

# Exploiting Ground and Ceiling Effects on Autonomous UAV Motion Planning

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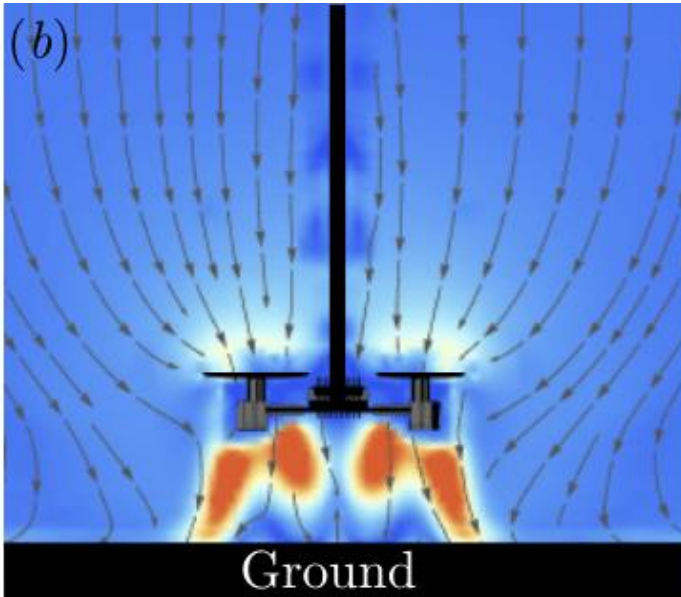
# Introduction



## *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

$$d = f(F)$$

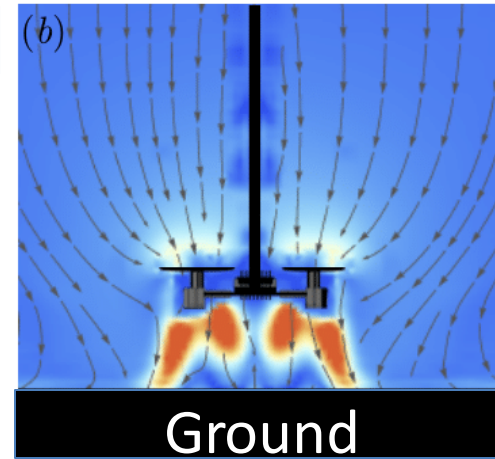
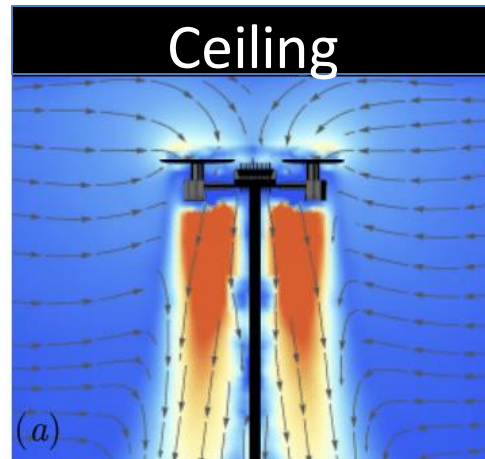
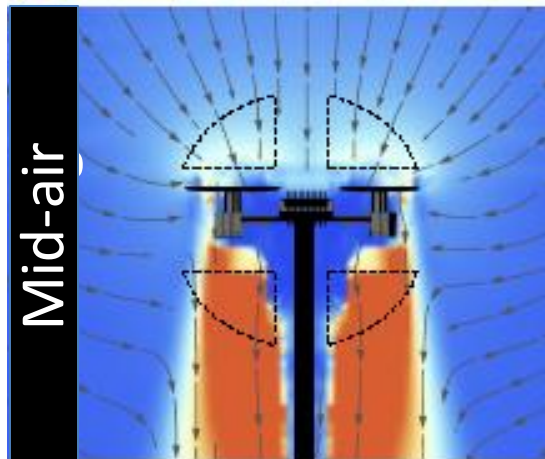
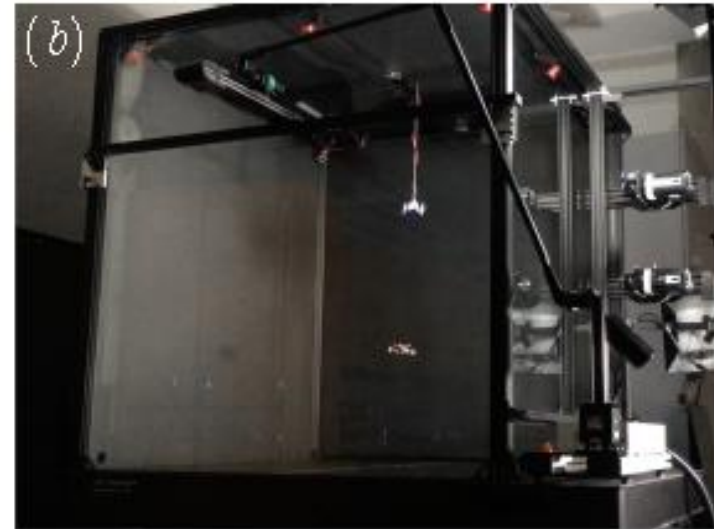
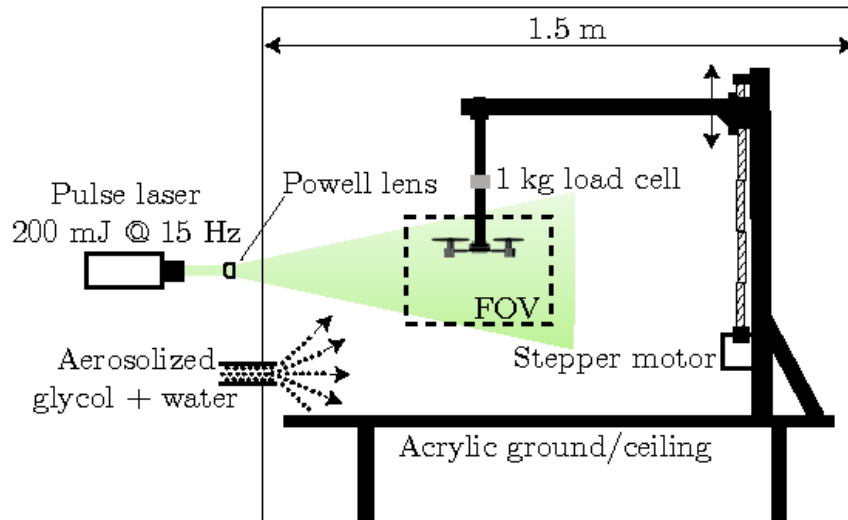
## *PROBLEM 2: Surface-based Optimal Path Planning:*

