European Workshop on Aircraft Design Education

Hybrid propulsion applied to a general aviation aircraft: a perspective for the future

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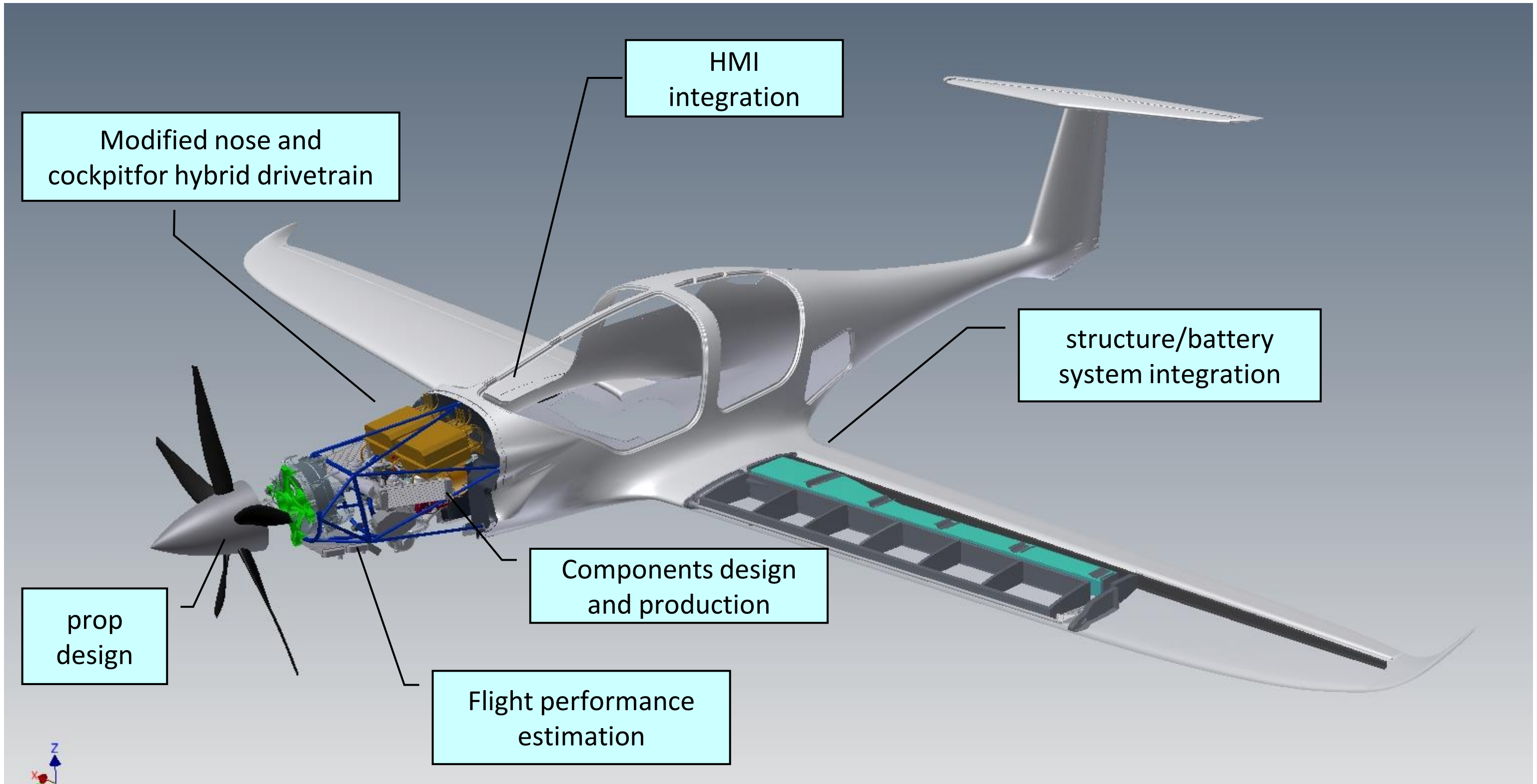
Agenda

- **Introduction on the performance analysis of hybrid powered aircraft**
- **Overview of the preliminary model**
    - **Overview of the calculation procedure**
    - **Results**
- **Set up of the simulator**
    - **HyPSim: general description**
    - **Results**
- **Conclusions, future developments, challenges**

The Hypstair Project

Development and validation of hybrid propulsion system components and sub-systems for electrical aircraft: qualification procedures for a serial production.



Small general aviation CS-23 four seat aeroplane with 1315 kg MTOM

PIPISTREL

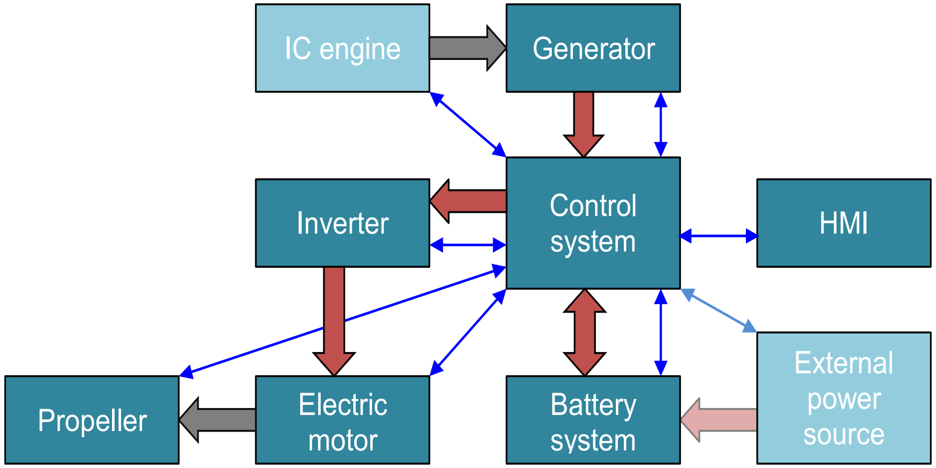
SIEMENS

Univerza v Mariboru

MBVision

Forewords

A vehicle can be defined *hybrid,* when two or more, different energy sources are used for the motion in a alternative way or at the same time



Performance depend on power system settings:

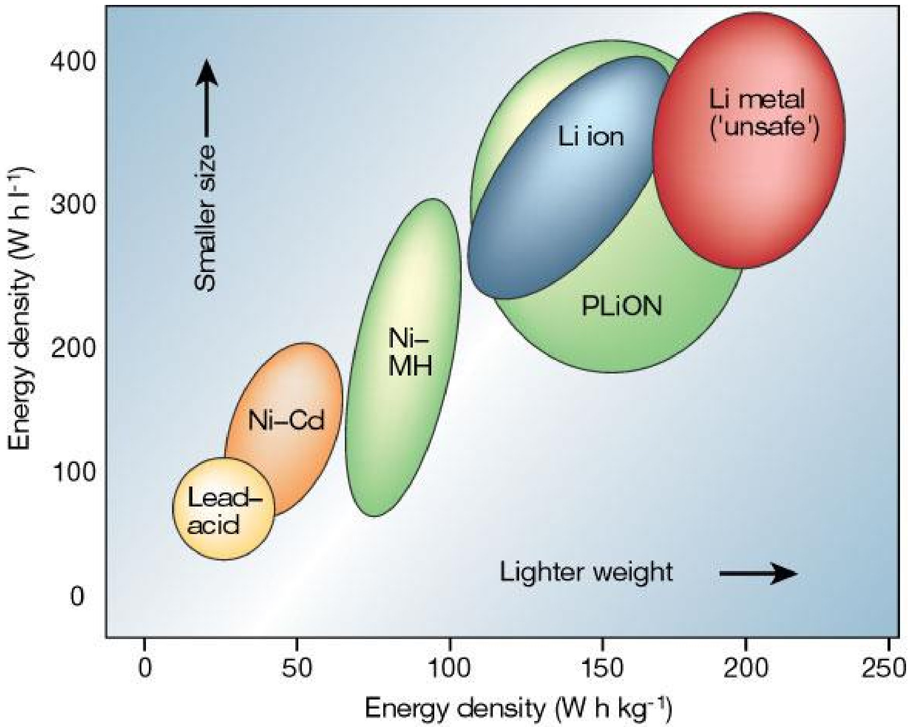
•General arrangement of the system

• Power flow control

Power management ensures bigger design space

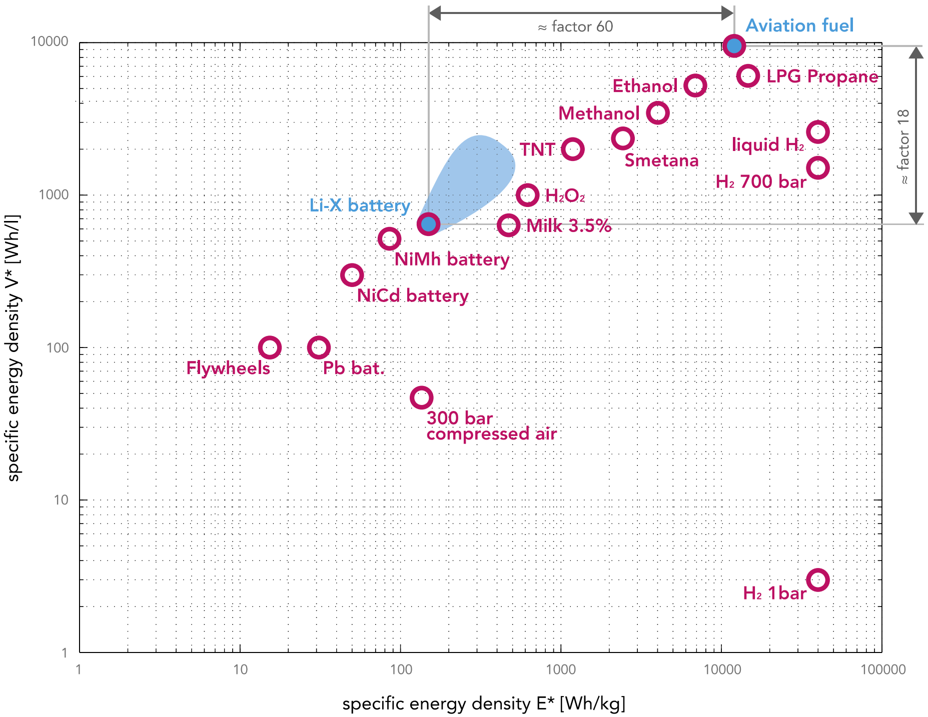
More complexity

Forewords



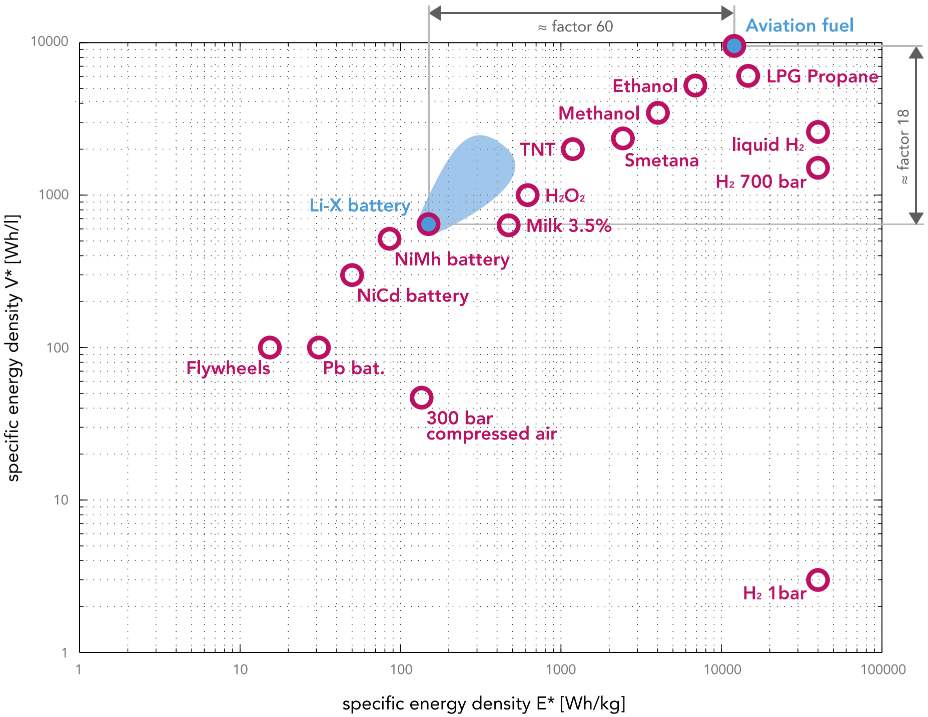
Energy density (W h l⁻¹)
400
300
200
100
0
Smaller size
Li ion
Li metal ('unsafe')
PLiON
Ni–MH
Ni–Cd
Lead–acid
Lighter weight
0
50
100
150
200
250
Energy density (W h kg⁻¹)

