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Scuola Superiore
Sant'Anna

Energy-Aware Coverage Path Planning of UAVs

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About me



I'm Carmelo Di Franco a 3° year PhD. Student in Embedded Systems at the ReTiS Lab of the Scuola Superiore S. Anna, in Pisa



Research topics

- Indoor Localization in Wireless sensor Networks
- Navigation and Path planning of autonomous robots
- Drones in agriculture



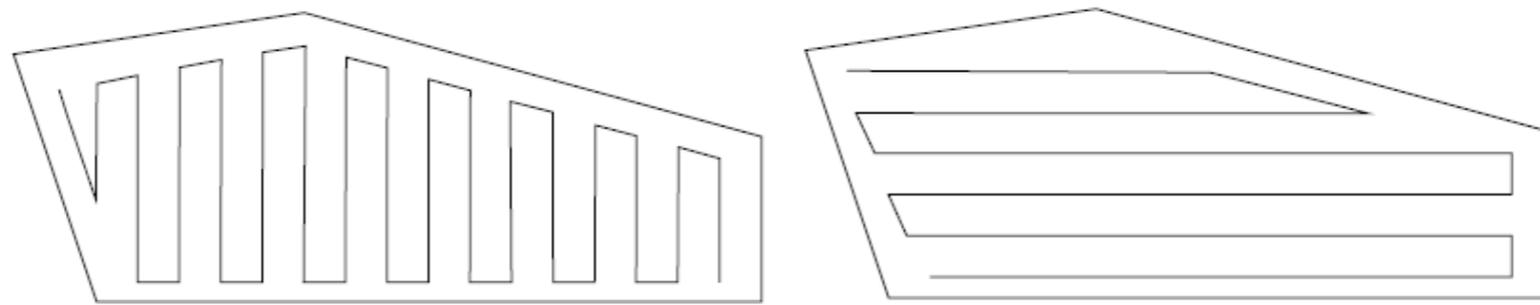
Motivation

Unmanned Aerial Vehicles (UAVs) are starting to be used for photogrammetric sensing of large areas in several application domains, such as agriculture, rescuing, and surveillance.

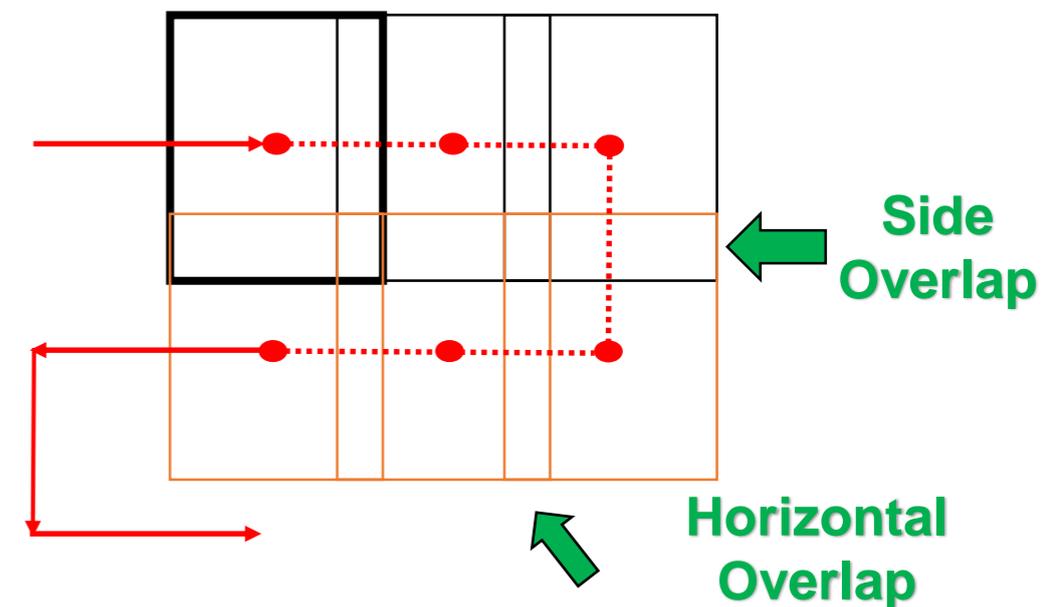
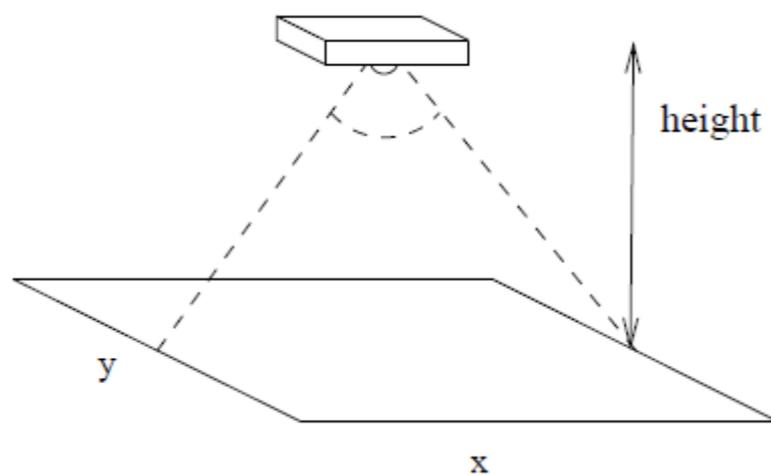


Coverage path planning (CPP)

Coverage path planning is the operation of finding a path that covers all the points of a specific area.

