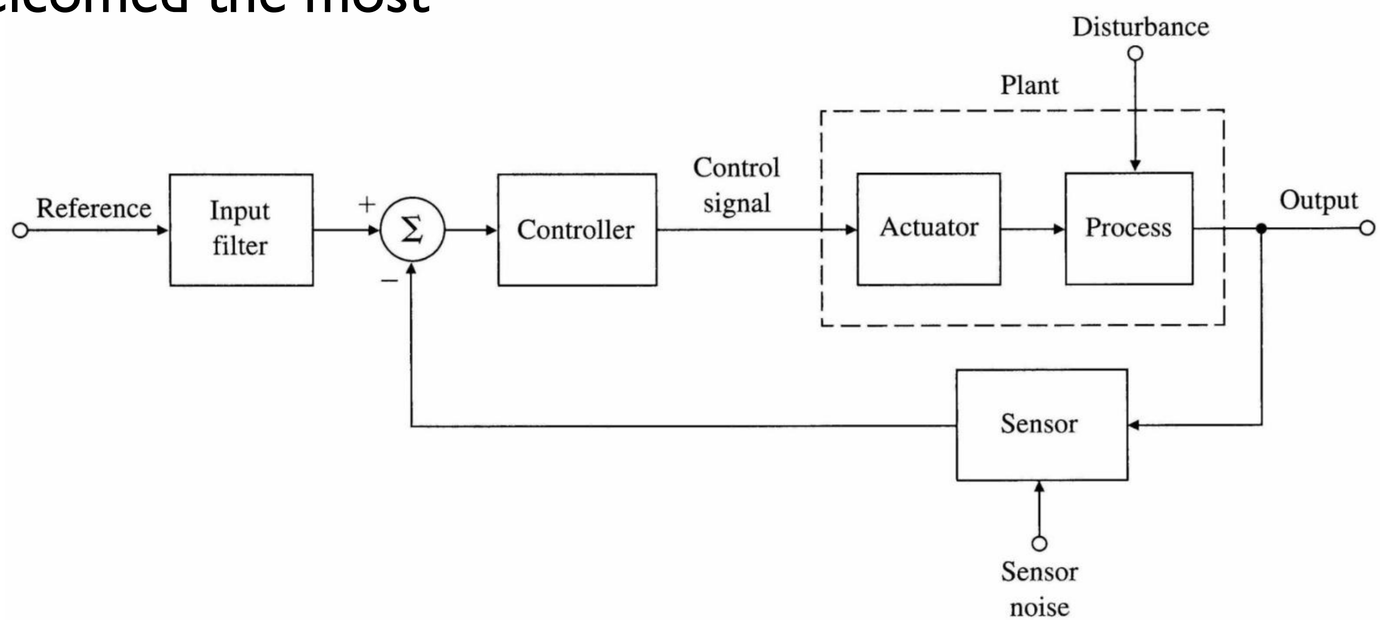
$$\ddot{\alpha}_{s1} = \omega_{iz}^2 \sin\alpha_{s1}\cos\alpha_{s1} - \omega_{iz}^2 \sin\eta_s\cos\eta_s + \frac{2\dot{\alpha}_{s1}\dot{\beta}_{s1}\sin\beta_{s1}}{\cos\beta_{s1}} - \frac{2\dot{\beta}_{s1}\omega_{sy}\sin\beta_{s1}}{\cos\beta_{s1}} + 2\dot{\beta}_{s1}\omega_{iz}\cos\alpha_{s1}\sin\eta_s$$
$$- 2\dot{\beta}_{s1}\omega_{iz}\sin\alpha_{s1}\cos\eta_s - 2\omega_{iz}^2\sin\alpha_{s1}\cos\alpha_{s1}\cos^2\eta_s + 2\omega_{iz}^2\cos^2\alpha_{s1}\sin\eta_s\cos\eta_s - \frac{r\omega_{sy}^2\sin\alpha_{s1}}{\ell\cos\beta_{s1}}$$
$$+ \frac{\dot{\omega}_{iz}\cos\alpha_{s1}\sin\beta_{s1}\sin\eta_s}{\cos\beta_{s1}} - \frac{\dot{\omega}_{iz}\sin\alpha_{s1}\sin\beta_{s1}\cos\eta_s}{\cos\beta_{s1}} - \frac{b_{\alpha s}\dot{\alpha}_{s1}}{\ell^2 m\cos\beta_{s1}^2} - \frac{r\omega_{iz}^2\sin\alpha_{s1}\cos^2\eta_s}{\ell\cos\beta_{s1}}$$
$$+ \frac{r\omega_{iz}^2\cos\alpha_{s1}\sin\eta_s\cos\eta_s}{\ell\cos\beta_{s1}}$$

$$\ddot{\beta}_{s1} = 2\dot{\alpha}_{s1}\omega_{sy}\sin\beta_{s1}\cos\beta_{s1} - \dot{\omega}_{iz}\sin\alpha_{s1}\sin\eta_s - \dot{\alpha}_{s1}^2\sin\beta_{s1}\cos\beta_{s1} - \omega_{sy}^2\sin\beta_{s1}\cos\beta_{s1} - \frac{b_{\beta s}\dot{\beta}_{s1}}{\ell^2 m}$$
$$- \dot{\omega}_{iz}\cos\alpha_{s1}\cos\eta_s + \omega_{iz}^2\cos^2\alpha_{s1}\sin\beta_{s1}\cos\beta_{s1} + \omega_{iz}^2\sin\beta_{s1}\cos\beta_{s1}\cos^2\eta_s$$
$$- 2\omega_{iz}^2\cos^2\alpha_{s1}\sin\beta_{s1}\cos\beta_{s1}\cos^2\eta_s - \frac{r\dot{\omega}_{iz}\cos\beta_{s1}\cos\eta_s}{\ell} - \frac{r\omega_{sy}^2\cos\alpha_{s1}\sin\beta_{s1}}{\ell}$$
$$- 2\dot{\alpha}_{s1}\omega_{iz}\cos\alpha_{s1}\cos^2\beta_{s1}\sin\eta_s + 2\dot{\alpha}_{s1}\omega_{iz}\sin\alpha_{s1}\cos^2\beta_{s1}\cos\eta_s + 2\omega_{sy}\omega_{iz}\cos\alpha_{s1}\cos^2\beta_{s1}\sin\eta_s$$
$$- 2\omega_{sy}\omega_{iz}\sin\alpha_{s1}\cos^2\beta_{s1}\cos\eta_s + \frac{2r\omega_{sy}\omega_{iz}\cos\beta_{s1}\sin\eta_s}{\ell} - \frac{r\omega_{iz}^2\cos\alpha_{s1}\sin\beta_{s1}\cos^2\eta_s}{\ell}$$
$$- 2\omega_{iz}^2\sin\alpha_{s1}\cos\alpha_{s1}\sin\beta_{s1}\cos\beta_{s1}\sin\eta_s\cos\eta_s - \frac{r\omega_{iz}^2\sin\alpha_{s1}\sin\beta_{s1}\sin\eta_s\cos\eta_s}{\ell}$$

Solar Sailing

Lessons learned from solar sailing:

1. Just give up – do not waste your time to try and model the world.
2. You model what you think there is
3. Things are unpredictable
4. Do not try anything fancy – the conservative decisions are welcomed the most



The Ideal World

Objective = Robot needs to reach the goal

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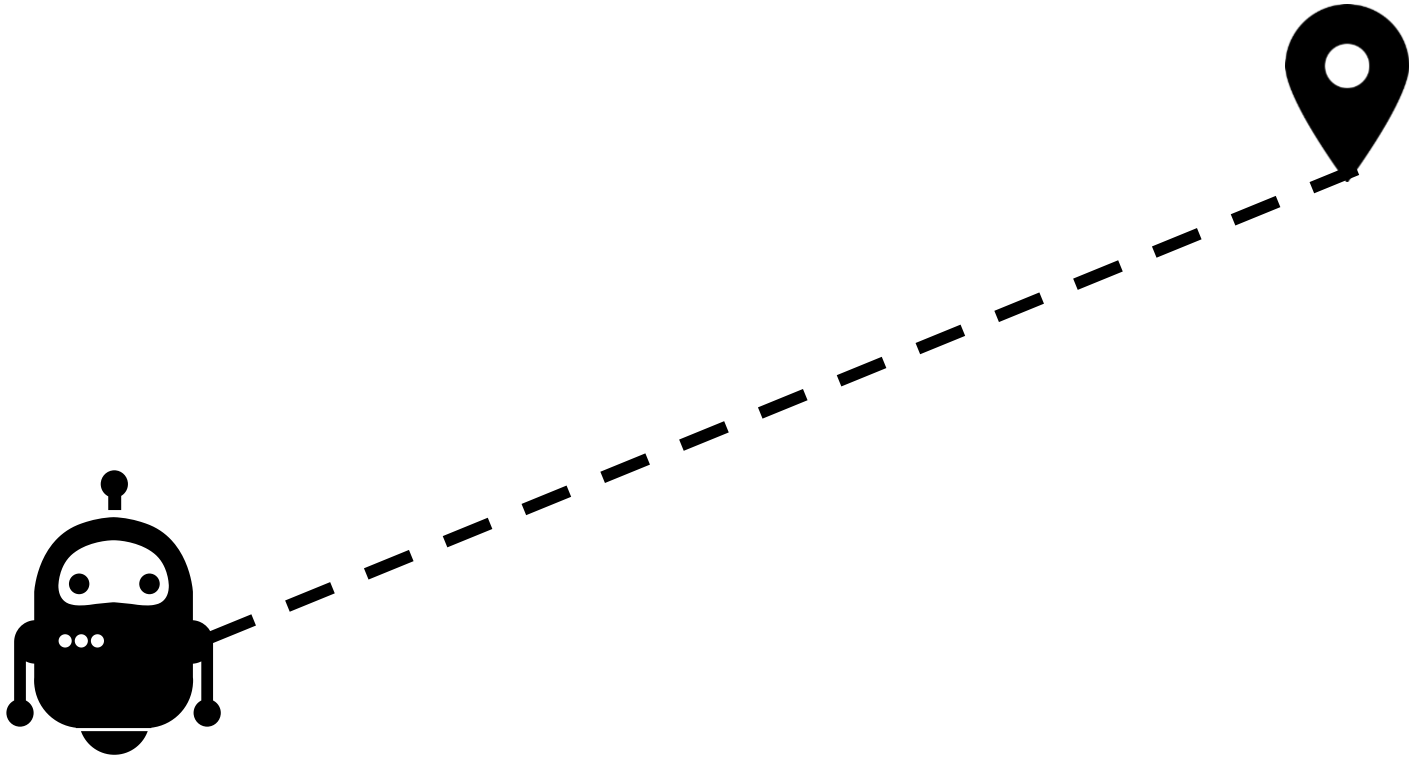