Forewords



≈ factor 60
Aviation fuel
LPG Propane
Ethanol
Methanol
TNT
Smetana
liquid H_2
H_2 700 bar
≈ factor 18
H_2O_2
Li-X battery
Milk 3.5%
NiMh battery
NiCd battery
Flywheels
Pb bat.
300 bar
compressed air
H_2 1bar
specific energy density V* [Wh/l]
specific energy density E* [Wh/kg]
10000
1000
100
10
1
1
10
100
1000
10000
100000

Forewords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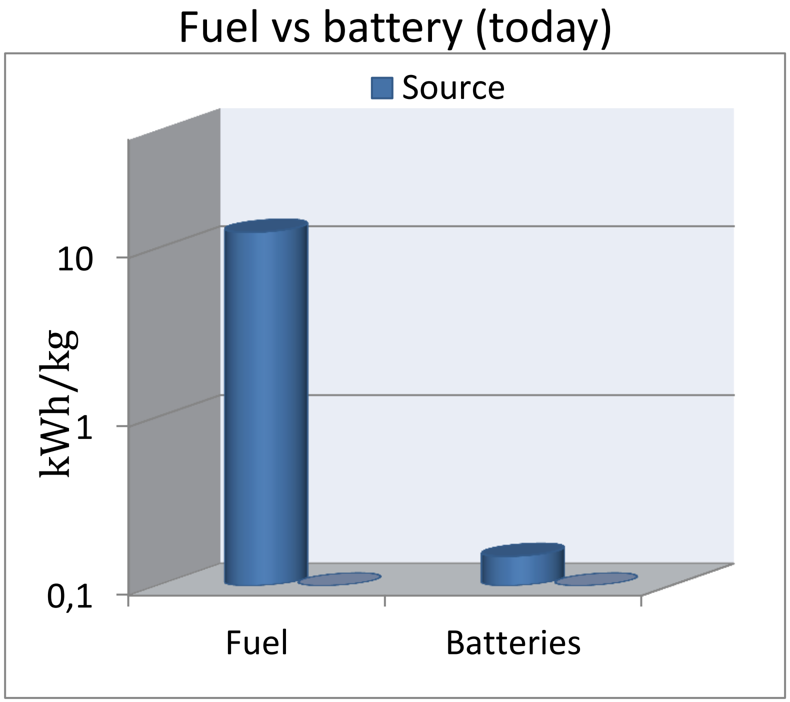
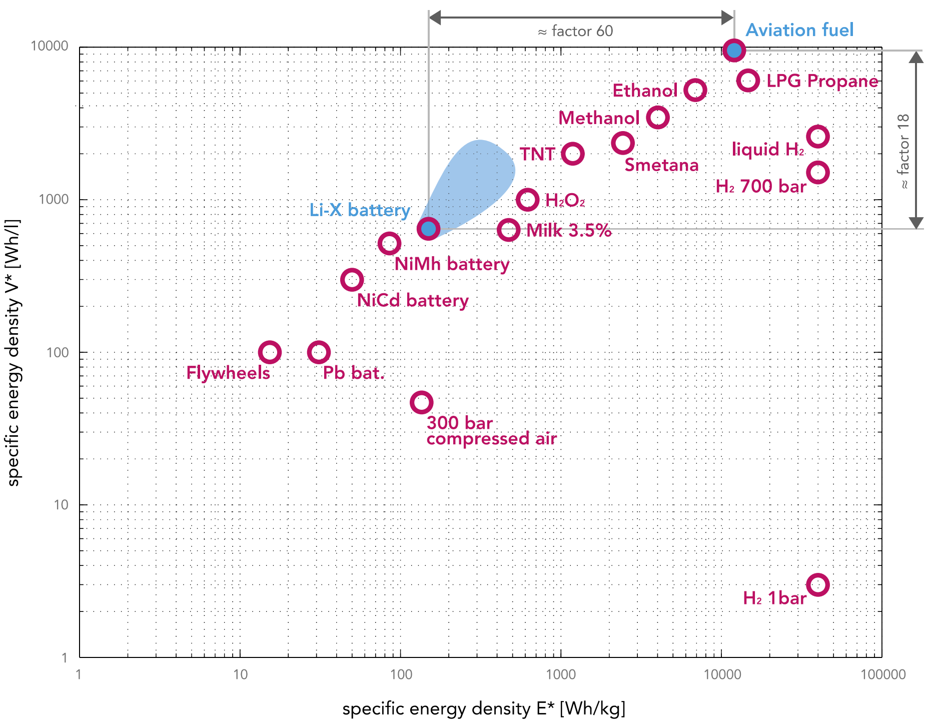

Fuel vs battery (today)
Source
10
1
0,1
kWh/kg
Fuel
Batteries

Forewords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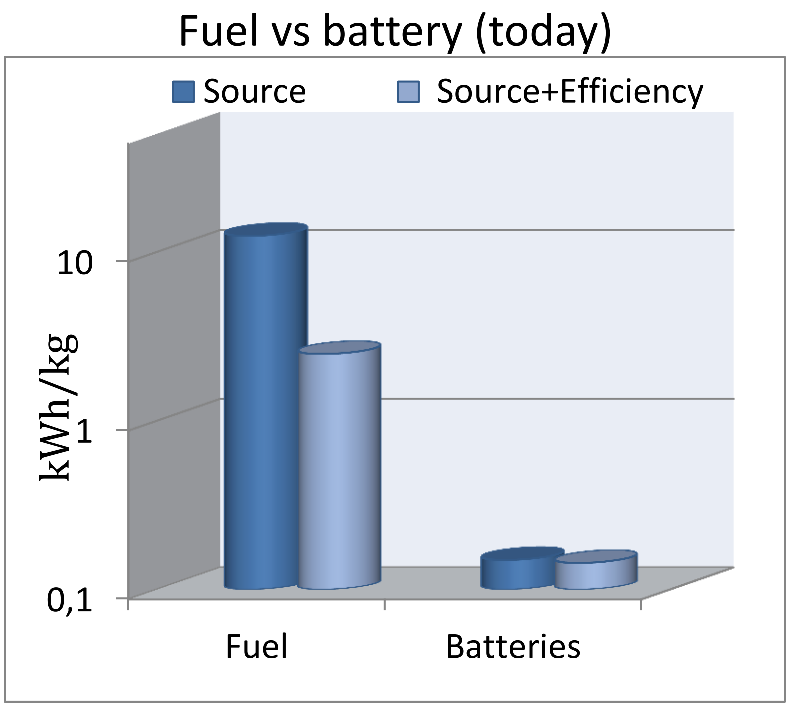
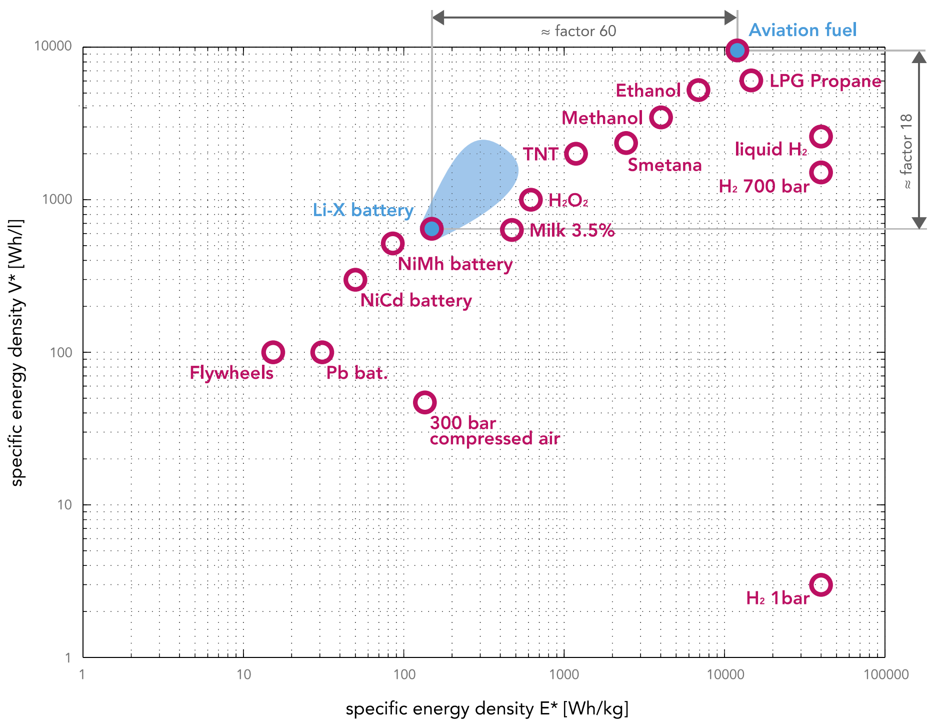
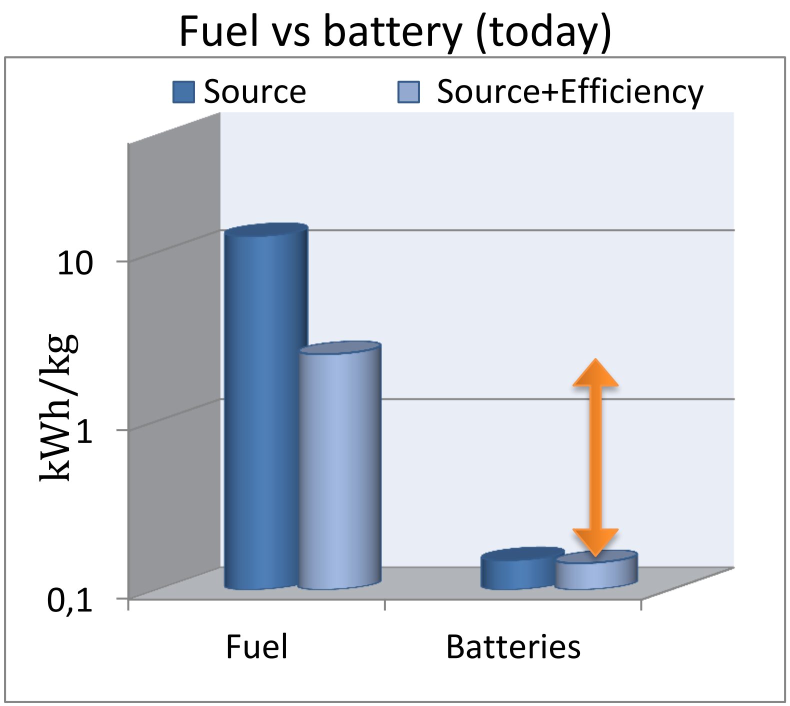
specific energy density V* [Wh/l]
specific energy density E* [Wh/kg]
10000
1000
100
10
1
1
10
100
1000
10000
100000


Fuel vs battery (today)
Source
Source+Efficiency
kWh/kg
10
1
0,1
Fuel
Batteries

Forewords



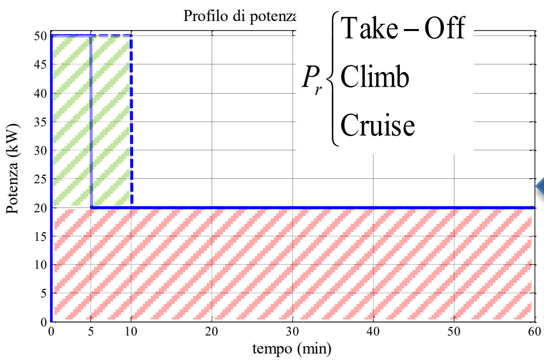


Definition of the optimum requirements in terms of cruise speed, cruise altitude, flight programs in order that the propulsion system works at the optimum point.

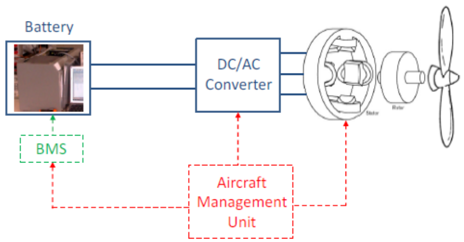
Evaluation of the system efficiency when different flight programs are performed.