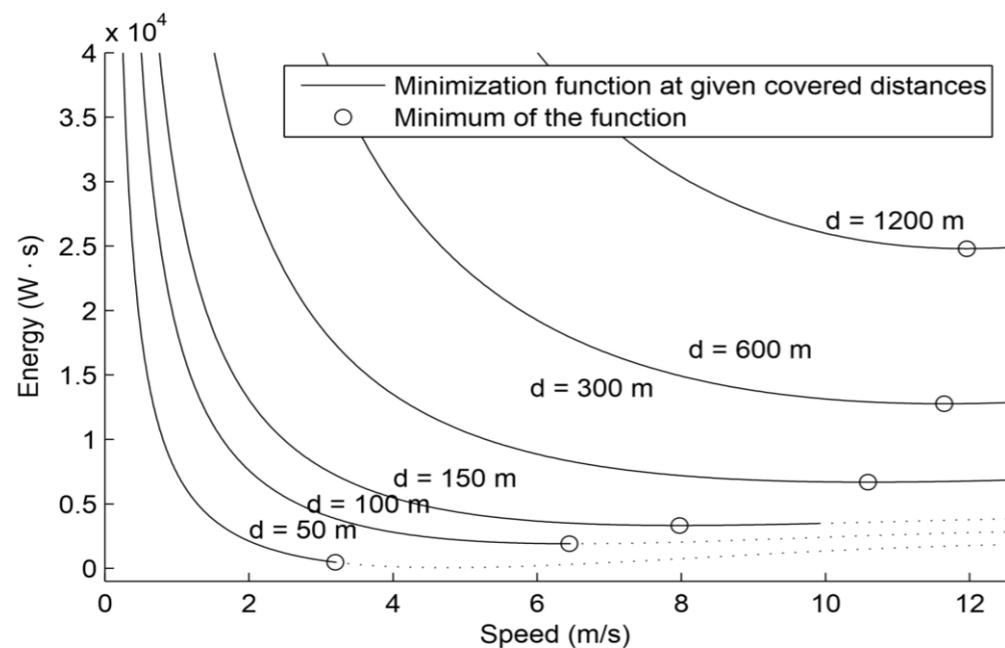


Of course, the path depends on the spatial resolution that we want to obtain



Our goal

1. Have **guarantees** about how much energy is needed to perform a particular path.
2. Perform a **feasibility test** to ensure the complete fulfillment of the required application
3. Find the **optimal speed** that minimizes the energy consumption while satisfying sensor constraints



Building the energy model

We measured the energy consumed by the quadrotor during all the possible trajectories (acceleration, deceleration, constant speed,...).

Testbed: IRIS quadcopter

- px4 autopilot
- Weight: 1.2 Kg
- Battery 5500 mAh

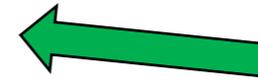
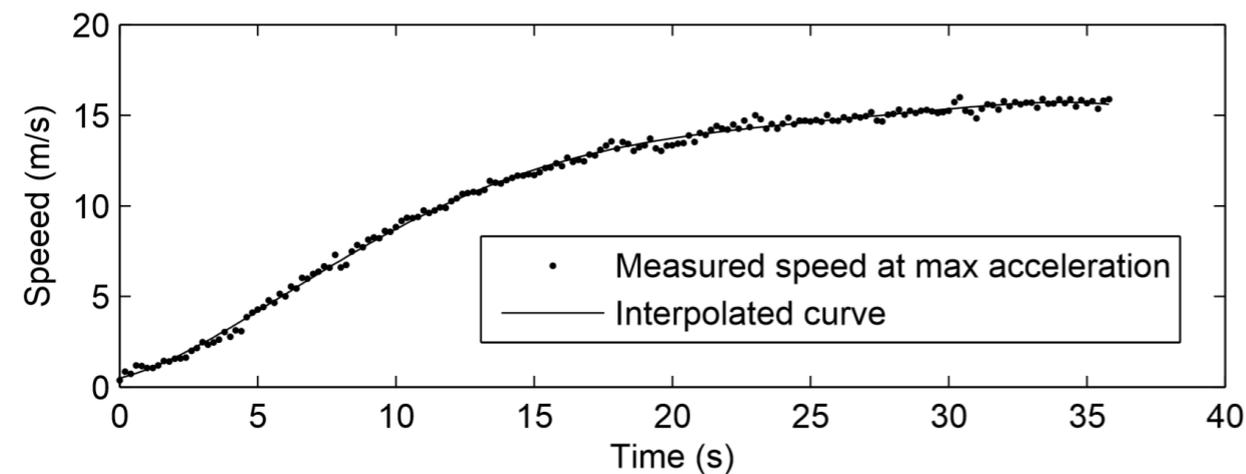


For each experiment a log containing all the possible measurements (GPS data, Inertial measurements, energy consumed) is stored.

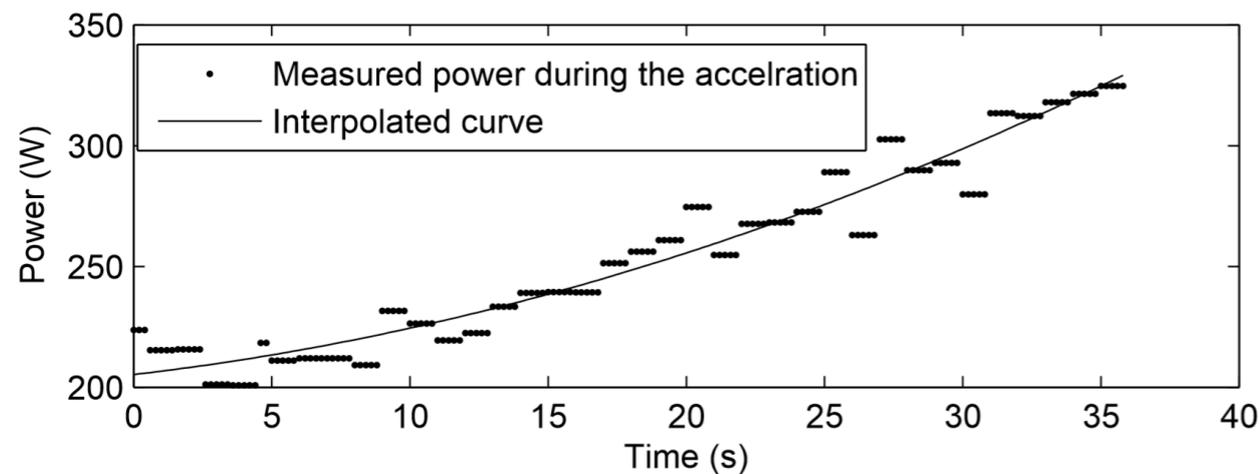
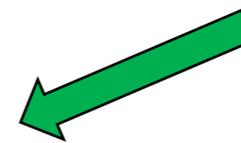


Building the energy model

Measured acceleration from 0 m/s to its maximum speed (~15 m/s)