**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

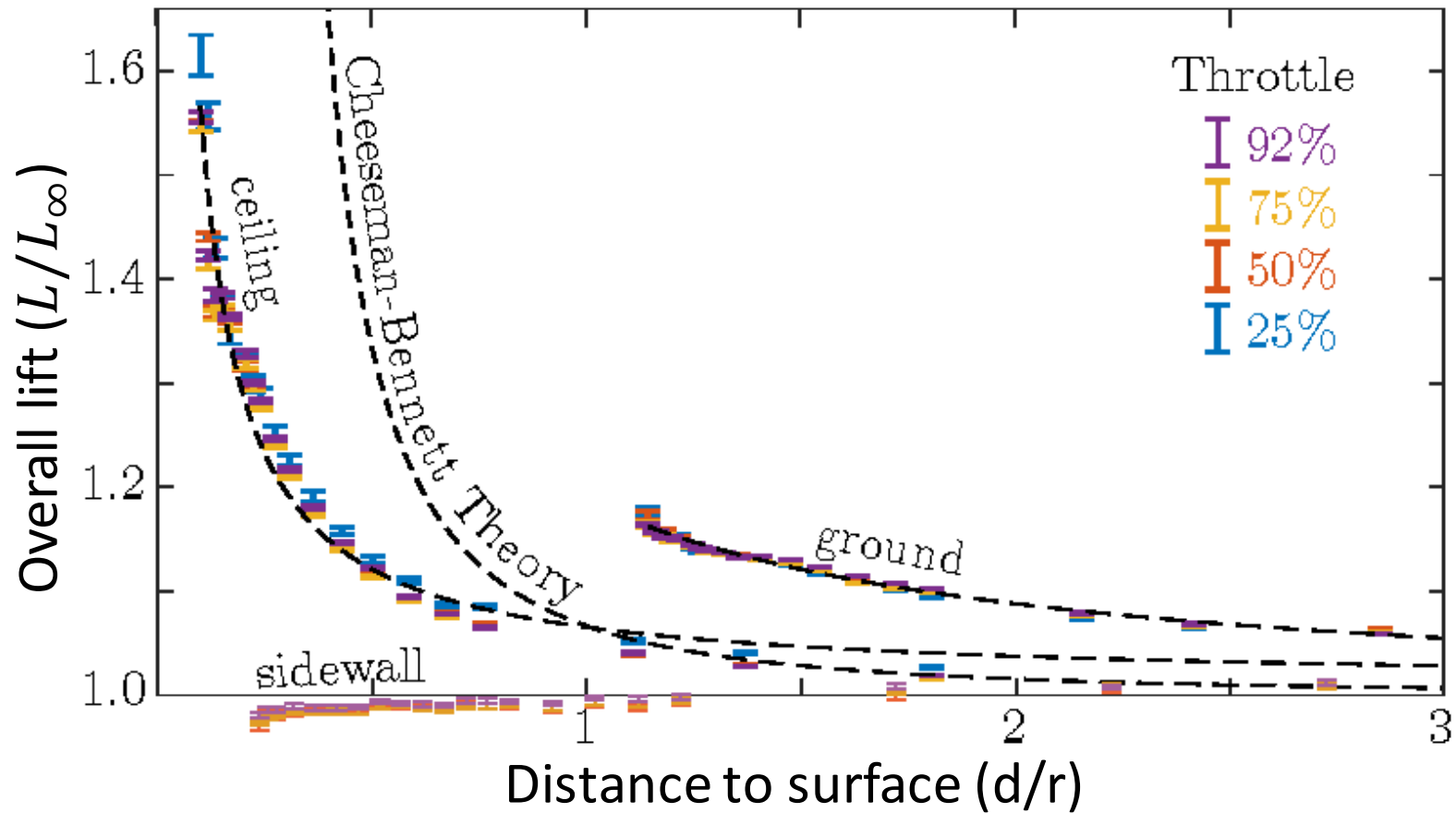
## Visualization of air flow fields



0  7  
airspeed (m/s)