Preliminary design activities

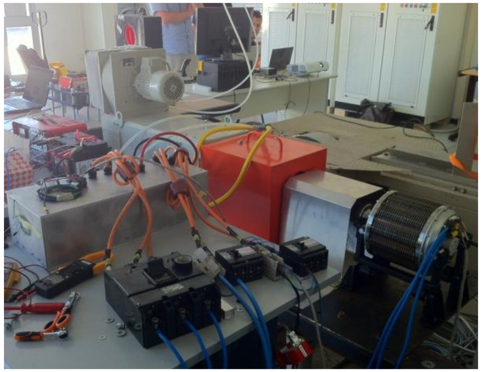
Performance analysis

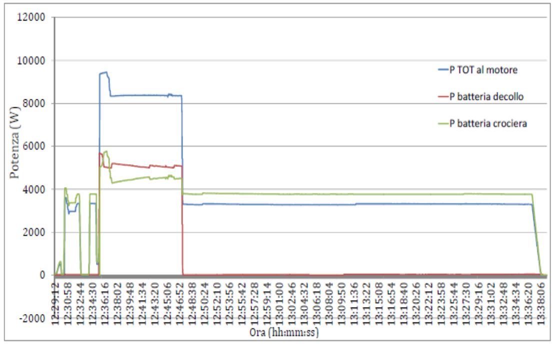


Component sizing



Testing





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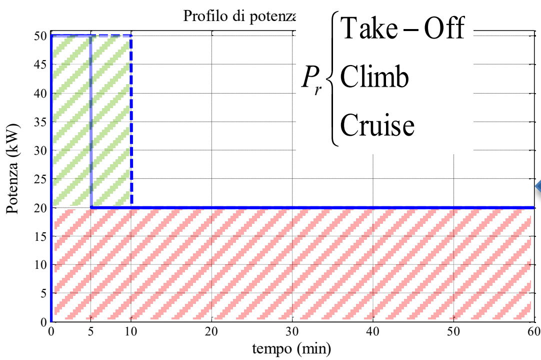
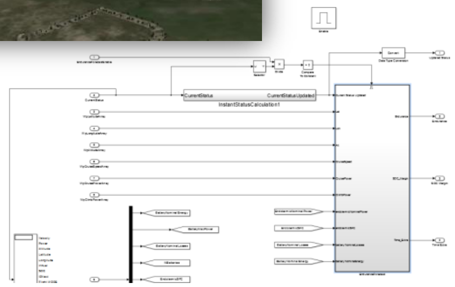


Simulator



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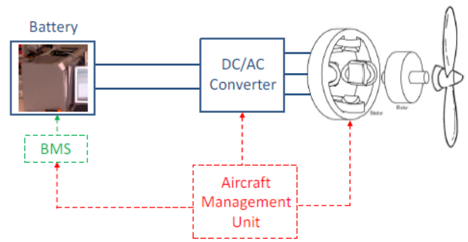

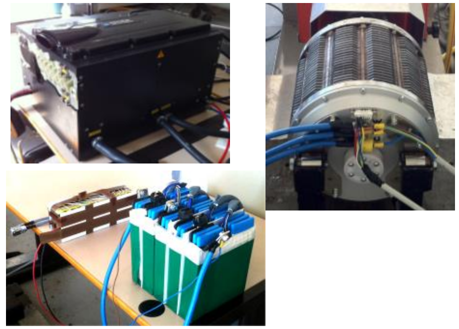

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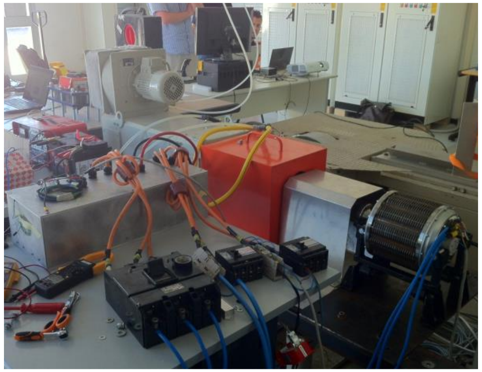
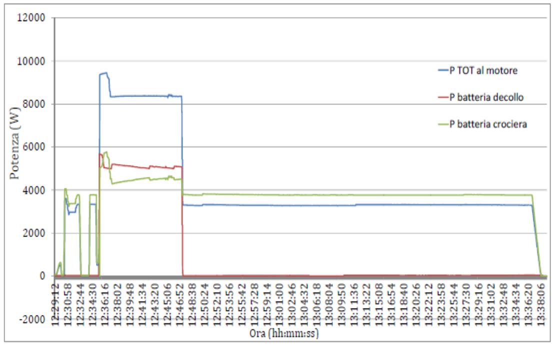
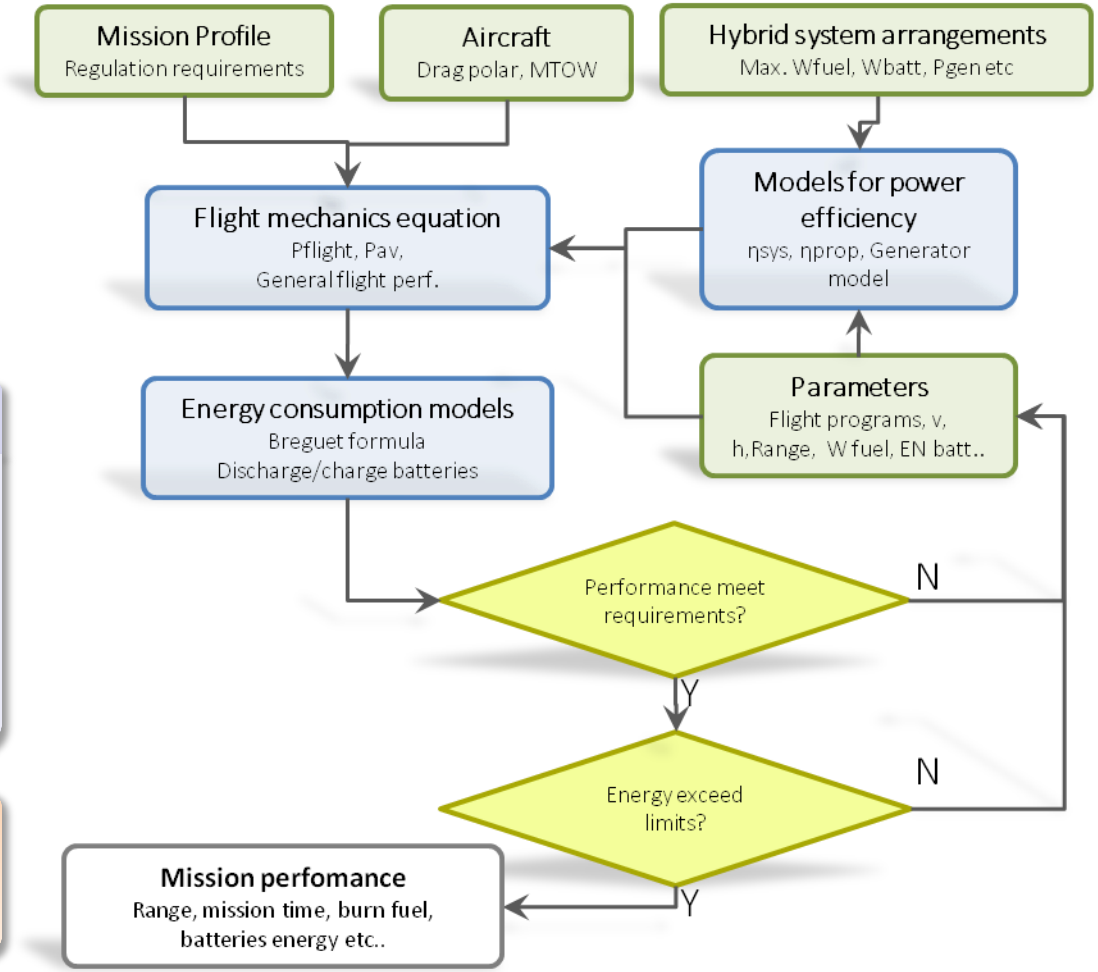




General preliminary procedure

Definition of a simple, time-saving and reliable hybrid A/C performance model



Two different approaches

- Optimum flight performance to maximize range with imposed amount of fuel and batteries.
- Optimum flight performance to minimize the takeoff weight with imposed nominal range.

Important: each input data can be easily modified or changed to a variable of the procedure

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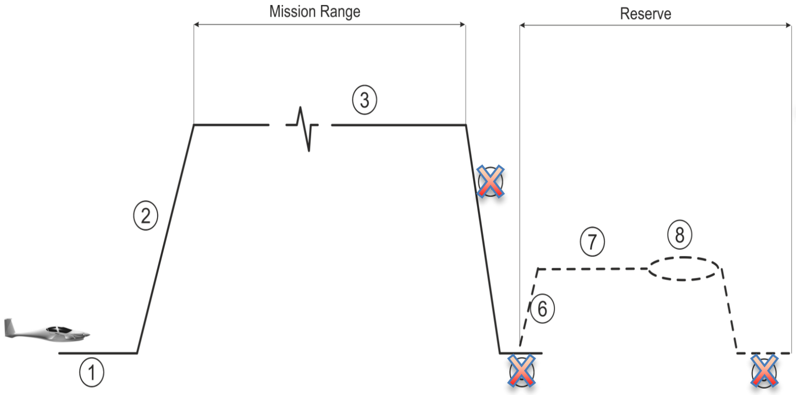

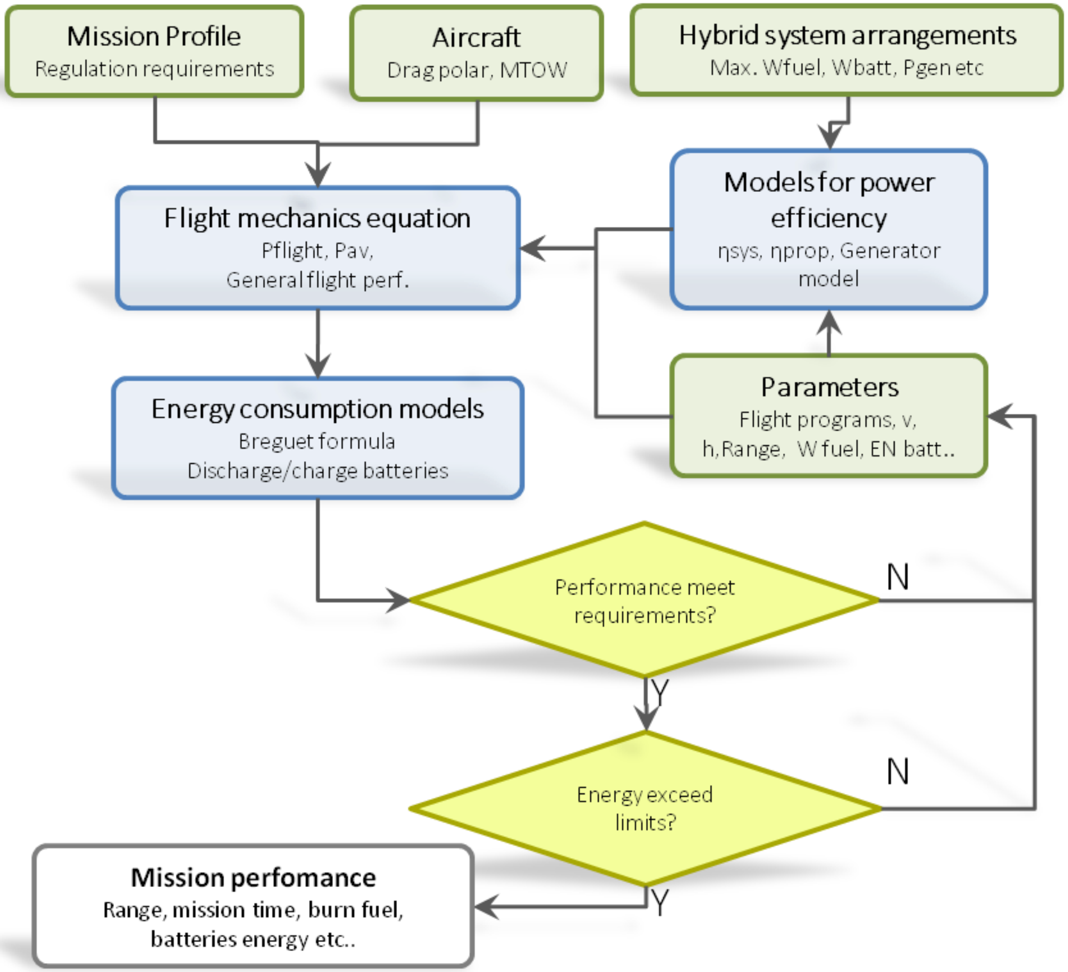

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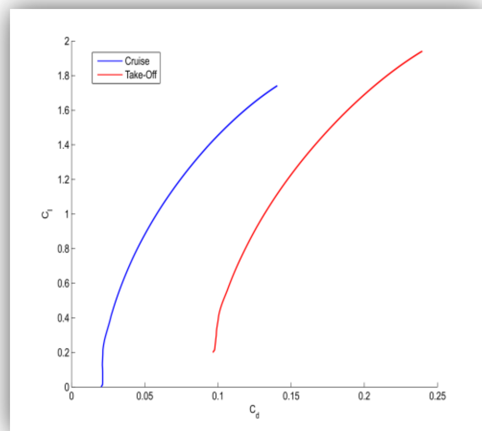
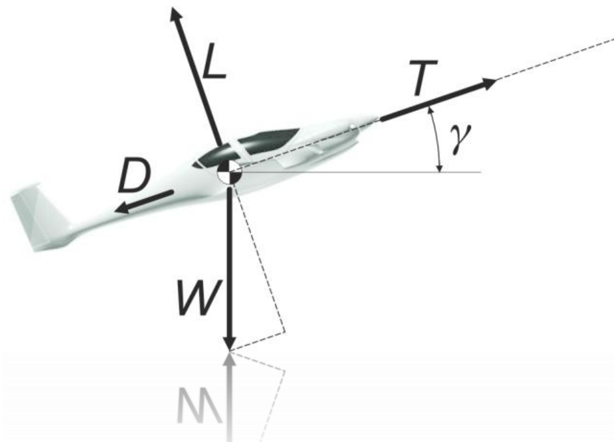
Flight mechanics

