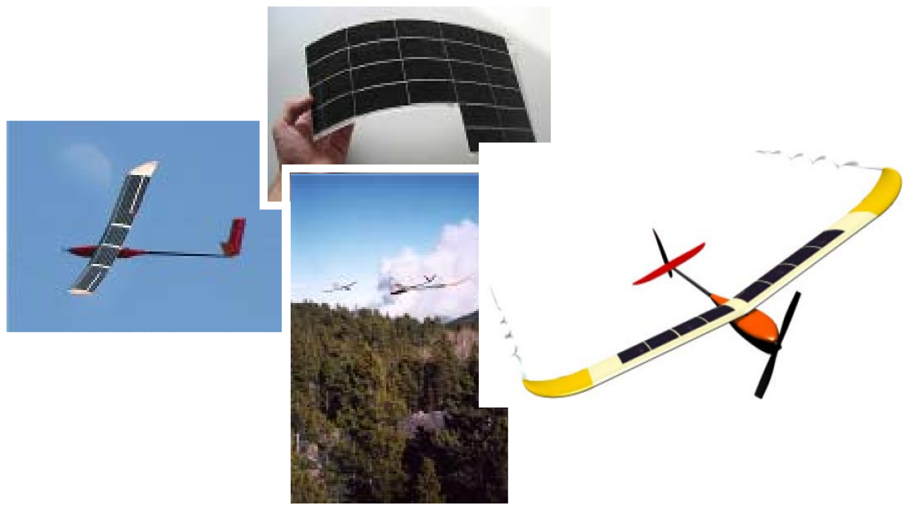
Design of Solar Powered Airplanes for Continuous Flight



André Noth

Doctoral Exam – September 30, 2008

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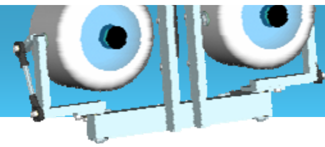
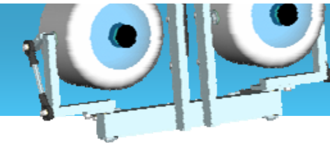
Outline

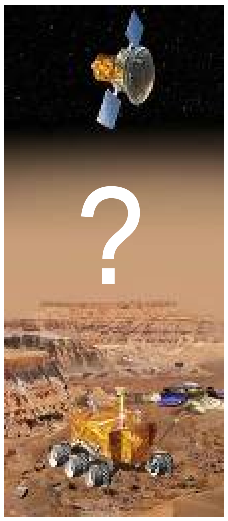


- Introduction
- Design Methodology
- Sky-Sailor Design
- Sky-Sailor Prototype
- Scaling
- Conclusion

Motivations & Objective



- Project started with an ESA feasibility study



Mars exploration

Satellites + extensive coverage, good resolution
- place of interest not freely selectable

Gap for systems with + high-resolution imagery
+ extensive & selectable coverage

Rovers + excellent resolution, ground interaction
- reduced range, limited by terrain

➔ Study the feasibility of solar powered flight on Mars

➔ Develop and realize a fully functional prototype on Earth and demonstrate continuous flight

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History of Solar Flight

- Started in 1974
- 90 solar powered airplanes listed from 1974 to 2008

Sunrise (1974)
1st solar powered flight

Gossamer Penguin (1980)
1st manned solar powered flight

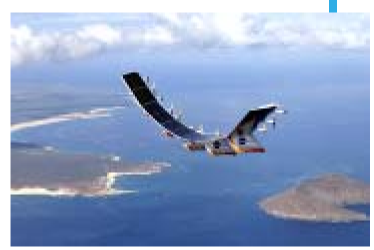
Sunseeker (1990)
manned, crossed the USA in 21 flight

Solong (2005)
1st continuous flight, used thermals

70's | 80's | 90's | 2000's

Solar Riser (1979)
manned, battery solar charged for short flights

Solar Challenger (1981)
manned, channel crossing



Helios (1999)
umanned, flew at > 29'000 m

Zephyr (2005)
umanned, flew 83h

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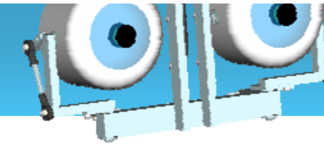


State of the art

Many solar airplanes in History

➔ … but no clear design methodologies explained

➔ anyway useful practical papers on case studies

[**BOUCHER79, MACCREADY83, COLELLA94**]

[ULM96,BRUSS91]

Many design methodologies…

➔ … but rarely validated with a prototype **[REHMET97, WEIDER06]**

➔ very often nice design methods

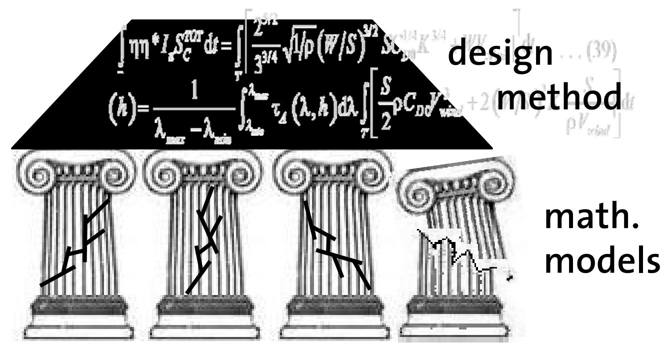
[IRVING74, YOUNGBLOOD82, BAILEY92]

but based on weak models for:

- **Weight prediction**
- **Efficiencies**

➔ ends with irrealistic designs

[RIZZO08, ROMEO04]



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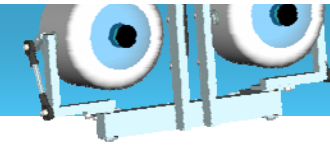
Contributions



- **Design methodology**
  - Simplicity
  - Large design space
  - Concrete and experienced based
  - Flexible and versatile
- **Theory validation with a prototype**
  - Achieve > 24h flight
  - Autonomous control
- **Draw up a state of the art on solar aviation**
  - History
  - Publications

Design Methodology

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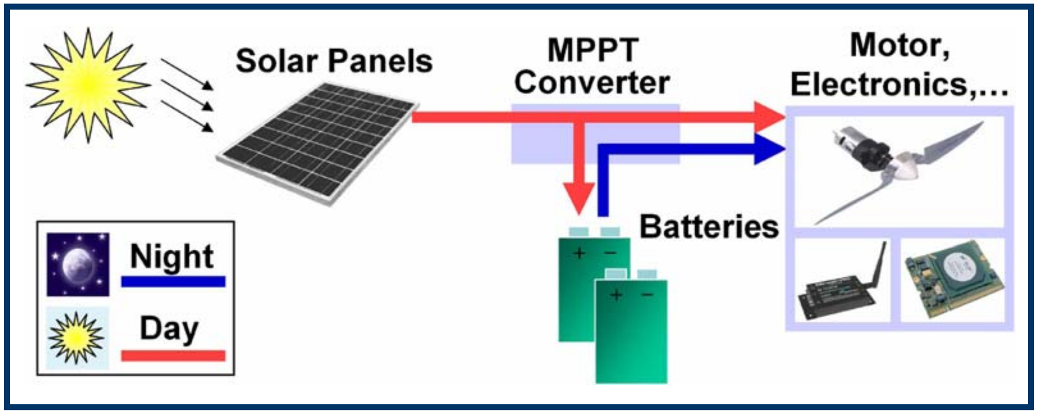
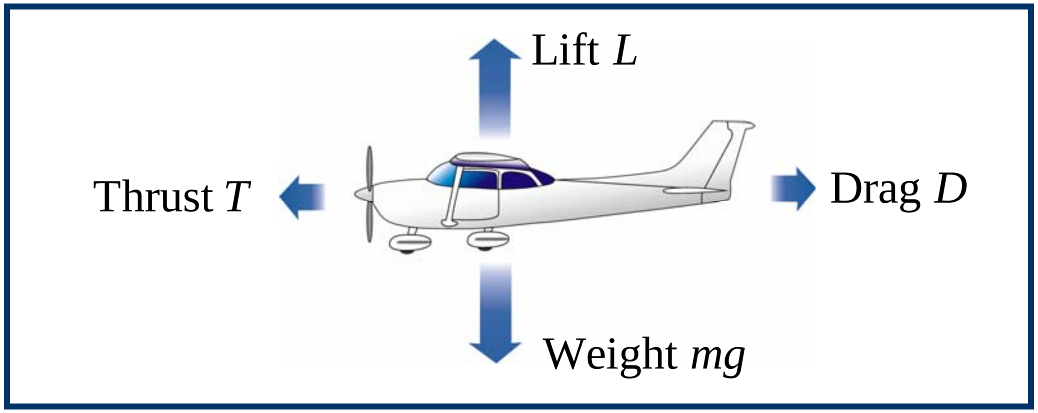
Energy balance



Weight balance



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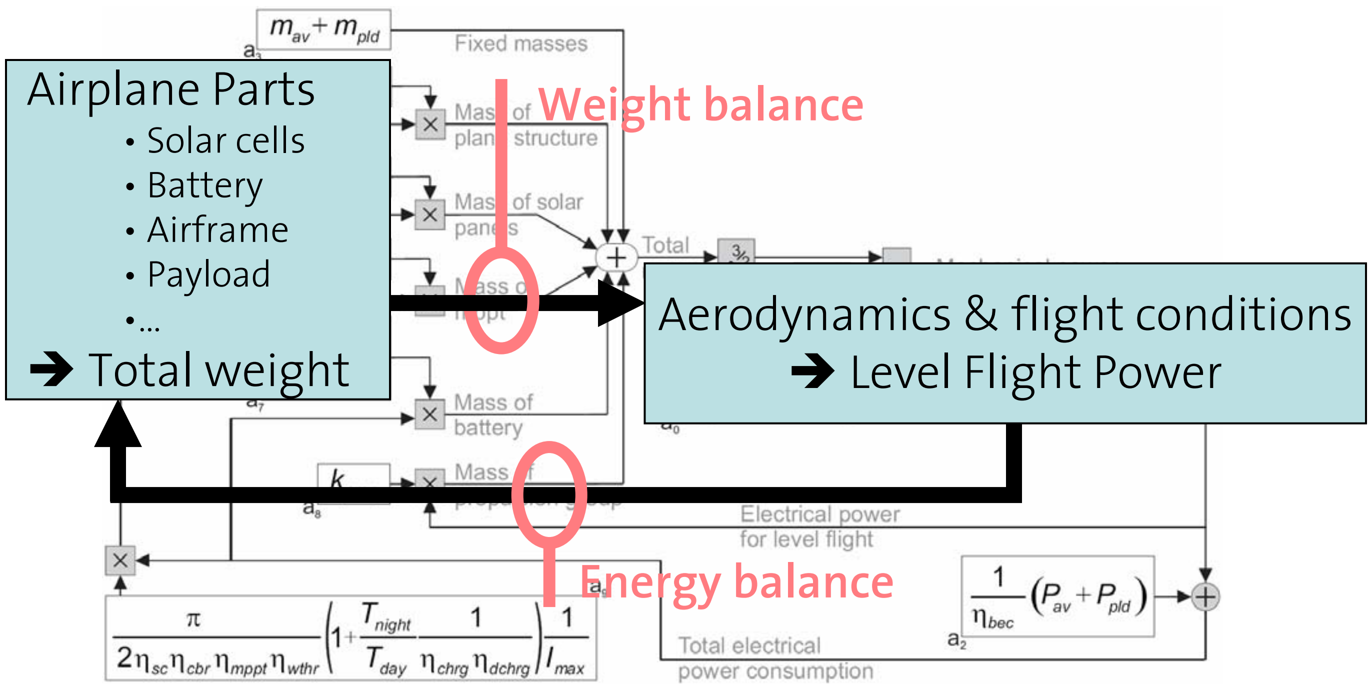
Methodology

