MULTIROTOR DRONE SIZING & TRAJECTORY OPTIMIZATION WITHIN MODELON IMPACT

October 26th, 2022

Modelon

AGENDA

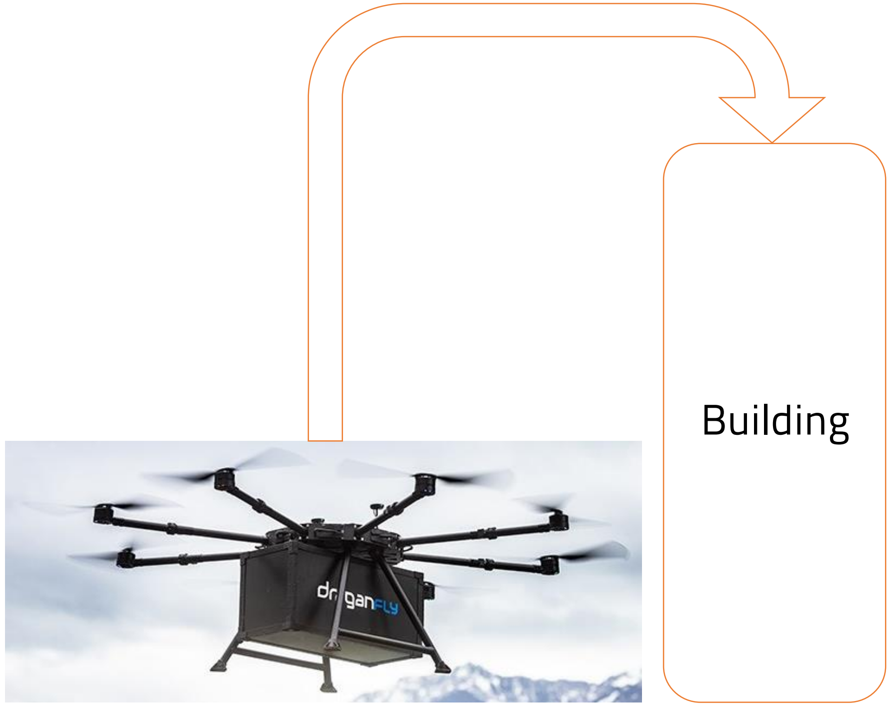
- Case study
  - Use case
  - Drone architecture
- Drone model
  - Model choices
  - Propeller model (as an example)
  - Sizing scenarios
- Optimization
  - Problem statement
  - Solving
  - Implementation and results
- Conclusions and Perspectives


CASE STUDY

CASE STUDY PAYLOAD LIFTING

- Use case - lifting small payloads on top of buildings
  - Maximum 25 kg
  - 150 climbs of 10m height with 5secs hovering

- What we want to solve,
  for a fixed drone architecture – simultaneously:
  - Optimize the drone trajectory to minimize energy consumption
  - Size the drone main parts



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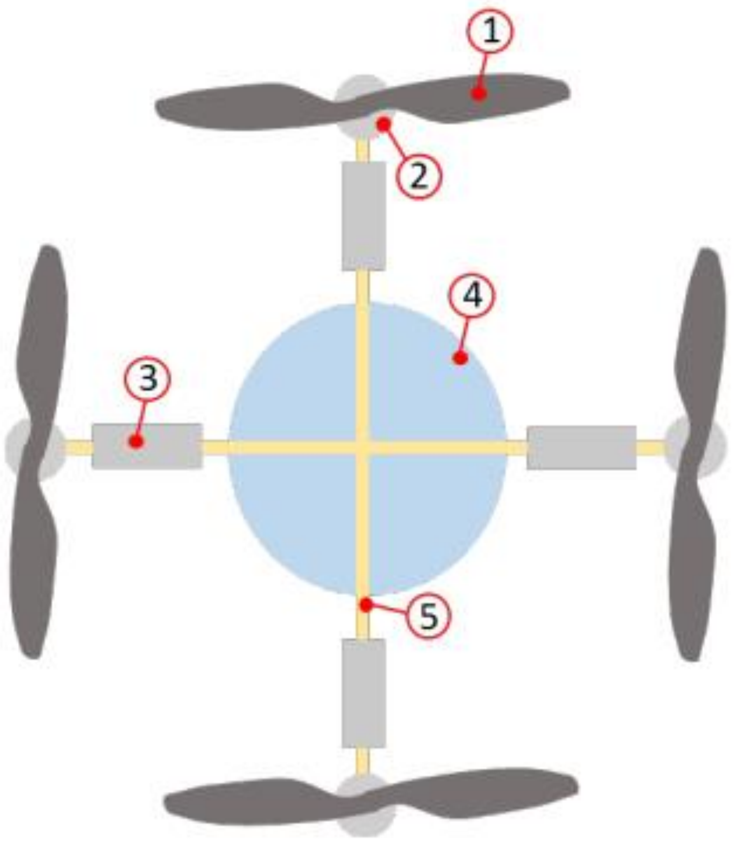
DRONE ARCHITECTURE SELECTED



