Exploiting Ground and Ceiling Effects on Autonomous UAV Motion Planning

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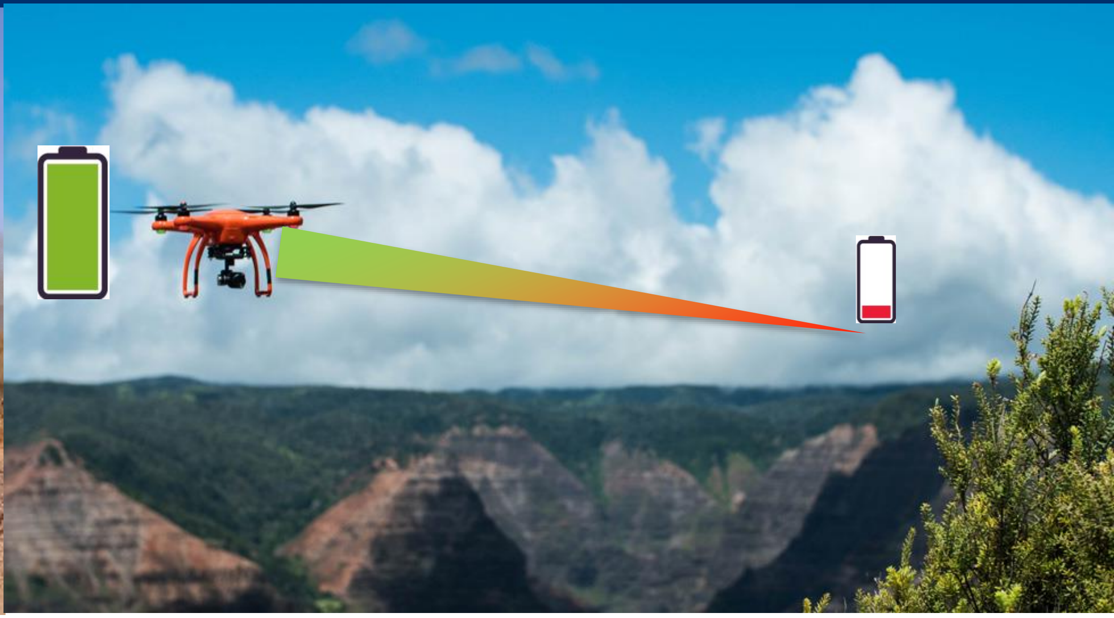
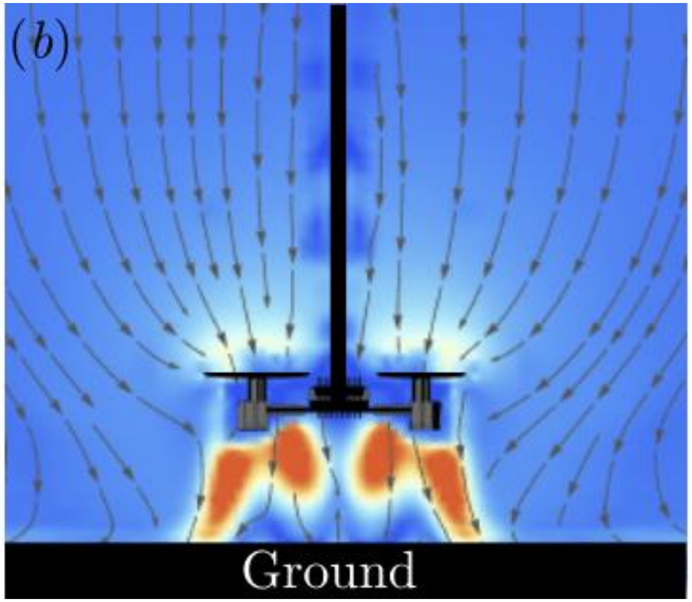
Introduction

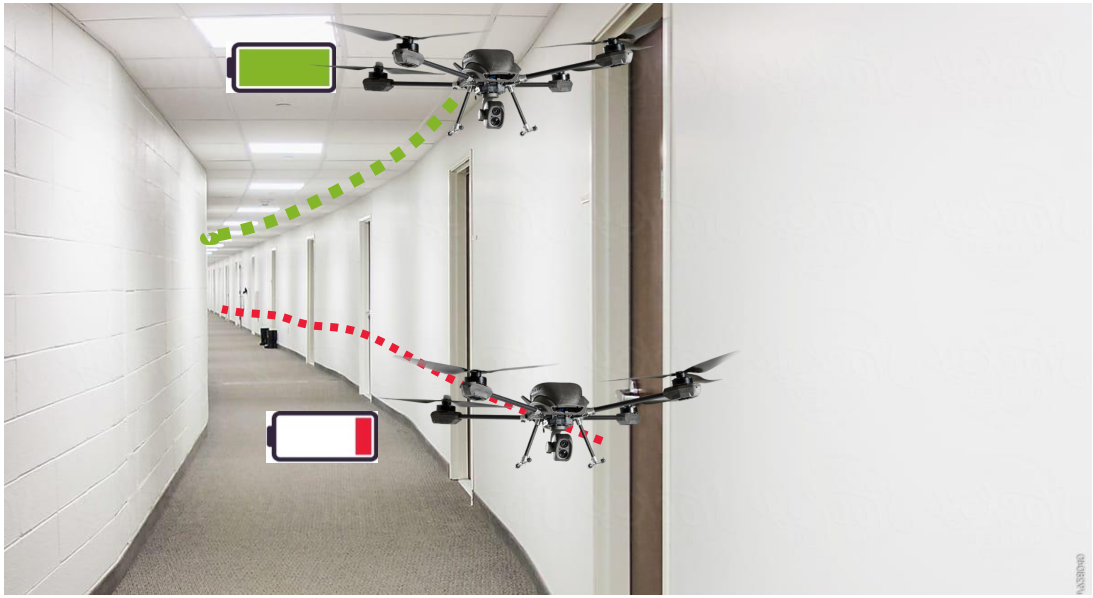


Challenges in UAVs Applications

- Micro aerial vehicles have **limitations**, like **limited battery life**, **payloads** and **size** constraints
- Sensors on UAV are **bulky**, **energy consuming**, and **not always reliable**