**interpolating
data with fifth
order
polynomials**

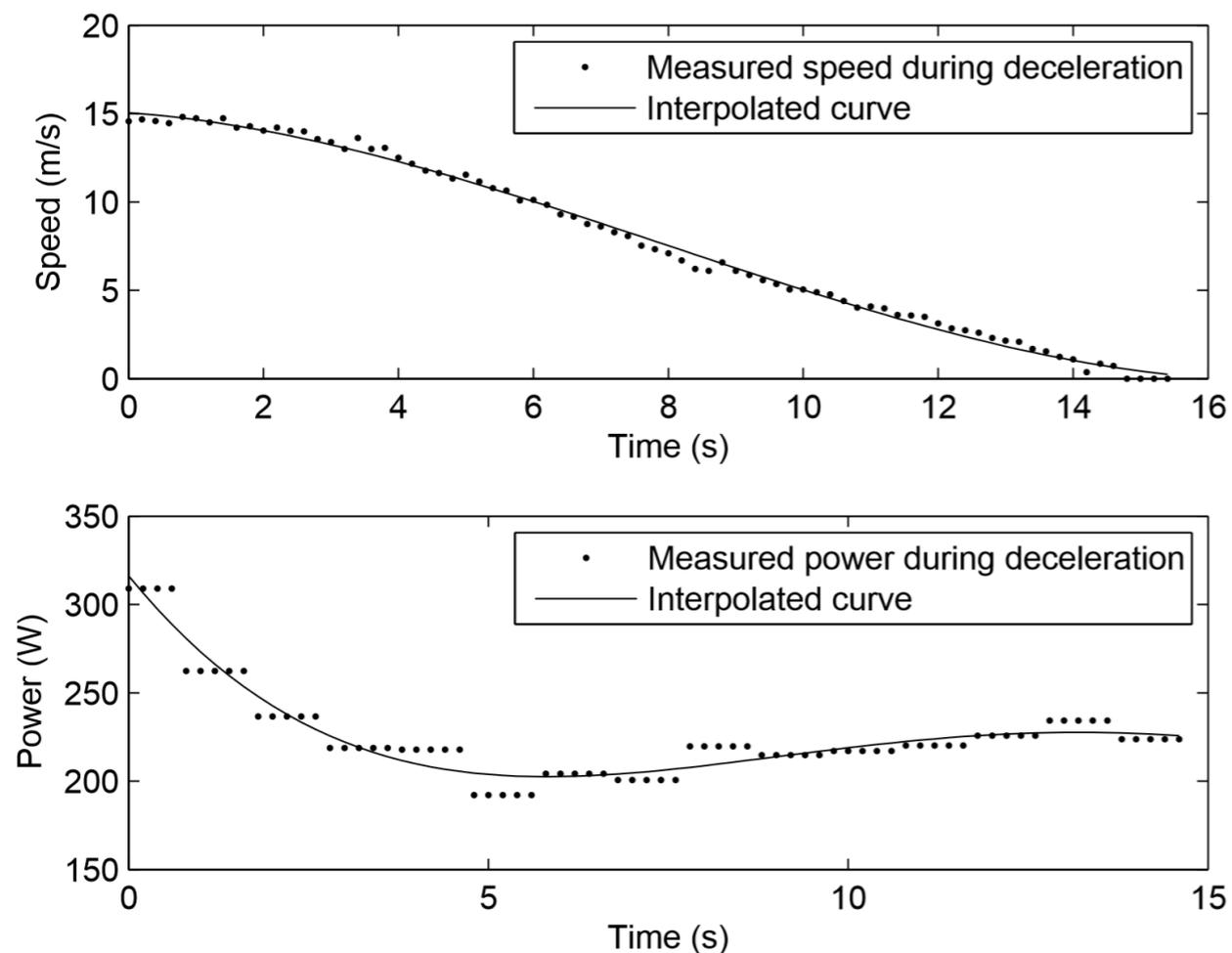


$$E_a = \int_{t_1:v=v_1}^{t_2:v=v_2} P_{acc}(t) dt$$



Building the energy model

Measured acceleration from its maximum speed to of 0 m/s

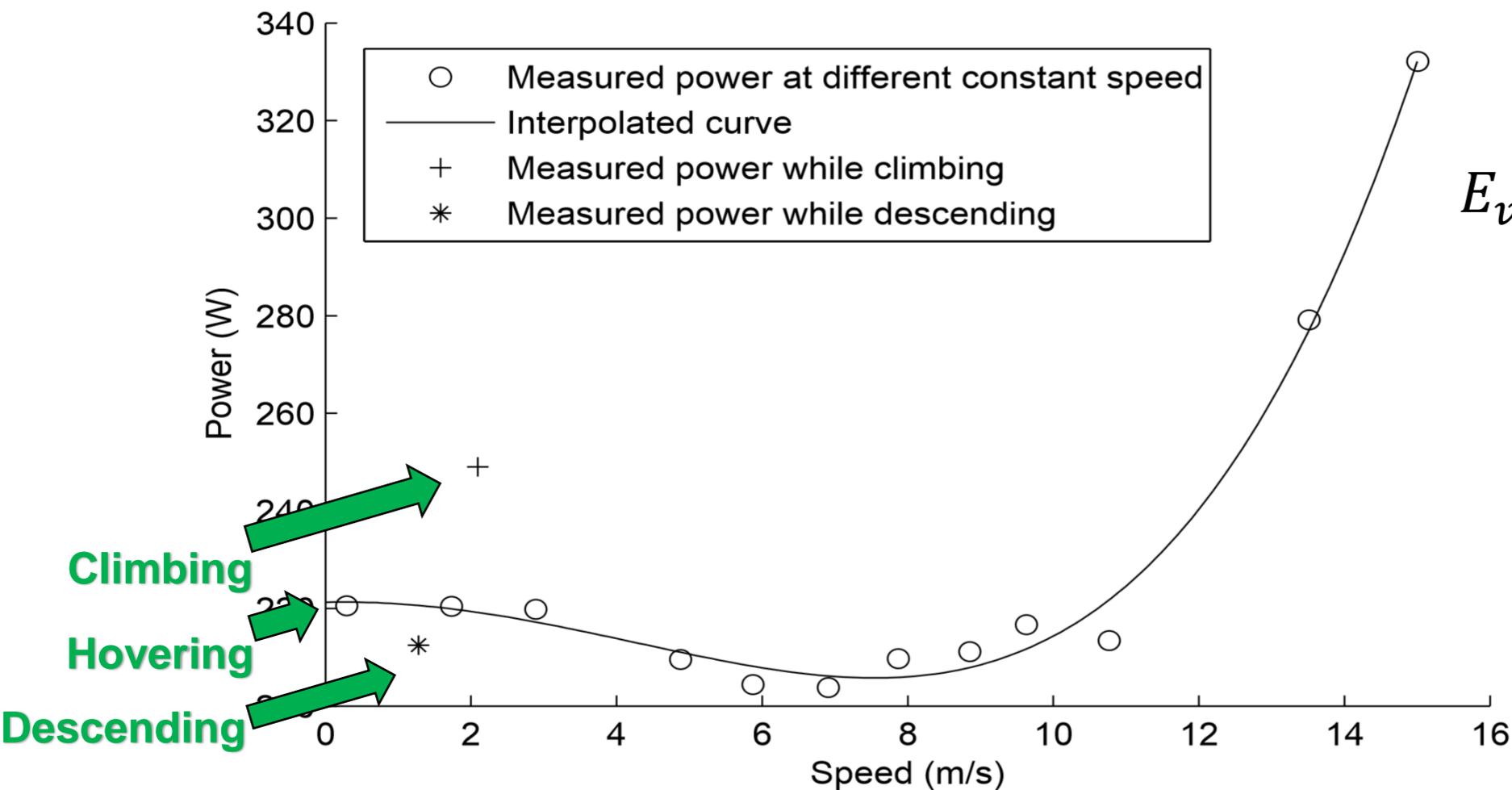


$$E_a = \int_{t_1:v=v_1}^{t_2:v=v_2} P_{dec}(t) dt$$



Building the energy model

Then we measured the power consumed at different constant speeds. Also when climbing, descending, and hovering.