1. Four fixed pitch propellers
2. Four out-runner brushless motors
3. Four electronic speed controllers (ESC) mainly made from MOSFET inverters
4. One battery based on Li-Ion cells
5. One mechanical structure (frame) consisting of four arms and one central body

DRONE MODEL

DRONE MODEL CHOICES

- Model purpose
  - 1-D trajectory optimization
  - Component sizing

All equations are, at least, C2-continuous (optimization algorithm based on gradients)

Design variables have max, min, nominal attributes for bounds and scaling

Initial (not optimized) trajectory provided

A-causality: use of Modelica language

- Sizing requires inverse simulation
- Performance flight simulation requires direct simulation

Scaling laws and meta models for sizing

Efficiency-based modeling (low fidelity)

DRONE PROPELLER MODEL

- Model purpose
  - Physics (performance)
  - Scaling laws (sizing)

$$Thrust = C_T \rho_{air} n^2 D^4$$
$$Power = C_P \rho_{air} n^3 D^5$$

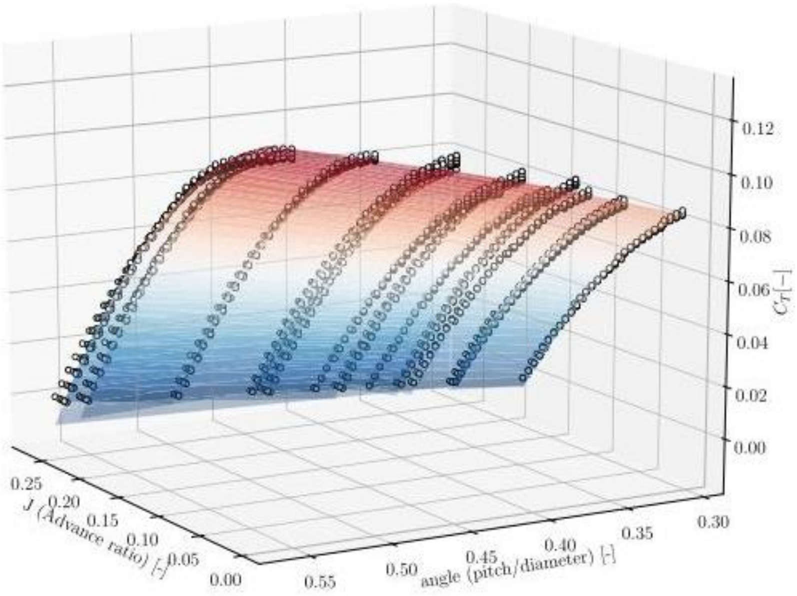
Buckingham
π theorem

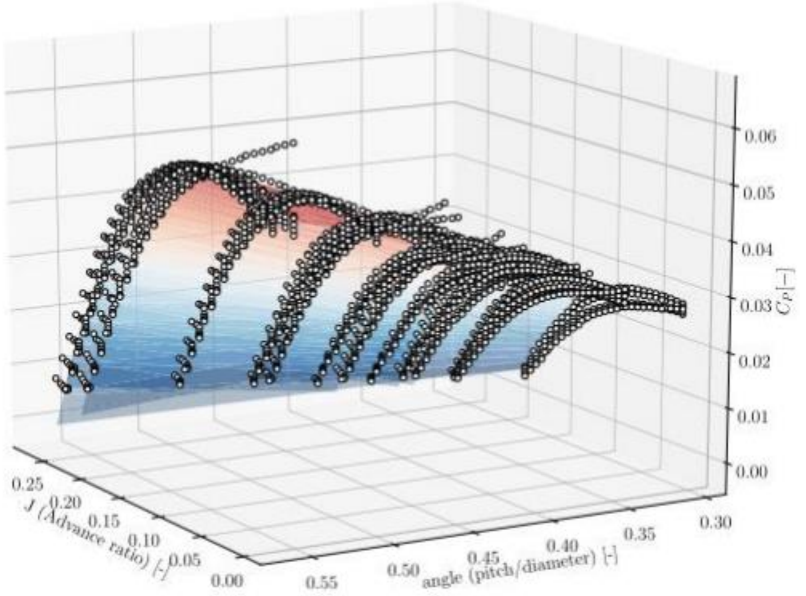
$$\begin{cases} C_T = f(\beta, J, B) \\ C_p = f(\beta, J, B) \\ \beta = pitch/D \\ J = V/(nD) \\ B = K/(\rho n^2 D^2) \end{cases}$$