Motivation





Surface effects (ground/ceiling effect) provide extra lift when UAV flying close to the surface

- We can leverage this effect to sense the distance from the ground
- Moreover, the extra lift can be used to **save energy**

Problem Formulation

PROBLEM 1: ***Surface Detection***

Find a function f which **maps** the **thrust values** to the **distance** from the surface

$$d = f(F)$$

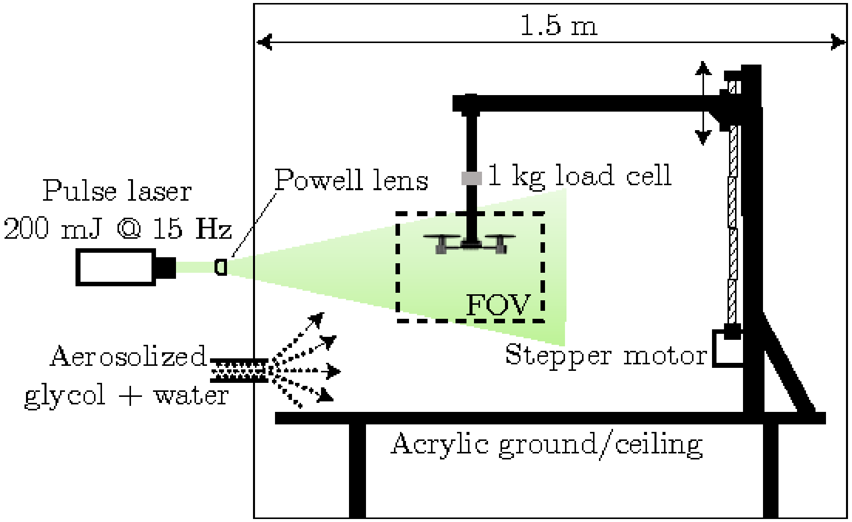
PROBLEM 2: ***Surface-based Optimal Path Planning****:*

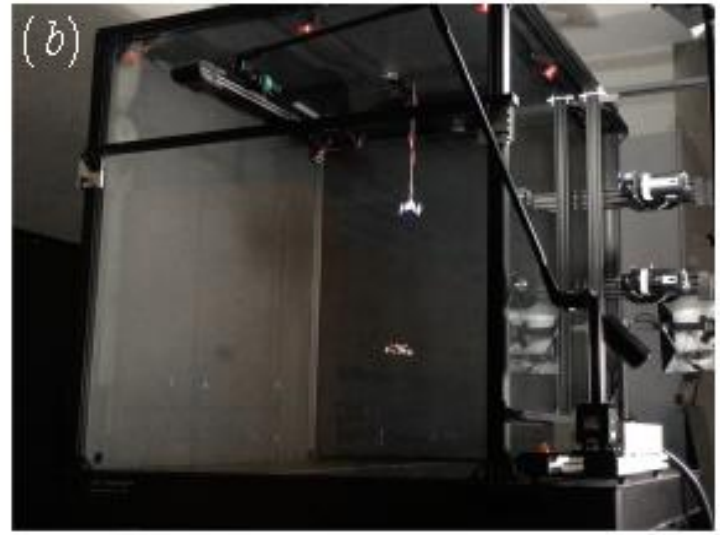
Minimize the **energy consumption** during waypoint navigation in a known environment by leveraging the extra lift provided by nearby surfaces

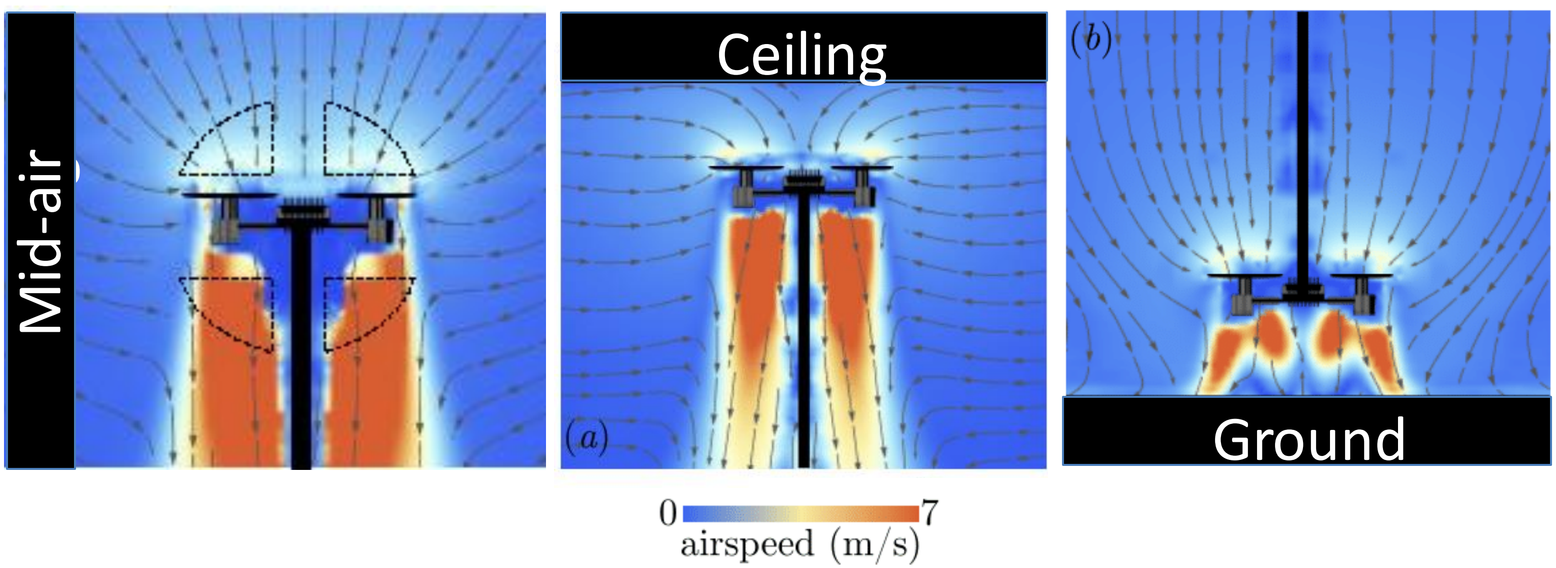
Surface detection and autonomous landing