$$E_v = \int_0^{\frac{d}{v}} P_v(v) dt = P_v(v) \frac{d}{v}$$

$$E_{climb} = P_{climb} \frac{\Delta h}{\dot{v}_{climb}}$$

$$E_{desc} = P_{desc} \frac{\Delta h}{\dot{v}_{desc}}$$



Building the energy model

With all the collected data, we can compute the energy consumed to perform every movement combination

- $E_a = \int_{t_1:v=v_1}^{t_2:v=v_2} P_a(t) dt$
- $E_v = \int_0^v P_v(v) dt = P_v(v) \frac{d}{v}$
- $E_{climb} = P_{climb} \frac{\Delta h}{\dot{v}_{climb}}$
- $E_{hover} = \int_{t_1}^{t_2} P_{hover} dt = P_{hover} \Delta t$
- $E_{desc} = P_{desc} \frac{\Delta h}{\dot{v}_{desc}}$
- $E_{turn} = \int_{t_1}^{t_2} P_{hover} dt = P_{turn} \frac{\Delta \theta}{\omega_{turn}}$



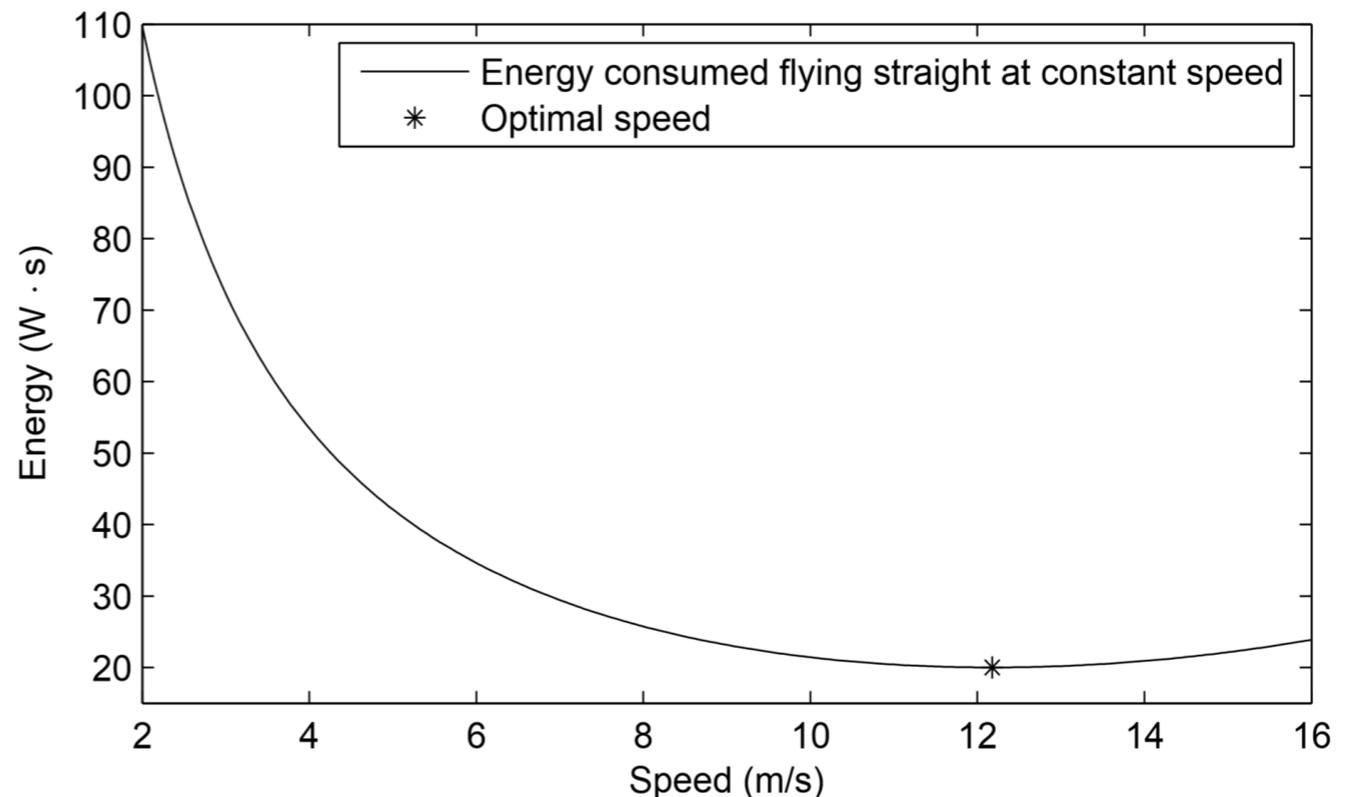
What is the speed that minimize the energy consumption?

High Power in less Time ?

Lower Power in more Time ?

With constant speed

$$\begin{aligned} v^* &= \min_v \int_0^{\frac{d}{v}} P_v(v) dt = \\ &= \min_v P_v(v) \frac{d}{v} \end{aligned}$$



What is the speed that minimize the energy consumption?