Polynomial fitting on maps

$$M_{prop} = \mathrm{M_{ref}}\left(D_{prop}/D_{ref}\right)^2$$
$$\mathrm{I_{prop}} = \mathrm{M_{prop}}\left(D_{prop}/2\right)^3/3$$

$\left\{\begin{array}{ll} \beta = pitch/D & \textit{pitch to diameter ratio} \\ J = V/(nD) & \textit{advance ratio} \\ B = K/(\rho n^2 D^2) & \textit{air compressibility indicator} \end{array}\right.$





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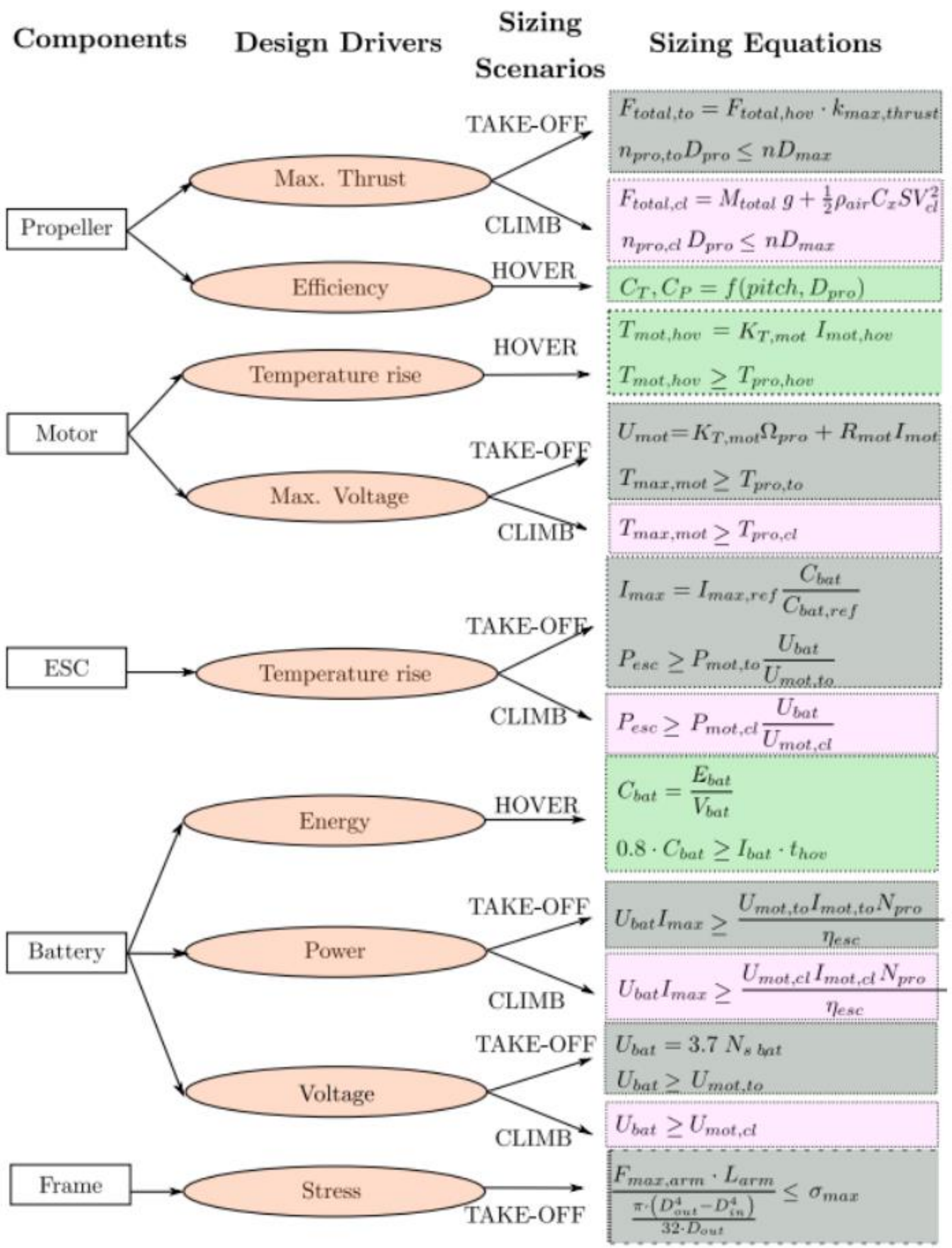
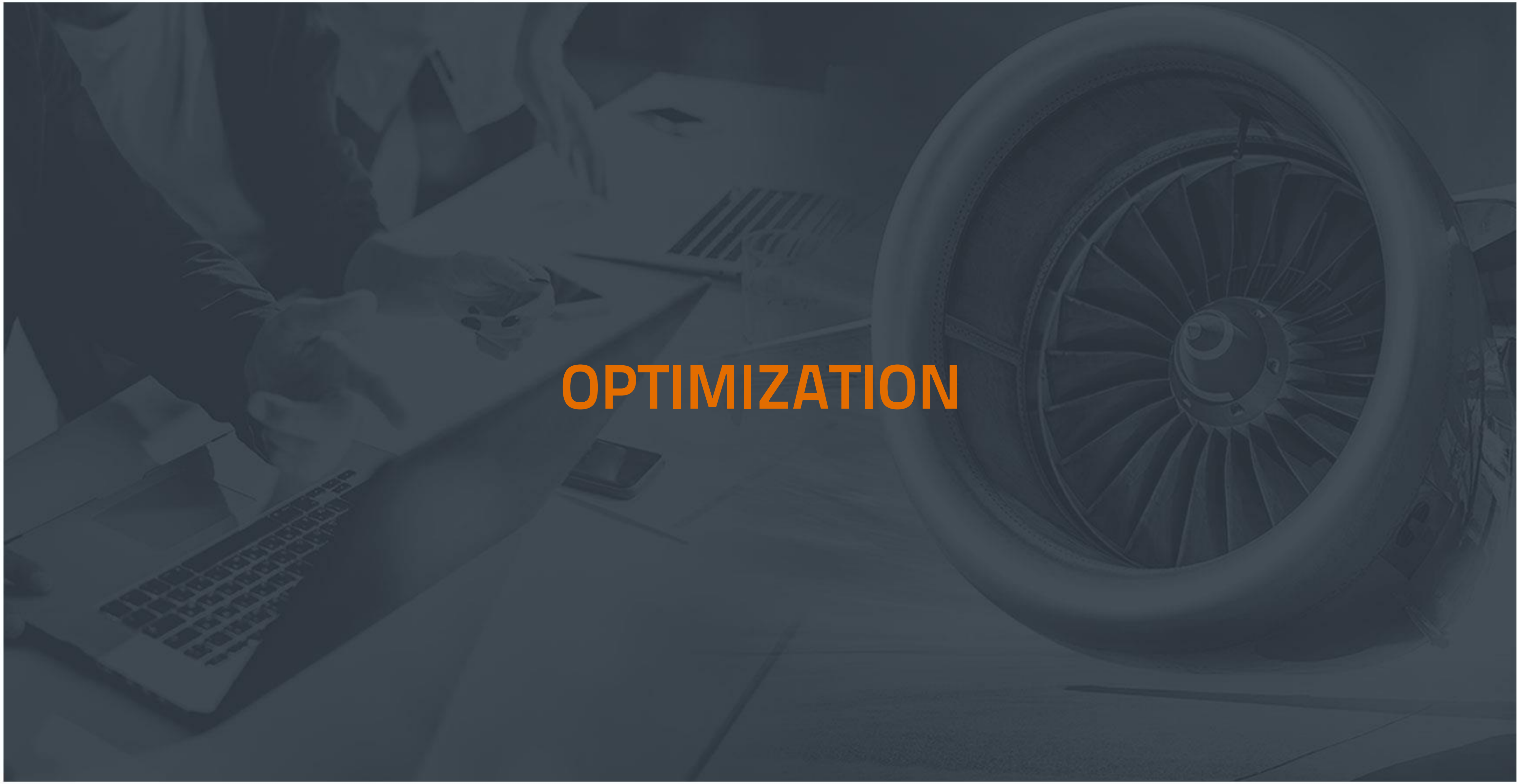
DRONE SIZING MODEL

- Sizing scenarios
  - Hover – J=0 (as V=0)
  - Takeoff – maximum power, increasing J
  - Climb – constant J

$$\begin{cases} \beta = pitch/D & \text{pitch to diameter ratio} \\ J = V/(nD) & \text{advance ratio} \\ B = K/(\rho n^2 D^2) & \text{air compressibility indicator} \end{cases}$$