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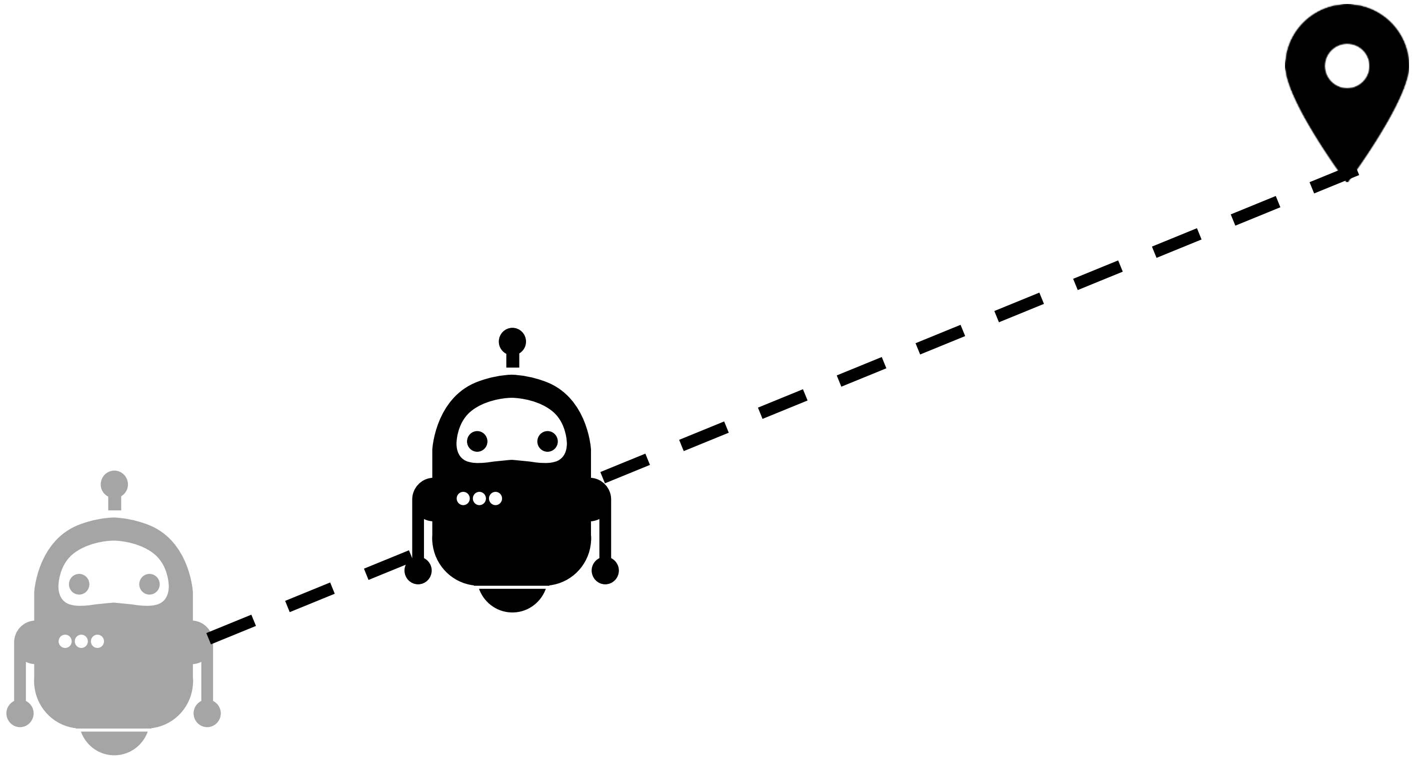

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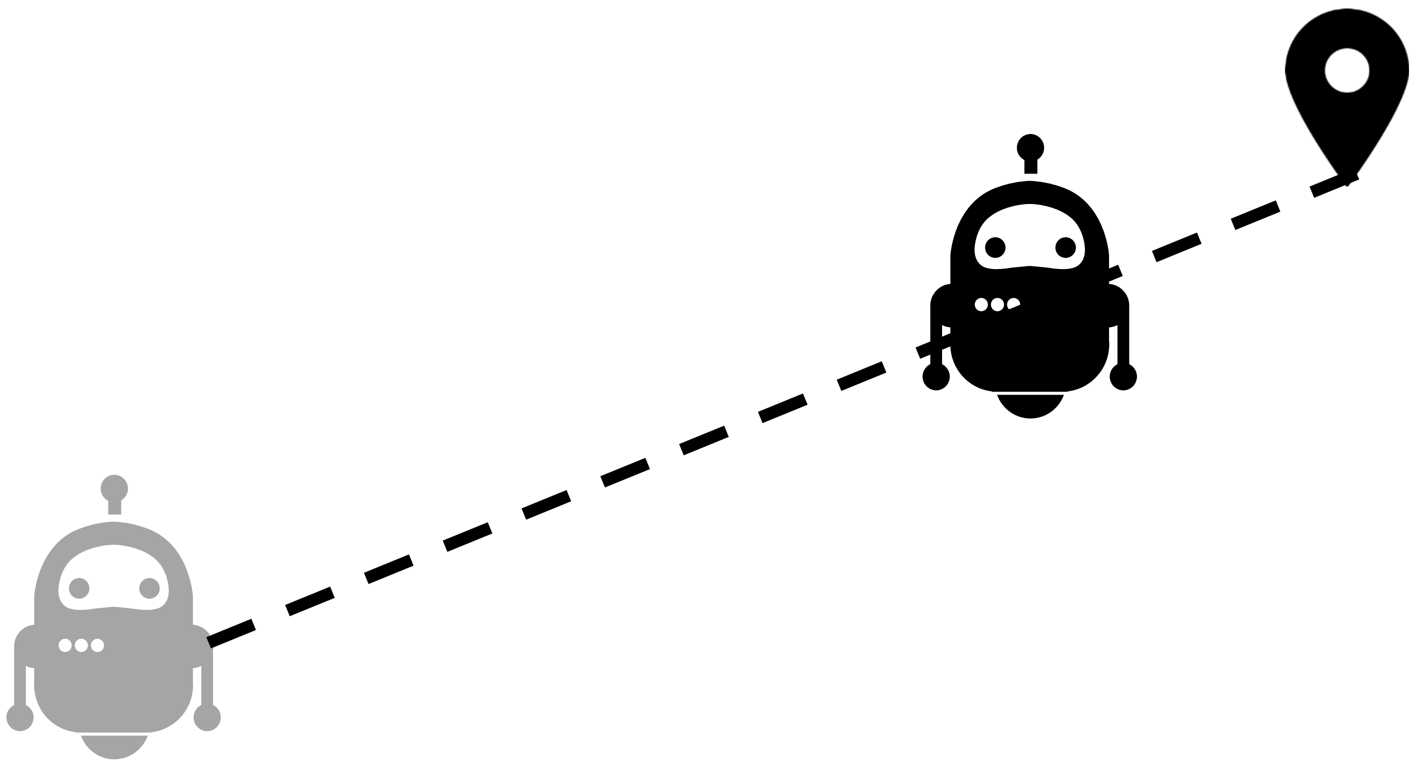
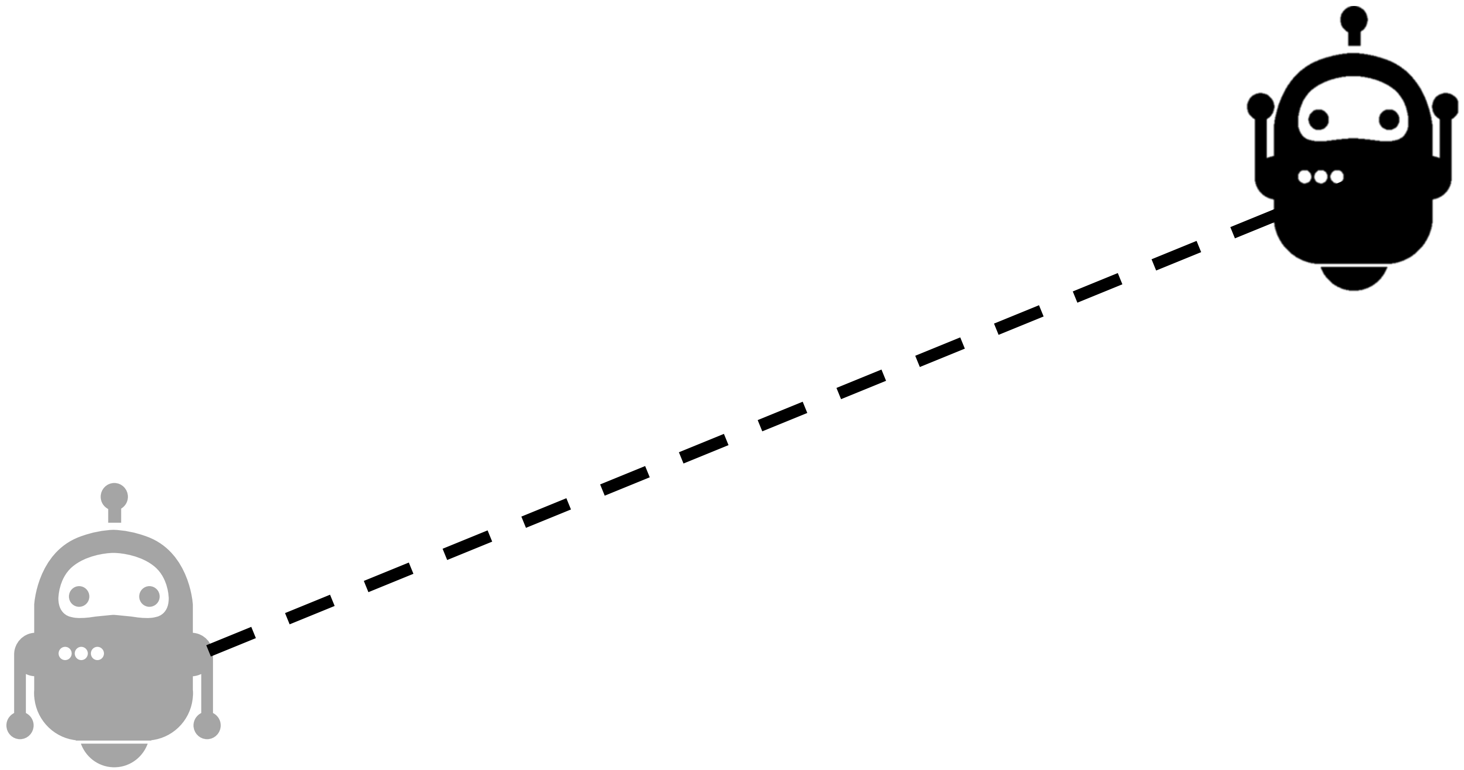