- Sizing the airplane : hen & egg problem



- This loop can be solved:

A **Iteratively** (trying existing components, refining the design)

B **Analytically** (using mathematic models of the components)

➔ **Allows to establish some general design principles**

Introduction
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• Required Energy
• Solar Energy
• Weight Models
• Resolution
Sky-Sailor Design
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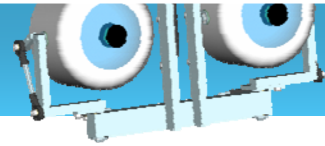
Required Energy

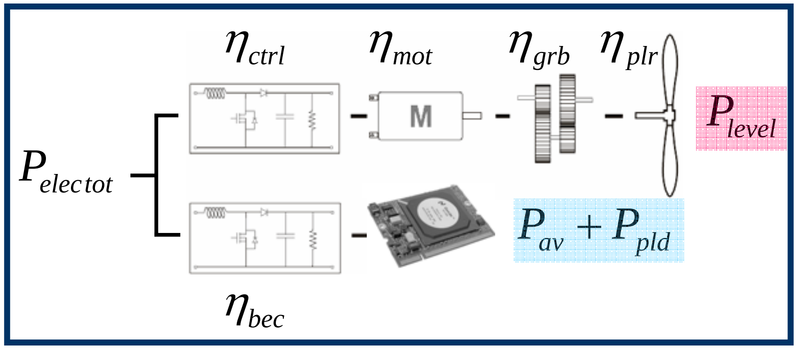


- Equilibrium at steady level flight

$$\left.\begin{aligned} L = mg = C_L \frac{\rho}{2} S v^2 \\ D = T = C_D \frac{\rho}{2} S v^2 \end{aligned}\right\} P_{level} = D v = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{(mg)^3}{S}} \sqrt{\frac{2}{\rho}}$$

- Power required

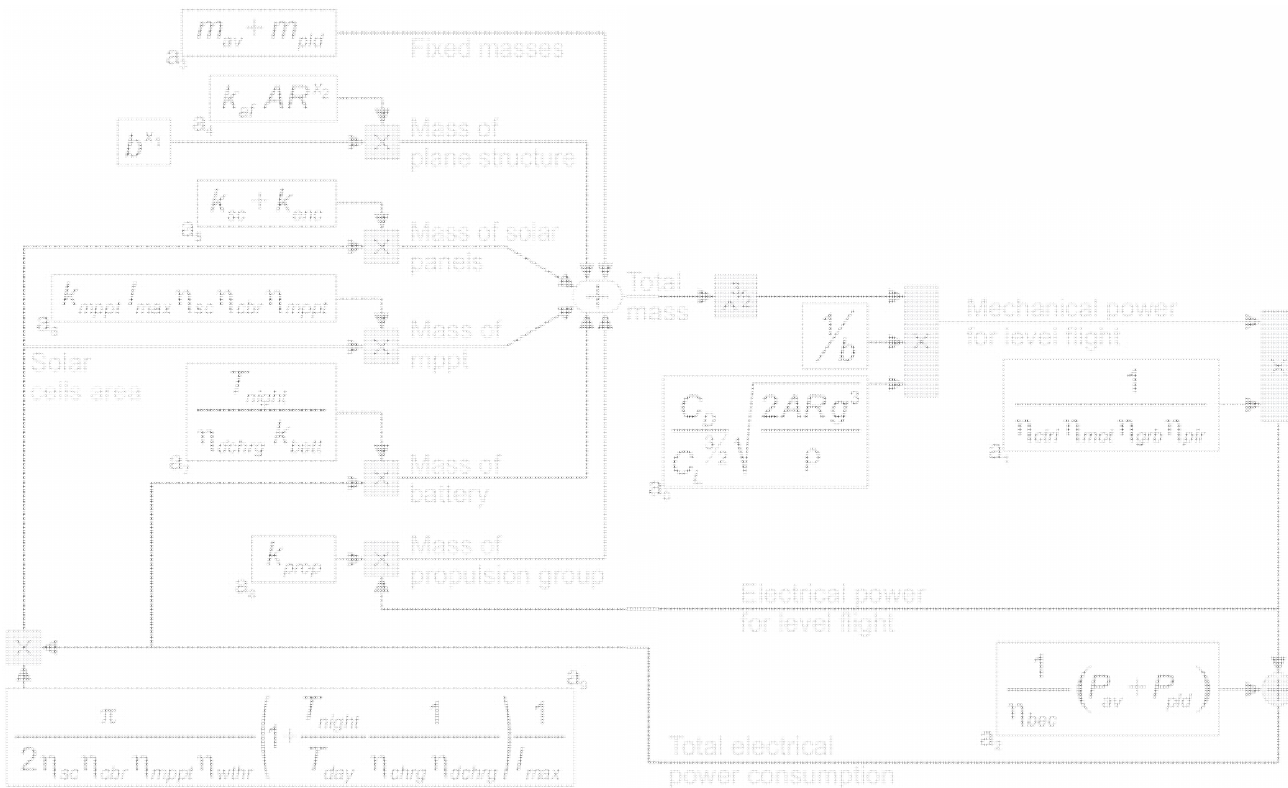
$$P_{elec\,tot} = \frac{1}{\eta_{ctrl}\eta_{mot}\eta_{grb}\eta_{plr}} P_{level} + \frac{1}{\eta_{bec}} (P_{av} + P_{pld})$$



- Daily energy required

$$E_{elec\,tot} = P_{elec\,tot} \left(T_{day} + \frac{T_{night}}{\eta_{chrg}\eta_{dchrg}} \right)$$

Required Energy



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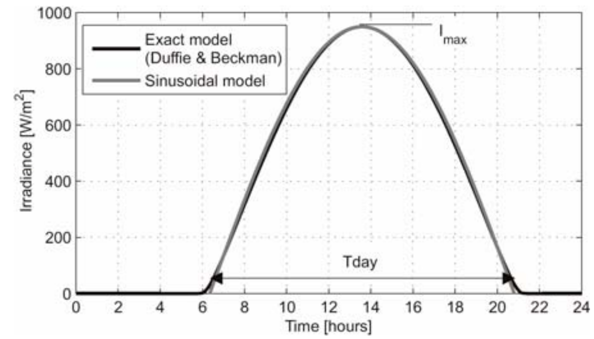
- Daily average solar irradiance
  - Irradiance ~ cosine

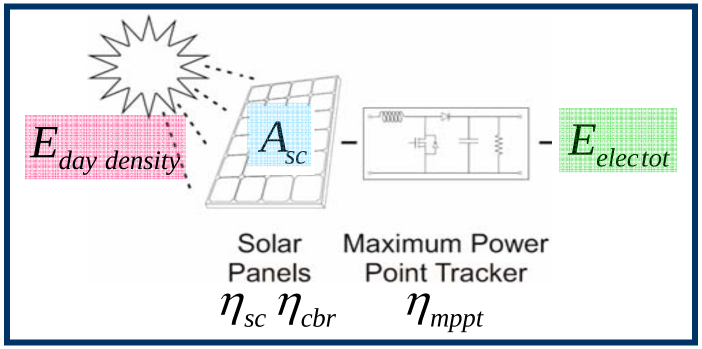
$$E_{day\ density} = \frac{I_{max} T_{day}}{\pi / 2} \eta_{wthr}$$

  - $I_{max}\ T_{day} = f(date, location, weather)$



- Daily energy obtained

$$E_{elec\,tot} = E_{day\ density} A_{sc} \eta_{sc} \eta_{cbr} \eta_{mppt}$$



- Daily energy required = Daily energy obtained

➔ We compute A_{sc}

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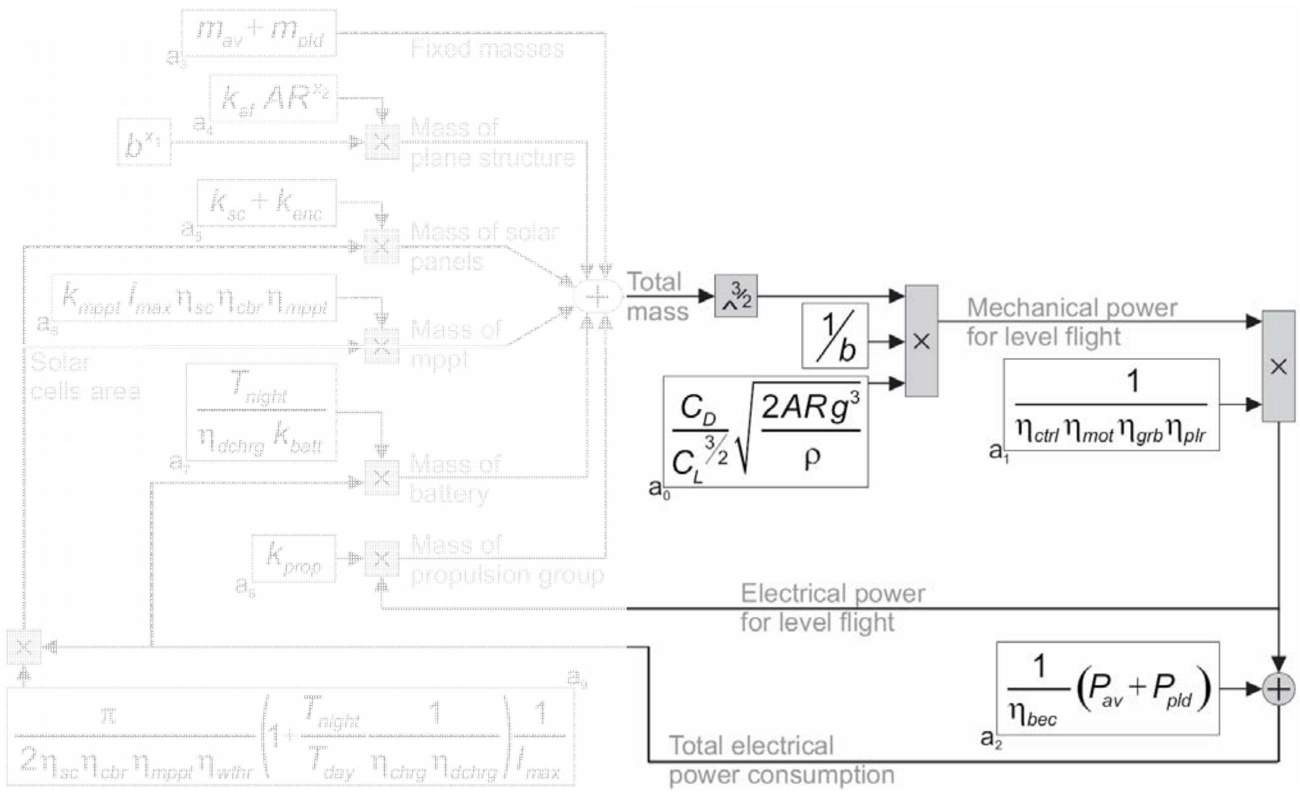
Required Energy