Considering accelerations and decelerations

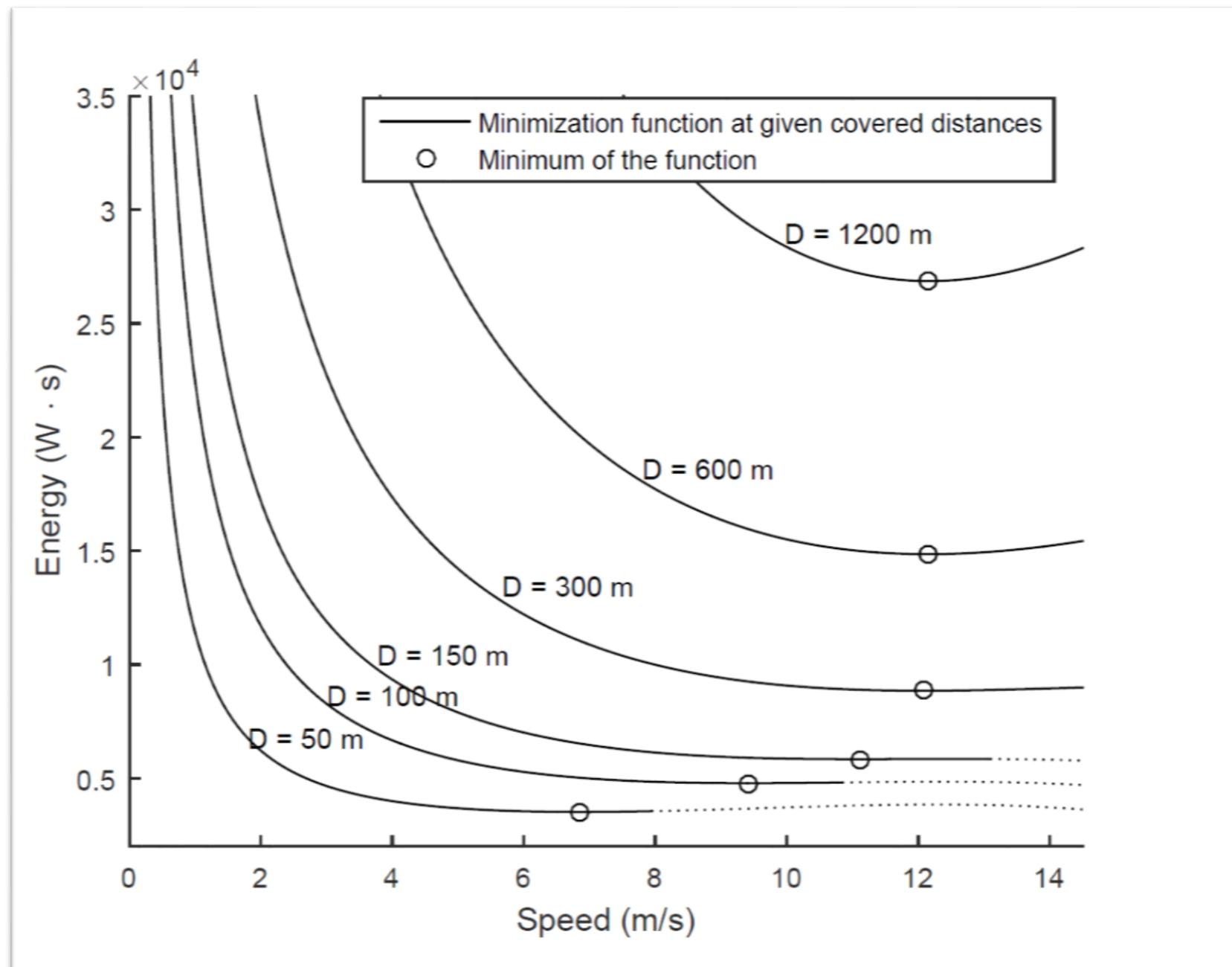
$$E(d) = \int_0^{t_1} P_{acc}(t) dt + \int_{t_1}^{t_2} P_v(v) dt + \int_{t_2}^{t_3} P_{dec}(t) dt$$

- $t_1: v_{acc}(t_1) = v$
- $t_2: \frac{d - d_{acc} - d_{dec}}{v} = \frac{d - \int v_{acc} dt - \int v_{dec} dt}{v}$
- $t_3: v_{dec}(t_3) = 0$



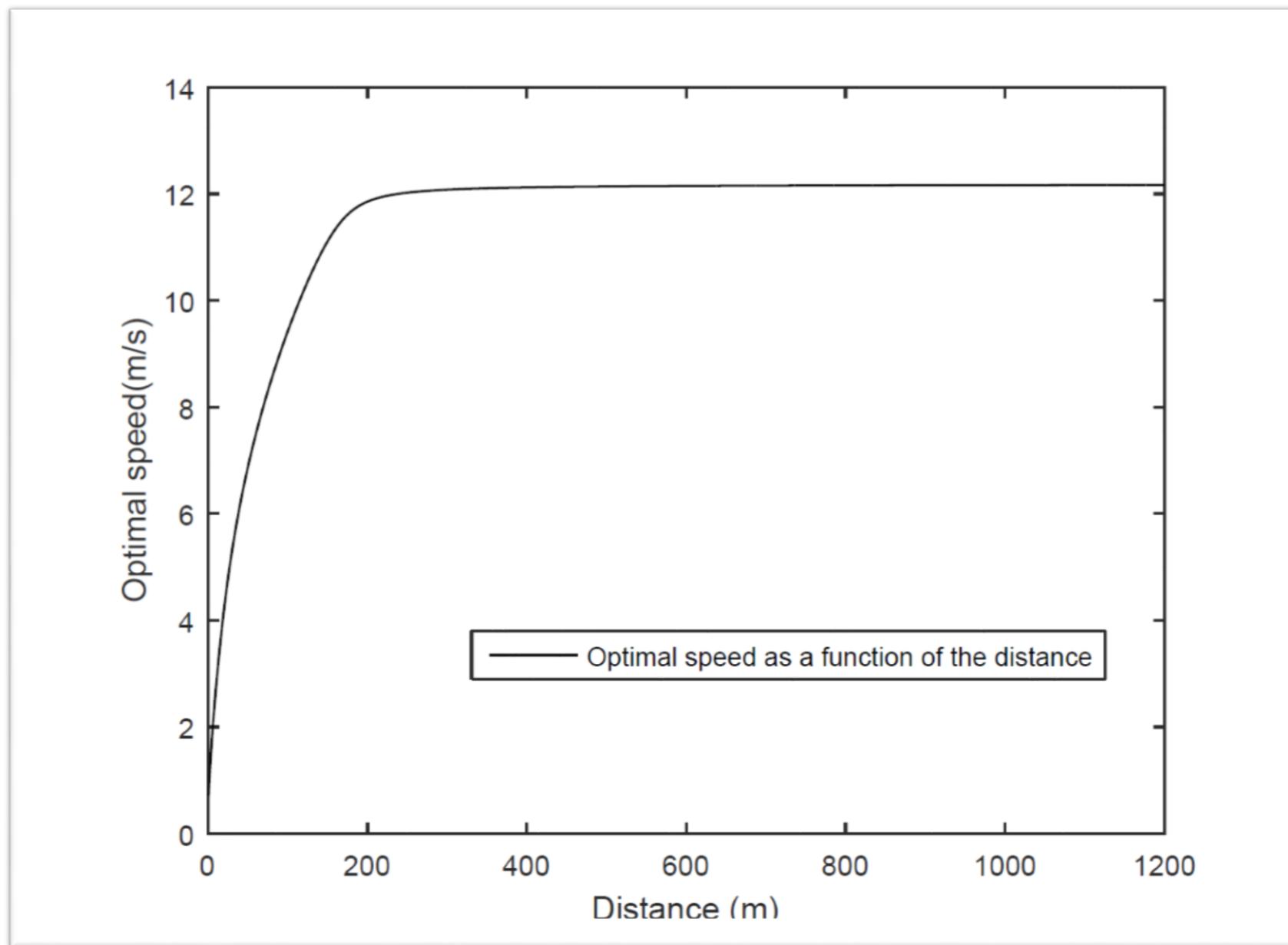
Optimal Speed that minimizes the Energy consumption

For every distance we have a curve of the energy consumption as a function of the speed



Optimal speed as a function of the distance

When the distance increases the optimal speed tends to the optimal value computed assuming constant speed



Optimal speed

For each portion of the path, it is possible to have the minimum energy consumption by setting different speeds.