Aerodynamics and weight limits are given



Weights breakdown [kg]
MTOW
W payload
W_{max} fuel
W_{max} batteries



Point mass model

Forces equilibrium

$$\begin{cases} L = W\cos\gamma \\ (D + W sen\gamma)v = P_{mot}\,\eta_{prop} \\ D = \frac{1}{2}\rho v^2 S\, c_D \\ c_D = f(c_L) \end{cases}$$

Breguet formula for fuel consumption estimation:

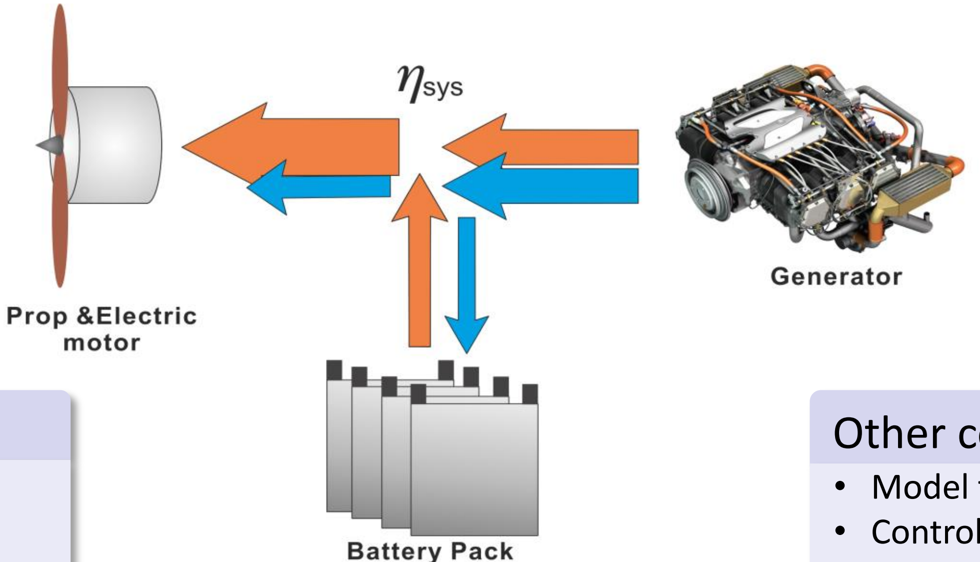
$$\frac{dW}{dt} = -SFC \cdot P_{eng}$$

Equations are specialized for each flight segment

Novelty: P_{mot} depends on both, the generator and the batteries:

$$P_{mot} = \eta_{sys} \cdot \left(P_{eng} + P_{batt}\right)$$

Modeling the hybrid propulsion system



Propeller

- Given aerodynamic characteristics
- Efficiency calculation by means of actuator disk theory

Electric motor

- Maximum continuous power: 200 kW
- Efficiency 95%

Batteries

- Cells typology and pack arrangement.
- Charge/discharge efficiency related to internal losses

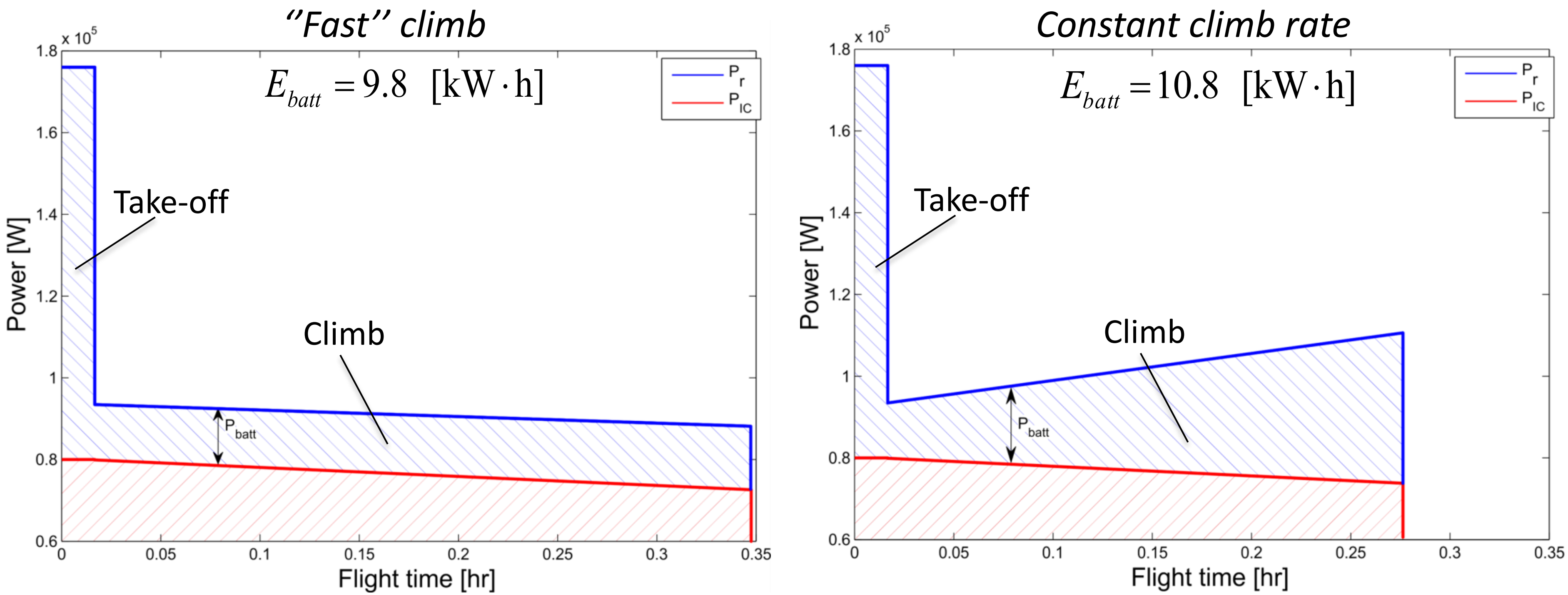
Other components

- Model for power efficiency.
- Control laws for the power flows

IC engine

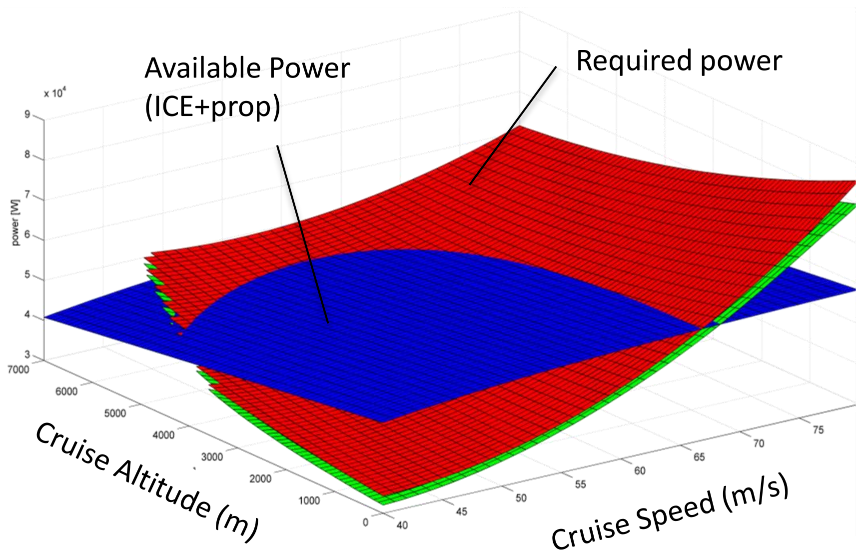
- Maximum continuous power: 80 kW
- Performance vary with altitude
- Turbocharger!

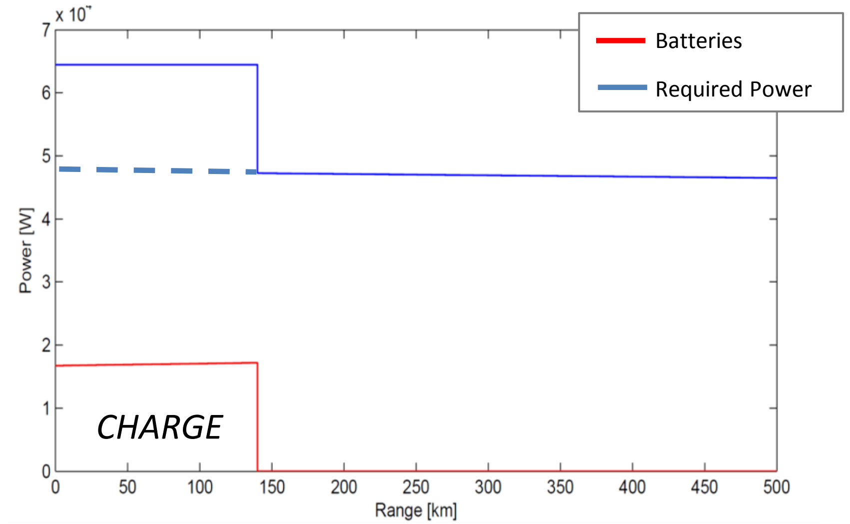
Preliminary results: takeoff and climb



- Fast or deepest climb flight programs "loss" their meaning;
- Performance during climb depend strongly on the utilization of the battery.

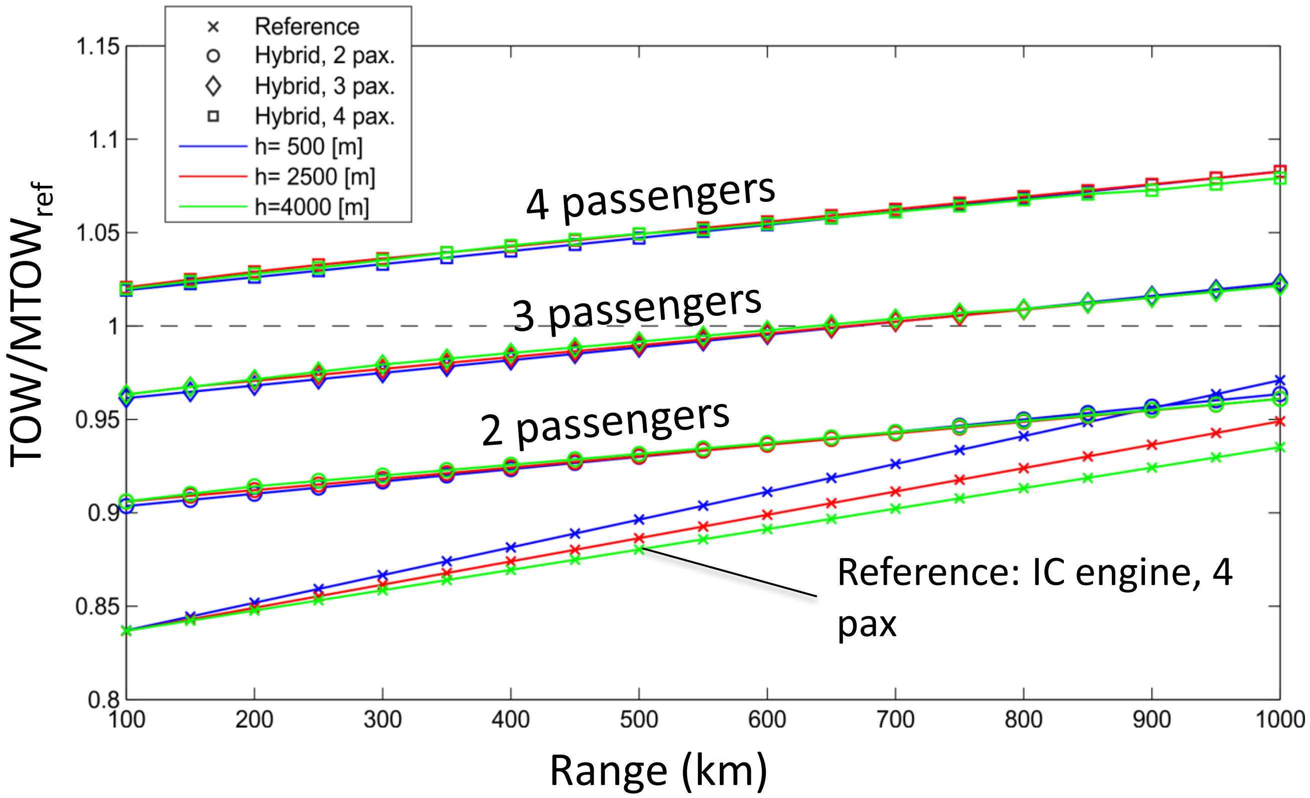
Preliminary results: cruise





- For most of the cruise, power for flight can be provided by the IC engine;
- After climb batteries need to be charged, therefore their influence is more evident in short range flights