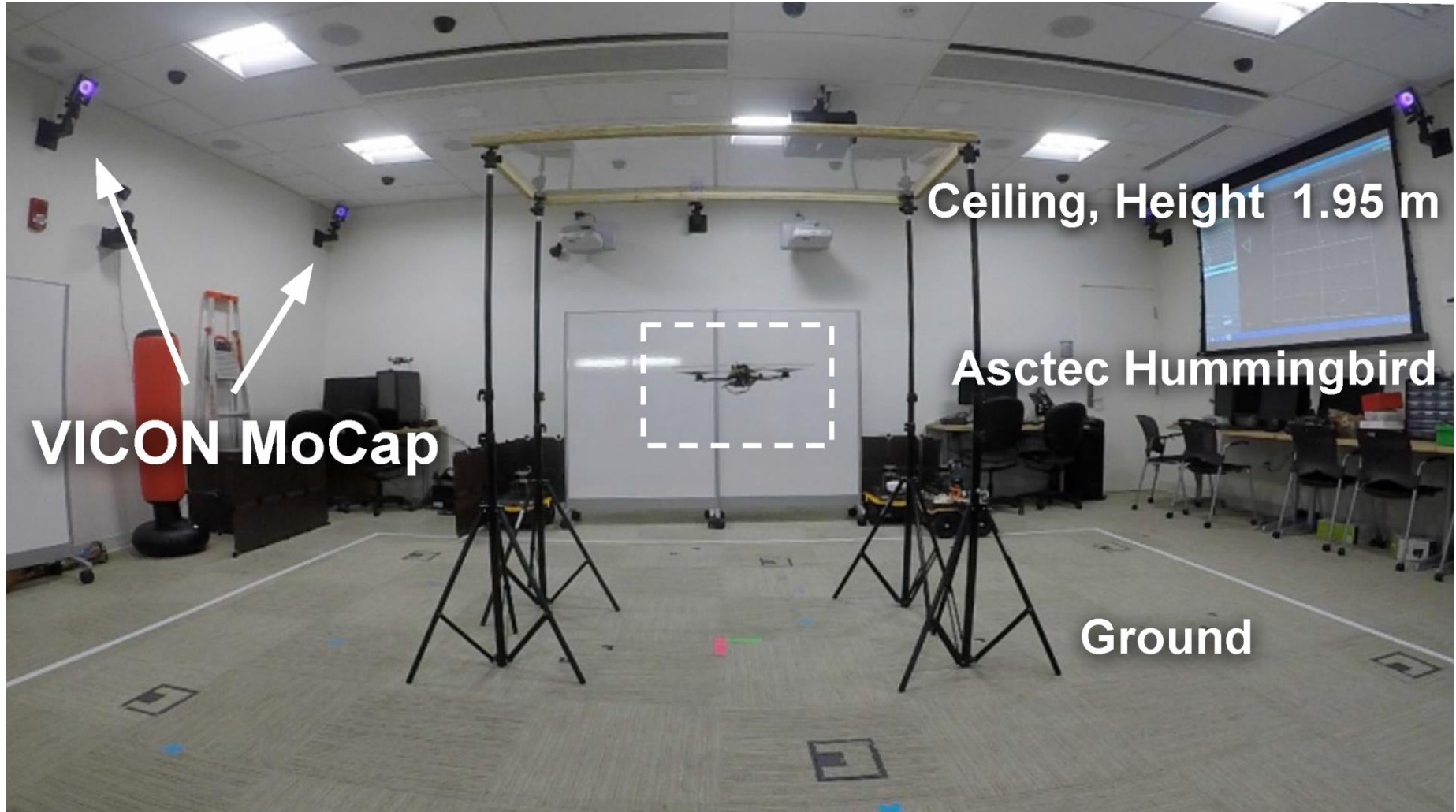
# Ground and Ceiling Effects Characterization

## Experiment versus theory



# Ground and Ceiling Effects Characterization

## Experiment setup





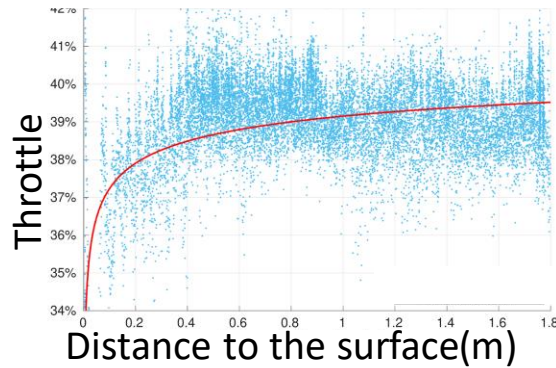
# Ground and Ceiling Effects Characterization

## Throttle – Distance Model

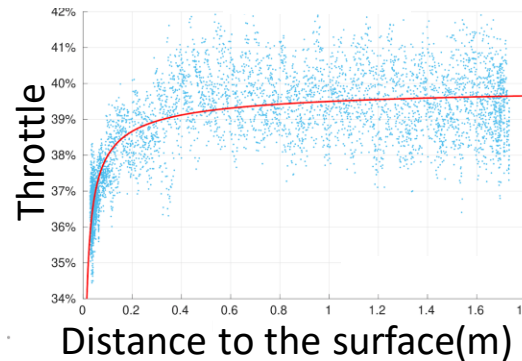
- Four models (hover at ground/ceiling, ascending/descending) are found by fitting the collected data with **power models**