Given any path, we can minimize the energy consumption traveling it by setting different speeds along all the portions of the path.



Energy guarantees

A feasibility test is proposed to check if the computed path can be actually flight with the energy available in the battery

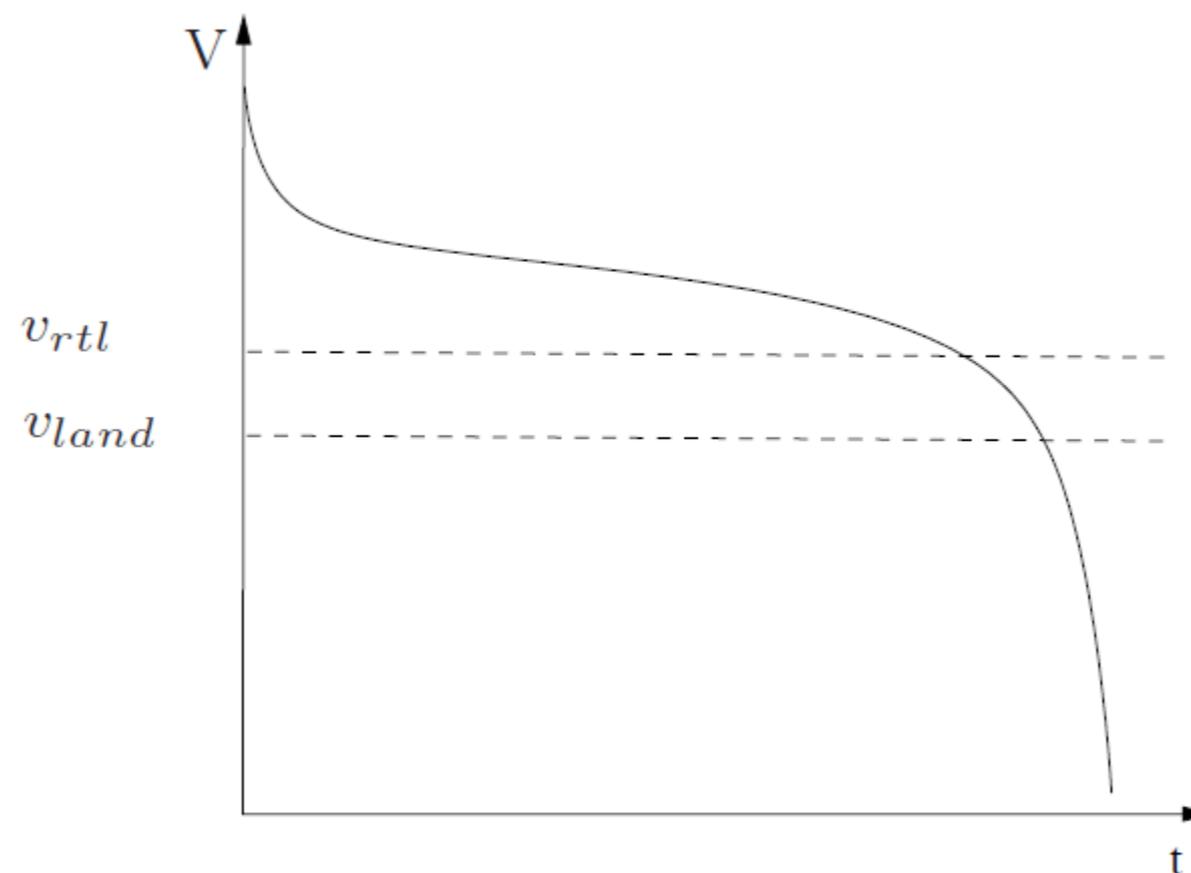
$$E_{tot} = E_{climb}(0, h_{max}) + E_{desc}(h_{max}, 0) + n_t E_{turn} \\ + \sum_i (E_{acc}(0, v_i^*) + E_v(d_i, v_i^*) + E_{dec}(d_i, v_i^*))$$

- **if ($E_{tot} < E_a$)**
the feasibility test is passed. the remaining energy ($E_a - E_{tot}$) can be used to increase the spatial resolution of the acquired images.
- **Else**
the feasibility test is not passed, the path has to be redesigned. That energy can be traded with the spatial resolution



Energy-Failsafe

Check if the remaining energy is greater than the energy required to come back to the starting point.