Ground and Ceiling Effects Characterization

Visualization of air flow fields

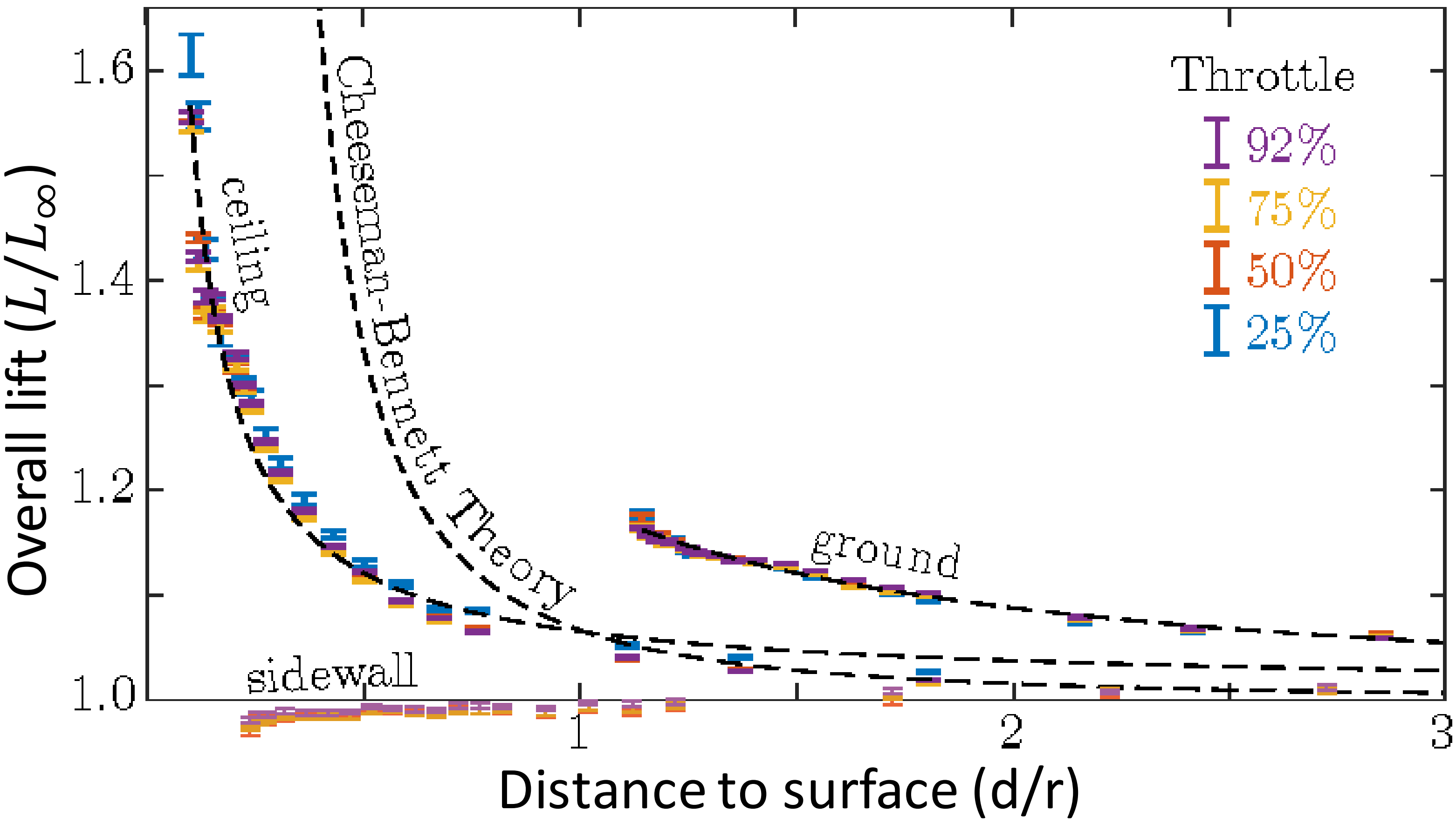






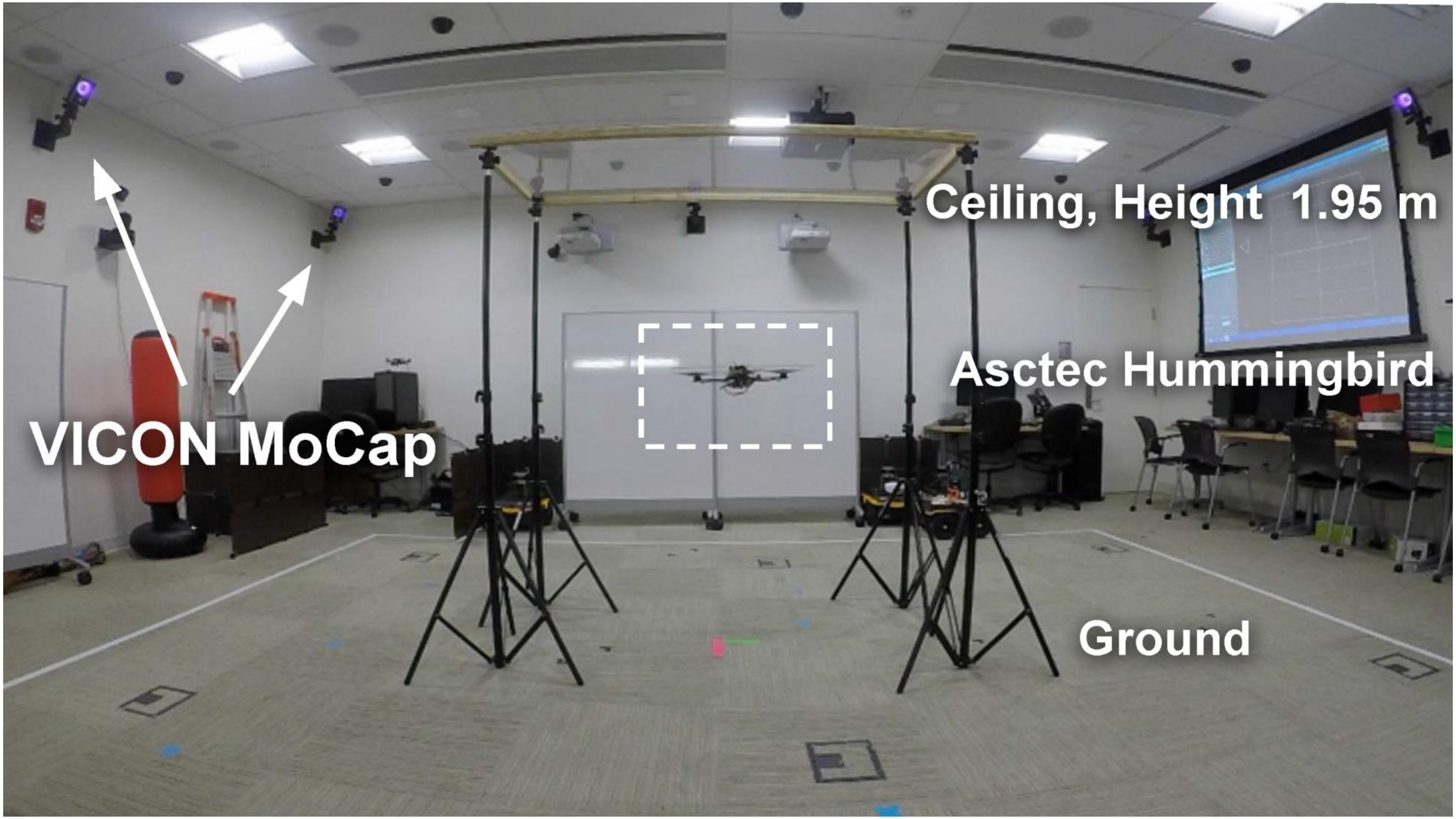
Ground and Ceiling Effects Characterization

Experiment versus theory



Ground andCeiling Effects Characterization