Preliminary results: Range vs TOW

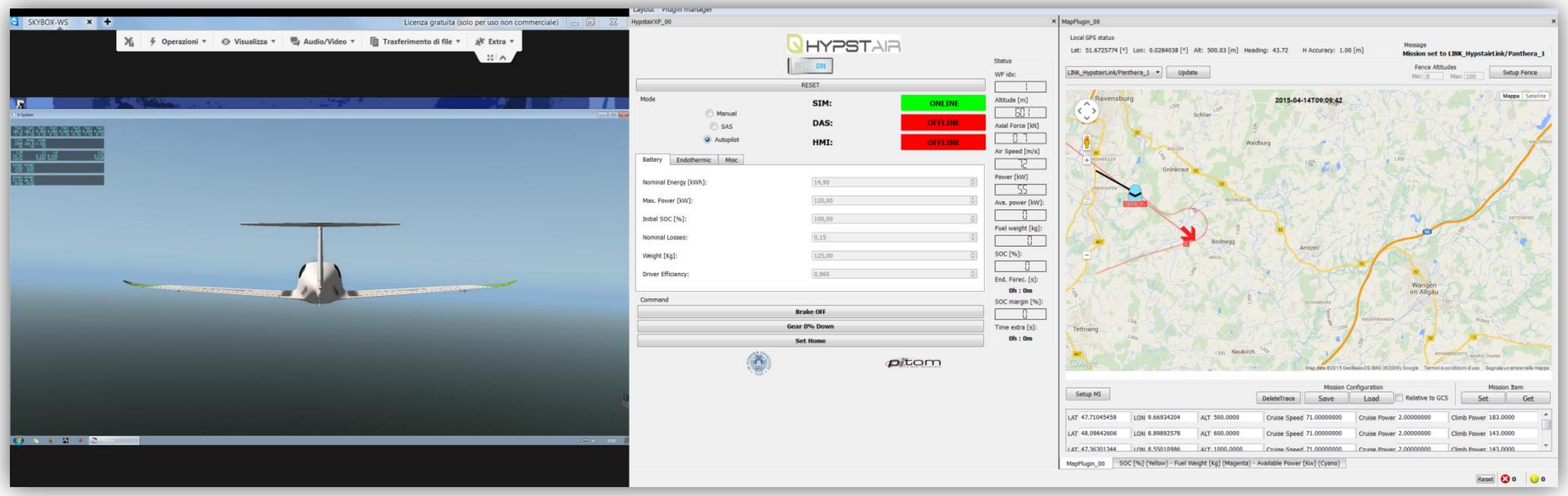


- Batteries increase empty weight, limiting payload capabilities

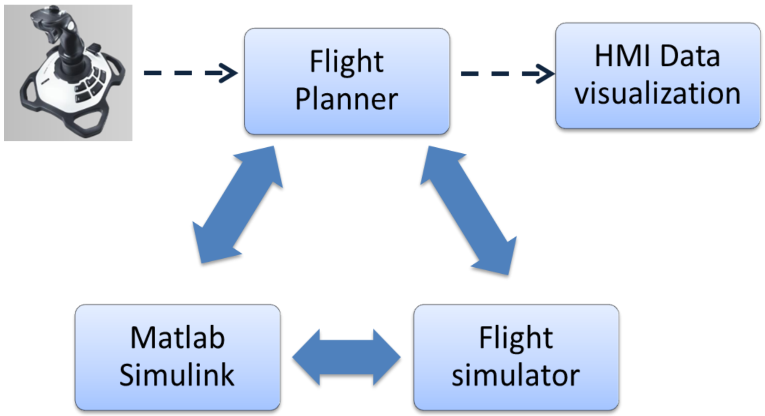
- Weak MTOW vs Range dependency
- Low sensitivity to cruise altitude
- More flexibility in mission definition

HyPSim: main goals

- Verification of the results carried out during the preliminary procedure;
- Introducing the human-in-the-loop effects;
- Introducing new mission profiles;
- Identification of possible critic conditions (battery discharge, demanding maneuvers,…);
- Dissemination activities;
- HMI integration conceptual simulation;



HyPSim: general architecture



- The simulator is composed by three main software that communicate each other in real time.
- The modular architecture allows to use a unique or multiple laptops and easy modifications by any user.
- FS is used as aerodynamic solver.

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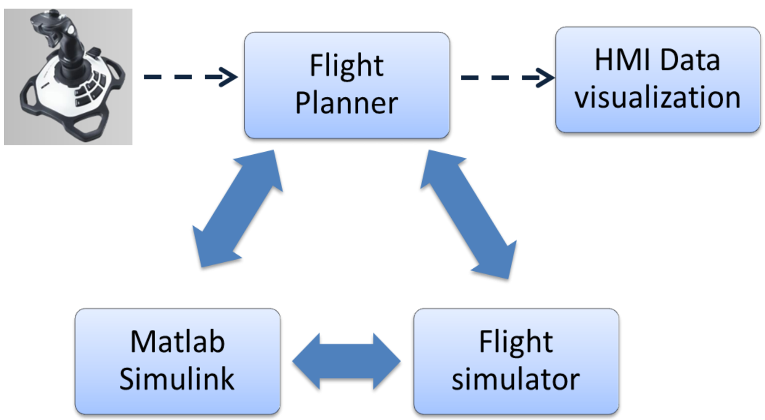

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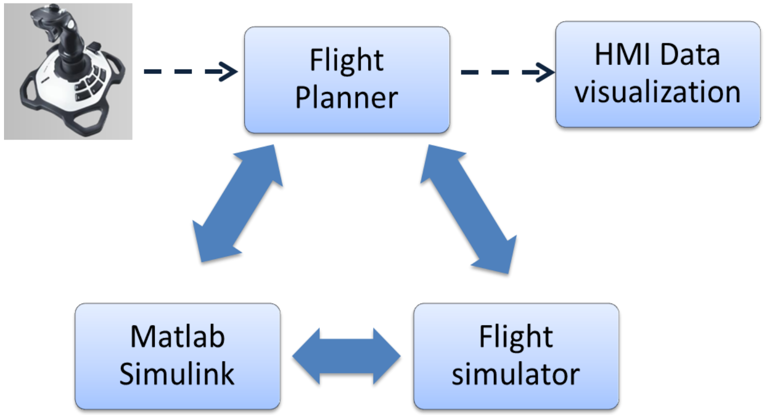
Data flows are divided into matrix and arrays:

1. $Aircraft = [W_{fuel\ in} \quad SoC_{in} \quad En_{batt\ max} \quad Aerodynamic \quad SFC_{IC} \quad P_{IC} \quad S]$

Hybrid system models



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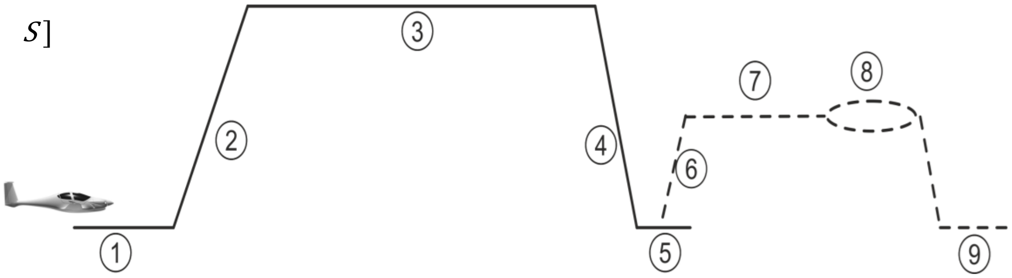
2. $WPList = \begin{bmatrix} lat_1 & lon_1 & h_1 & v_1 & P_{cr1} & P_{cl\,1} & (t.b.d.) \\ \dots & & & & & & \\ lat_n & lon_n & h_n & v_n & P_{cr\,n} & P_{cl\,n} & \end{bmatrix}$



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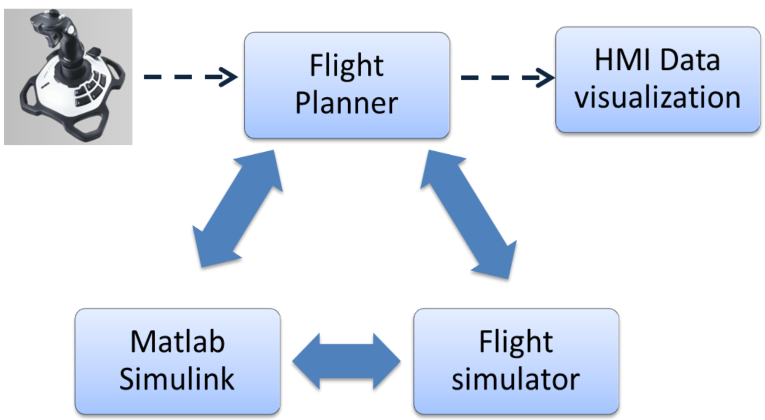

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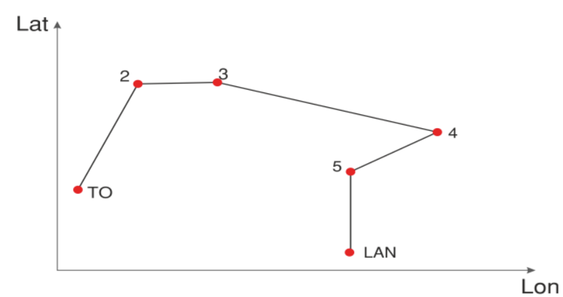

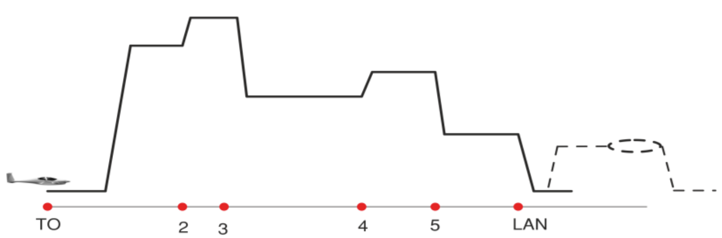

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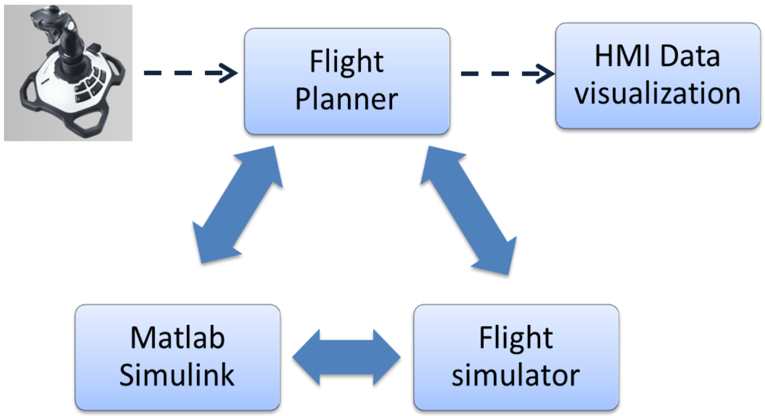