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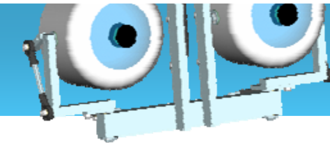
Weight Prediction Models



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- **Fixed Masses**
  - Payload m_{pld}
  - Avionic System (Autopilot) m_{av}
- **Airplane Structure**
  - In the literature
    - [BRANDT95, GUGLIERI96,...] consider $W_{af} = k \cdot S$

      ➔ valid locally
    - [HALL68] calculated all airframe elements separately

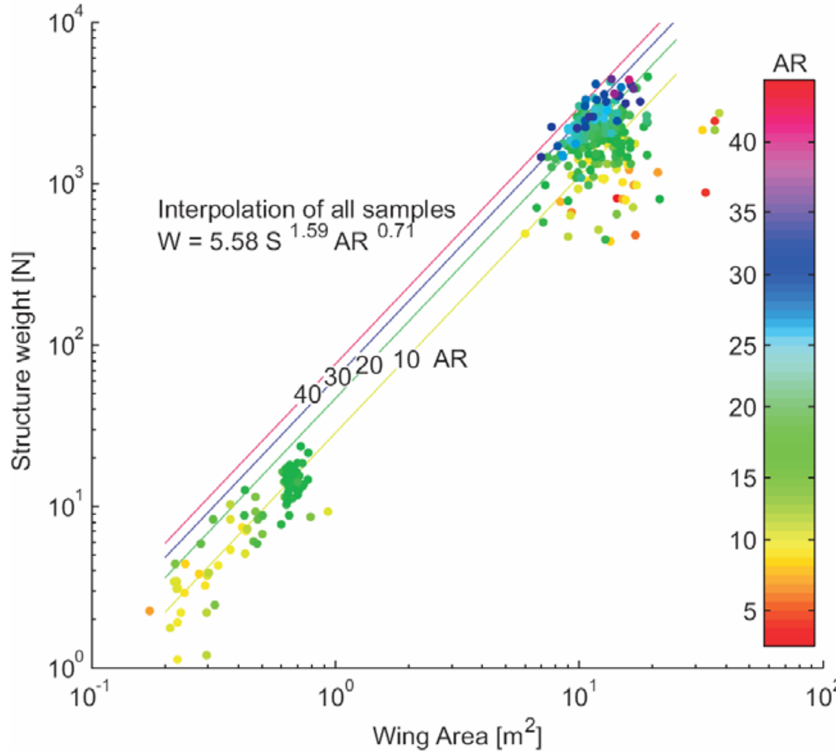
      ➔ complex, only valid for 1000-3000 lbs airplanes
    - [STENDER69] proposed $W_{af} = 8.763\, n^{0.311}\, S^{0.778}\, AR^{0.467}$

      ➔ very widely adopted

      ➔ adapted by [RIZZO04] to UAV $W_{af} = 15.19\, S^{0.656}\, AR^{0.651}$

Weight Prediction Models

- Verification of these models
  - Database of 415 sailplane
  - Structure Weight vs Area
  - ➔Models don't fit well



- New model proposed
  - Same equation, new coef.
  - Least square method fit
  - Data set divided in two
  - 5 iterations = 5 qualities
  - Best 5% model:

$$W_{af} = 0.44\, b^{3.10} \cdot AR^{-0.25}$$

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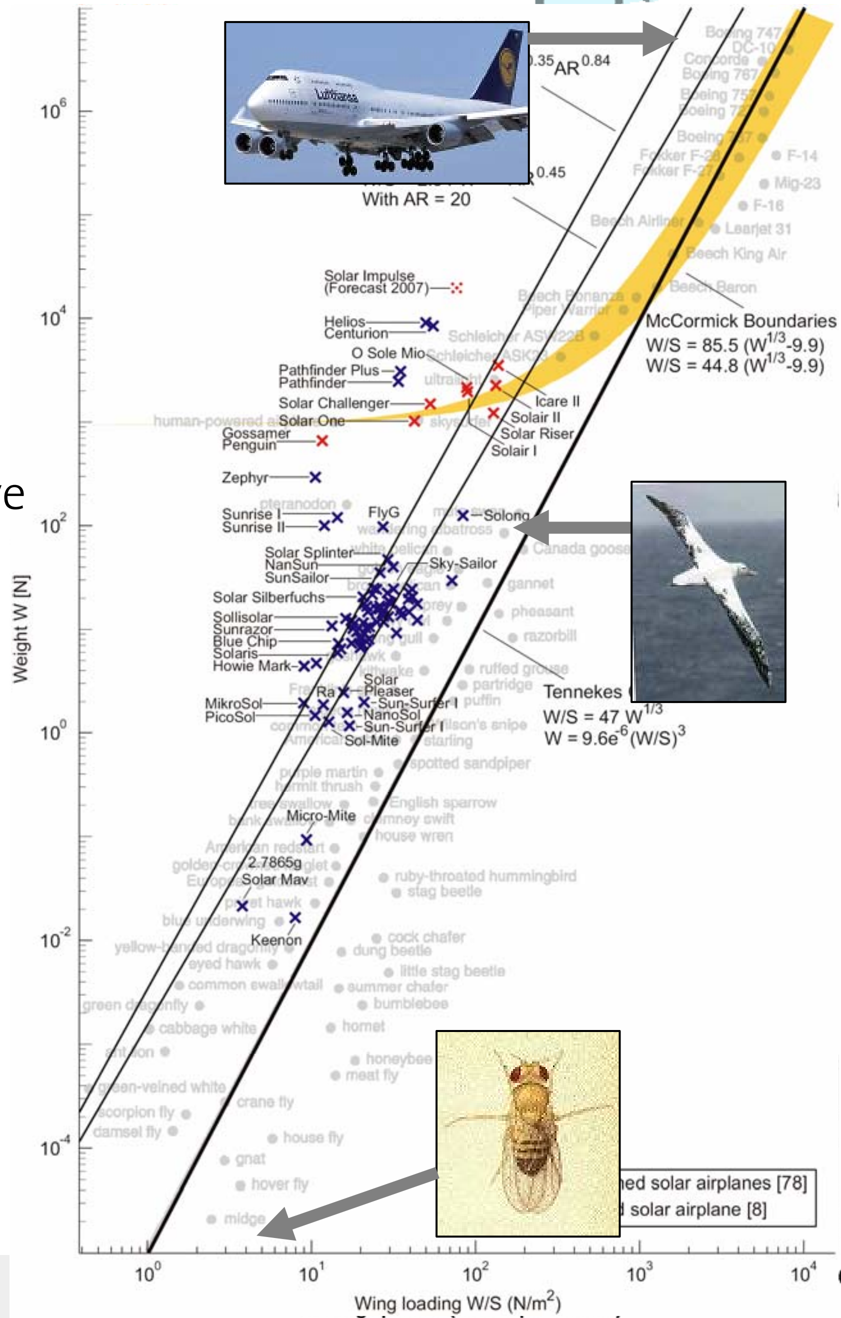
Weight Prediction Models

Biologists already studied flying in nature to extract tendencies

[TENNEKES92] presented the « Great Flight Diagram »
Clear cubic tendancy

Our model is // to Tennekes curve

[STENDER69,RIZZO04] seem incoherent



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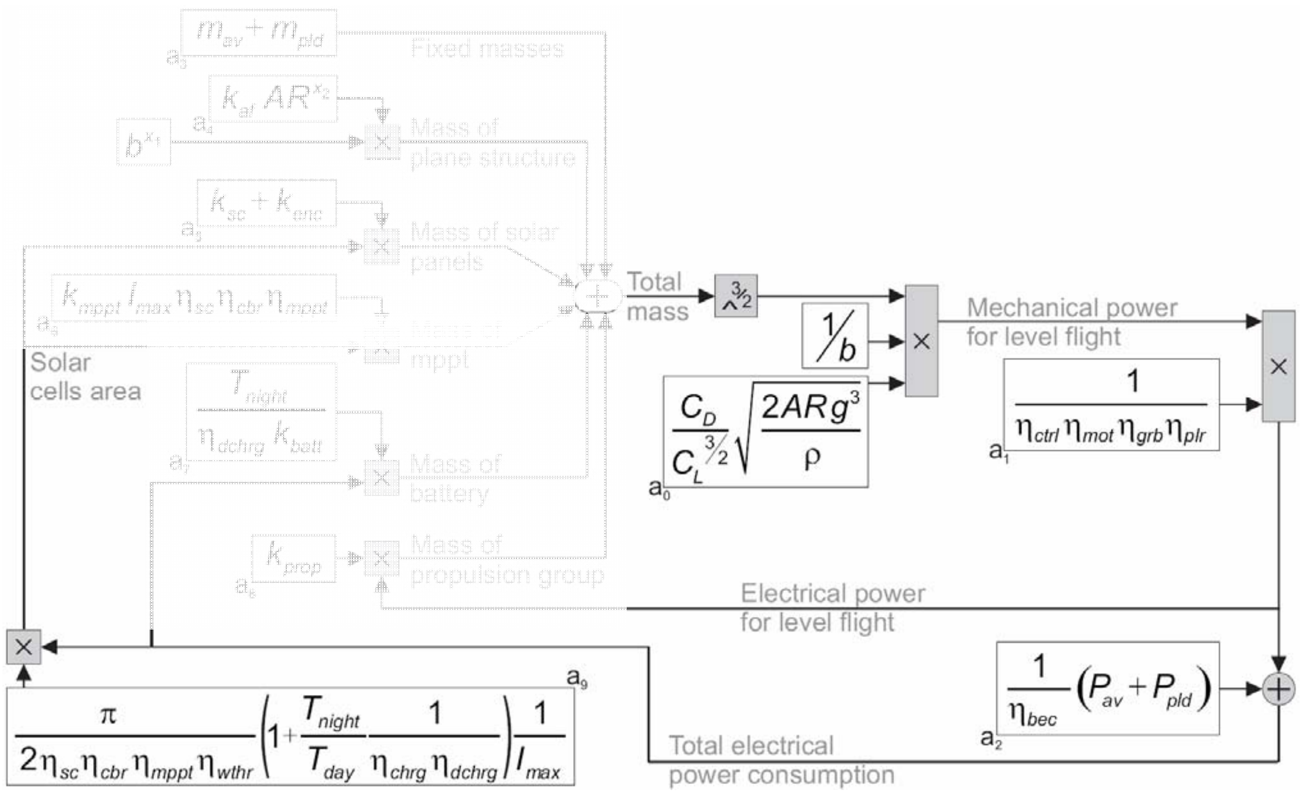
Required Energy