Experiment setup



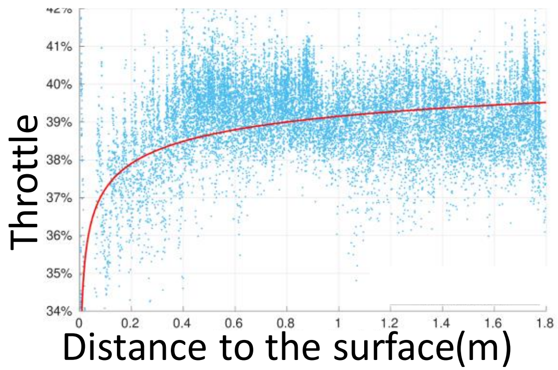
Ground and Ceiling Effects Characterization

Throttle – Distance Model

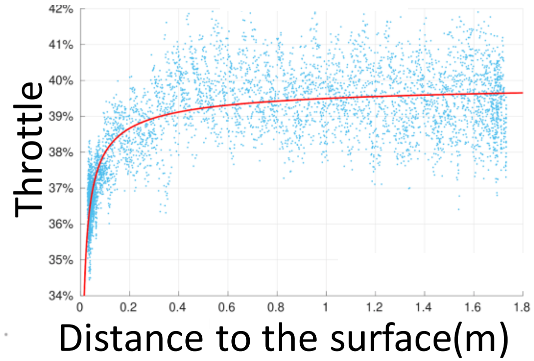
- Four models (hover at ground/ceiling, ascending/descending) are found by fitting the collected data with **power models**