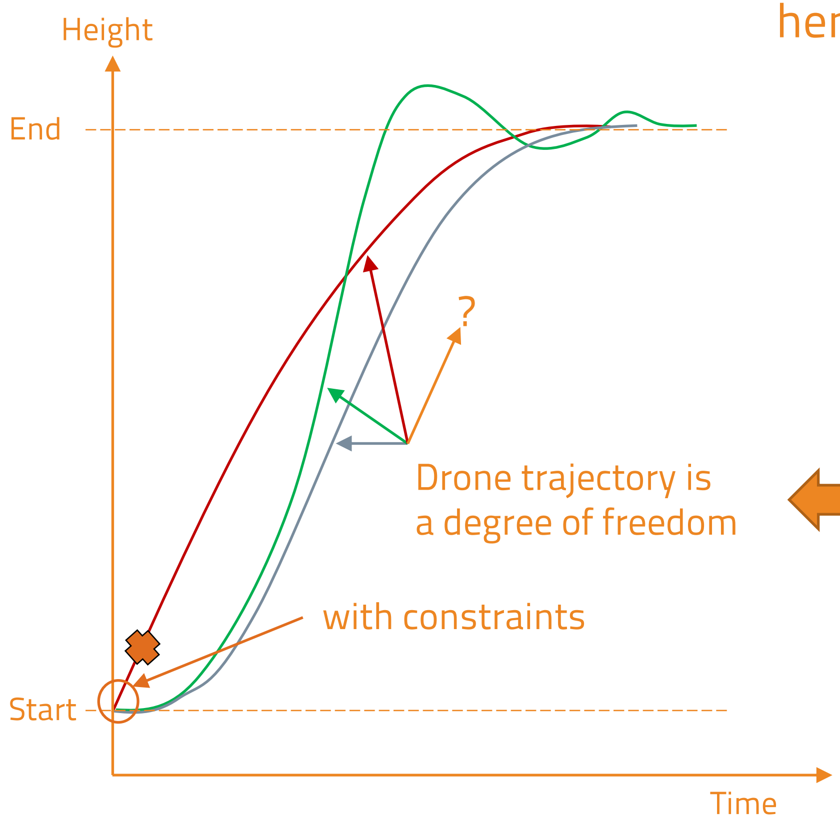


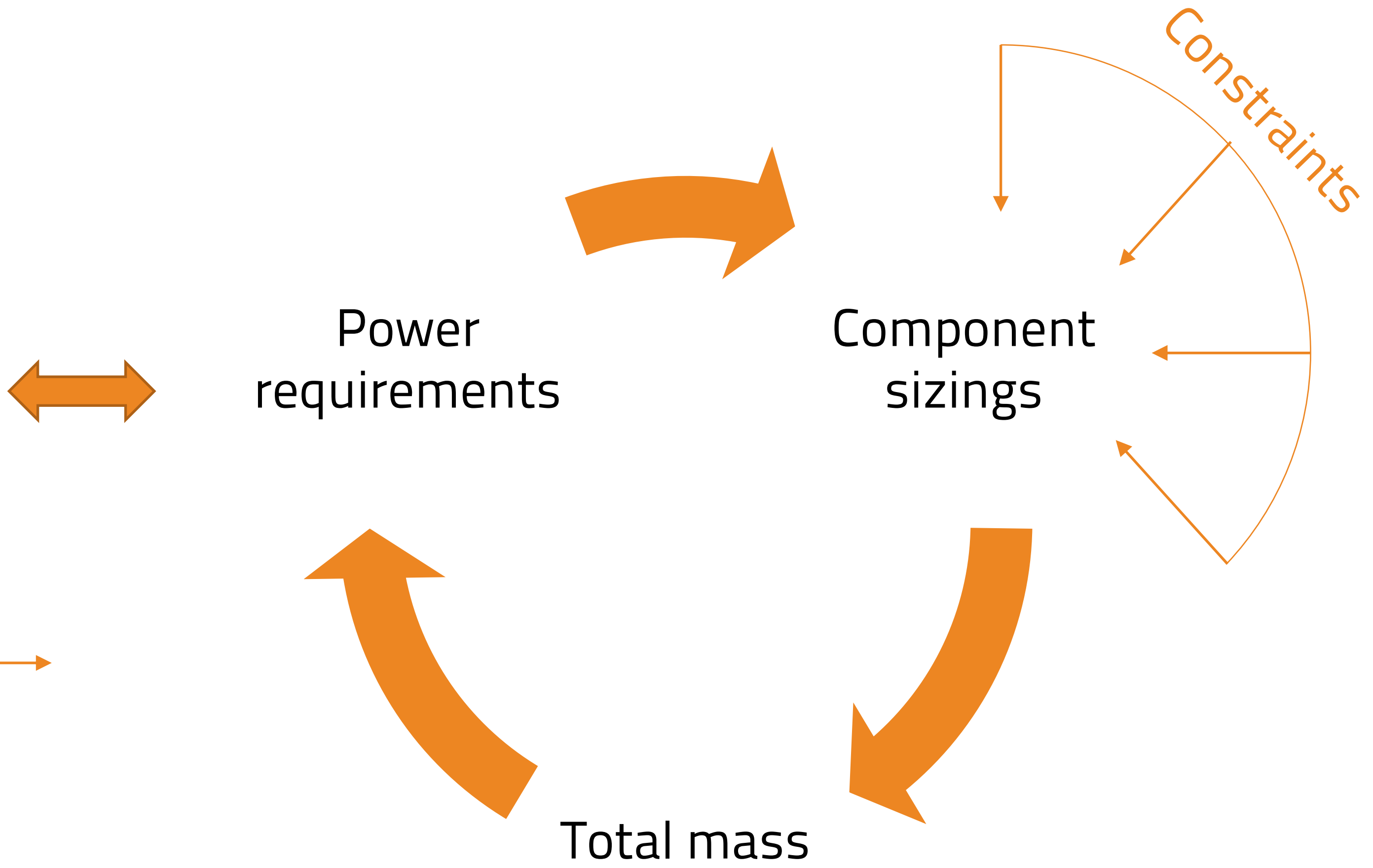
OPTIMIZATION



OPTIMIZATION PROBLEM STATEMENT

We want to maximize the number of flights;
hence our objective is to minimize the energy consumption per flight.





OPTIMIZATION PROBLEM SOLVING

Optimica model including
- Objective
- Trajectory optimization
- Constraints

Modelica Drone model with
- Pre-sizing
- Mass estimation
- Behavior

OPTIMIZATION OPTIMICA IMPLEMENTATION

```
optimization SizingAndTrajectoryOptim (
  objective=M_total(startTime),
  finalTime(free=true, min=1, max=10, start=5))
// Minimize the total drone mass and relax the final simulation time within bounds.

  import Modelica.Units.SI.DimensionlessRatio;

  extends Drone(
    x(start = 0, fixed=true),
    xp(start = 0, fixed=true),
    a(start = 0, fixed=true),
    beta(free=true, min=0.3, max=0.6, start=0.4),
    D(free=true, min=0, max=1),
    T_nom_mot(free=true, min=0),
    K_mot(free=true, min=0),
    M_bat(free=true, min=0, max=100),
    P_esc(free=true, min=0),
    k_D(free=true, min=0.01, max=1, start=0.05),