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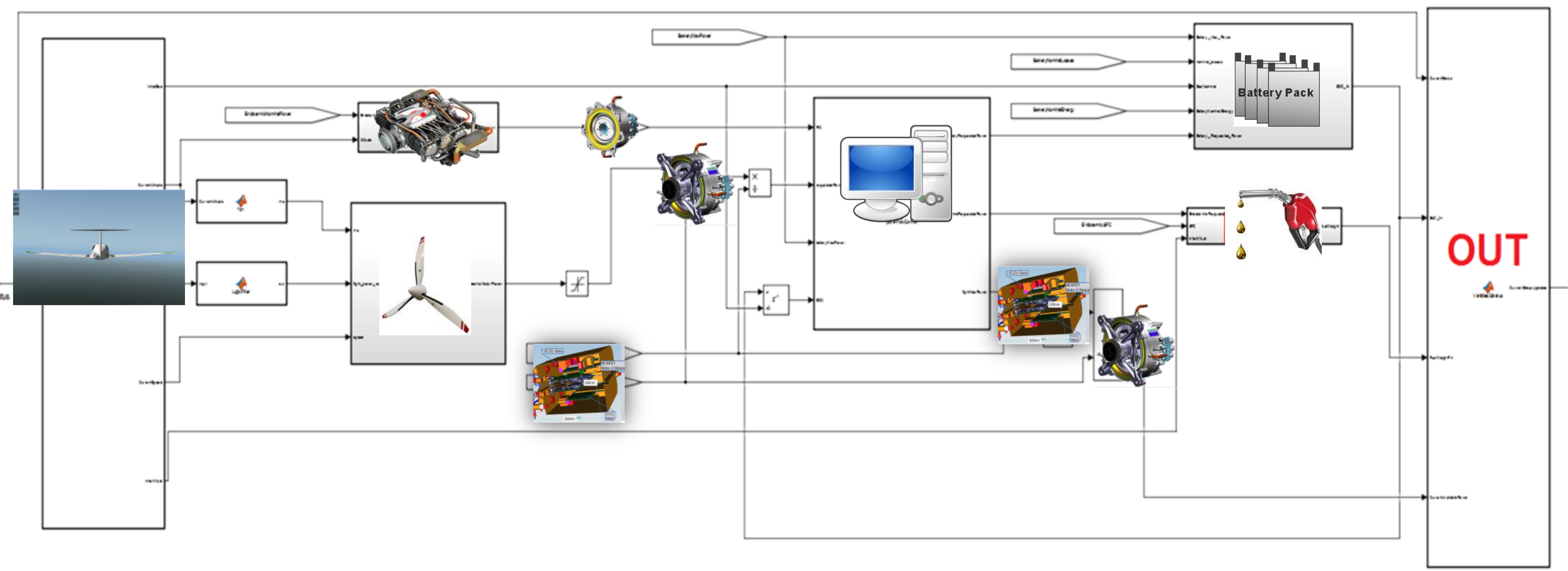
3. $CurrentStatus = [v \quad P_{flight} \quad h \quad lat \quad lon \quad W_{fuel} \quad SoC \quad Fl.Program] = f(t)$

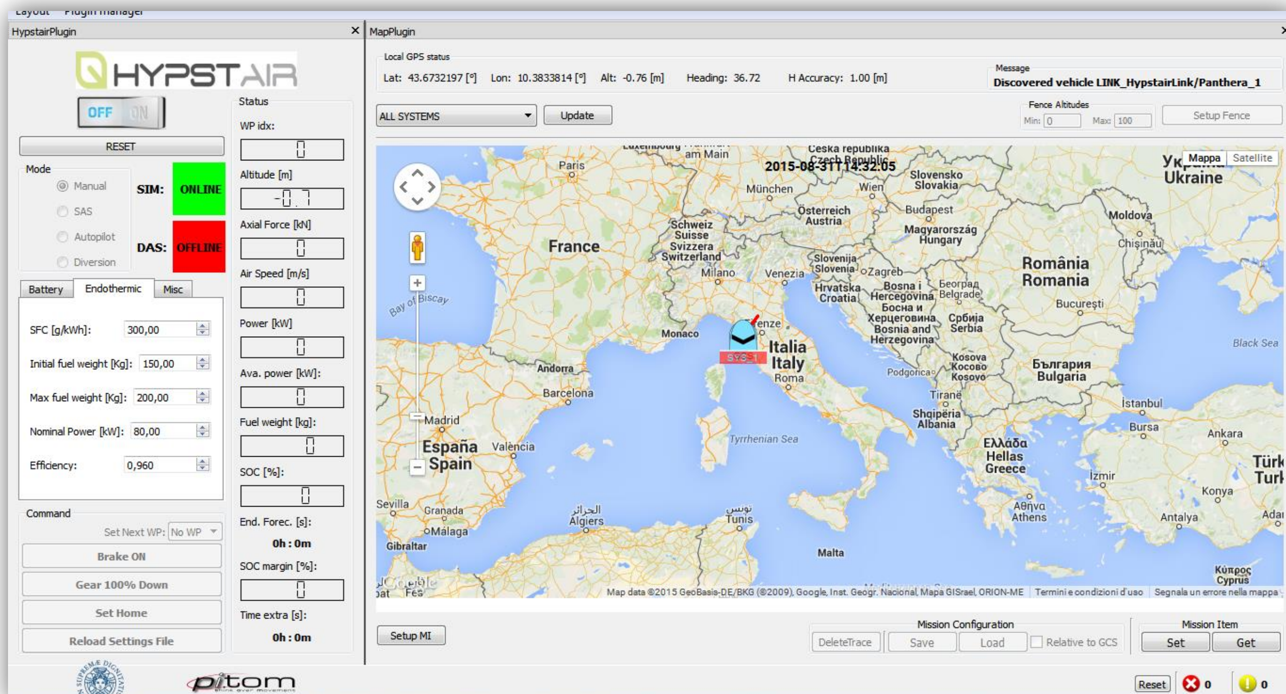
Hybrid propulsion system in Simulink

- Each component of the power train is modeled;
- Output**: Fuel consumption**, **battery SoC**, and **maximum available power**;
- Battery performance are evaluate through the charge/discharge profiles;
- Very simple laws are implemented in the controller in order to manage the power flow.



The Flight Planner

In house software mainly developed to control the flight in automatic mode.
Several features are added by means of plugins that can be activated/deactivated by the user.



Plugins

- **“Hypstair main window”;**
- **“MapPlugin”;**
- “LogtoFile”;
- “Data Plot”;
- “HMI visualization”;

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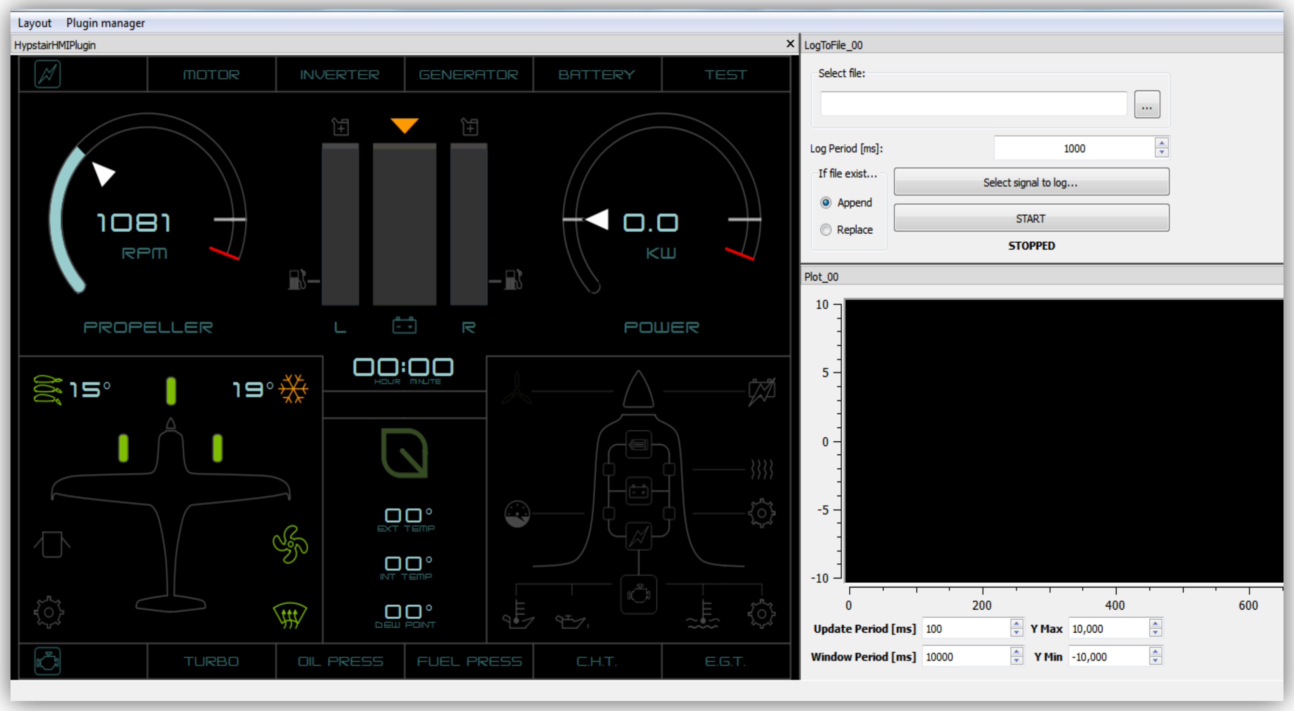

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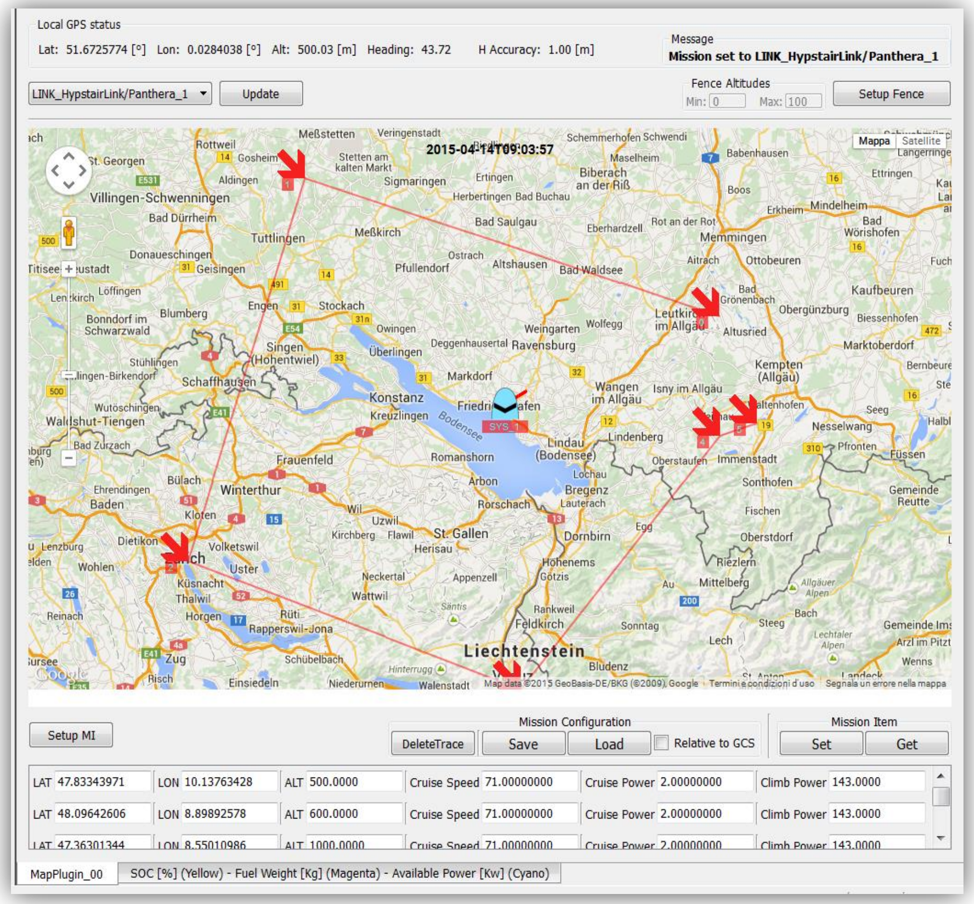

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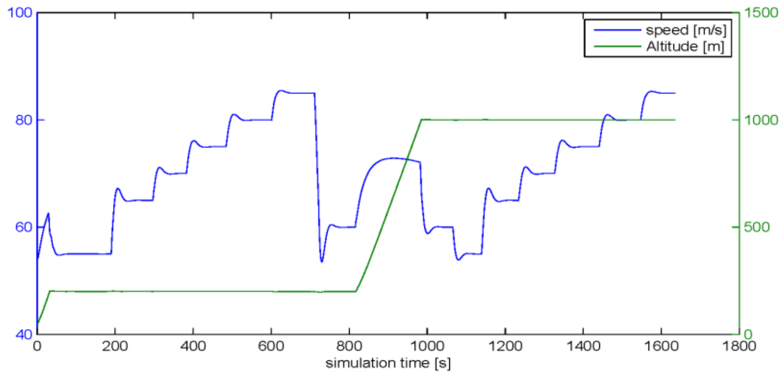
Results: straight steady flight