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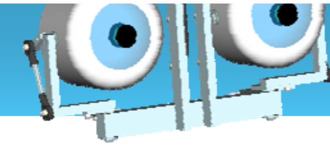
Weight Prediction Models

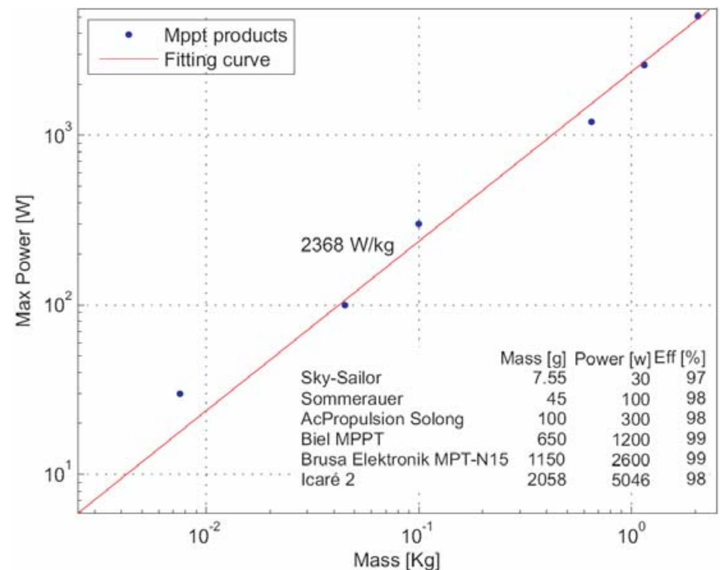


- **Solar Cells**
  - Surface = f(cells properties, required energy)
  - Weight proportionnal to the surface

$$m_{sc} = A_{sc}\left(k_{sc} + k_{enc}\right)$$

- **Maximum Power Point Tracker**
  - Study of high efficiency MPPT
    - ➔ Weight linear with P_{max}

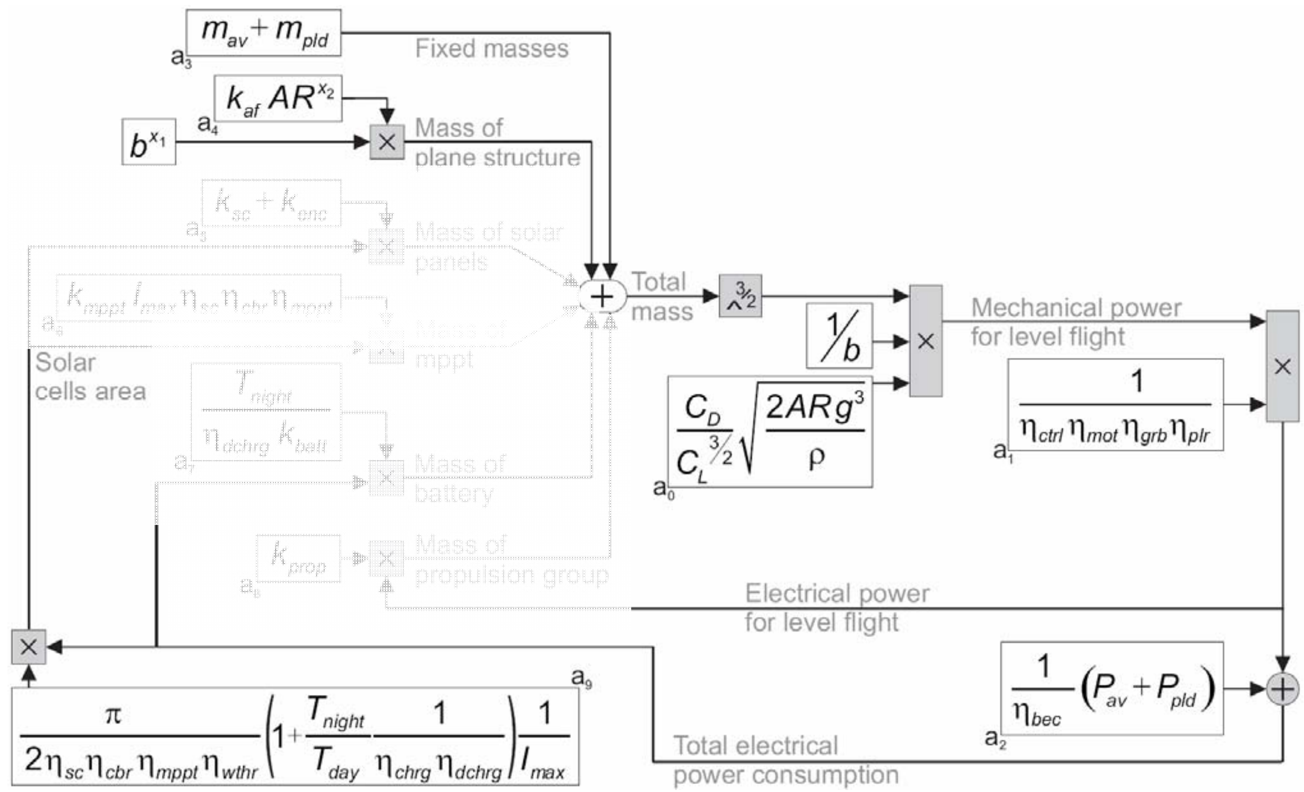
$$m_{mppt} = k_{mppt} P_{sol\ max}$$
$$= k_{mppt}\, I_{max}\, \eta_{sc} \eta_{cbr} \eta_{mppt} A_{sc}$$



- **Batterie**
  - Weight proportionnal to capacity

$$m_{bat} = \frac{T_{night}}{\eta_{dchrg} k_{bat}} P_{elec\ tot}$$

Required Energy



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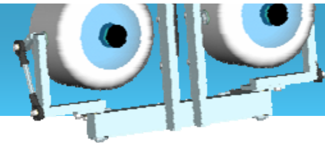
Weight Prediction Models



- Propulsion group
  - **Existing models but none is proven on a large range**
  - **Very large databases created**