$$T_t = a \cdot {d_t}^b + c$$

Ascending to ceiling

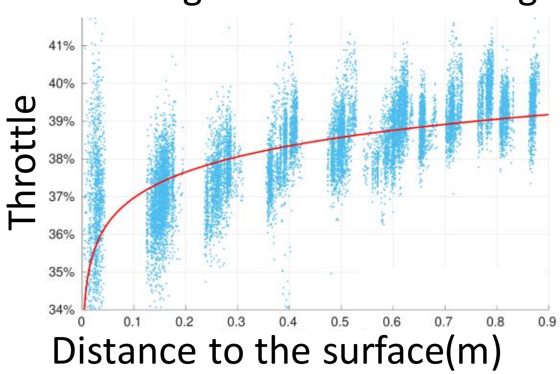


Descending to ground

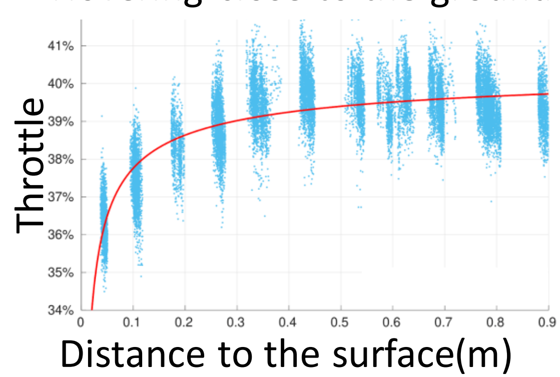


$$T = f(d)$$

Hovering close to the ceiling



Hovering close to the ground

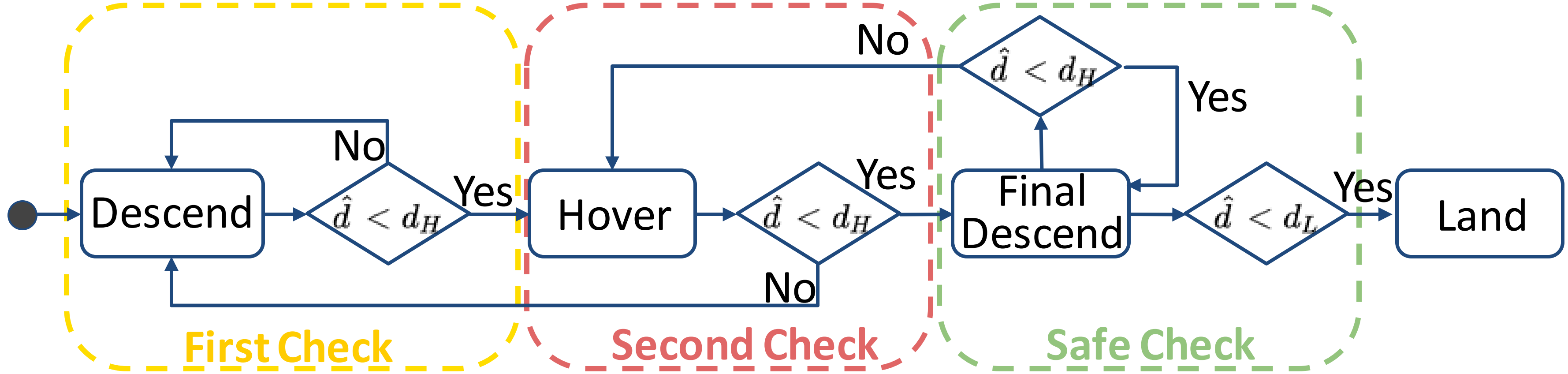


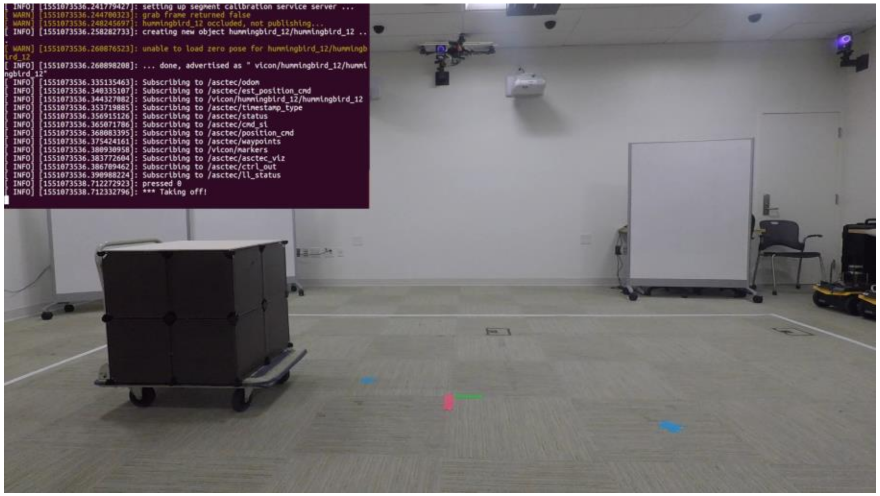
$$\widehat{d_t} = f^{-1}(T_t)$$

Surface Detection & Autonomous Landing

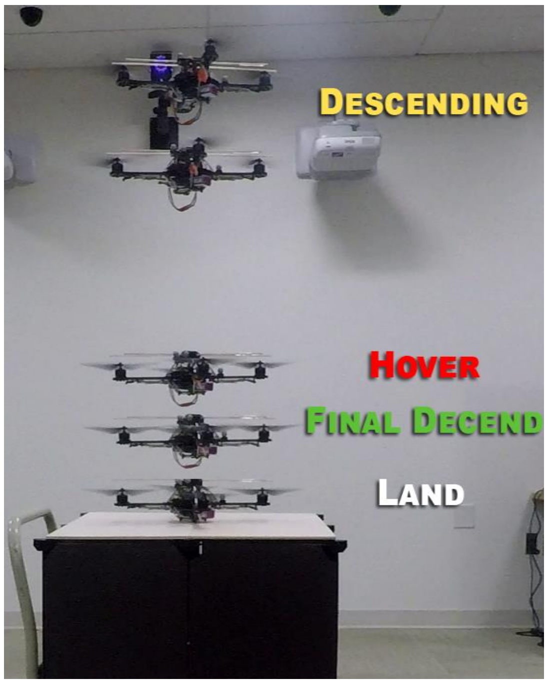
Model based distance estimation

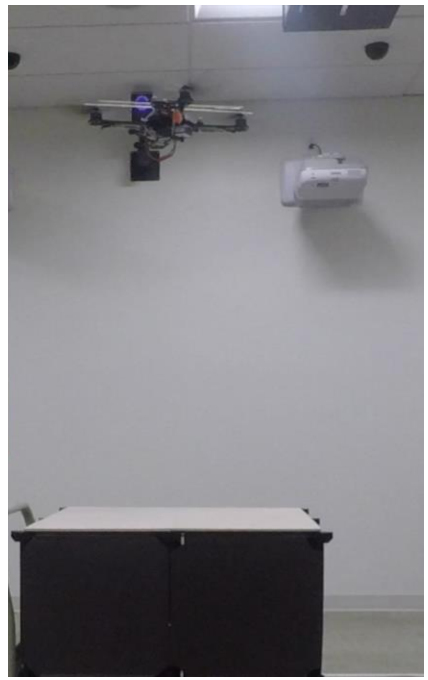
- A three-stage state machine is proposed for **safe sensorless autonomous** surface detection and landing