- Speed: [55 85] m/s;
- Constant altitudes: [100 1000] m;



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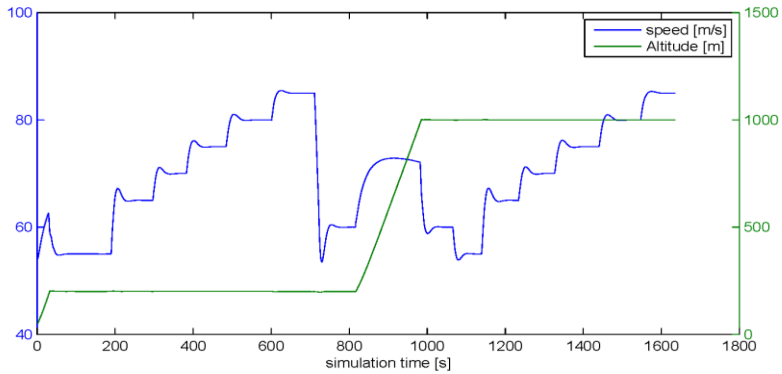

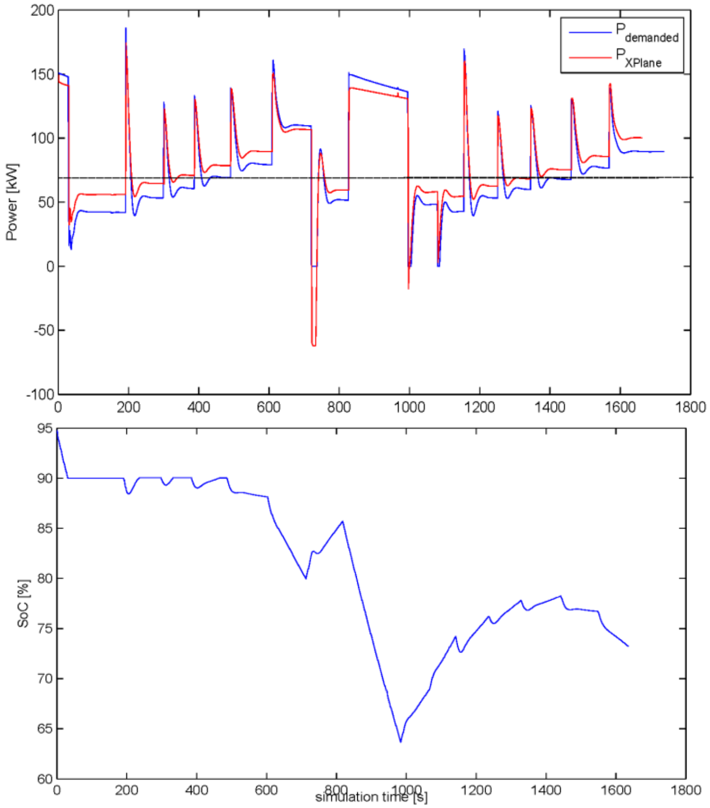

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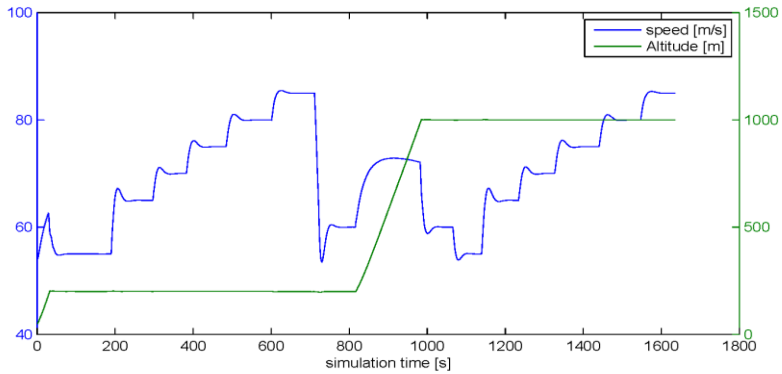
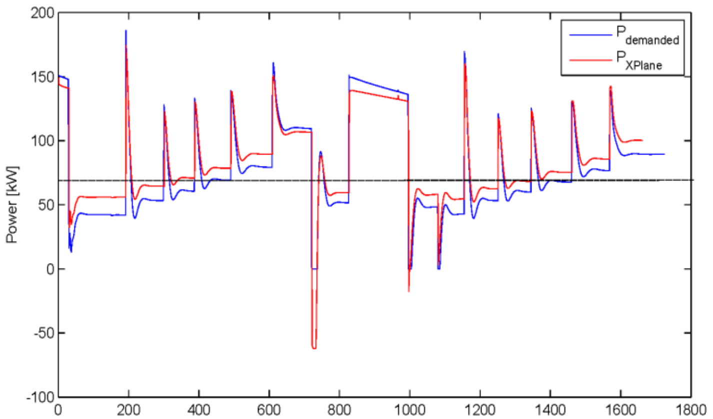
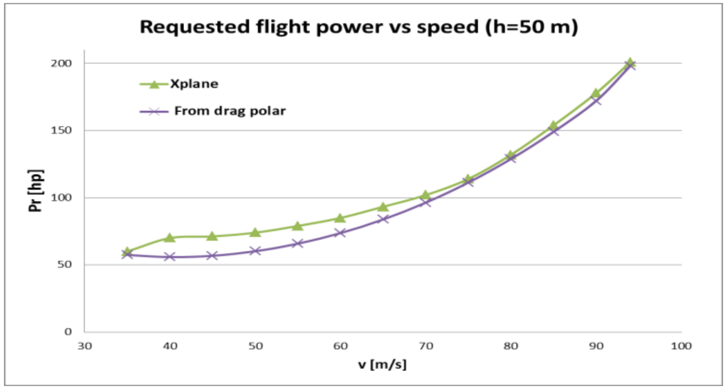
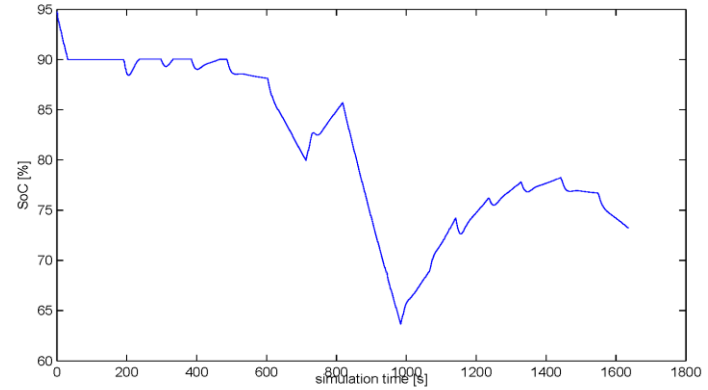






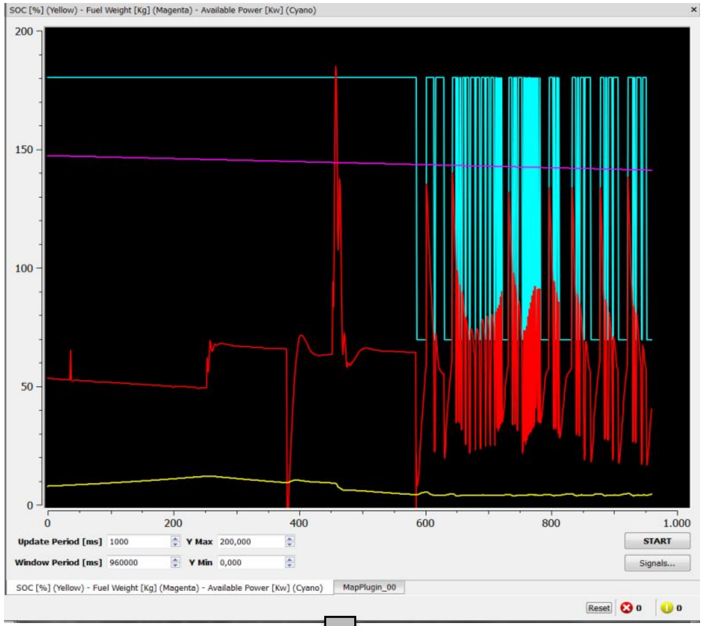


Results: fully discharged batteries

$$Battery = \begin{cases} Discharging\ if\ SOC > 4\% \\ Charging\ if\ SOC < 4\% \end{cases}$$

Bad control logic:

$$P_{\max avail} = \begin{cases} P_{mot}\ if\ SOC > 4\% \\ P_{ICE}\ if\ SOC < 4\% \end{cases}$$



Oscillations in terms of v and h

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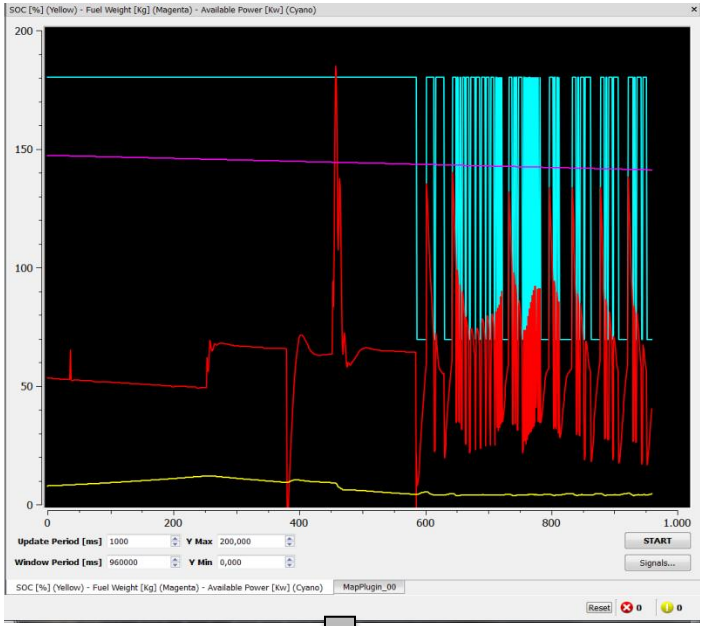
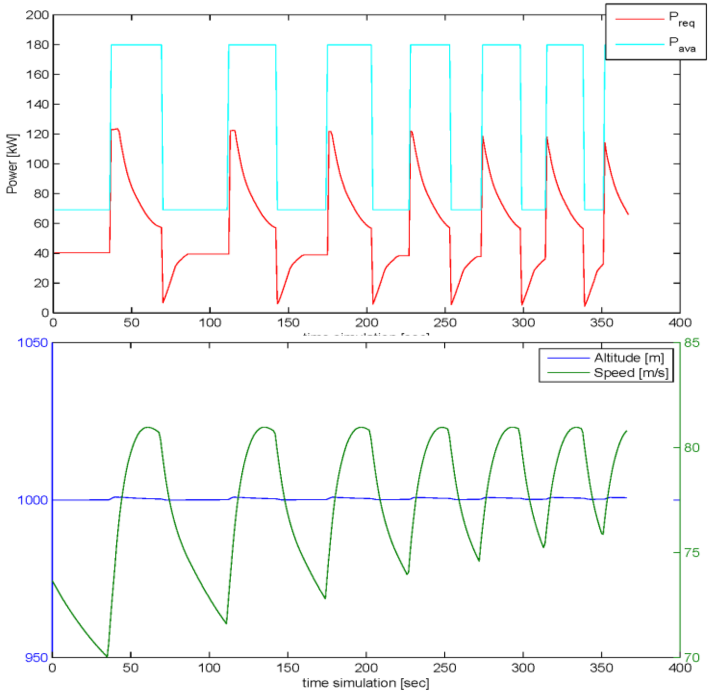


Oscillations in terms of v and h

Possible solution:

$$P_{\max avail} = \begin{cases} P_{mot}\ if\ SOC > 4\% \\ P_{ICE}\ if\ SOC < 7\% \end{cases}$$