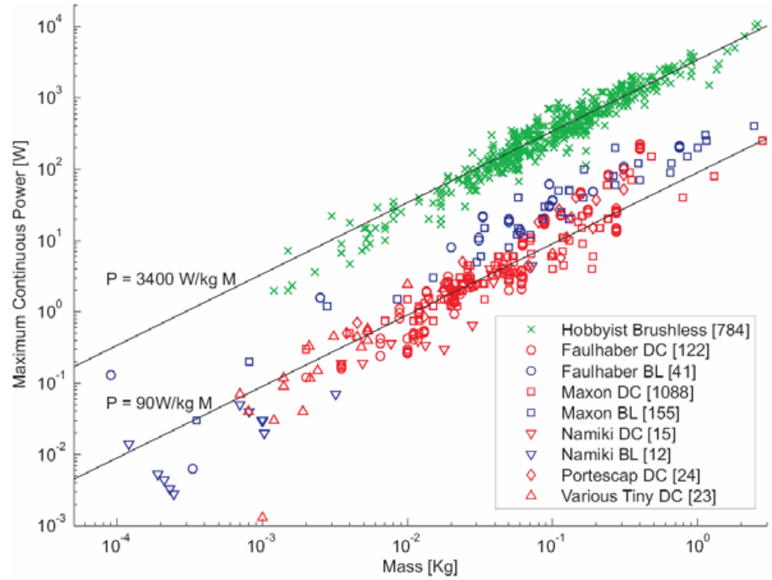
2264 motors

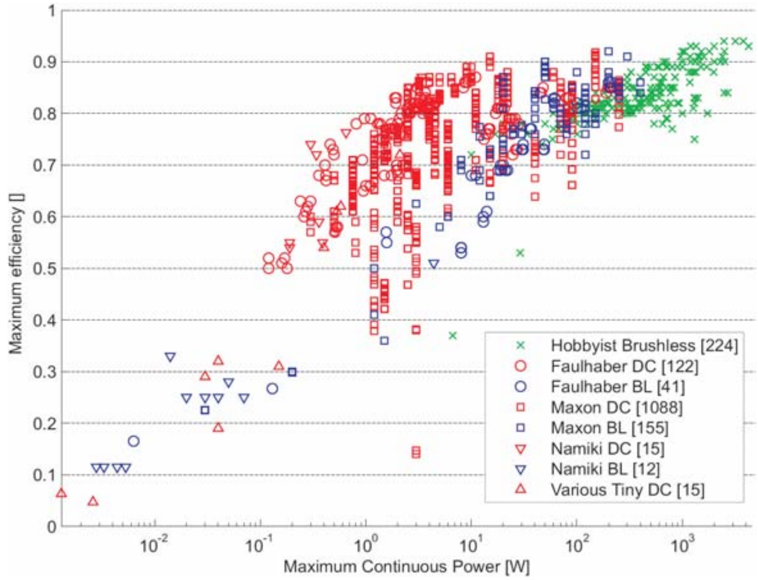
170 electronics controllers

997 gearboxes

673 propellers

→ Interpolated Models





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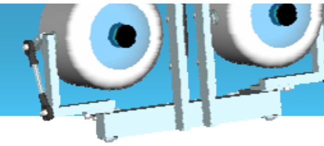
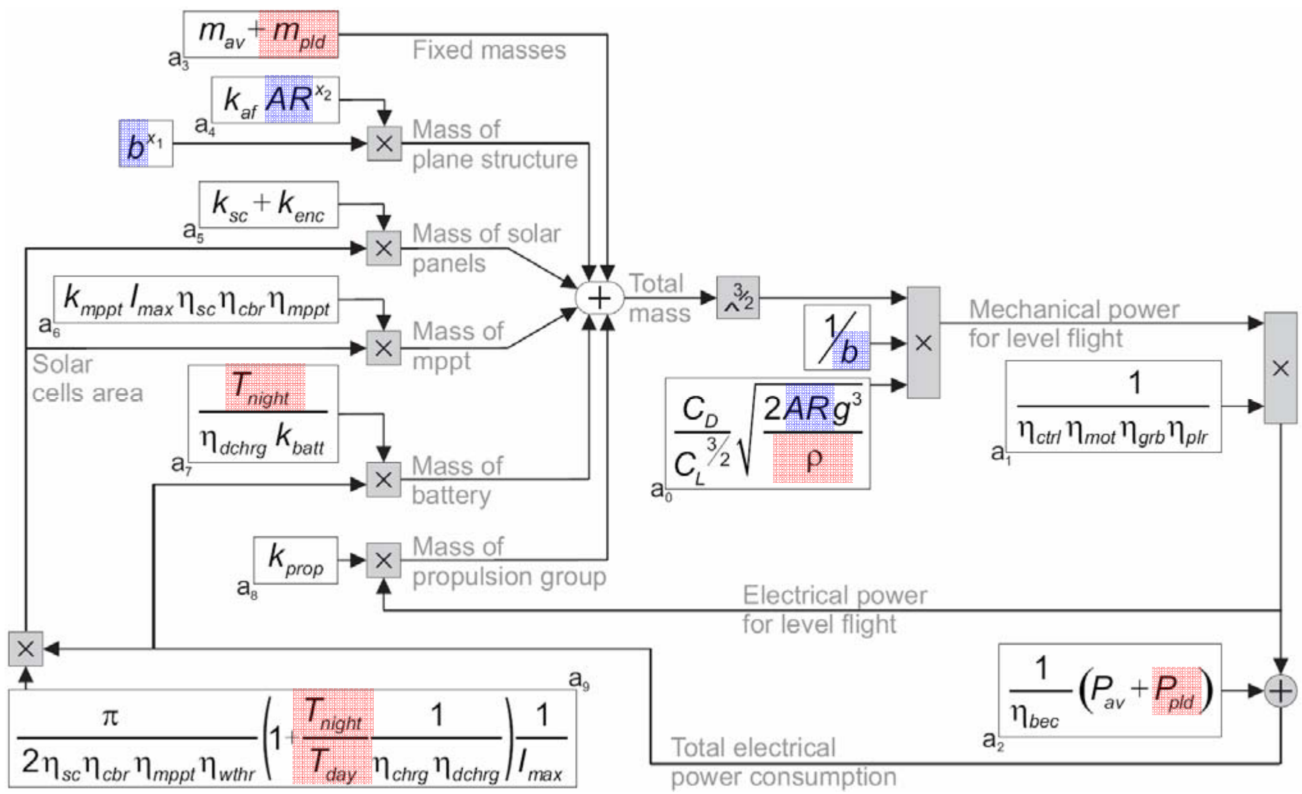
Keywords: Mass to power ratio of motors / Power to mass ratio of electrical motors, piezoelectric motors, Motor mass to power ratio / Motor power to mass ratio of electromagnetic motors, brushed and brushless motors energy density, power density, density of energy, density of power.

Summary and Resolution





(red)	Mission parameters
(blue)	Airplane's shape variables
	Others: Technological parameters

➔ Search b and AR for which the loop has a solution

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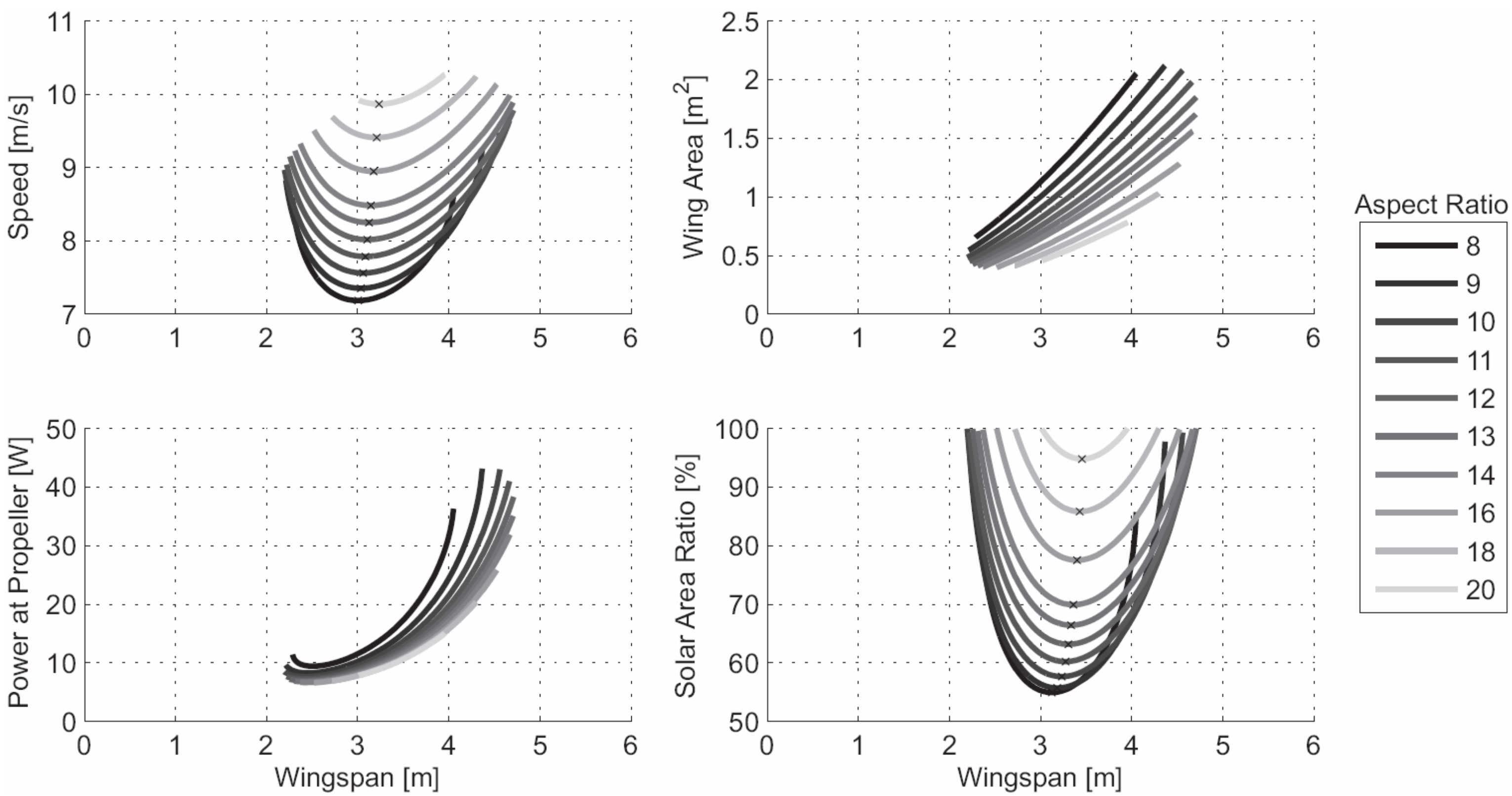
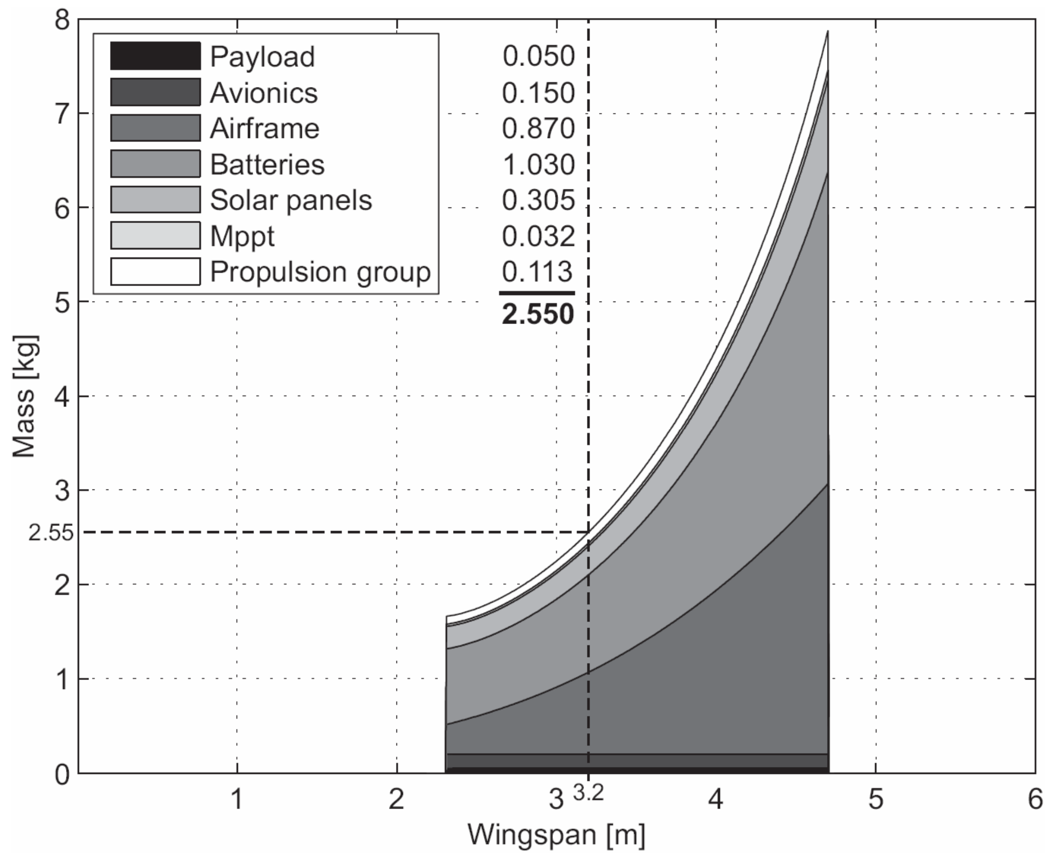
Sky-Sailor Design

Methodology application

- **Mission parameters**
  - Solar flight possible 3 months in summer (T_{day}=13.2h)
  - 50g payload consuming 0.5W
  - Flight location CH, at 500m above sea level





- **Sky-Sailor Layout**
  - 3.2m wingspan
  - 0.78m² wing area (0.525m² covered by cells)
  - 14.2W for level flight (electrical)