    D_out_arm(free=true, min=0.001, max=1));
// Inherit the Modelica drone model, fix initial conditions and relax design parameters
within bounds.

  Modelica.Blocks.Interfaces.RealInput Traj_in;
// Add input to the trajectory to optimize

...

  DimensionlessRatio n_norm(start=1, fixed=true)=n/n_hover;

  DimensionlessRatio N_norm(min=-1, max=1, nominal=0.8)=ND/ND_max;

  DimensionlessRatio T_hov_norm(min=0, max=1, nominal=0.6) = T_hover/T_nom_mot;

  DimensionlessRatio T_norm(min=-1, max=1, nominal=0.95) = T/T_max_mot;

  DimensionlessRatio U_norm(min=0, max=1, nominal=0.5) = U_mot/V_bat;

  DimensionlessRatio P_norm(min=0, max=1, nominal=0.5) = P_mot/P_esc;

  DimensionlessRatio E_norm(min=0, max=1, nominal=0.25) = E_drone/E_bat;

  DimensionlessRatio sigma_norm(min=-1, max=1, nominal=0.15) = sigma/sigma_max;
// Create additional normalized variables with bounds as inequality constraints

equation

  T=Traj_in; // Bind drone trajectory with optimization input

constraint

  x(finalTime) = 10;

  xp(finalTime) = 0;

  a(finalTime) = 0;
// Define end time constraints.

end SizingAndTrahjectoryOptim;
```