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

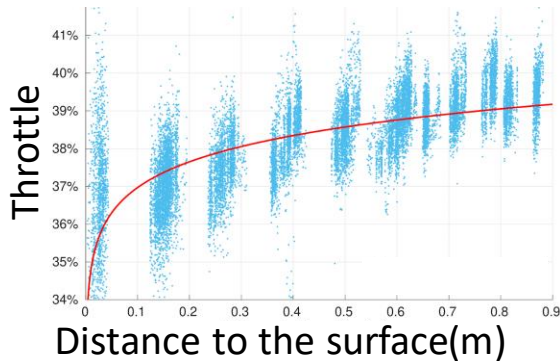
Ascending to ceiling



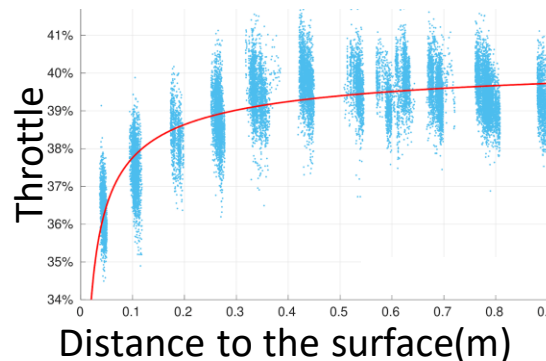
Descending to ground



Hovering close to the ceiling



Hovering close to the ground



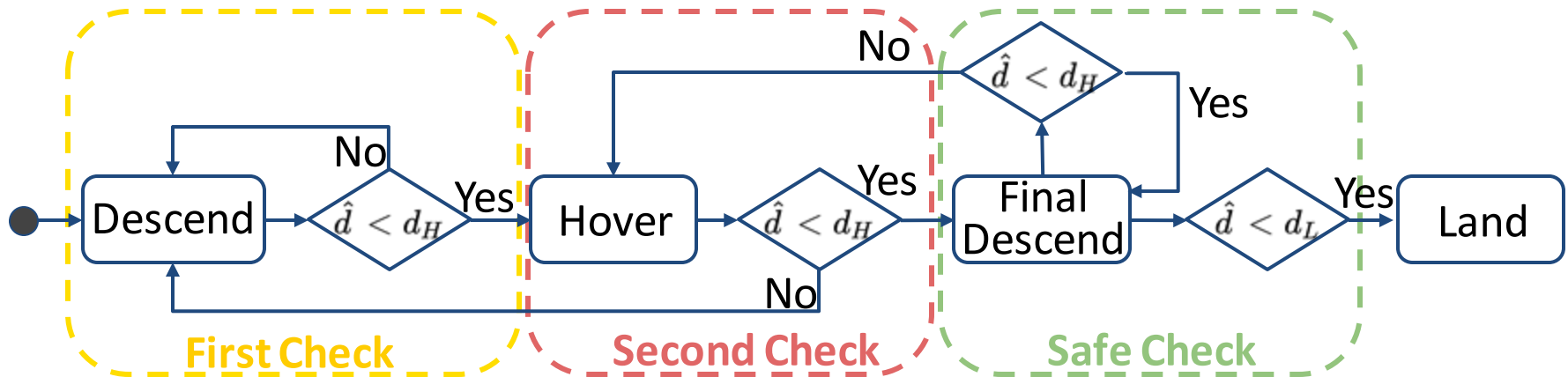
$$T = f(d)$$

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

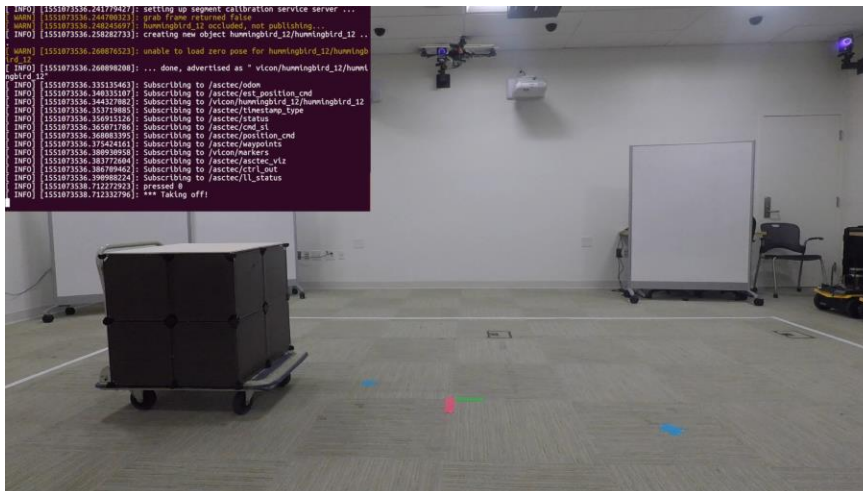
# Surface Detection & Autonomous Landing