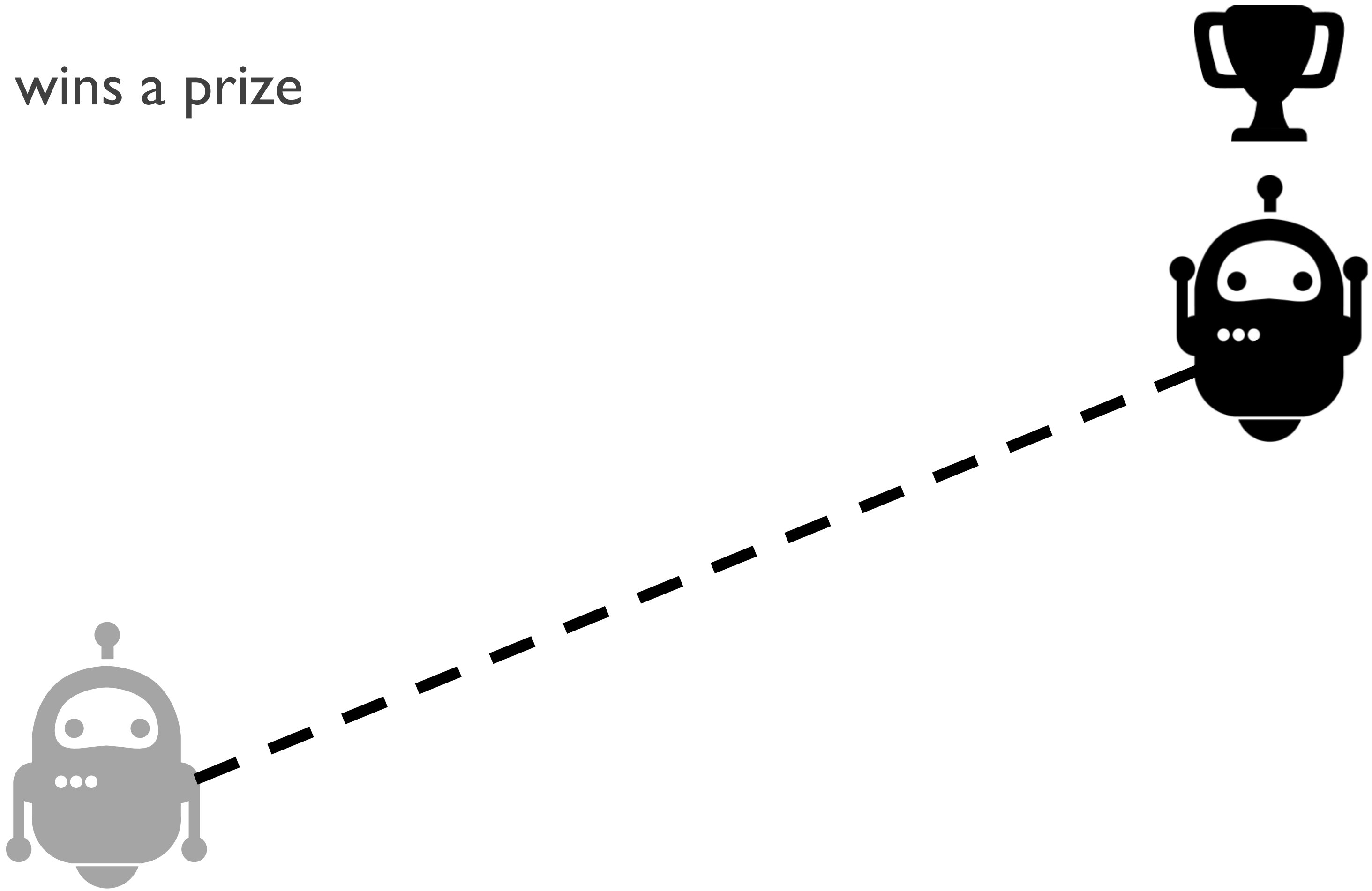
The Ideal World

Robot reached the goal



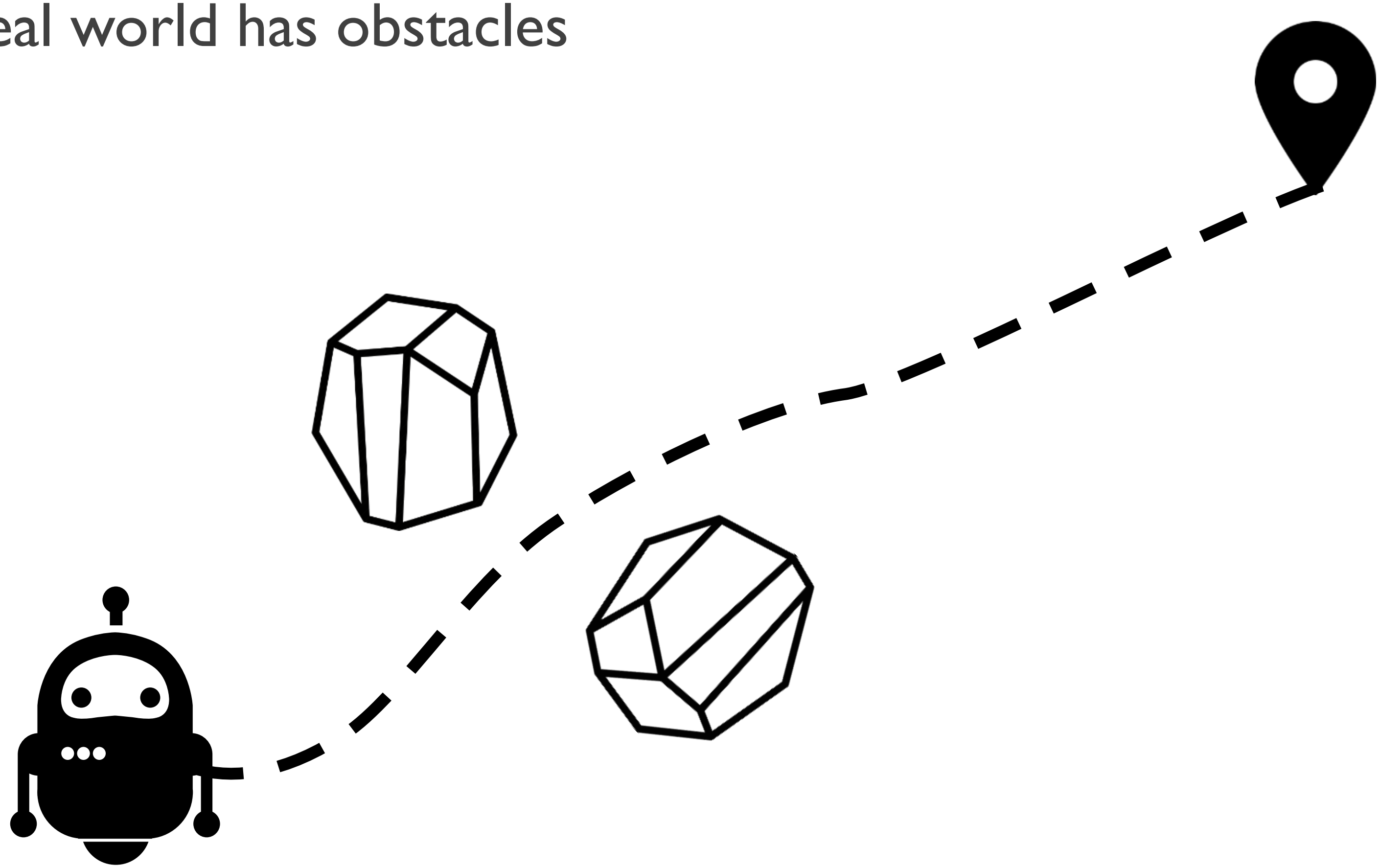
The Ideal World

Robot wins a prize



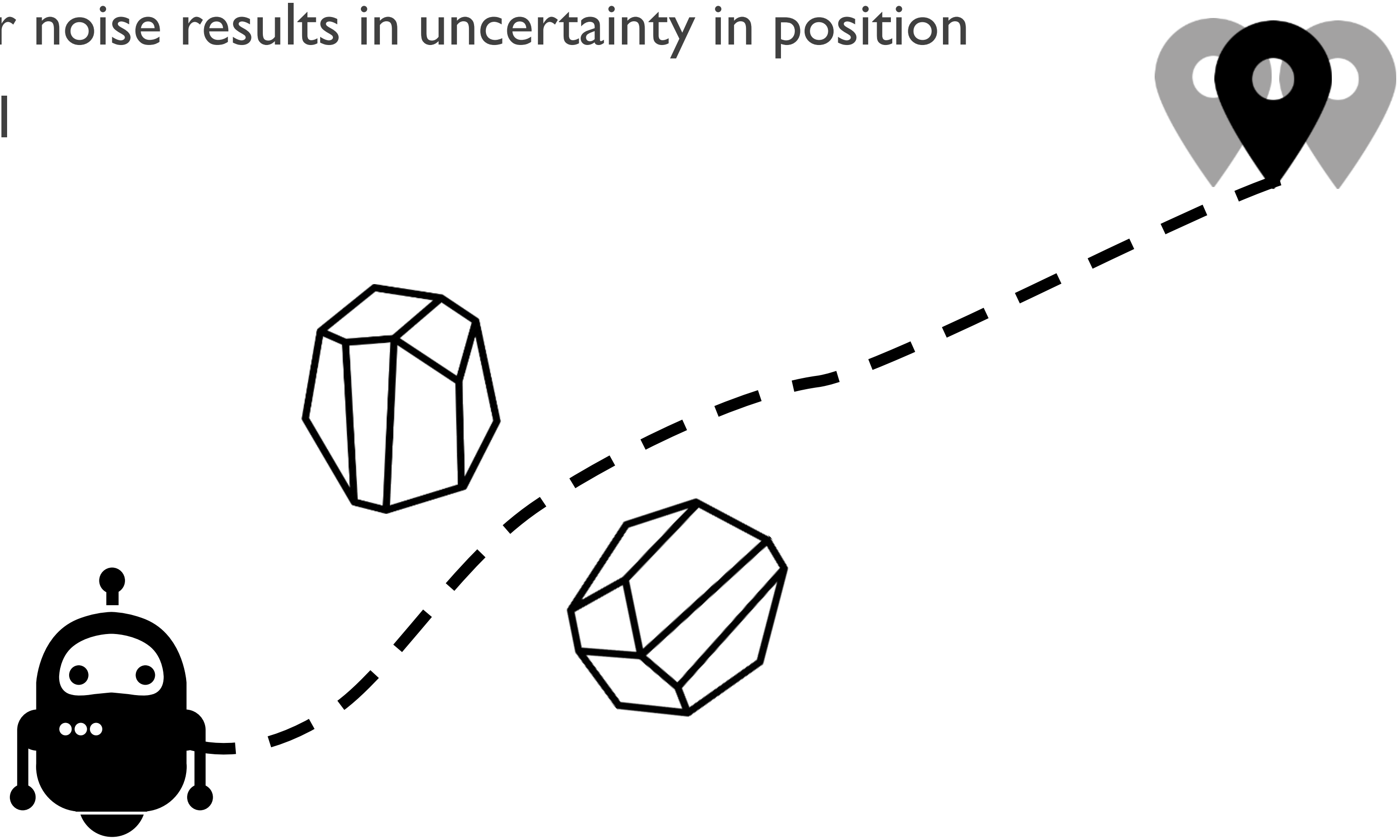
The **Real** World

The real world has obstacles



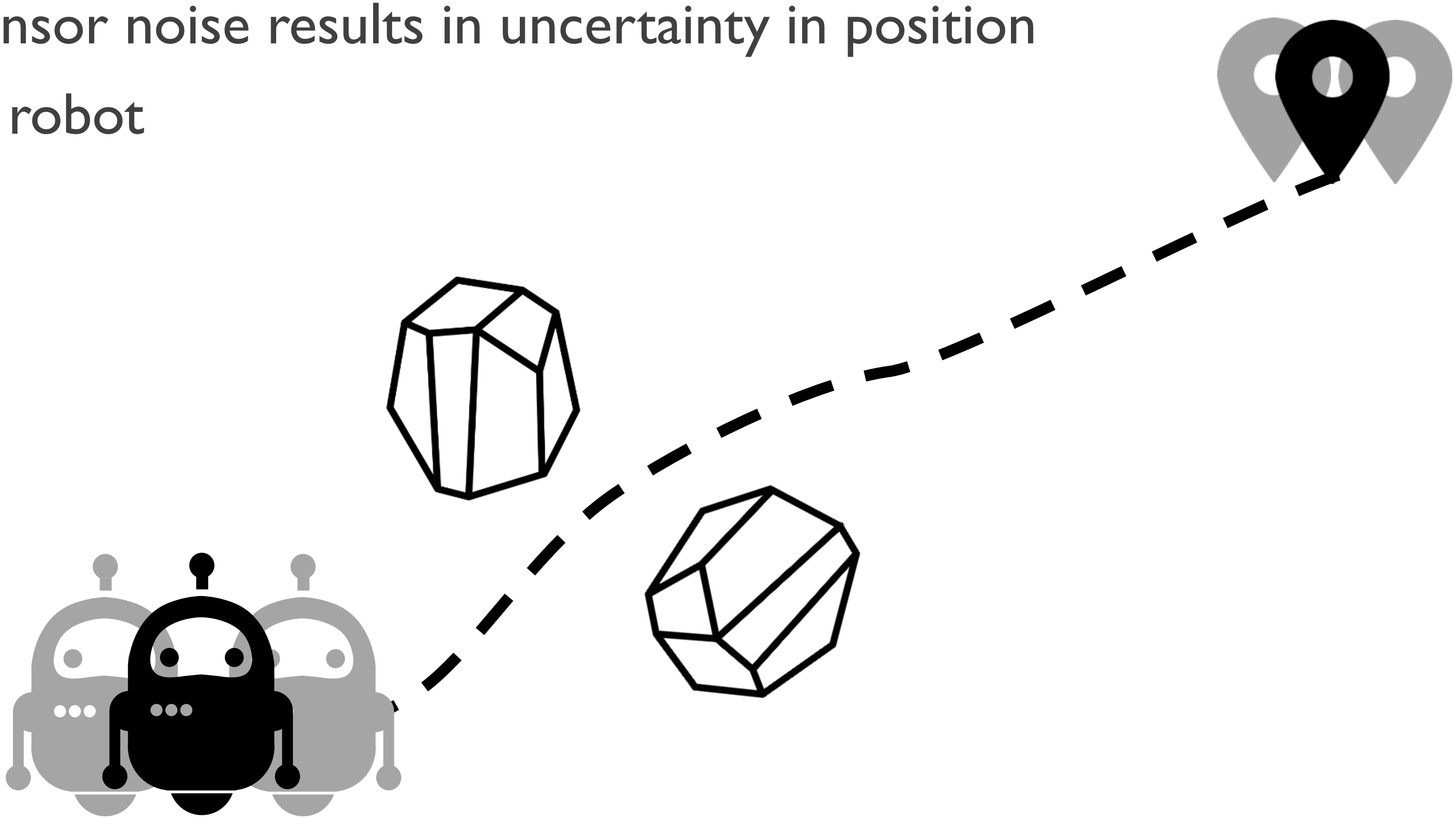
The **Real** World

Sensor noise results in uncertainty in position of goal



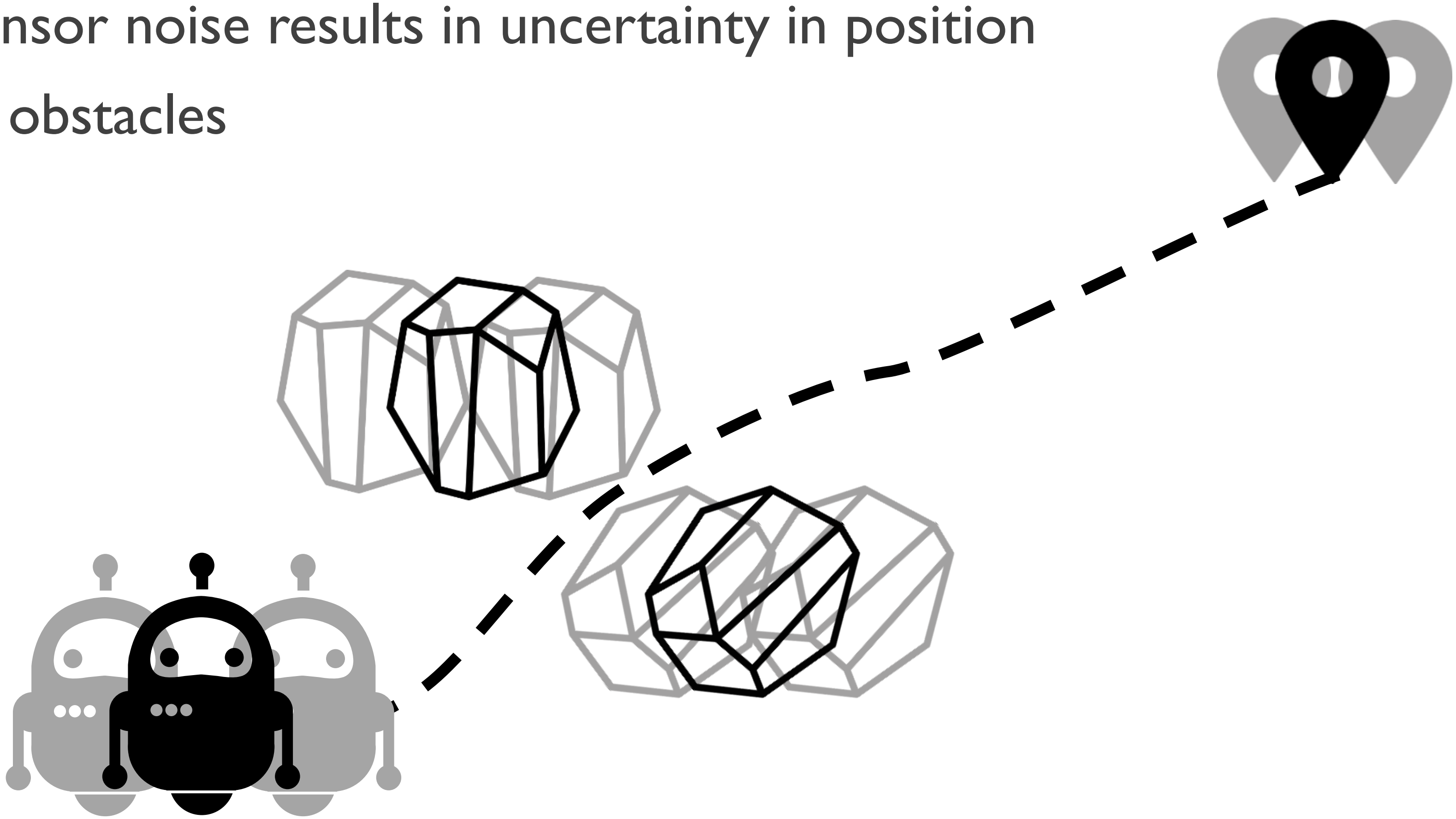
The **Real** World

Sensor noise results in uncertainty in position of robot



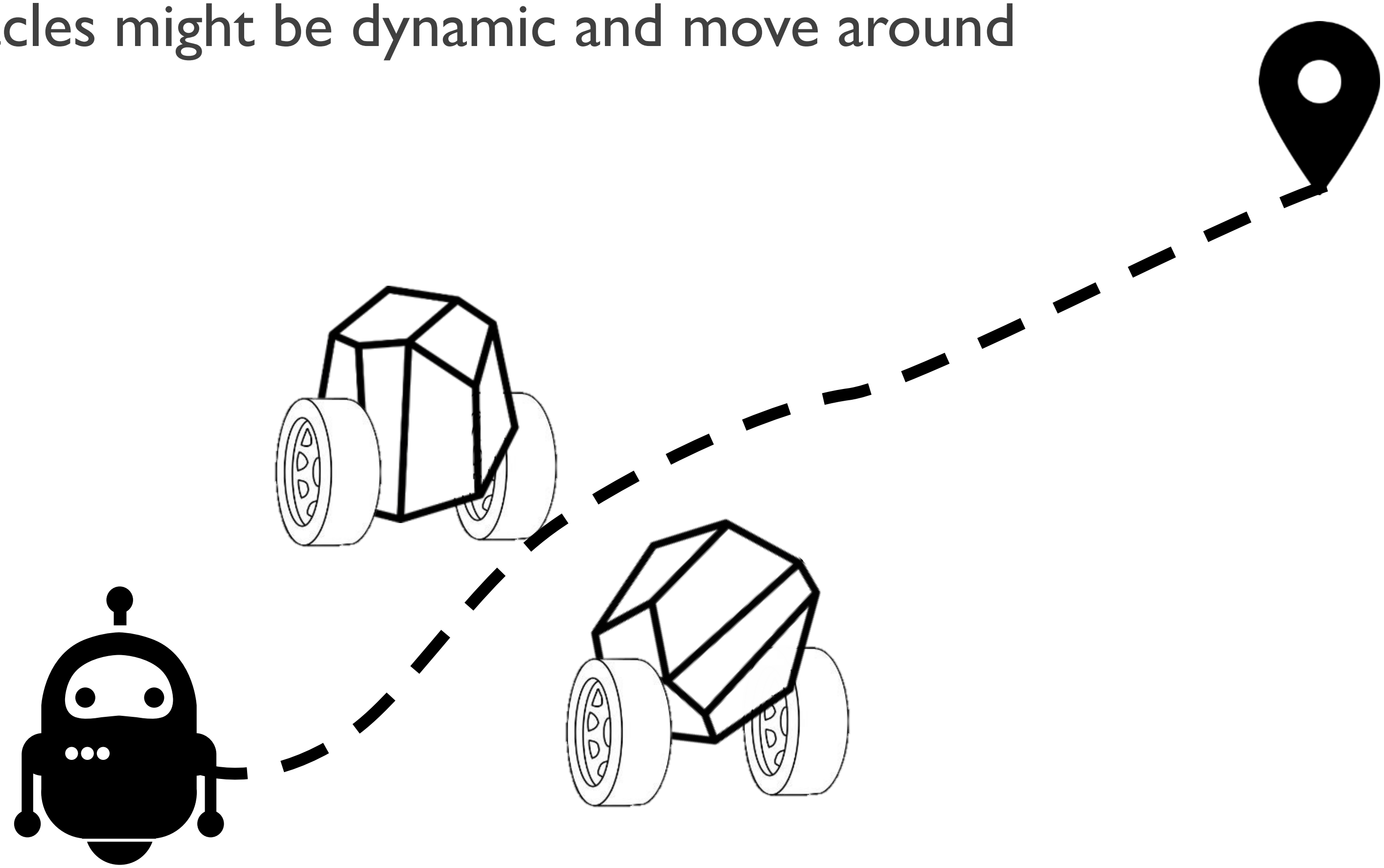
The **Real** World

Sensor noise results in uncertainty in position of obstacles



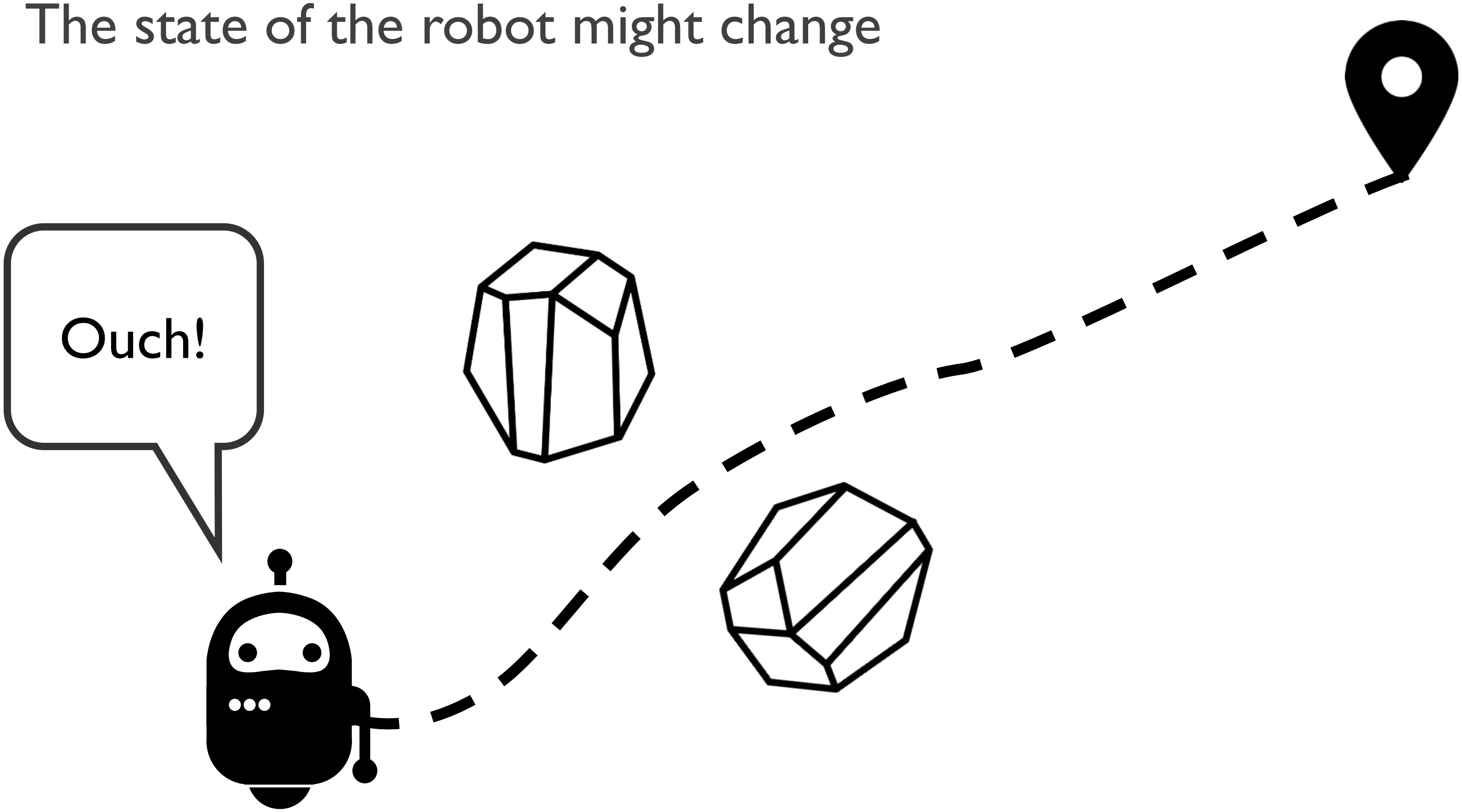
The **Real** World

Obstacles might be dynamic and move around



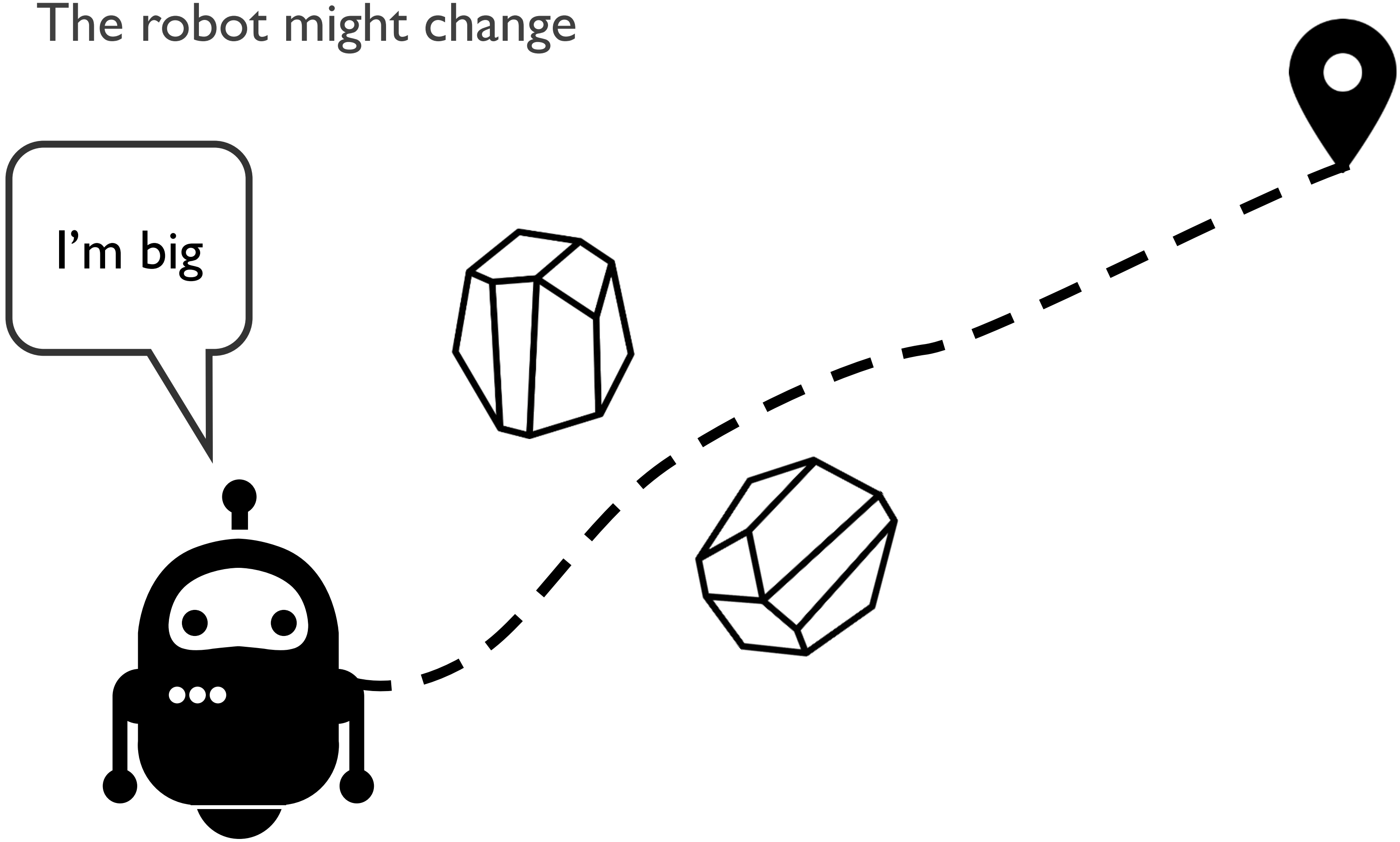
The **Real** World

The state of the robot might change



The **Real** World

The robot might change



Future Autonomous Systems

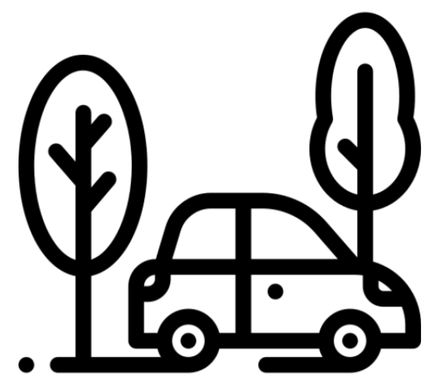
- Can we build systems that learn how to drive and handle information similar to a human?
- How do you learn how to drive?
  - Learn how to drive from textbook
  - Practice in controlled environment
  - Go through a test
  - Get license, ready for the world?

Future Autonomous Systems

- Can we build systems that learn how to drive and handle information similar to a human?
- How do you learn how to drive?
  - Learn how to drive from textbook / Model your system
  - Practice in controlled environment / Implement and test in simulation
  - Go through a test / Lab based tests