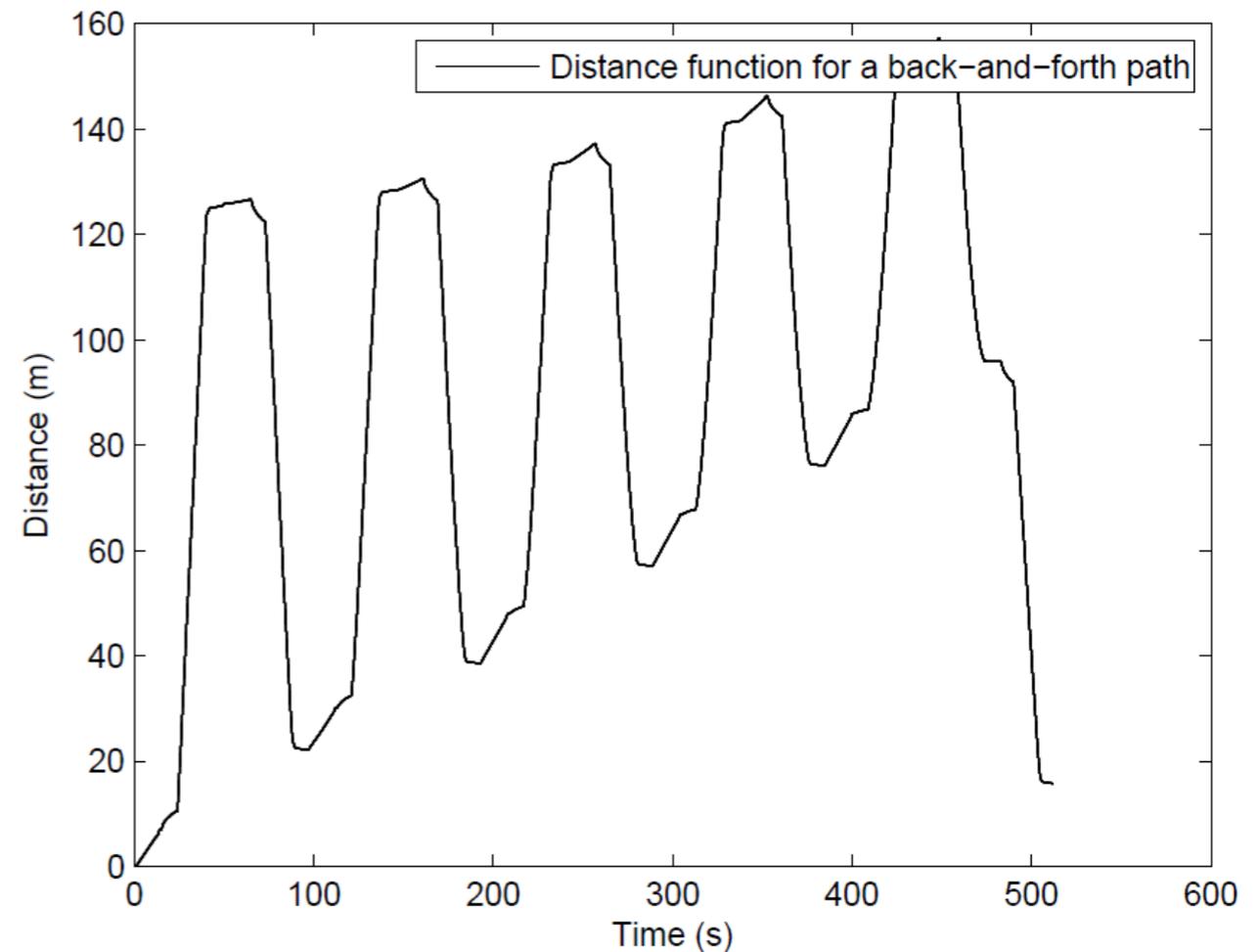
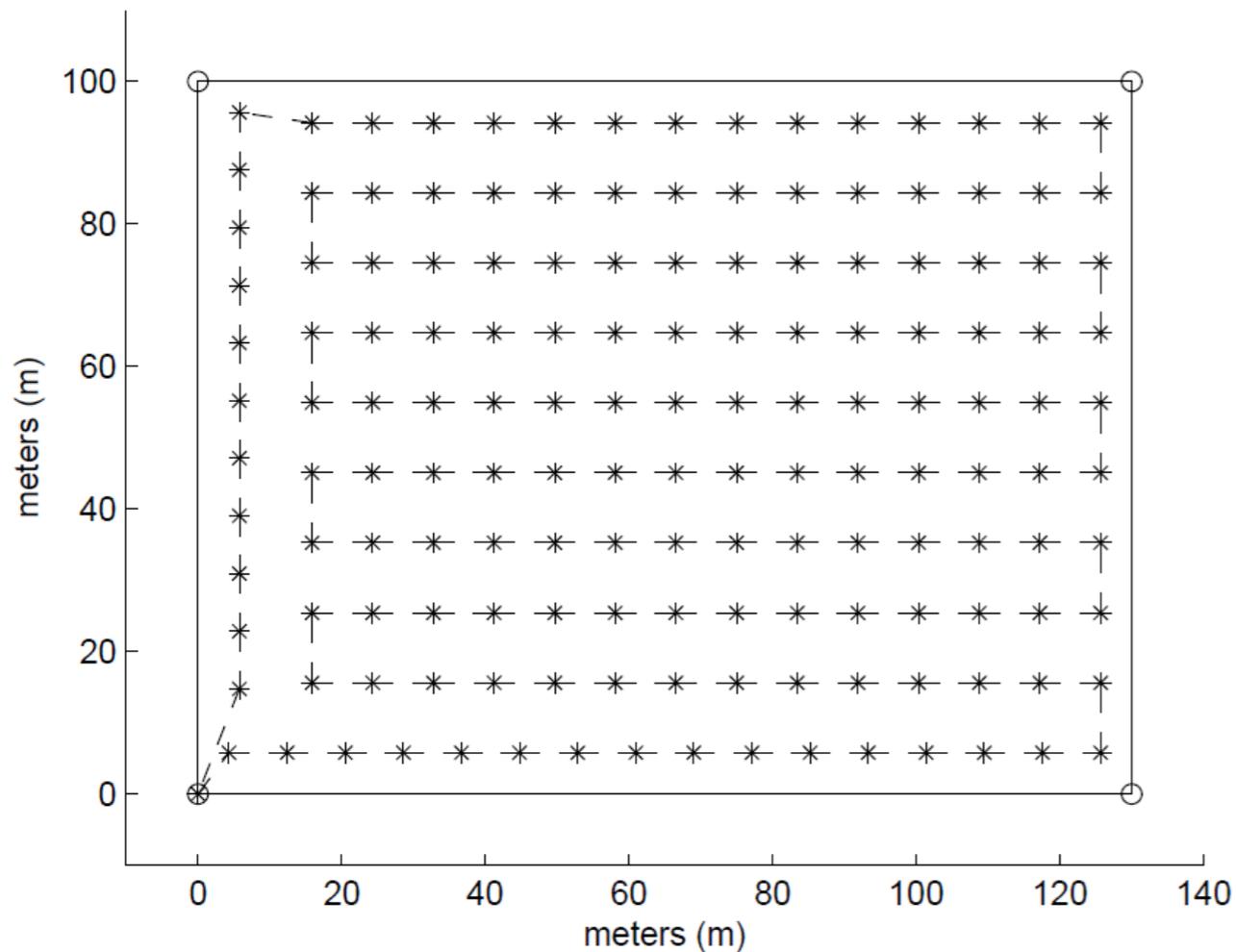


Example of discharging voltage curve of a 3S liPo battery during a flight.



Energy-Failsafe

Check if the remaining energy is greater than the energy required to come back to the starting point.