## Model based distance estimation

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

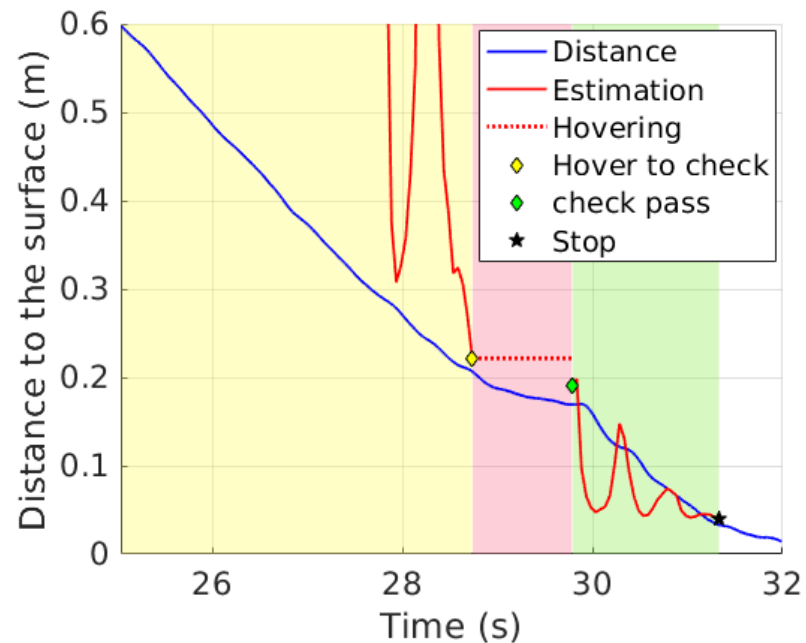
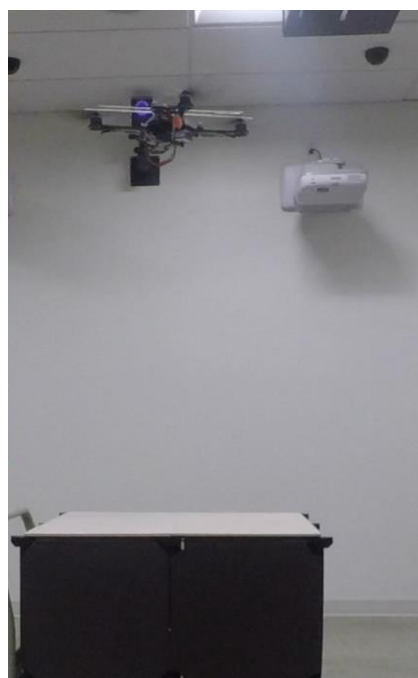
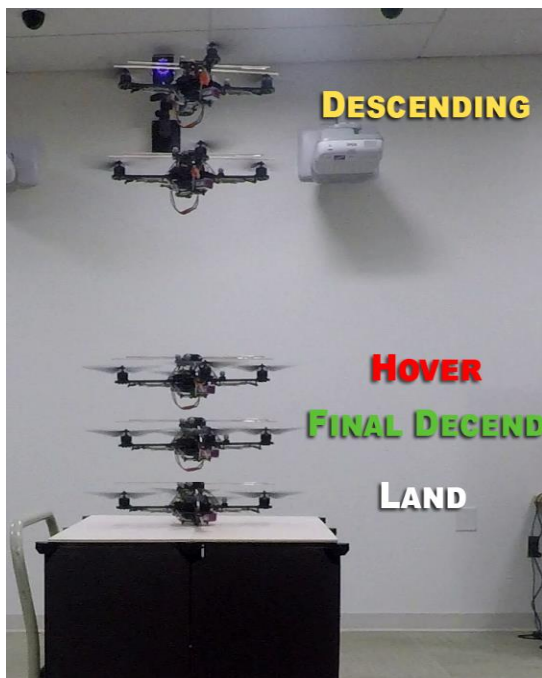


```
[INFO] [1551873536.241779427]: setting up segment calibration service server ...
[WARN] [1551873536.24860252]: gaze from camera false
[WARN] [1551873536.24822592]: hummingbird_12 occluded, not publishing
[INFO] [1551873536.258292793]: creating new object hummingbird_12/hummingbird_12
[INFO] [1551873536.260876523]: unable to load zero pose for hummingbird_12/hummingbird_12
[INFO] [1551873536.260890388]: .... done, advertised as "vicon/hummingbird_12/hummingbird_12"
[INFO] [1551873536.252135463]: Subscribing to /asctec/odom
[INFO] [1551873536.246335187]: Subscribing to /asctec/est_position_end
[INFO] [1551873536.244277882]: Subscribing to /vicon/hummingbird_12/hummingbird_12
[INFO] [1551873536.263789885]: Subscribing to /asctec/timestemp_type
[INFO] [1551873536.260911326]: Subscribing to /asctec/status
[INFO] [1551873536.26091786]: Subscribing to /asctec/now_s1
[INFO] [1551873536.260884395]: Subscribing to /asctec/position_end
[INFO] [1551873536.275484641]: Subscribing to /asctec/newpoints
[INFO] [1551873536.268938958]: Subscribing to /vicon/markers
[INFO] [1551873536.283772696]: Subscribing to /asctec/asctec_viz
[INFO] [1551873536.286789462]: Subscribing to /asctec/ctrl_out
[INFO] [1551873536.288982264]: Subscribing to /asctec/ll_status
[INFO] [1551873536.212272923]: pressed #
[INFO] [1551873536.21232796]: *** taking off
```