  - Get license, ready for the world? / Sign off, ready for the real world?

Future Autonomous Systems

- How do we make decisions when facing uncertainty?
  - handle it with caution and make conservative decision
  - harness previous experiences and try something which we did in a past similar scenario
  - use knowledge of system and predict best action
  - just simply try something and see if it works



Future Autonomous Systems

- Future autonomous systems will:
  - have increased autonomy.
    - Ability to execute a mission even in the presence of uncertainties (robust autonomy)
    - Be able to adapt to unknown scenarios (intelligent autonomy)
  - be more distributed with a collective function.
    - Specialized systems working together to perform a common task (organizational autonomy)

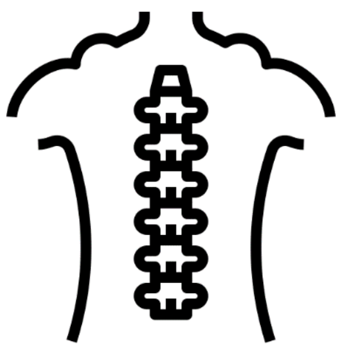
Future Autonomous Systems

- The way to approach the problem is to look at hybrid solutions
  - Combine a number of tools to exploit their own unique advantages
    - Conventional Control – fast, robust and predictable
    - Adaptive Control – investigate own performance relative to benchmark
    - Neural Networks – classifying experiences/data
    - Probabilistic Models – reason with uncertain data
    - Many others
- Obtain systems that are practically feasible and implementable
- Need to conform to stability and safety requirements.

Constraints

Only add complexity when and where it is required – make black-box as small as possible.

- Advanced and complex solutions