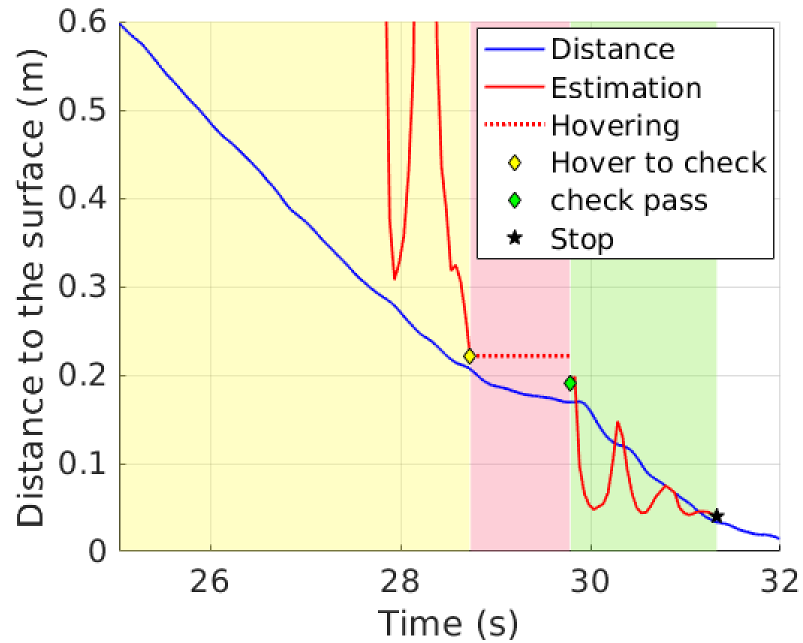




Landing on the box

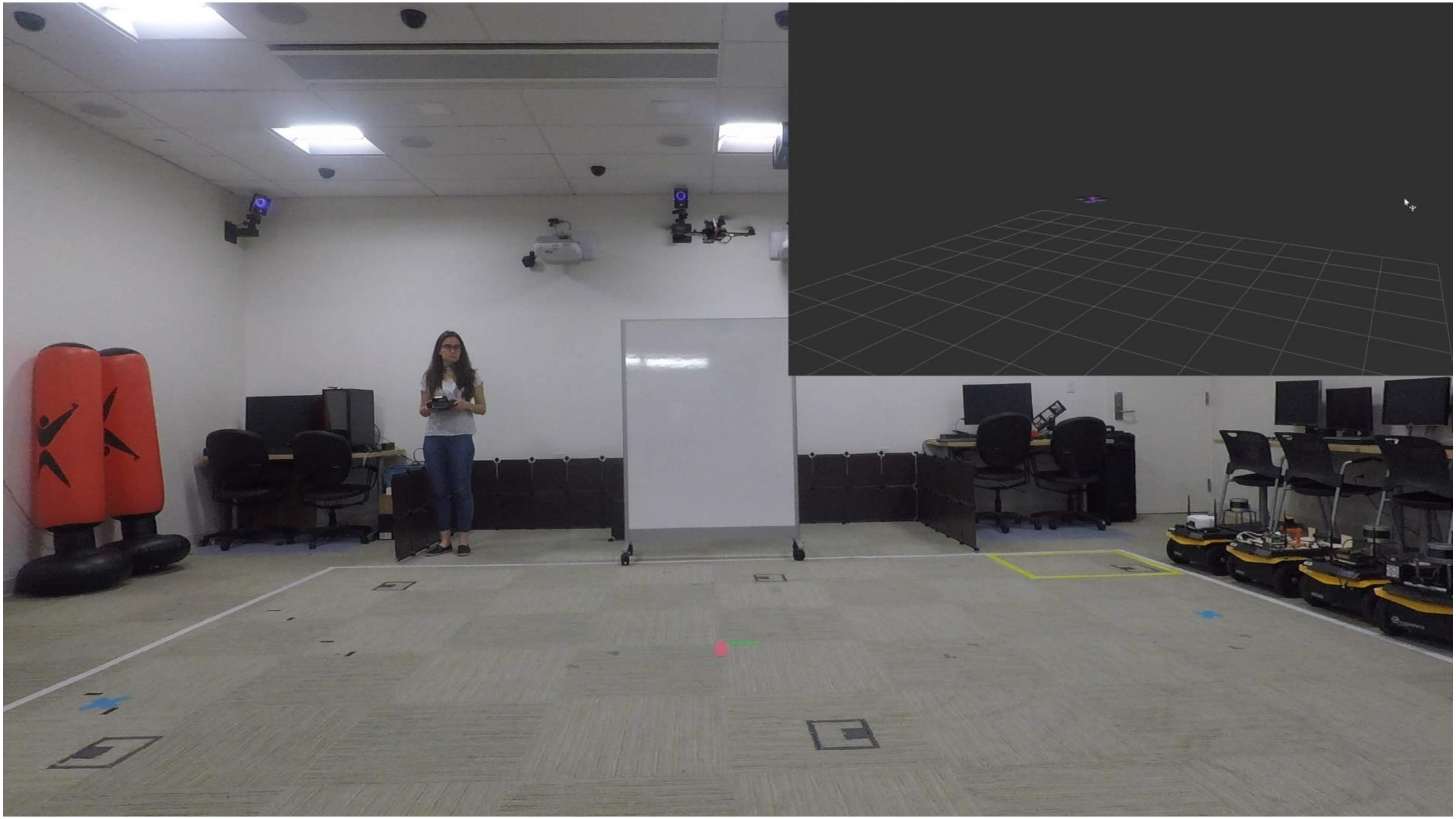






Experimental Results – Surface Detection & Landing

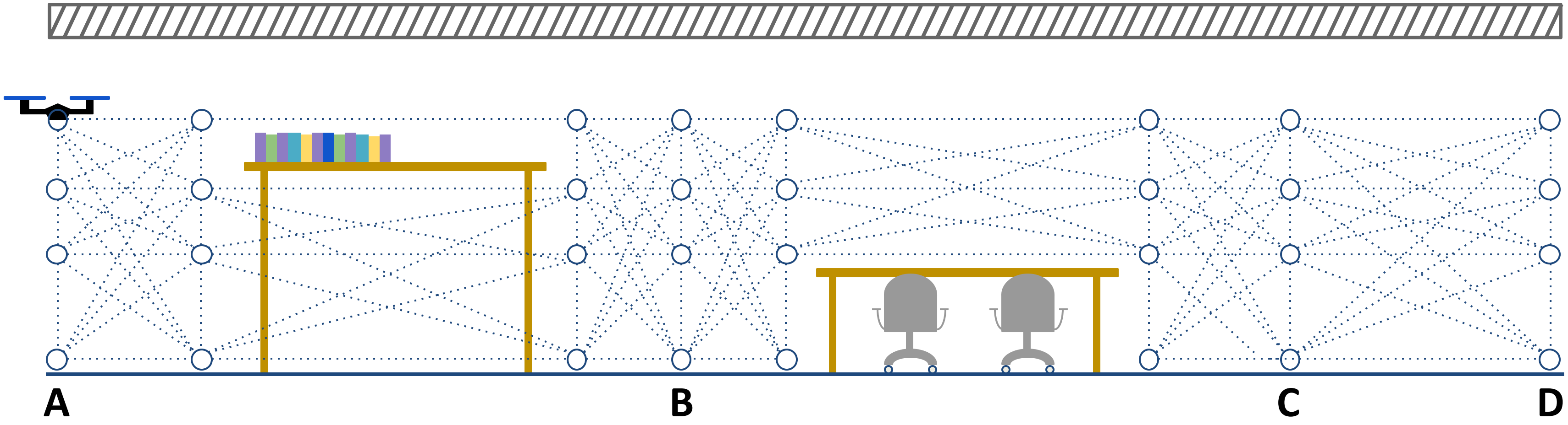
Autonomous landing with moving surface



Thrust-based Path Planning

Build directed graph

- A directed graph is constructed considering:
  - Intermediate waypoints (e.g. $\{A, B, C, D\}$ in the example)
  - Surfaces along the path



Energy Model based on thrust surface correlation