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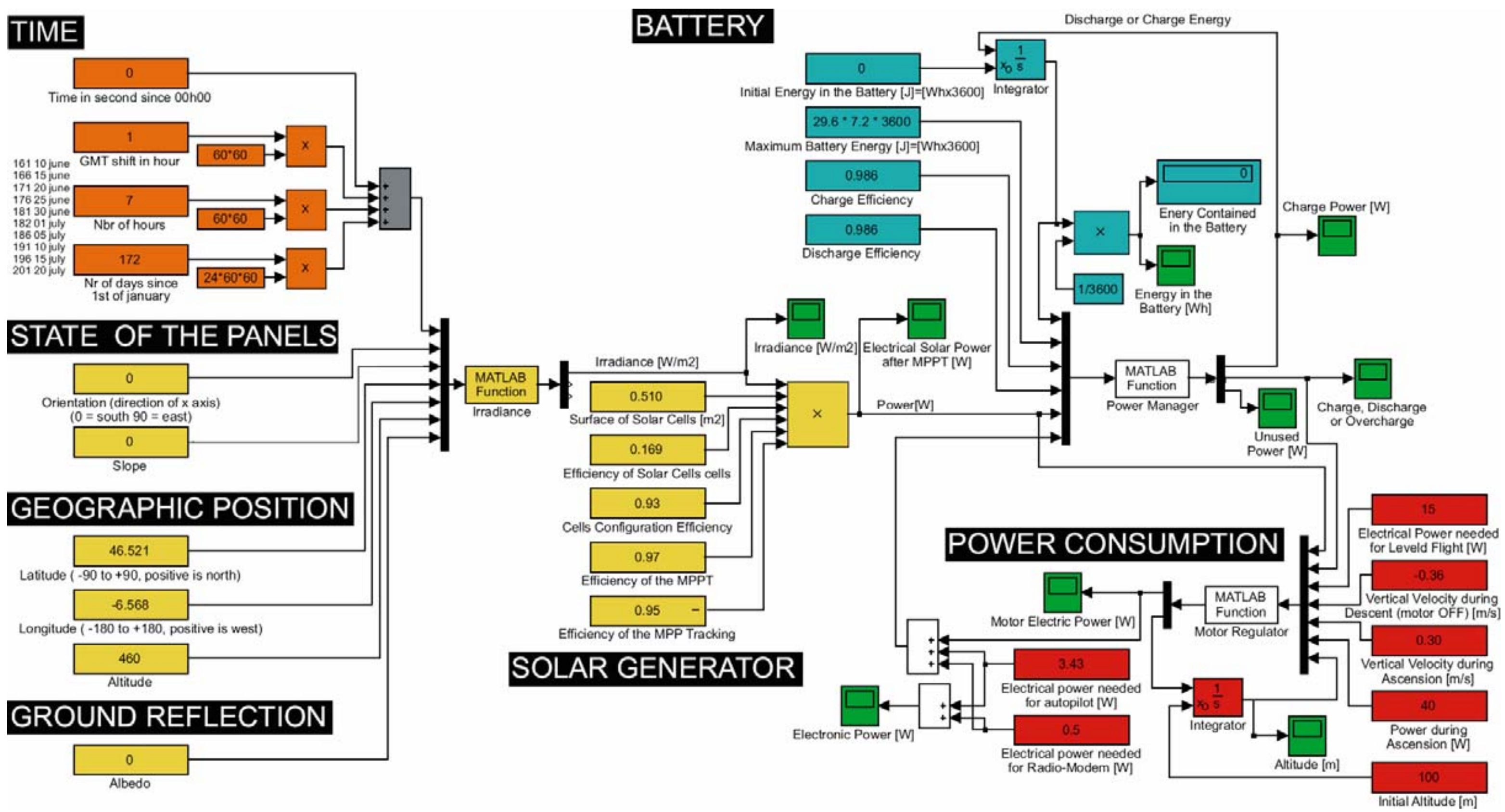
Objectives

– Validate the design

– Analyze energy flows on the airplane each second

– Rapidly see influence of parameters change



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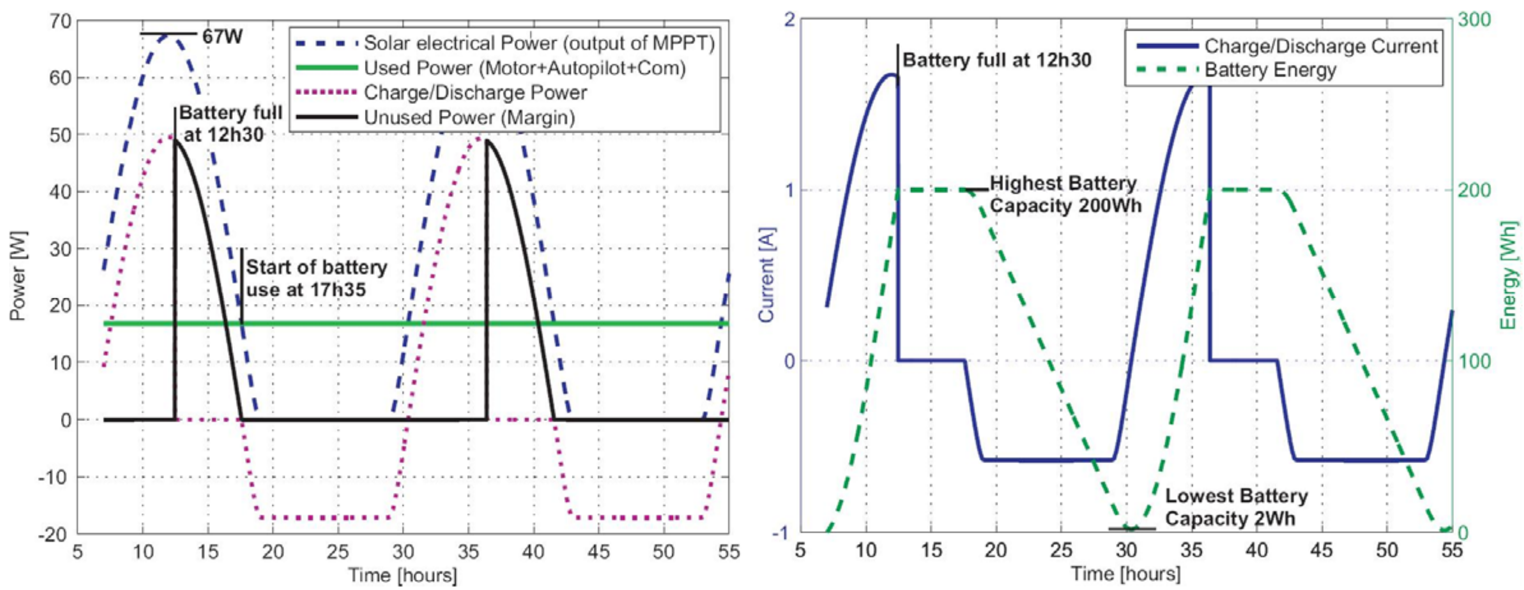
Simulation of a 48 h flight

– On the 21st of June

– On the 4th of August (+1.5 month)



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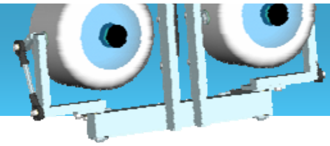
Sky-Sailor Prototype



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Sky-Sailor Prototype

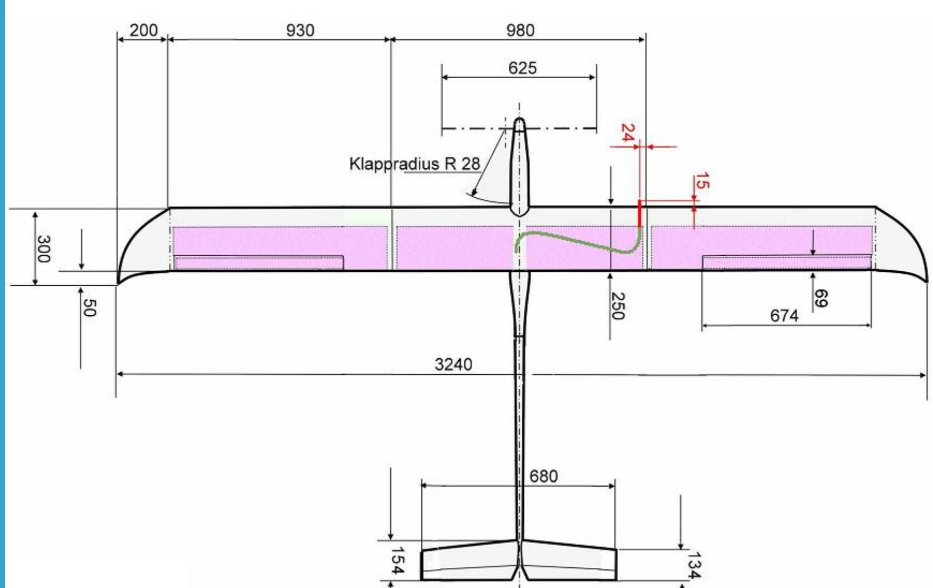
Configuration

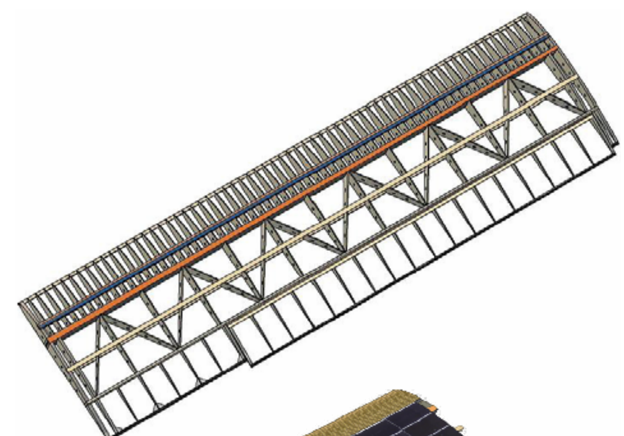
3 axis glider, V-tail, constant chord
Adapted from « Avance » record airplane of W. Engel
Naturally stable

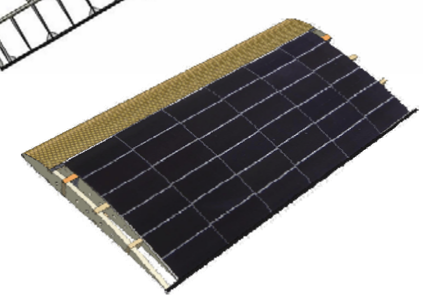
Structure

Composite materials (Carbon, Aramide, Balsa)
Spar-Ribs construction method

Wingspan	3.2 m
Surface	0.776 m²
Empty Weight	0.725 kg







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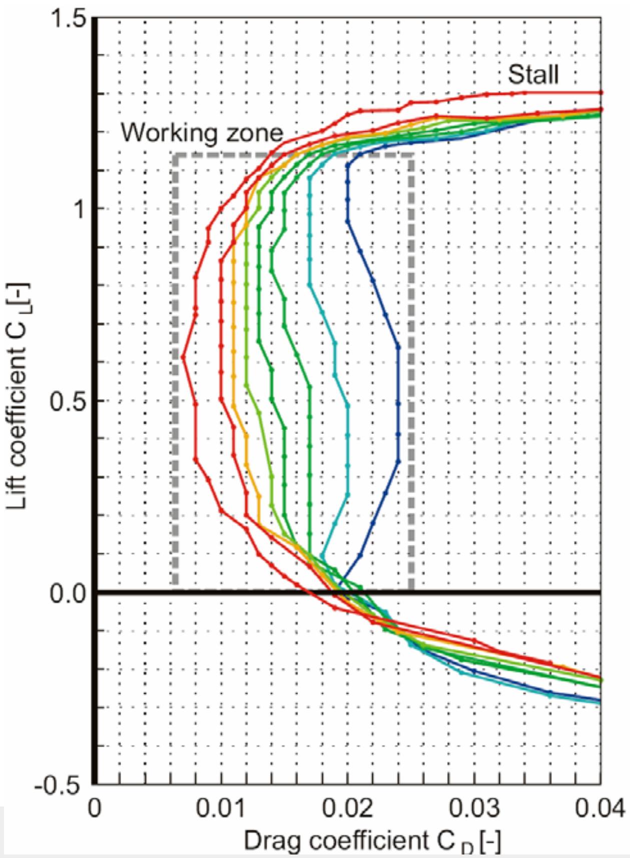
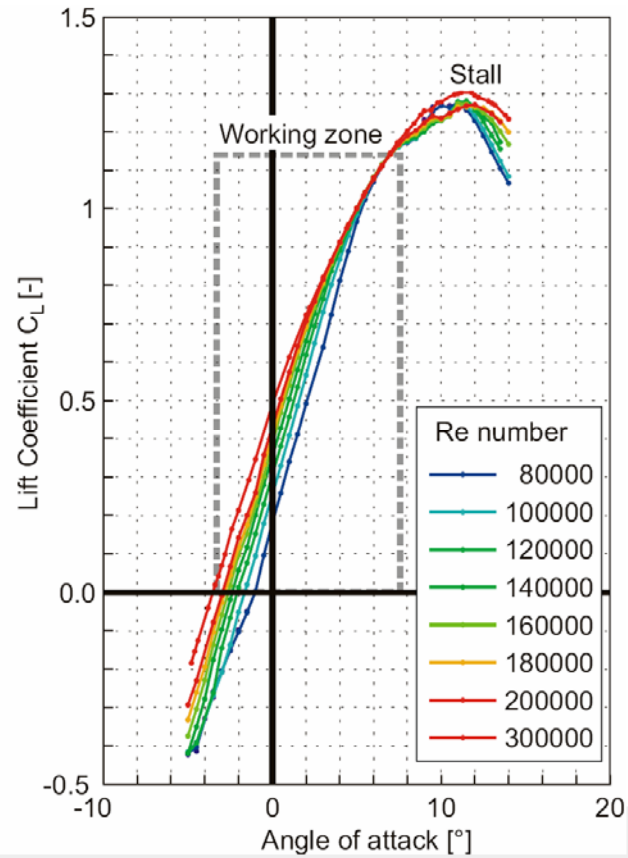
Aerodynamics