- Focus on uncertain or unknown scenarios
- High-level decisions, have time to think
- Machine-learning based techniques



- Fundamental and reflex behavior
- Stable and fast
- Very predictable behavior
- Conventional model based control and maneuvers

Different Problems

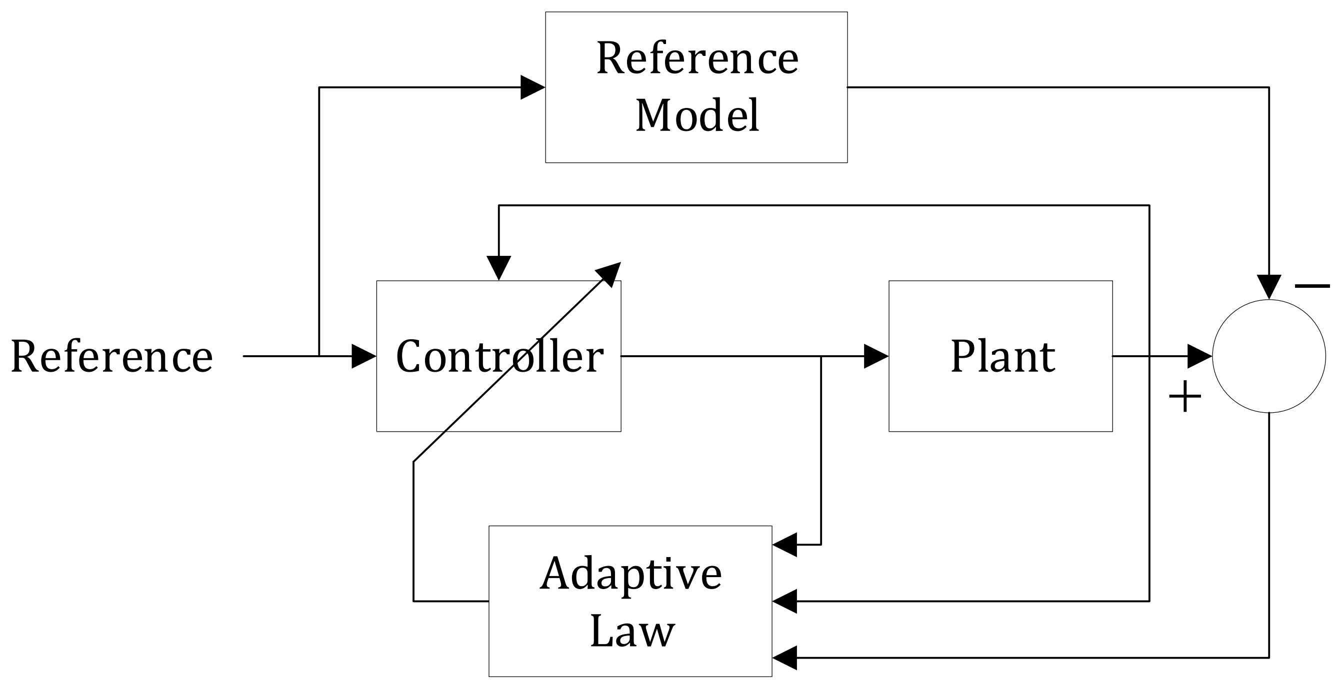
- Can break research approach into two categories:
  - Model Uncertainty – Drone with an Unknown Payload
  - Event Uncertainty – Autonomous Vehicle Racing and Satellite Manager

Drone with Unknown Payload

- A drone needs to transport a payload one to point to another, but do not have full knowledge of the payload.
- Conventional, static controllers might be able to execute mission but result in extremely high and dangerous oscillations of the vehicle and payload.
- Other options:
  - Adaptive control
  - Vision-based systems
  - Unknown disturbance estimation
  - Data-driven system identification
  - Coarse-ID control

Drone with Unknown Payload

Adaptive control – continuously inspect current behavior and use a adaptation function to change the control system to obtain a required dynamic response.



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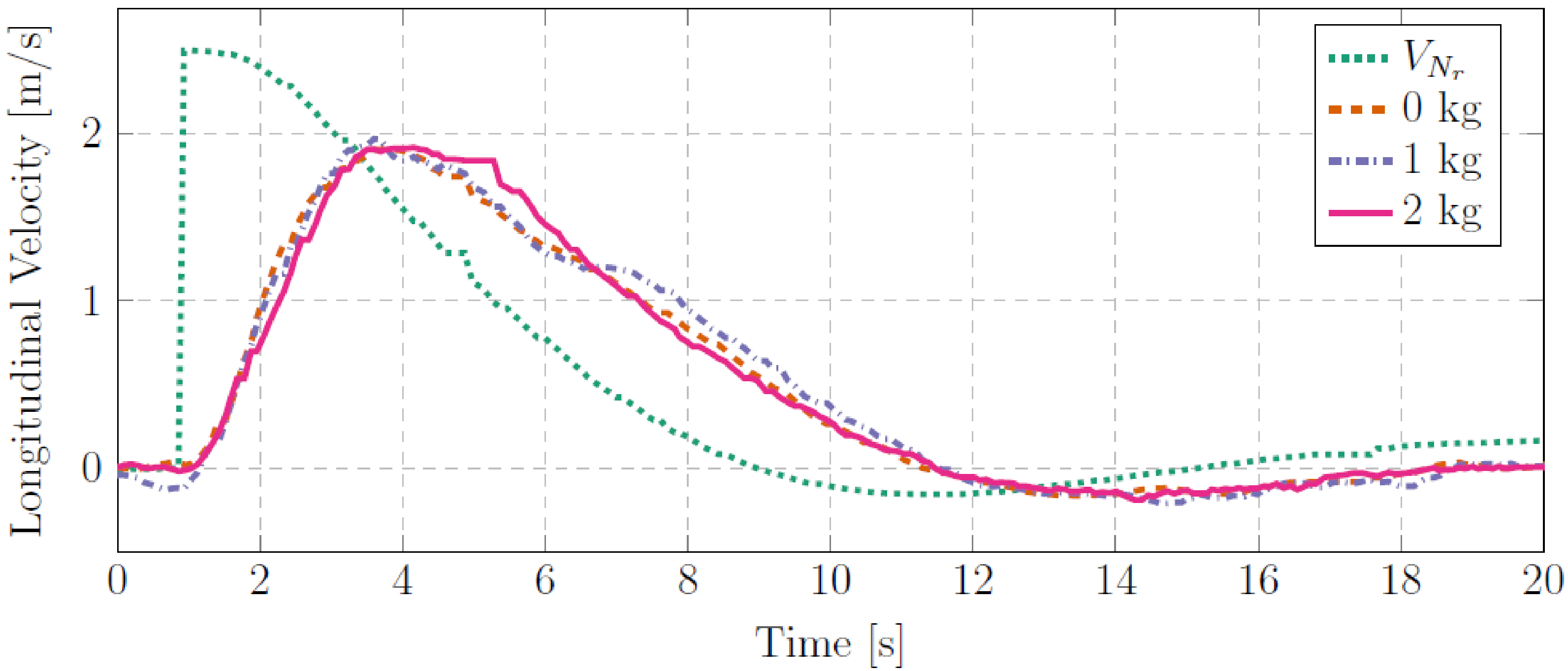

Drone with Unknown Payload

Vision-based control of unknown payload – downward facing camera tries to identify a payload with unknown form and estimate its parameters. Use this information to automatically generate optimal linear controllers and input filters to minimize oscillations.