- For each propeller i the thrust $\mathrm{F_i}$ and the torque τ_i is:

$$F_i = k_f \omega_i{}^2,\ \tau_i = k_m \omega_i{}^2,\ i = 1, \ldots, 4 \qquad (1)$$

- The total power consumed is:

$$\mathrm{P} = \sum_i^4 \tau_i \omega_i = \left[\frac{k_m}{k_f{}^{\frac{3}{2}}} \sum_i^4 \left(\frac{\boldsymbol{F_i}}{\boldsymbol{F}}\right)^{\frac{3}{2}} \right] F^{\frac{3}{2}} \qquad (2)$$

- If approximate $F_i = \frac{1}{4} F$, the total power P is:

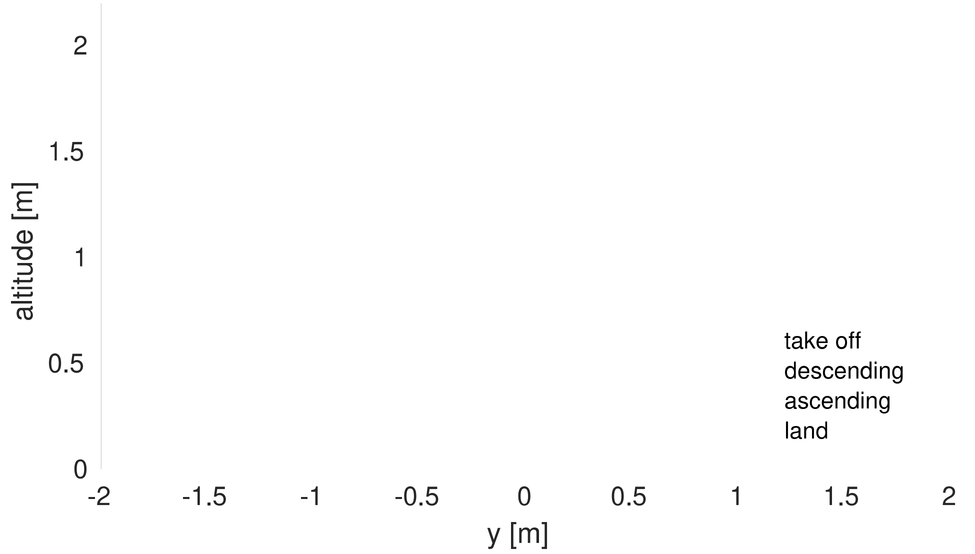
$$P \propto \boldsymbol{T}^{\frac{3}{2}} \qquad (3)$$