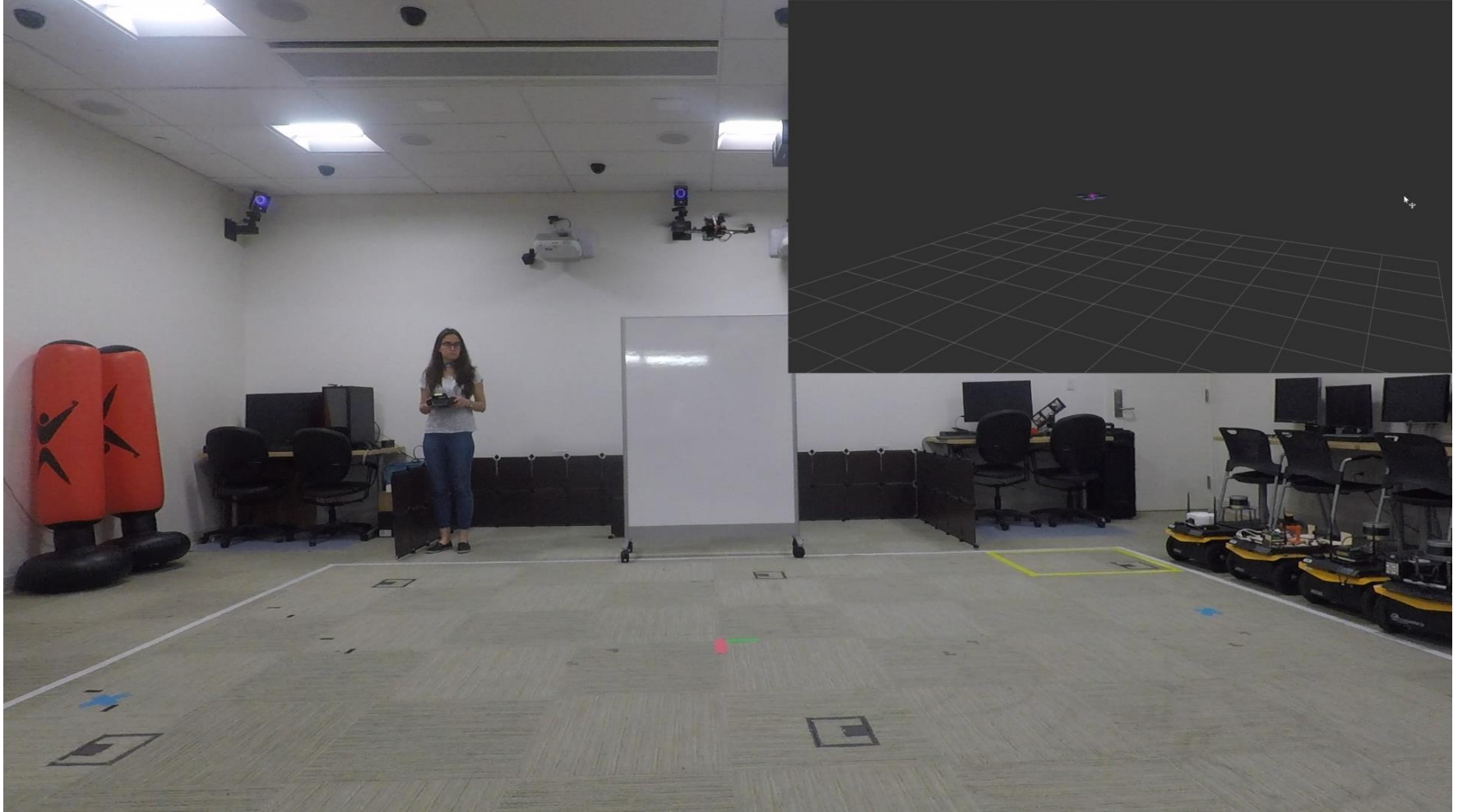
# Experimental Results – Surface Detection & Landing