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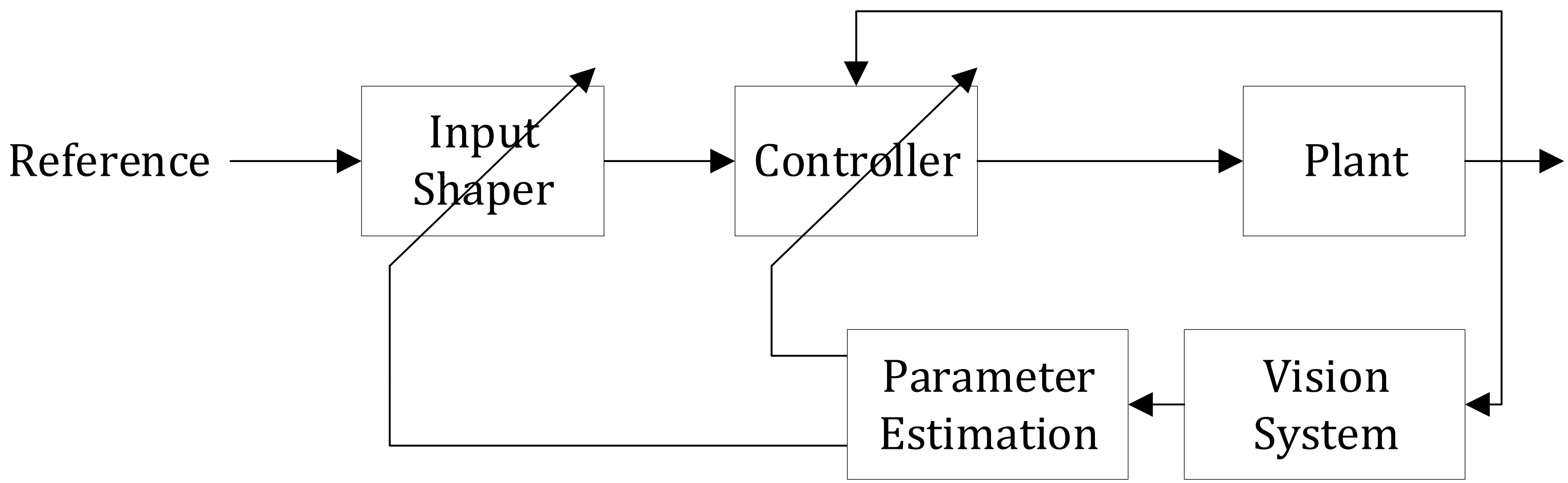
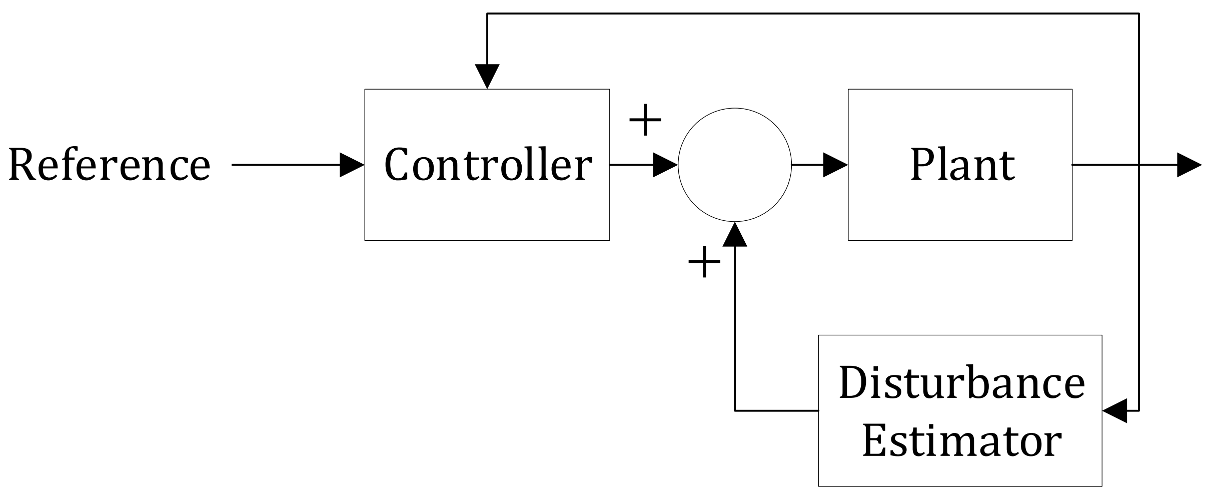


Drone with Unknown Payload

Unknown disturbance estimation – learn the nominal behavior of the system, compare expected behavior to measured behavior to determine disturbances and generate control signals to minimize its effect.



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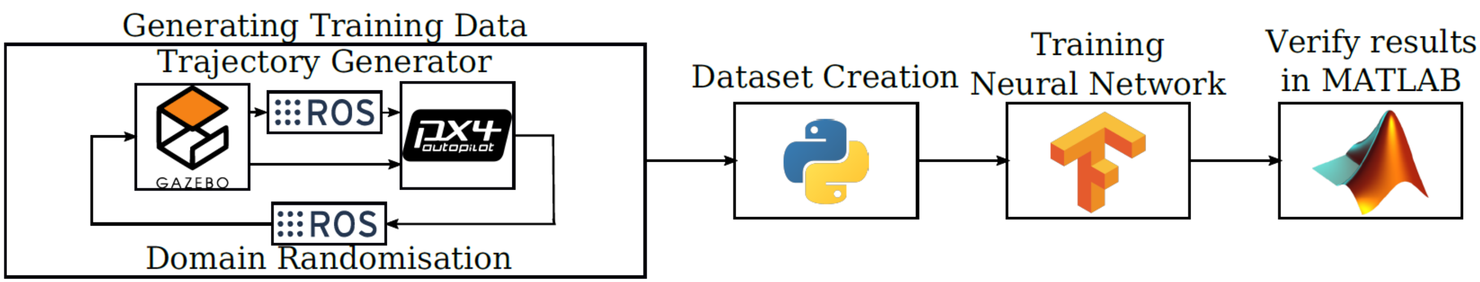
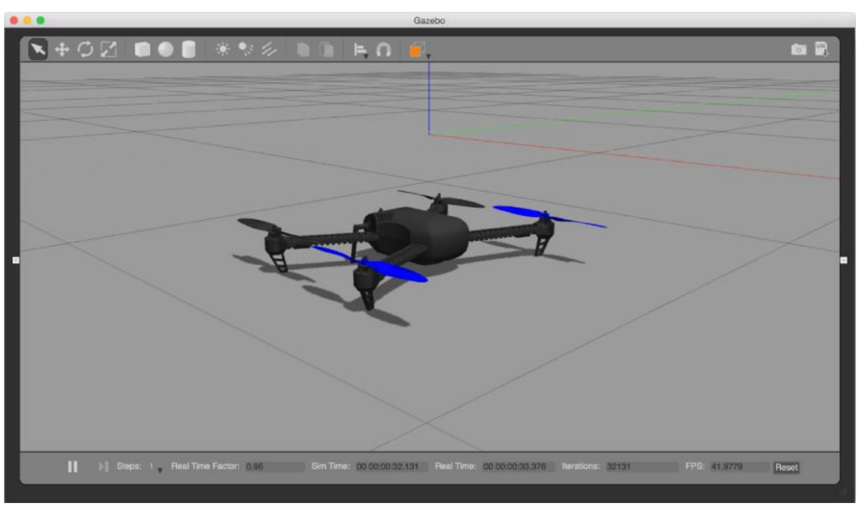
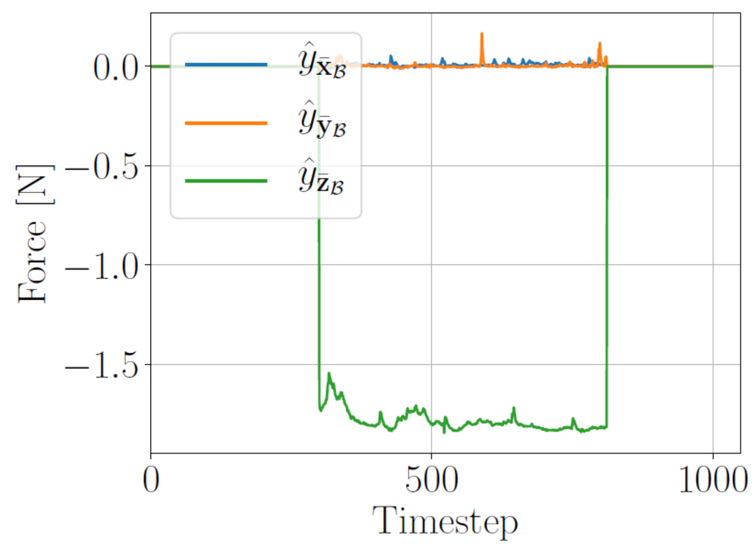
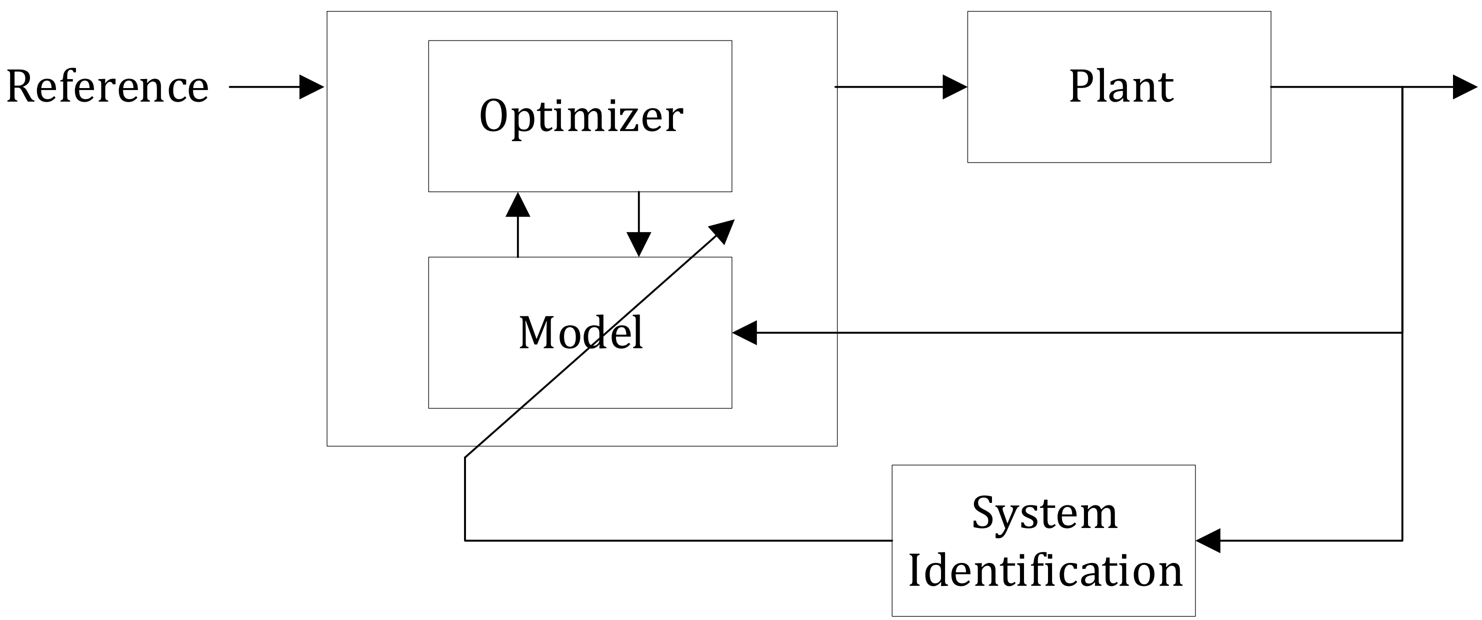






Drone with Unknown Payload

Data-driven system identification – use measurements from the system to model the current behavior, use optimization instead of conventional control to generate control signals.