Dedicated Airfoil we3.55-9.3

Nominal flight speed	8.4 m/s
Nominal flight power (2.55 kg)	9 W
Glide ratio	23.5
Vertical glide speed	0.35 m/s





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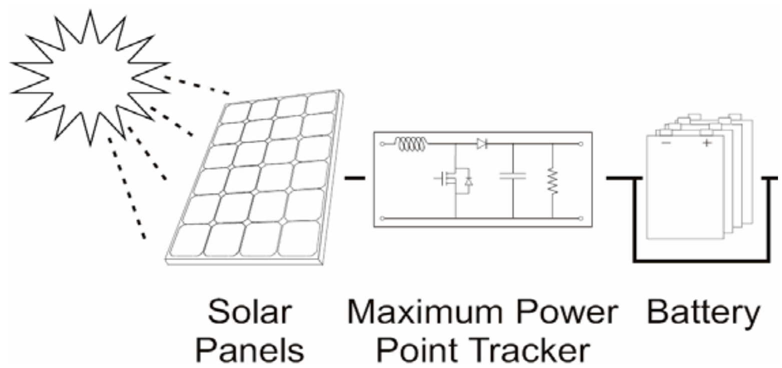
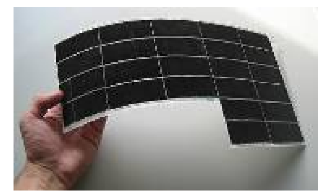
Solar Generator



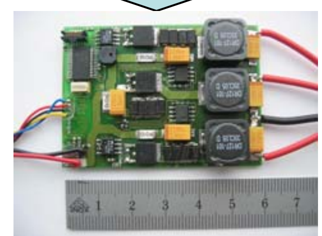
216 RWE solar cells (17% eff, ~90 W max)

- encapsulated into 3 solar panels
- non reflective encapsulation



Maximum Power Point tracker

- 97 % efficiency for 25 g and 90 W



Lithium-Ion battery

- 250 Wh, 1.056 kg ➔ 240 Wh/kg
- cycle efficiency 94.8 %

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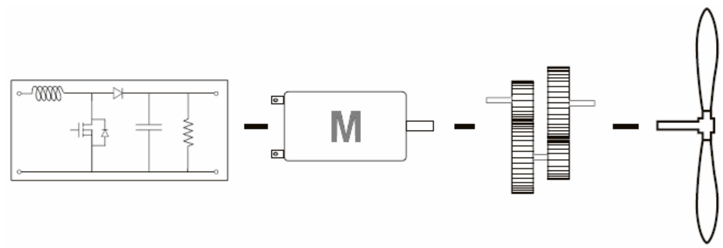
Propulsion group



High efficiency Propeller from E. Schöberl

- 60 cm diameter
- Carbon
- 85.6 % efficiency

➔ **Program created to select the best motor & gearbox combination out of 2600 motors**

Gearbox

- Spur gearhead, own development

Brushless Motor (LRK Strecker)

- 86.8% efficiency
- Excellent cooling
- Low weight

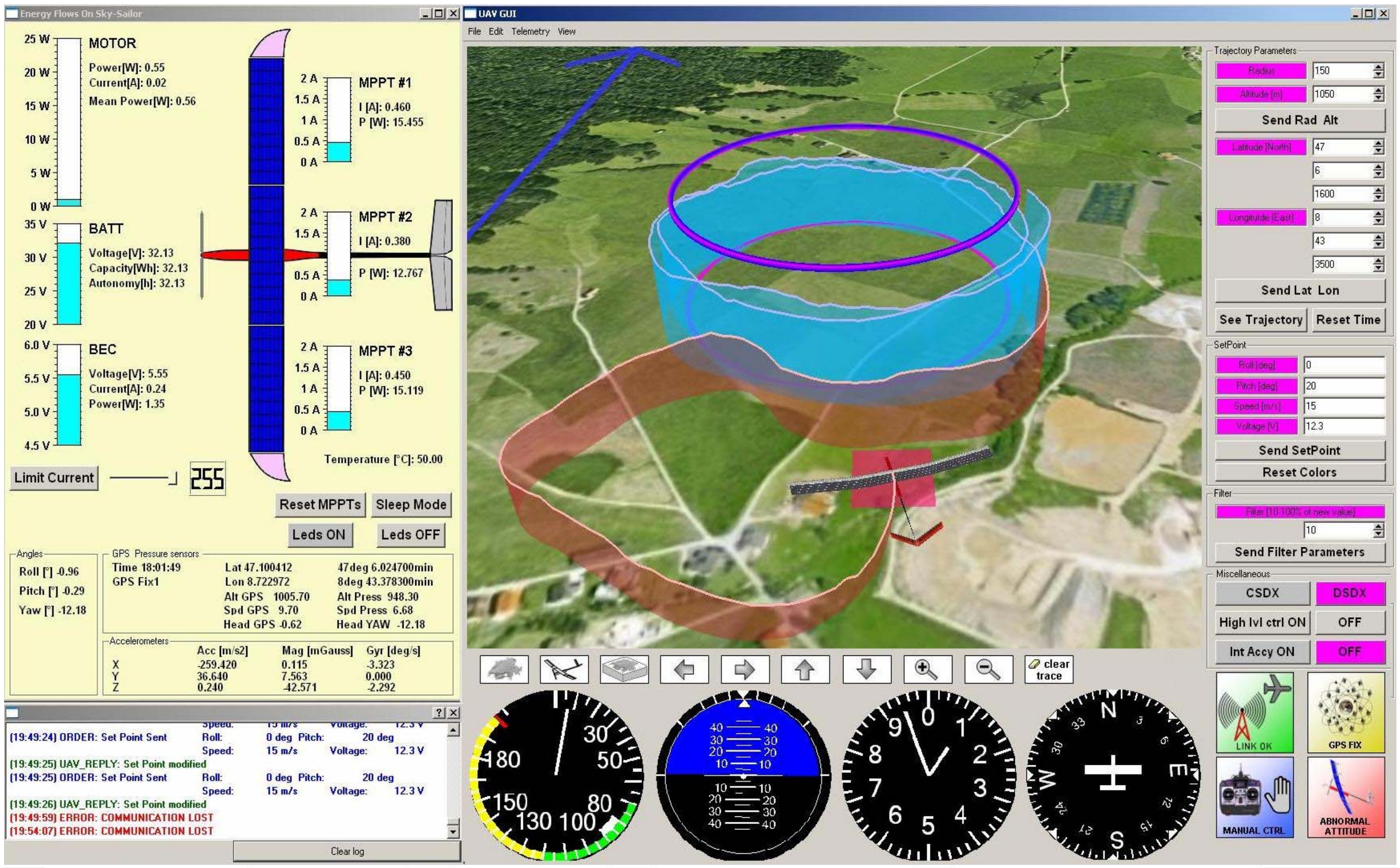
Jeti Advance 45 Opto Plus brushless controller

Autopilot

- Special needs (solar panels monitoring,…)
- Extreme weight & power constraints

➔ **Own Control & Navigation System**

Link to videos:
http://www.sky-sailor.ethz.ch/videos.htm



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Goals

Tune controller parameters
Test Navigation algorithms
Evaluate airplane capabilities

$$F_{tot} = F_{prop} + \sum_{i=1}^{7} F_{Li} + F_{di}$$

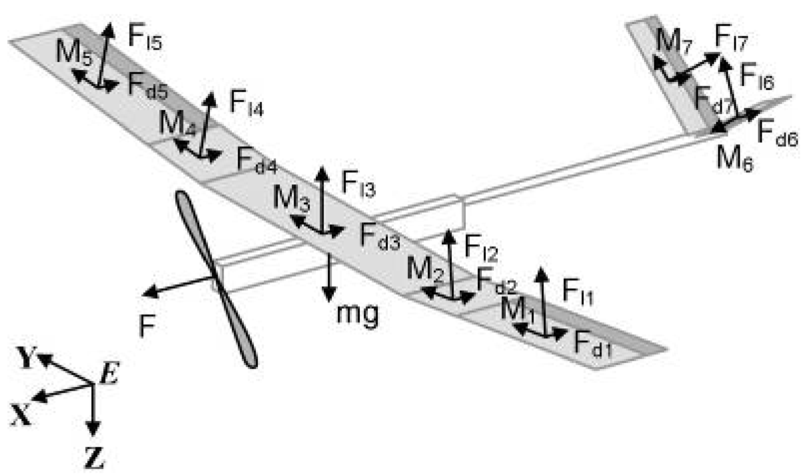
$$M_{tot} = \sum_{i=1}^{7} M_i + F_{Li} \times r_i + F_{di} \times r_i$$

$$F_{prop} = f(\dot{x}, U_1)$$

$$F_{li} = C_{li} \frac{\rho}{2} S_i v^2$$

$$F_{di} = C_{di} \frac{\rho}{2} S_i v^2$$

$$M_i = C_{mi} \frac{\rho}{2} S_i v^2 \cdot chord_i$$



$$[C_{l1}\ C_{d1}\ C_{m1}] = f(Aoa_i, U_2)$$

$$[C_{li}\ C_{di}\ C_{mi}] = f(Aoa_i) \qquad \text{for i=2,3,4}$$

$$[C_{l5}\ C_{d5}\ C_{m5}] = f(Aoa_i, U_3)$$

$$[C_{l6}\ C_{d6}\ C_{m6}] = f(Aoa_i, U_4)$$

$$[C_{l7}\ C_{d7}\ C_{m7}] = f(Aoa_i, U_5)$$

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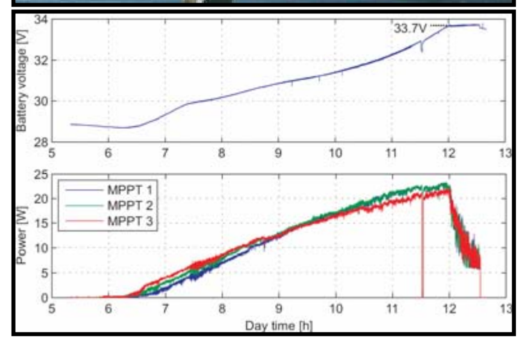
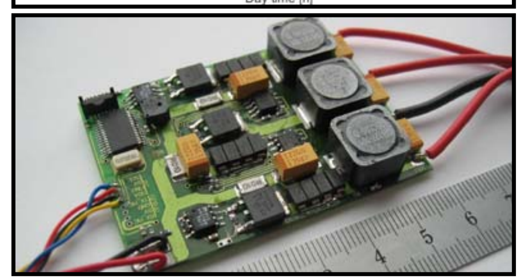
Experiments