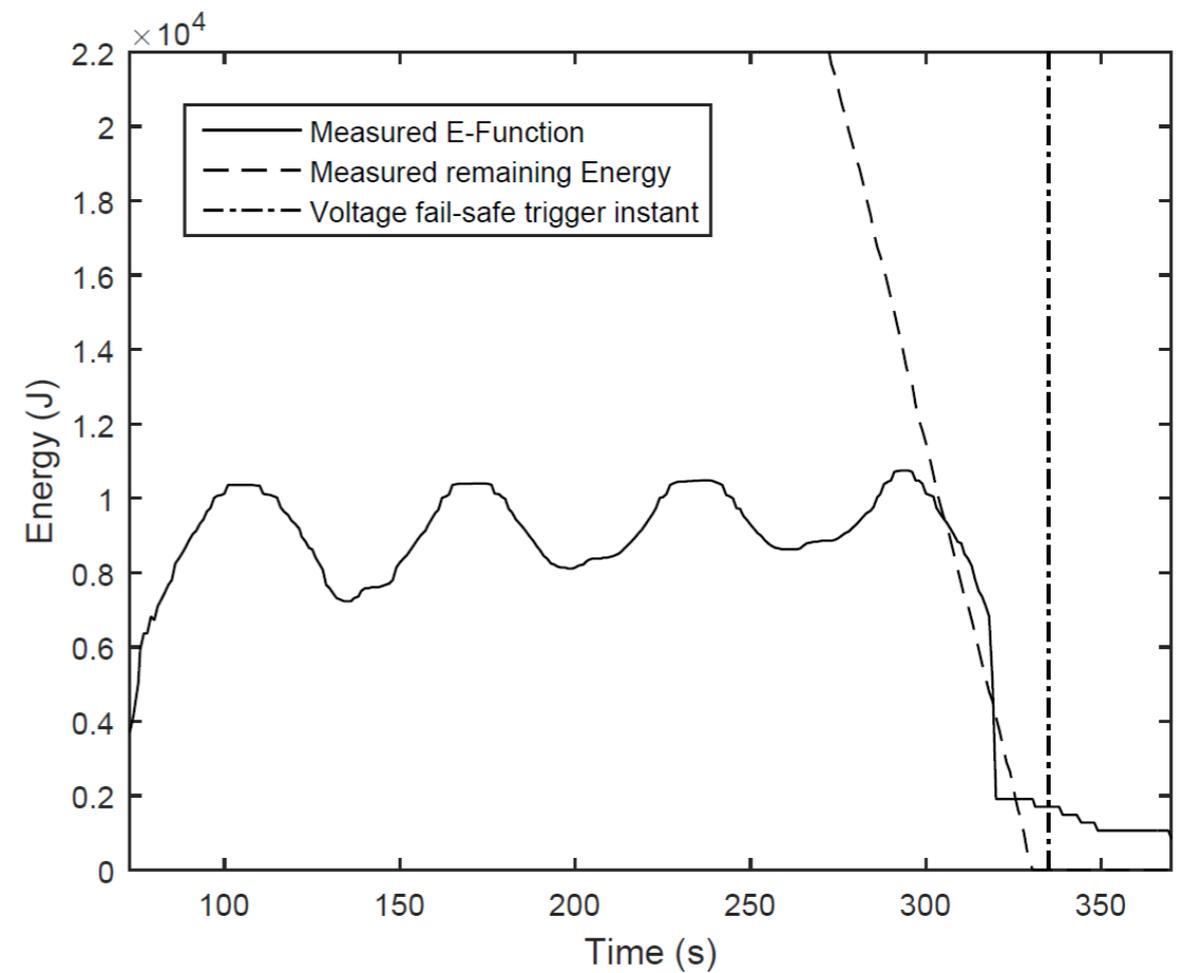
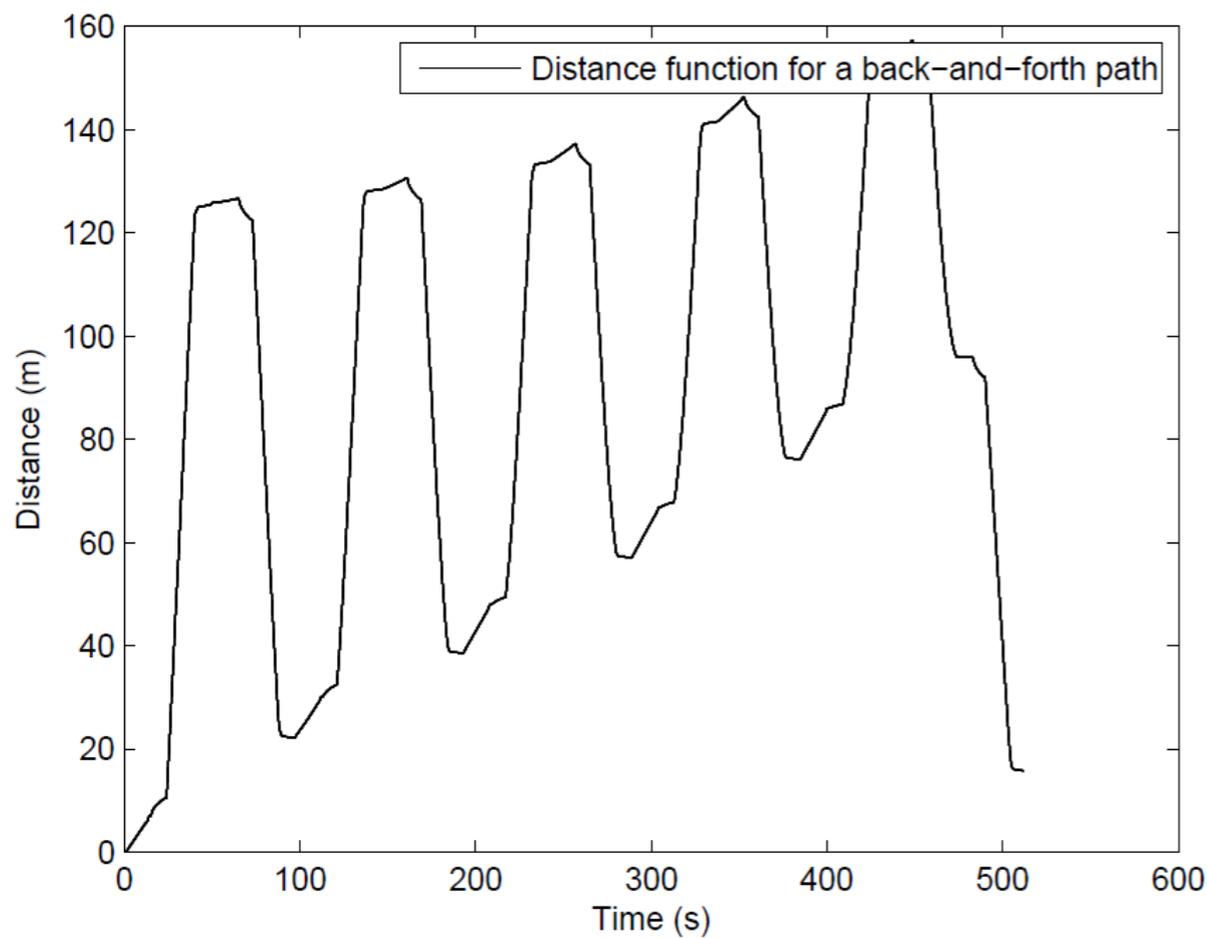


Energy-failsafe through the E-Function

Distance function



E-function



Closing remarks

- An energy model for a specific quadrotor is derived from real measurements
- By exploiting the energy model, is possible to set for each part of the path the **optimal speed that minimize the energy consumption**.
- **An offline-feasibility test is performed** to check if the computed path can be actually flight with the energy available in the battery.
- An **Online Energy-Failsafe** mechanism is introduced to prevent the UAV going further



thank you!

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