objective

Modelica Drone model with
- Pre-sizing
- Mass estimation
- Behavior

Optimization attribute

trajectory

constraints

Optimica

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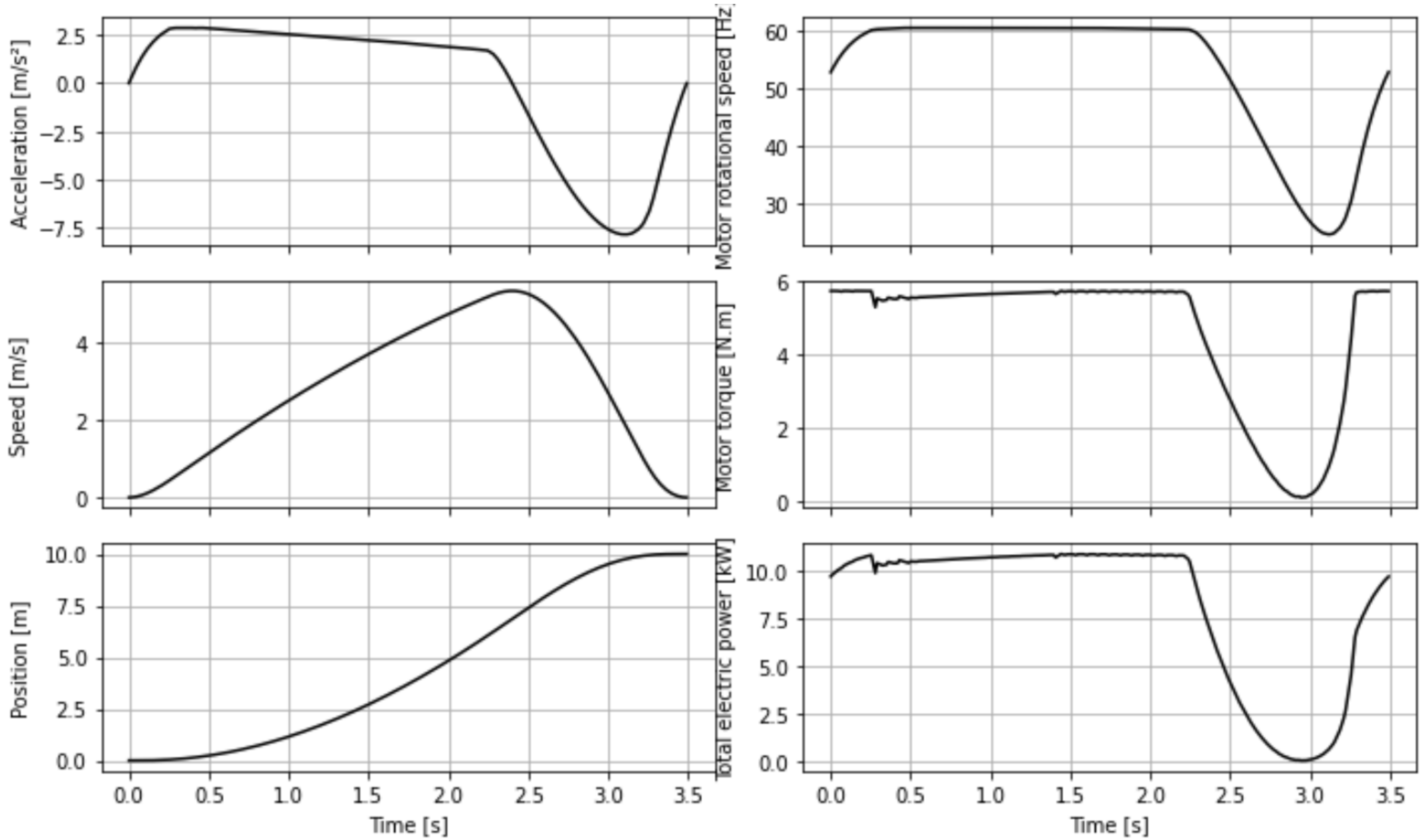
OPTIMIZATION RESULTS