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SINDY

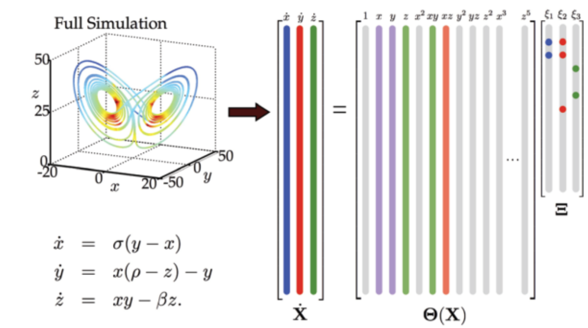


Image credit Data-Driven Science and Engineering

DMD

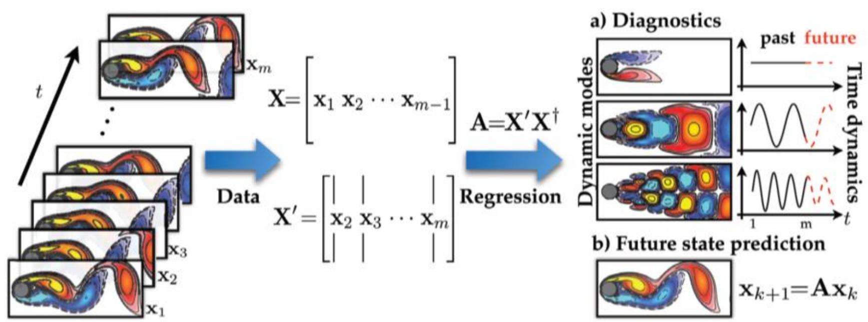
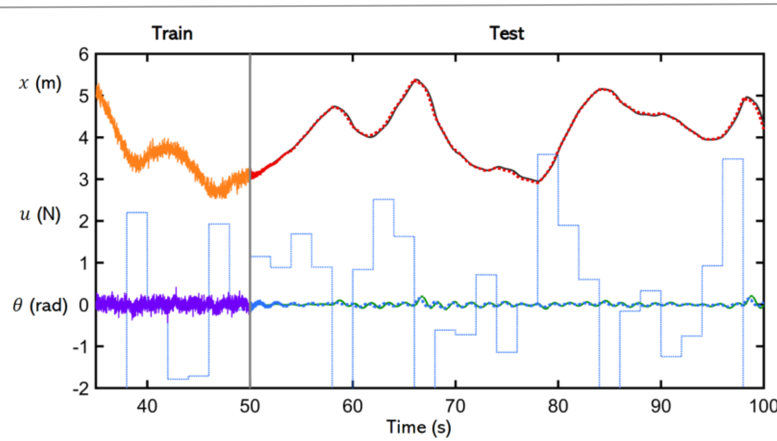
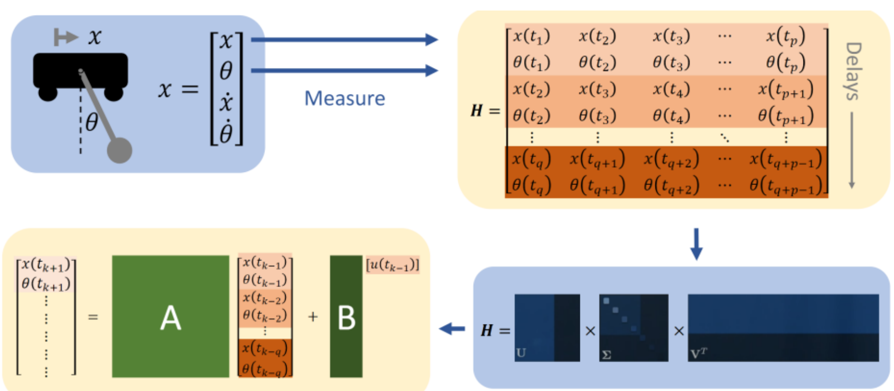


Image credit Data-Driven Science and Engineering

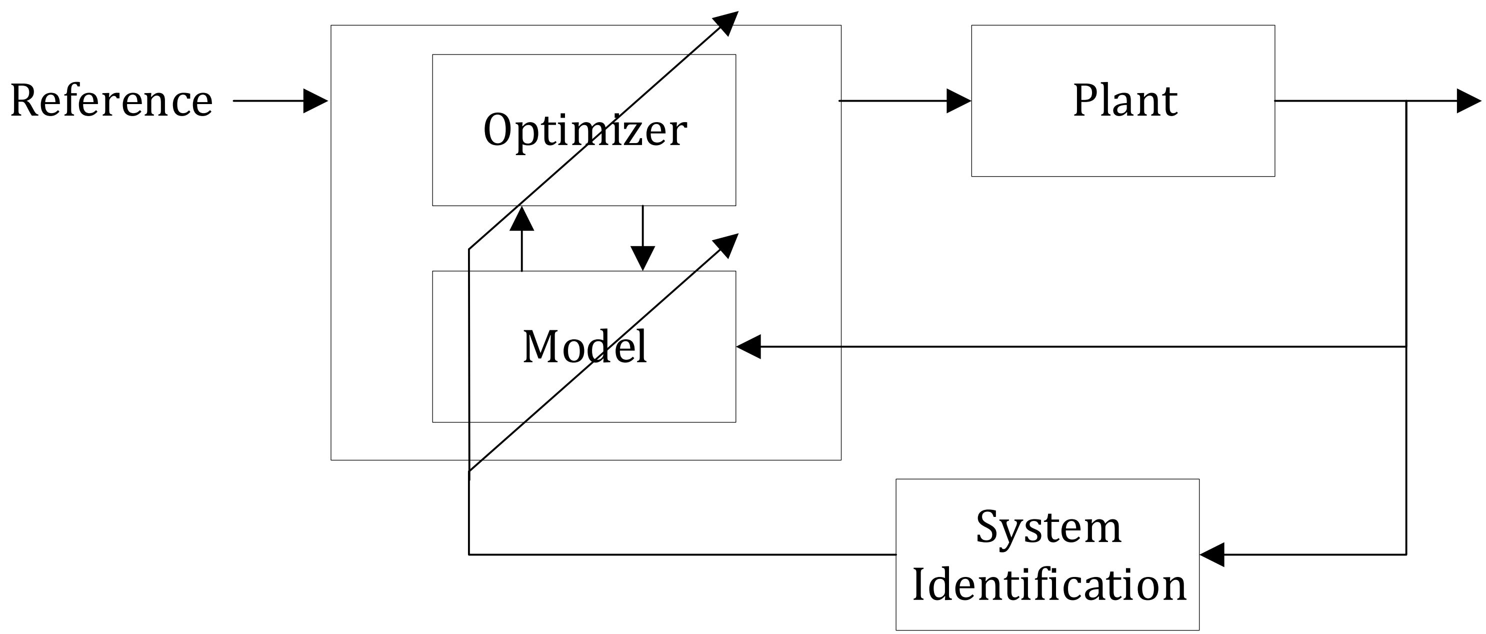
HAVOK





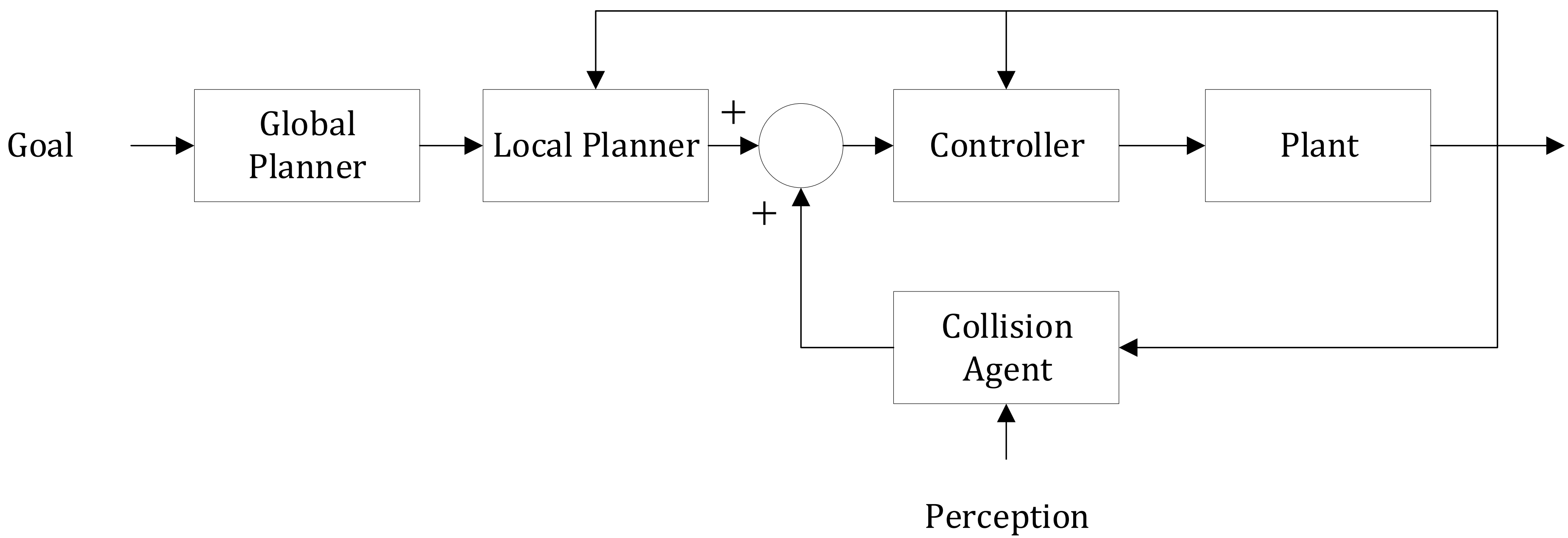
Drone with Unknown Payload

Coarse-ID control – determine a model of the current system and adjust performance to fit the current level of uncertainty. More sure of estimated behavior, faster maneuvering.



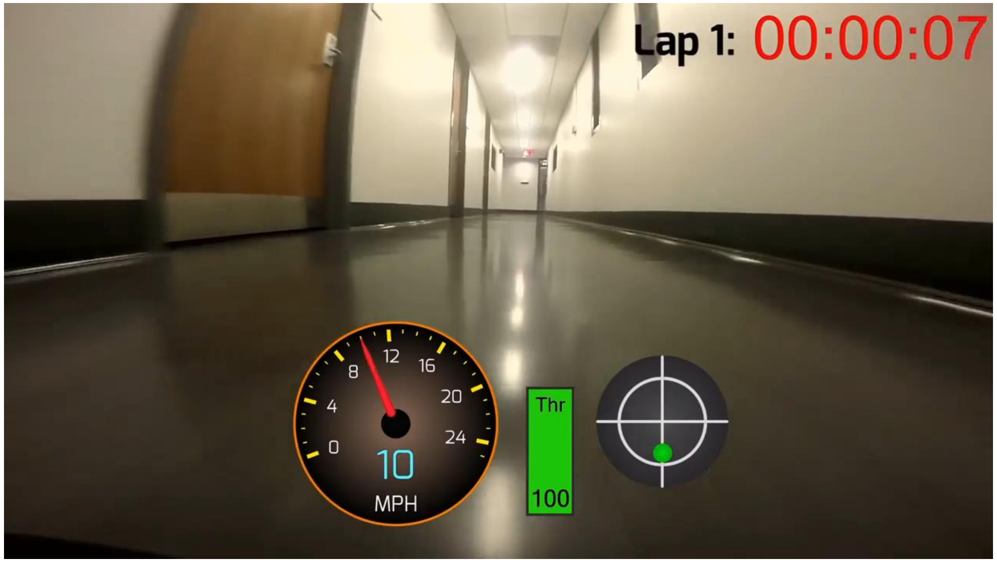
Autonomous Vehicle Racing

Policy-based collision avoidance – make use of a global trajectory and use a trained agent to make slight adjustments to vehicle references to reduce risk of collision.