## Landing on the box



# Experimental Results – Surface Detection & Landing

## *Autonomous landing with moving surface*

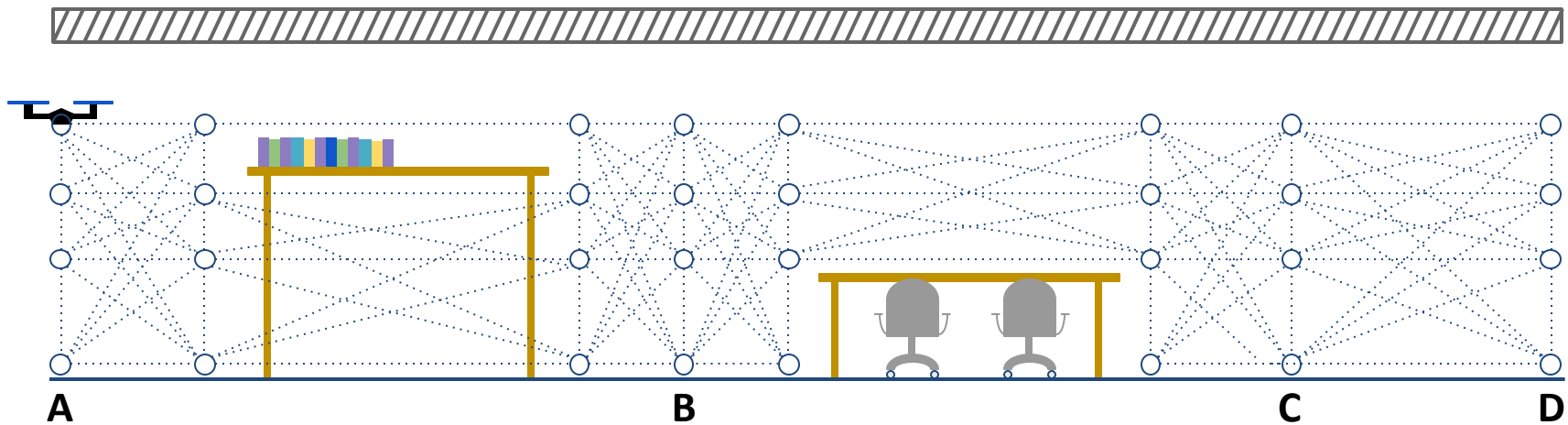


# Thrust-based Path Planning

# 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



# Thrust-based Energy Analysis

## *Energy Model based on thrust surface correlation*

- For each propeller  $i$  the thrust  $F_i$  and the torque  $\tau_i$  is:

$$F_i = k_f \omega_i^2, \quad \tau_i = k_m \omega_i^2, \quad i = 1, \dots, 4 \quad (1)$$

- The total power consumed is:

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

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

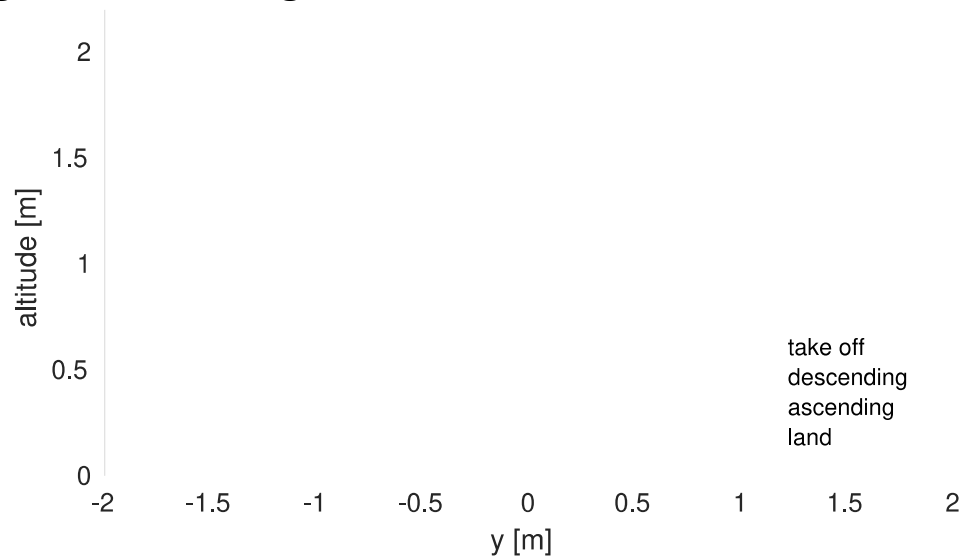
$$P \propto T^{\frac{3}{2}} \quad (3)$$

where throttle  $T$  is the percentage of the maximum thrust

# Thrust-based Path Planning

## Experiment Validation

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

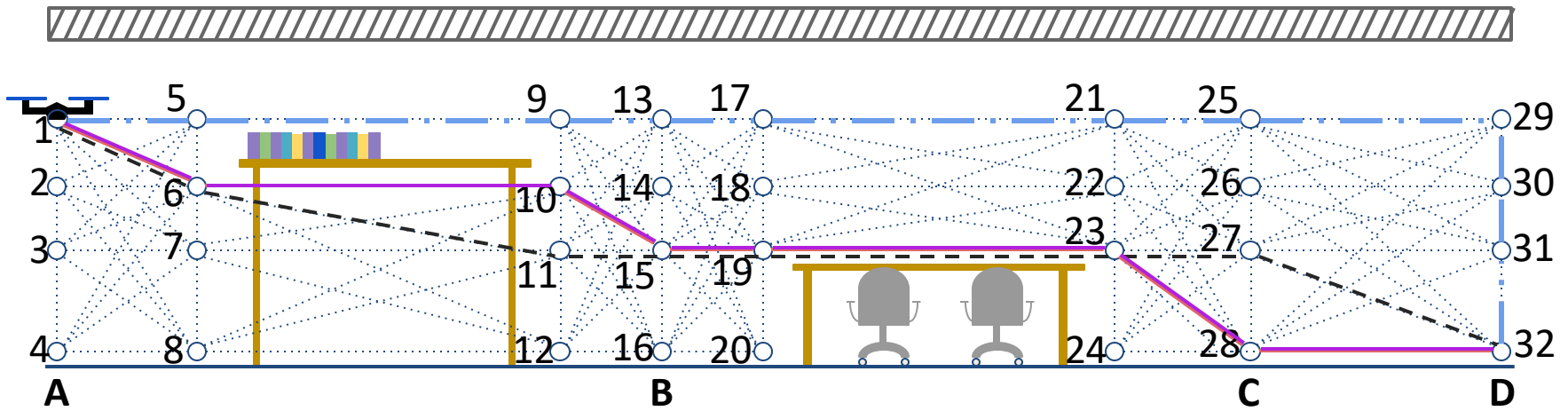


- The throttle given to the quadrotor is overall **constant** during the same type of trajectory maneuver (**ascending, descending, horizontal transition**)
- The energy cost for every edge in the directed graph is calculated by:

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



# Simulation Results – Path Planning

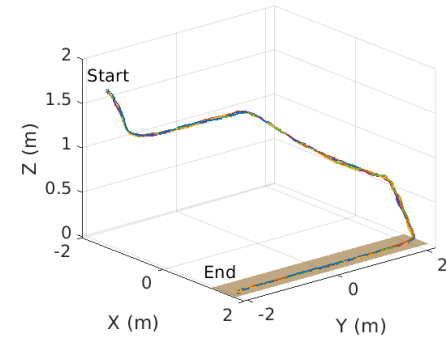
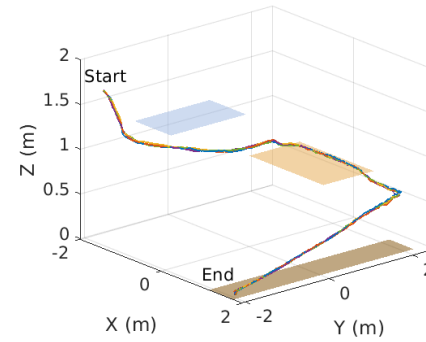
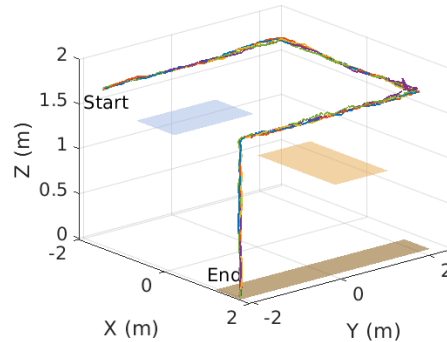
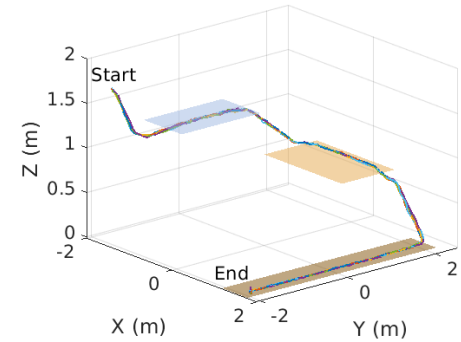


- The minimized energy path is planned by running Dijkstra on the constructed graph
- The total throttle  $T$  is proportional to the total energy:

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

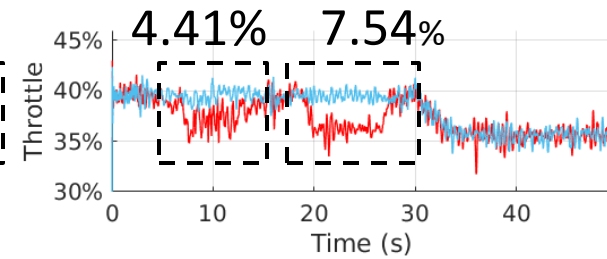
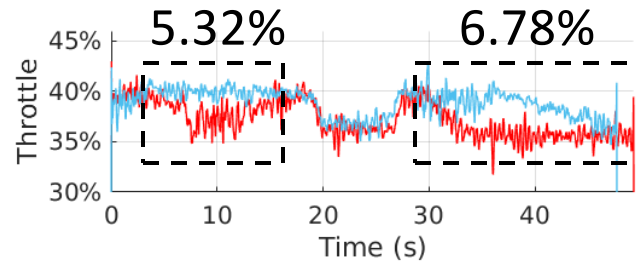
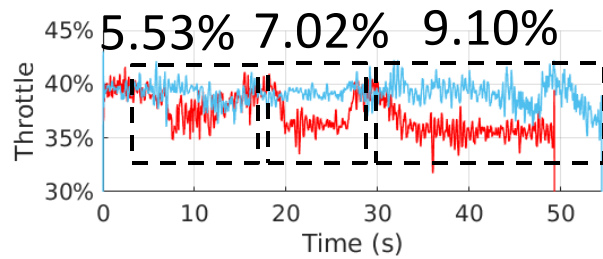
Path	Predicted Total Energy	Measured Total Energy	
		Mean	Std
<b>Optimal Path</b>	<b>10.7906</b>	<b>11.2050</b>	<b>0.0111</b>
<b>Basic Path</b>	13.0843	13.3168	0.0221
<b>Shortest Path</b>	11.2445	11.5944	0.0289
<b>Optimal Path(No Surfaces)</b>	11.2622	11.6627	0.0587

# Experimental Results – Path Planning



Throttle deduction

— Optimal Path — Compared Path



Shortest  $\neq$  Minimum energy

- **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!

We thank Esen Yel for assisting us on the experiments.