Drone ~45kg

Incl. ~27kg battery

+ 25kg payload

CONCLUSIONS & PERSPECTIVES

MODELON IMPACT BENEFITS

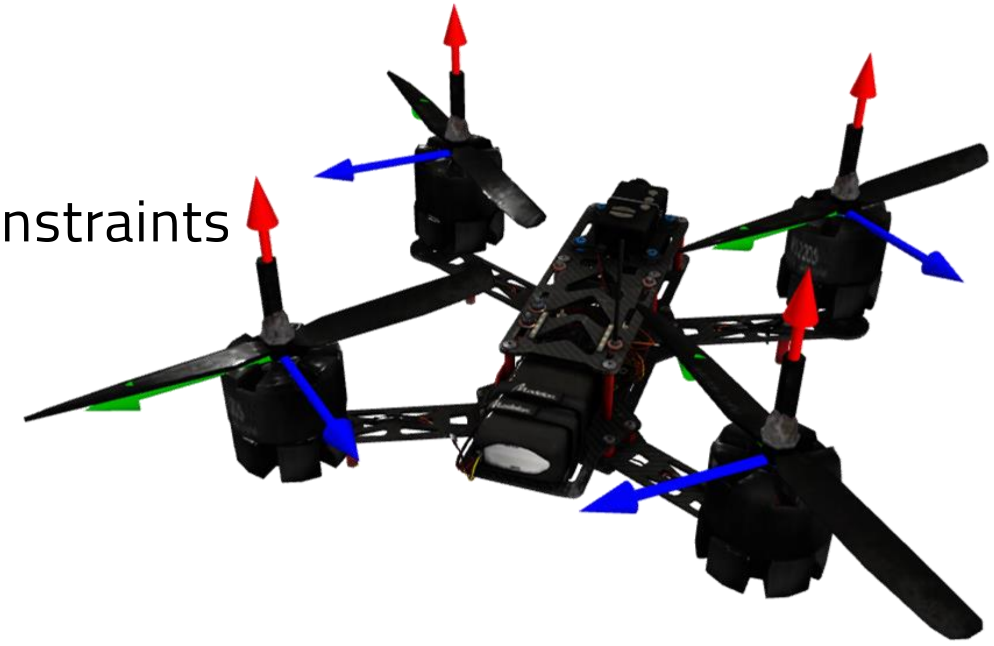
In comparison with a FAST-OAD optimization, relying on a drone FMU

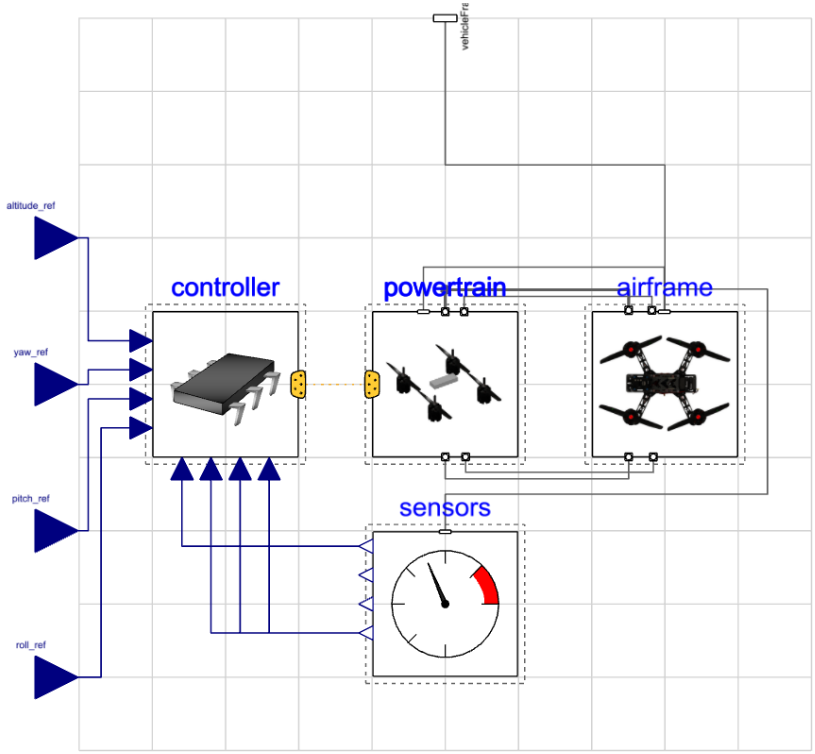
- Solving initialization problem
  - No need to adapt the code for solving an IVP
- A-causality
  - Torque trajectory optimization fed with an initial Position-controlled trajectory, simulated from the same model
- Normalization for convergence, based on nominal attributes and bounds
- Derivatives at hand of the optimizer
- "Simple, fast and robust"
  - Optimica language is similar to Modelica language (as it is an extension from it)
  - 30sec optim vs 2min for the FAST-OAD solution
- Everything is never all black or white: FAST-OAD allows integration of models from different fidelities (e.g. CFD) and well suited for large scale optimizations

CONCLUSION & PERSPECTIVES

- Simultaneous drone 1-D trajectory optimization and sizing, in Modelon Impact
- Scaling-law based sizing and efficiency-based performance models
- Results obtained with FAST-OAD and Modelon Impact were similar – though the Optimica implementation was of low threshold for a Modelica engineer (the model requires preparation)

- 6-DOF
- Regulatory constraints





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THANK YOU

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