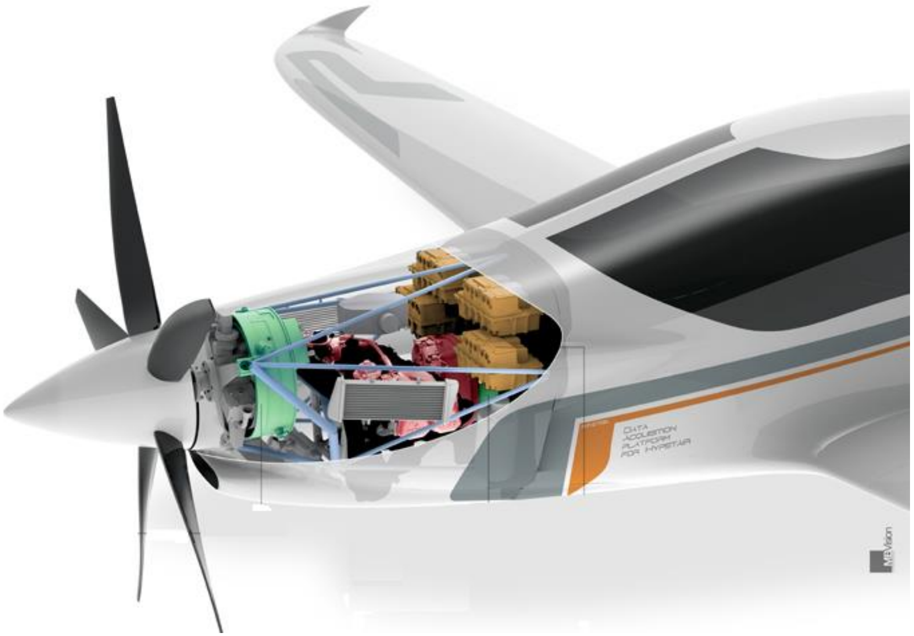


The oscillations are damped and the frequencies are lower

Conclusions

- Hybrid propulsion represents a feasible solution for a general aviation aircraft even if a reduction in range or maximum payload occurs
- Battery technology plays a key role for the future of electric and hybrid aviation
- Hybrid is flexible due to the extended operating performance of the electric components (high efficiencies, high power to weight ratio, low maintenances)
- Hybrid is significant in specific flight segments: **new design strategies** have to be set up to define "optimum" performance
- New challenges for the AD
- The flight simulator allows to evaluate performance (depending on the power train system) for a wide range of conditions with different possible control strategies
- Tool for HMI and for endurance prediction to enhance the safety level during flight

Thanks for your kind attention



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Extra 1 benefits/penalties of the electric propulsion

Electric Propulsion Penalties

Energy Storage Weight (50x worse than aviation fuel)
Energy Storage Cost (Tesla 65 kWh battery is ~$25,000)
Certification Uncertainties and Absence of Standards

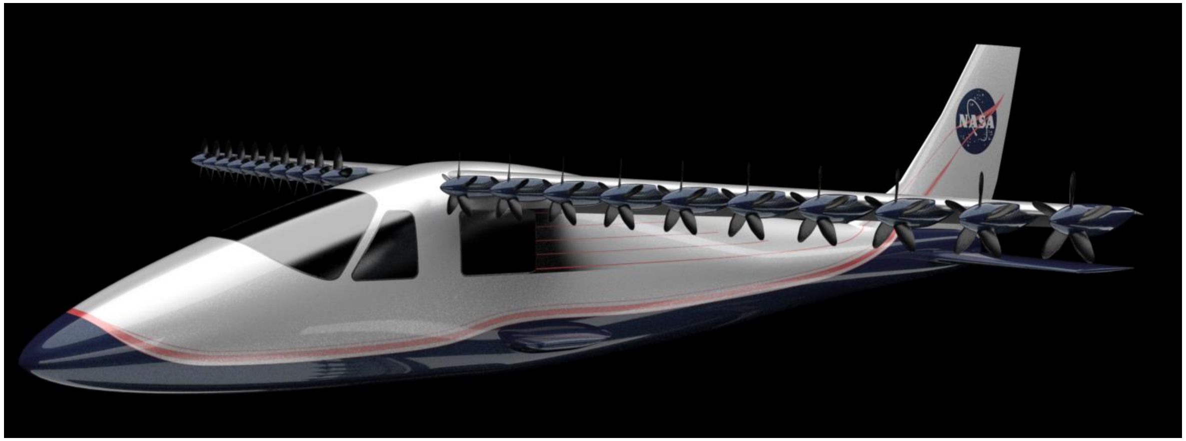
Electric Propulsion Benefits

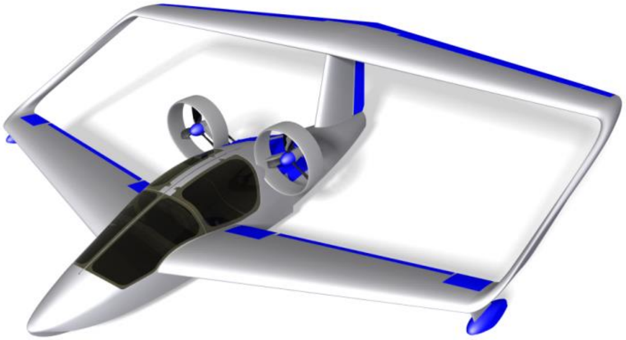
~2x efficiency of turbine engines, 3-4x efficiency of piston engines
High efficiency across >50% rpm range
6x the motor power to weight of piston engines
None air breathing - No power lapse with altitude or on hot days
Extremely Quiet
Zero vehicle emissions
10x lower energy costs

Electric Propulsion Integration Benefits

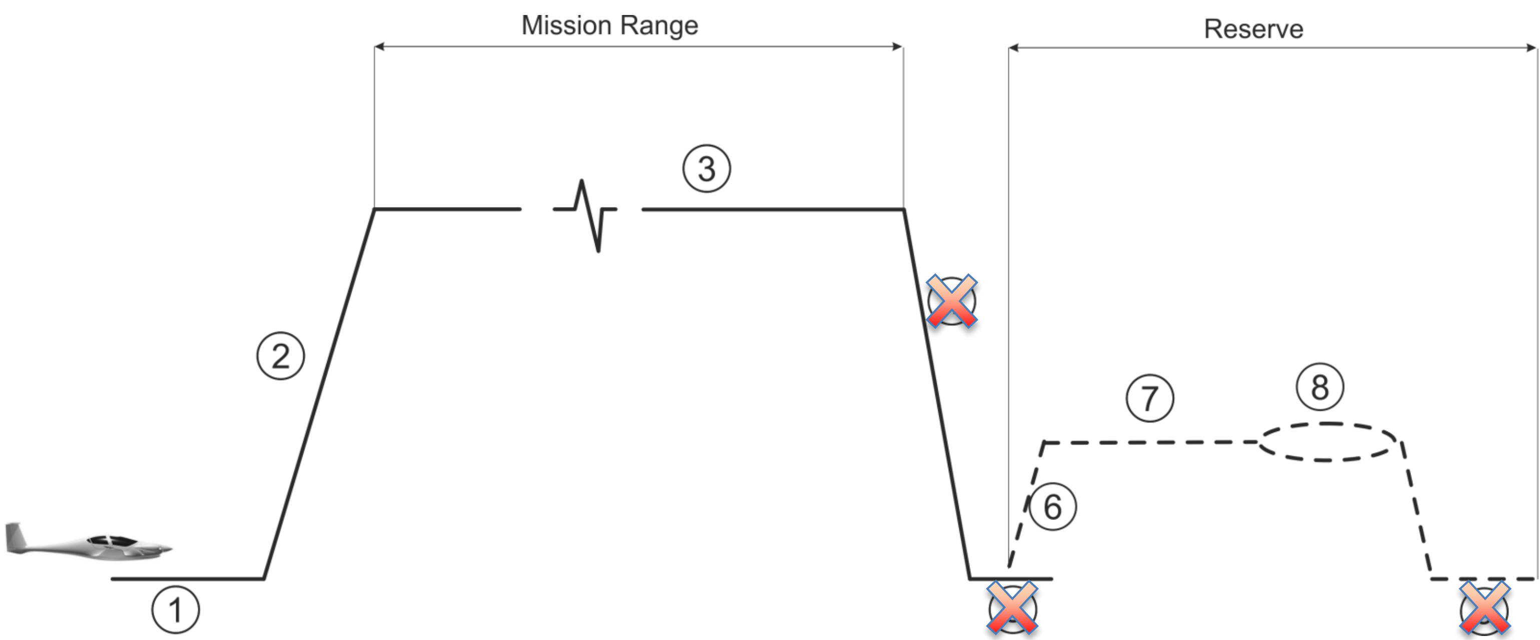
independence of efficiency and power to weight
Power to weight and efficiency don't degrade at smaller sizes
Extremely compact
High reliability – few moving parts

Extra 2





Extra 3 Reference Mission



For each flight segment can be defined:

- ✓ Flight programs
- ✓ Regulation requirements
- ✓ Minimum performance

Descend and landing segments are neglected in term of energy consumptions

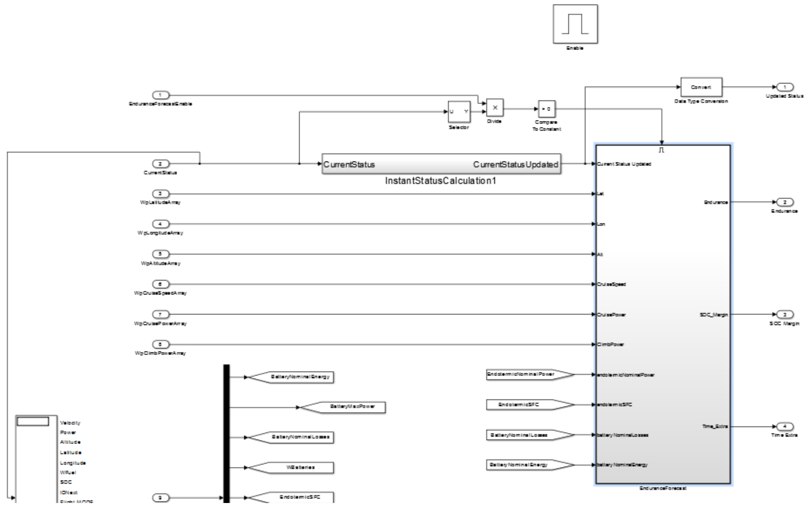
Extra 4

Many and new parameters that pilot has to check during flight;

Less information better it is;

How the pilot can evaluate the aircraft performance for the rest of the flight?

Idea: implement the preliminary model estimation in the simulink code (extended in the case of a generic mission defined in the):



$t_{mission}$

t_{extra}

SOC_{margin}

Extra 4

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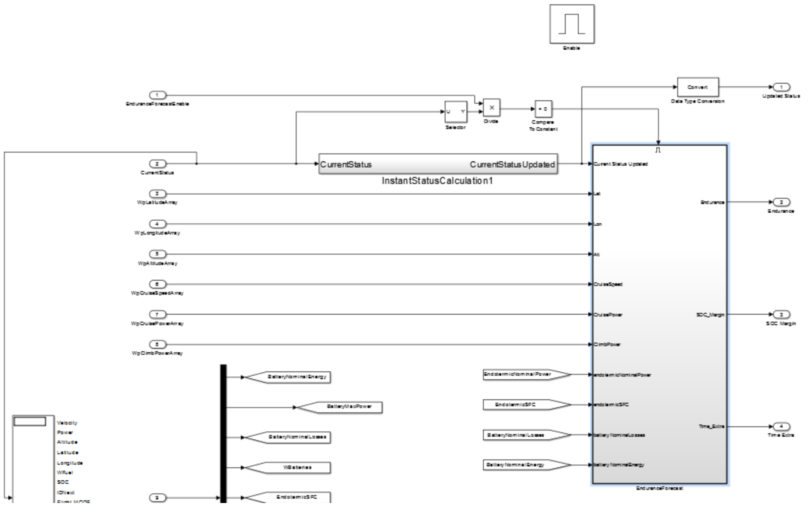
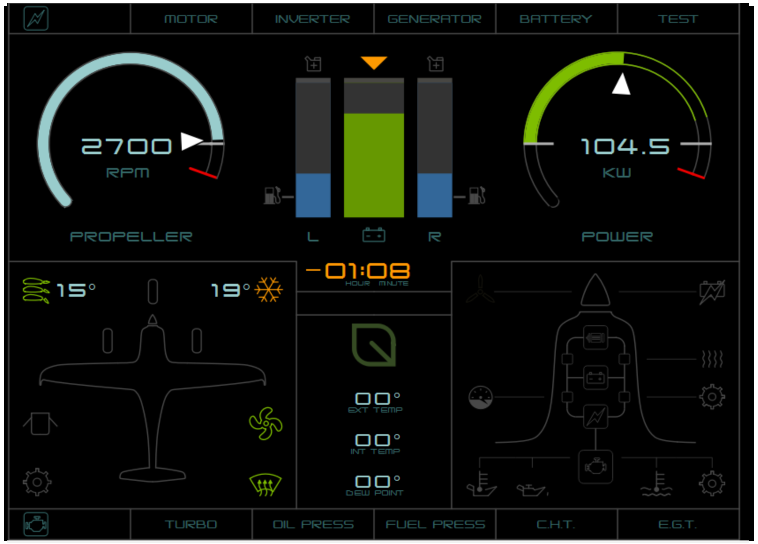


$$\left\{ \begin{array}{l} t_{mission} \\ t_{extra} \\ SOC_{margin} \end{array} \right.$$



Extra 4