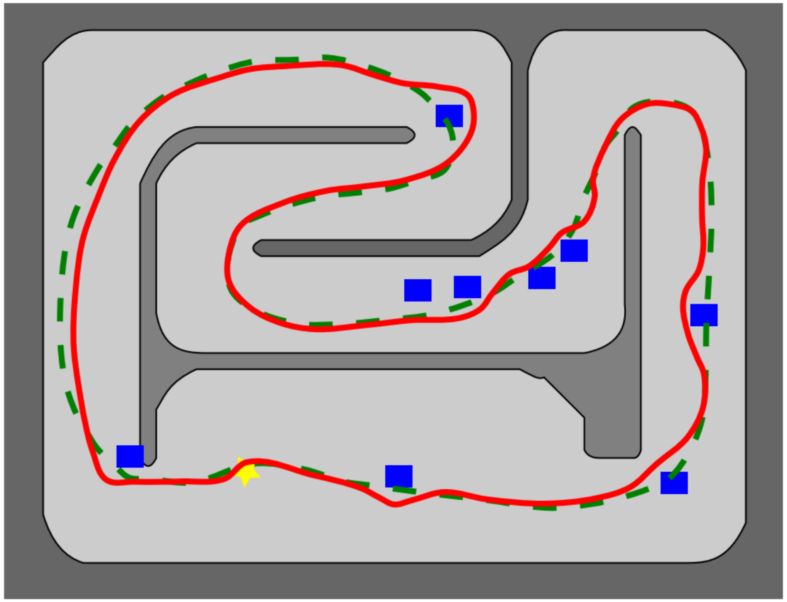


Autonomous Vehicle Racing

Collision avoidance agent – make use of a global trajectory and use a trained agent to make slight adjustments to vehicle references to reduce risk of collision.

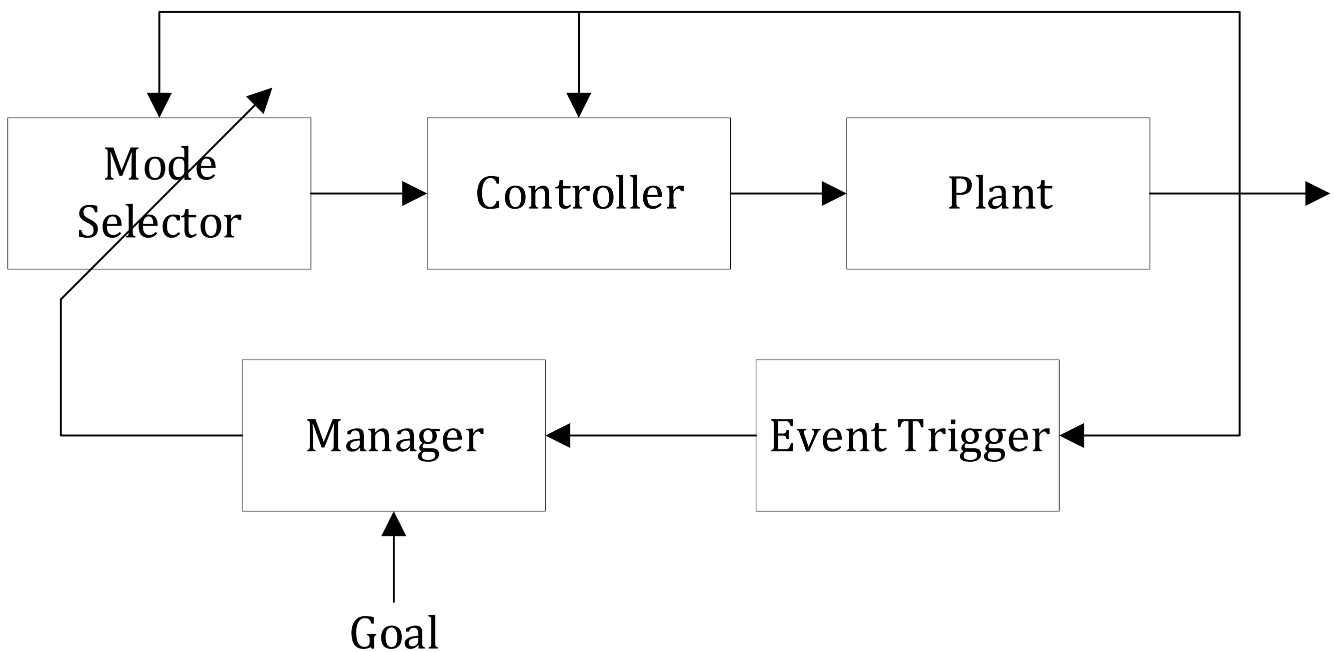


Video credit: University of Pennsylvania



Satellite Manager

Autonomous fault detection and reaction – detect possible errors in spacecraft operation and automatically make mode changes to maximize spacecraft health.



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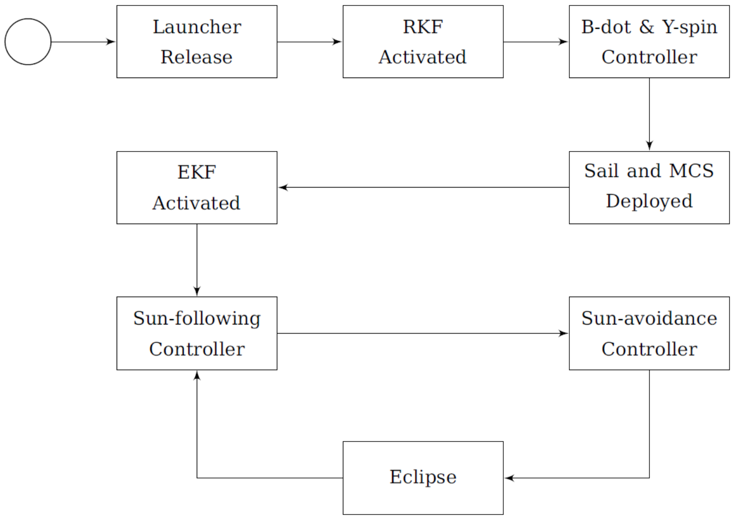
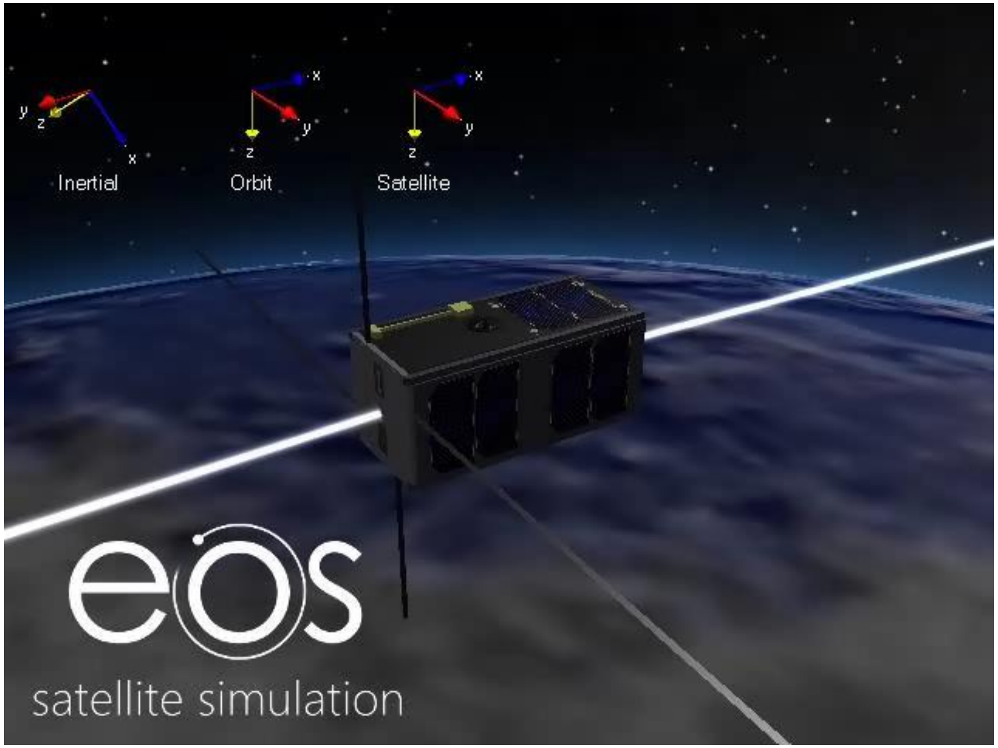


ADCS Control Modes for Solar Sailing Satellite



Future Autonomous Systems

In the paper "Survey of Advances in Control Algorithms of Quadrotor Unmanned Aerial Vehicle" by Li et al. the following conclusion is made

"

We must admit that vision-based navigation and guidance of quadrotor has become a research hotspot. But we believe that two aspects of quadrotor control will take some years of research in actual applications:

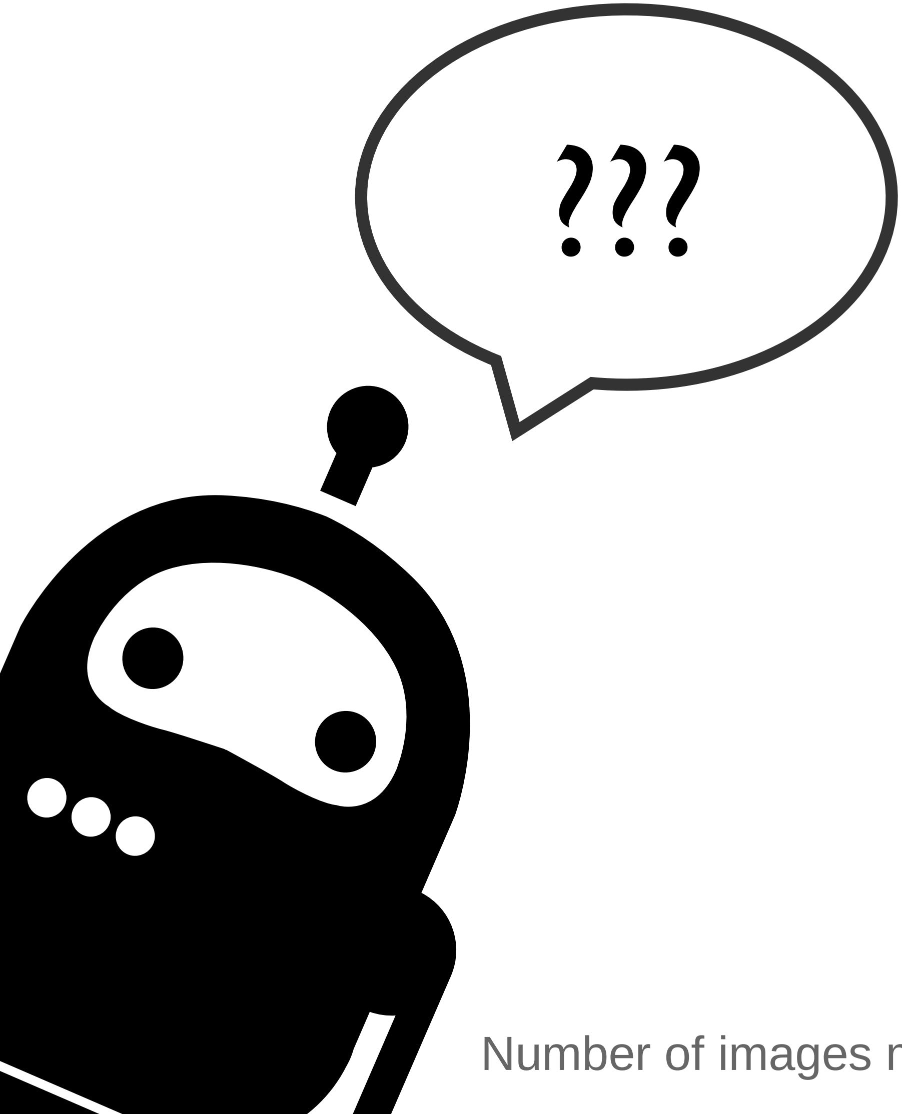
1) Robust controller should be designed to guarantee good flight performance, which can handle uncertainties.

2) Reconfigurable control system should be designed, which can change or switch between different control algorithms under different flight and mission conditions.

So, the use of hybrid control schemes is still the future trend.

"

Questions



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