where throttle $\boldsymbol{T}$ is the percentage of the maximum thrust

Thrust-based Path Planning

Experiment Validation

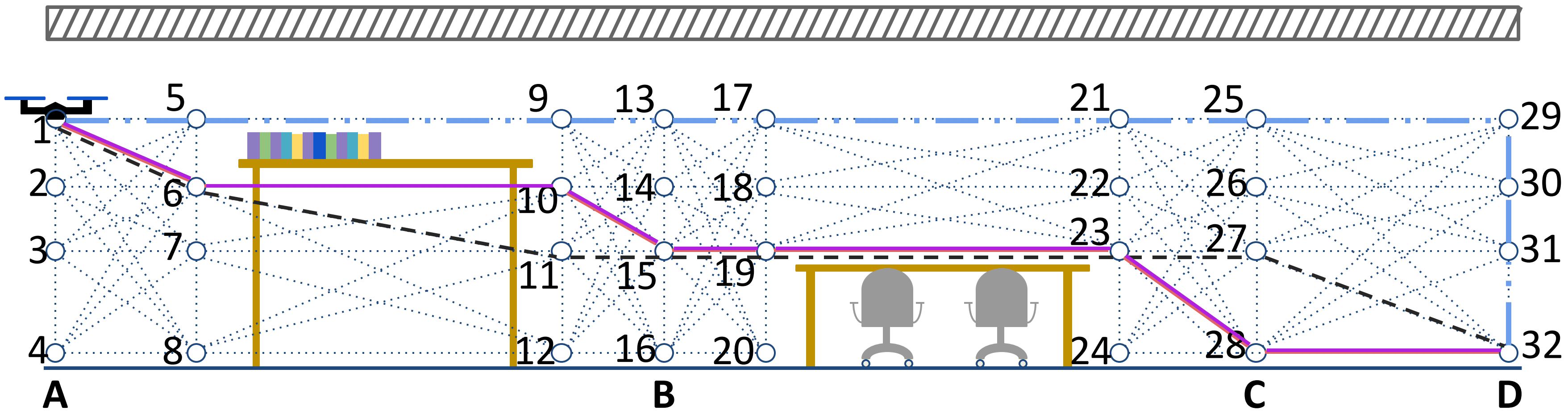
- Experiments are conducted to validate equation $P \propto \boldsymbol{T}^{\frac{3}{2}}$.
  - Ascending or descending from 0 to 90



- The throttle given to the quadrotor is overall **constant** during the same type of trajectory maneuver (**ascending**, **descending**, **horizontal transition**)
- The energy cost for every edge in the directed graph is calculated by:

$$E_{i,j} = \widehat{\boldsymbol{T}}^{\frac{3}{2}} \frac{d_{i,j}}{\left|\bar{v}_{i,j}\right|}$$

Simulation Results – Path Planning

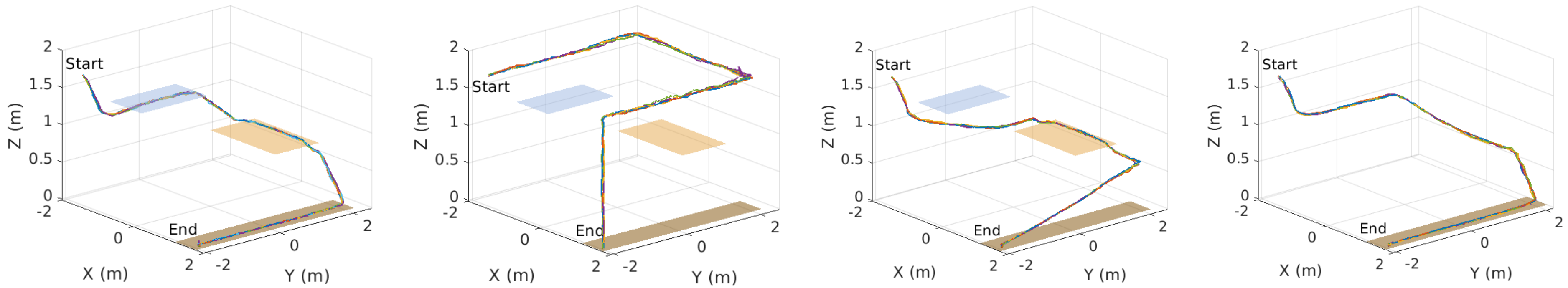


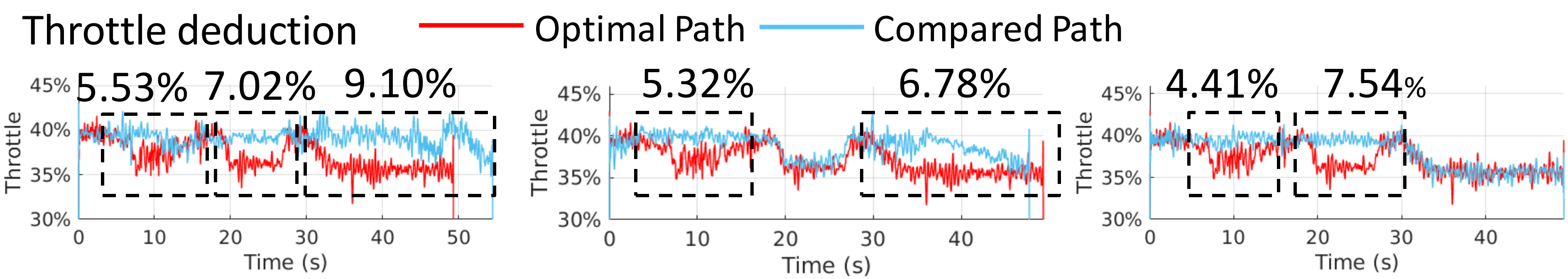
- The minimized energy path is planned by running Dijkstra on the constructed graph
- The total throttle T is proportional to the total energy:

$$\hat{E}_{Traj} = \sum E_{i,j}$$

Path	Predicted Total Energy	Measured Total Energy	
		Mean	Std
Optimal Path	**10.7906**	**11.2050**	**0.0111**
Basic Path	13.0843	13.3168	0.0221
Shortest Path	11.2445	11.5944	0.0289
Optimal Path(No Surfaces)	11.2622	11.6627	0.0587

Experimental Results – Path Planning





Shortest ≠ Minimum energy

Conclusions

- Conclusions:

Based on the surface effects:

- Thrust based surface detection for sensorless autonomous landing
- Graph based framework for energy efficient path plan algorithm

- Future Challenges:

- Surface effects under disturbances
- Characterization of flow dynamics effects in tight formations of UAV swarms
- Aggressive maneuvers of vehicles near vertical surfaces for wall detection

Thank you!

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