- **Several tests with subgroups**
  - Efficiencies increase
  - Weight reduction
  - Adding functionnalities
  - Safety increase
- **Flight tests with a non-solar proto**
  - Aerodynamics validation
  - Power consumption verification
  - Autopilot electronic tests
  - Control & Navigation tuning
- **Flight tests with the Sky-Sailor**
  - Solar charge
  - Long flights (>3h)
  - 24 hours flight

Flight videos:
http://www.sky-sailor.ethz.ch/videos.htm





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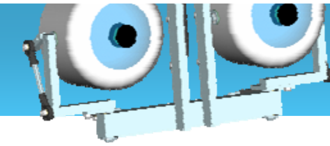
27 hours flight, 21st of June 2008

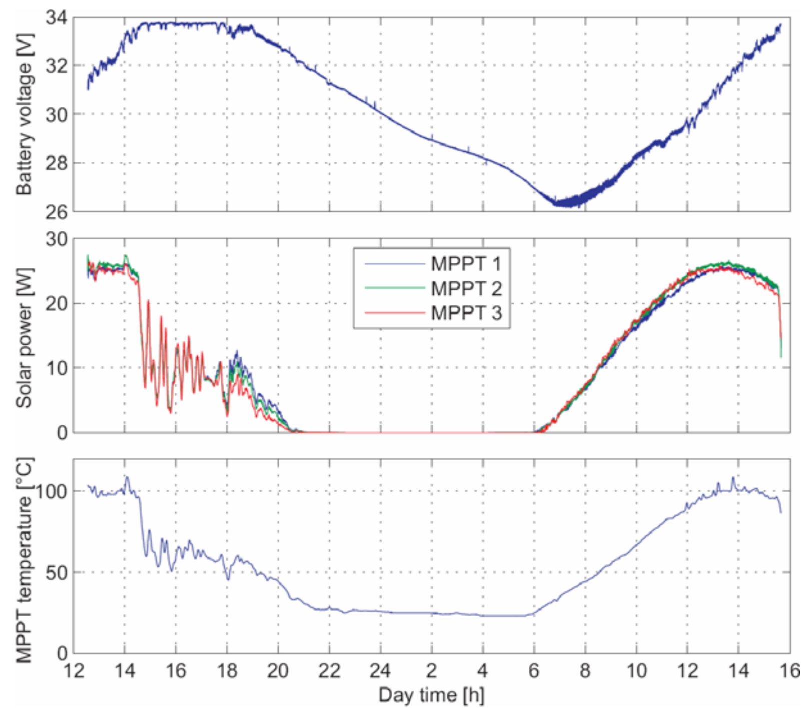


Conditions

– Excellent irradiance
– Bad wind conditions ➔ more power needed during the day

Achievements

– Duration:	27h05
– Distance:	874 km
– Av. speed:	8.4 m/s
– Mean power:	23+1.9W
– E_{used}:	675 Wh
– $E_{obtained}$:	768 Wh



➔ Continuous flight proved to be feasible without thermic or altitude gain

Scaling & Other considerations

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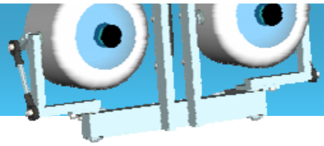
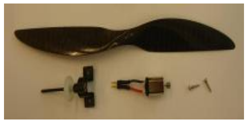
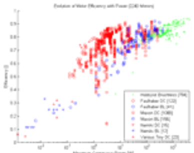
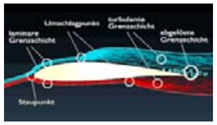
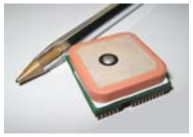
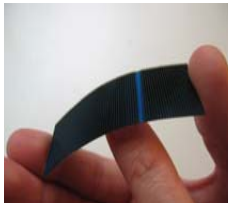


Down Scaling

Drawbacks

- Efficiency of propulsion group ↘

- At low power, DC motor but no BLDC

- Efficiency of aerodynamic ↘ (low Re)

- Servos below 5 grams → poor quality

- High $E_{density}$ batt not easily scalable


- Autopilot sensors limited (due to weight, ex: no tiny GPS or IMU

- Silicon solar cells scale in 2D (not 3D)
  - Not flexible for low radius
  
  - Weight percentage ↗
- MPPT efficiency ↘ ($V_{diode\ loss}/V_{MPPT}$ ↗)


→ No 24h solar flight at MAV size, but day flight possible

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Drawback

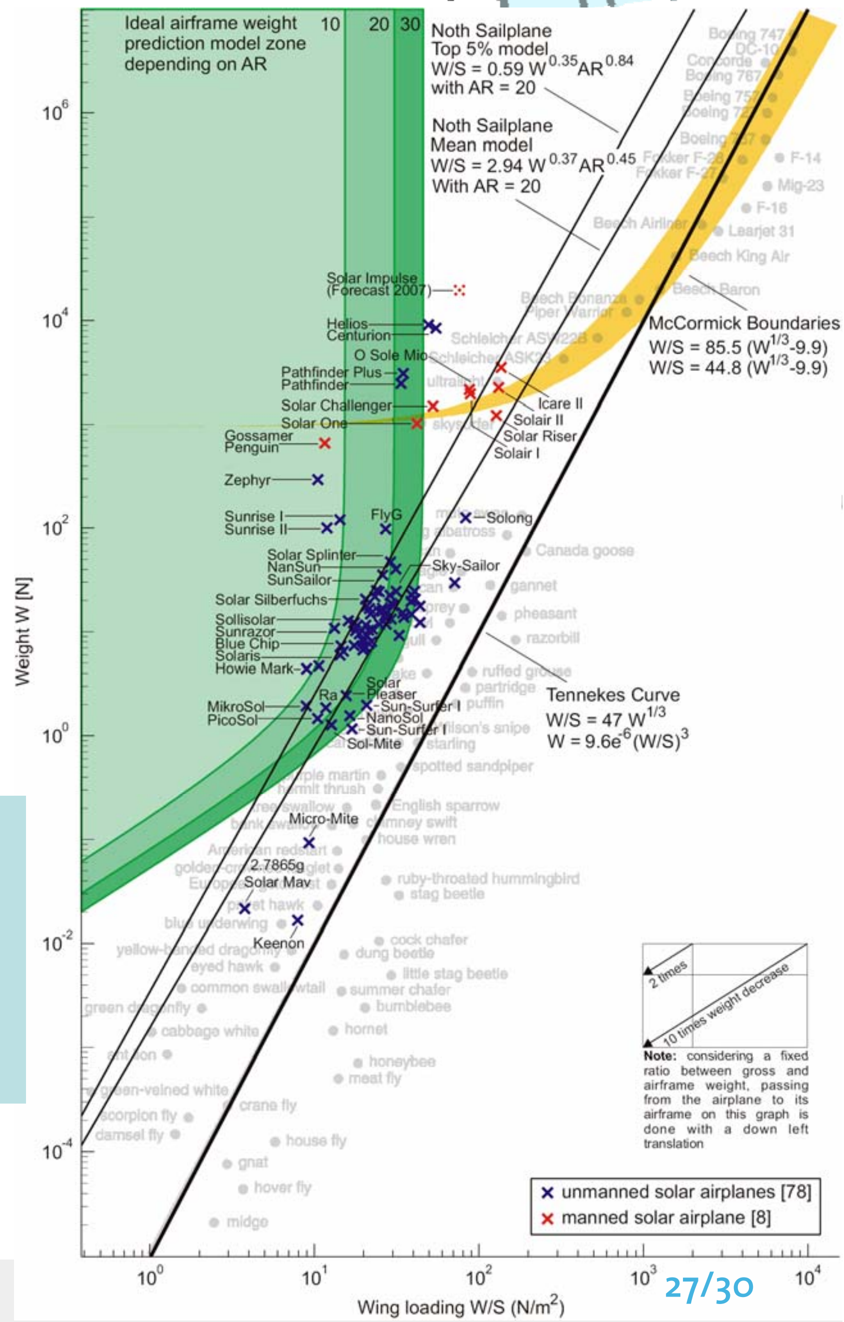
- Structure weight ~ b^3
- Theory said it should be ~ b^2

➔ The bigger they are, the lighter the construction method has to be

➔ Fragility & Risks

➔ Continuous flight possible only for 1 or 2 passengers but…

- ➔ Low speed (long flights)
- ➔ No comfort possible



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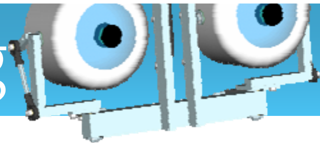

Two possibilities to increase flight endurance are:

– Use of altitude to store energy

  + less battery needed

  - altitude varies ➔ aerodynamics not optimized for a fixed density

– Thermal soaring

  + free climbing, save energy

  - require a method to detect & soar thermal

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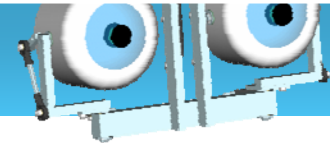
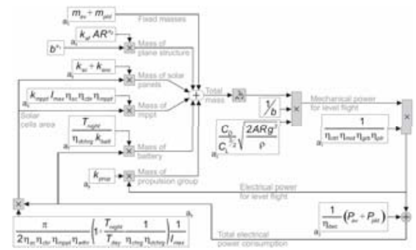
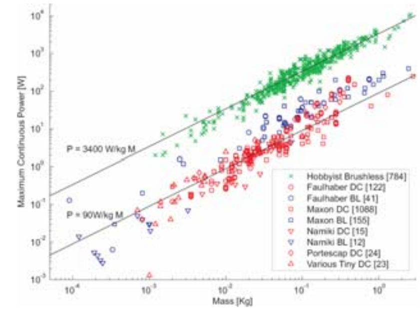
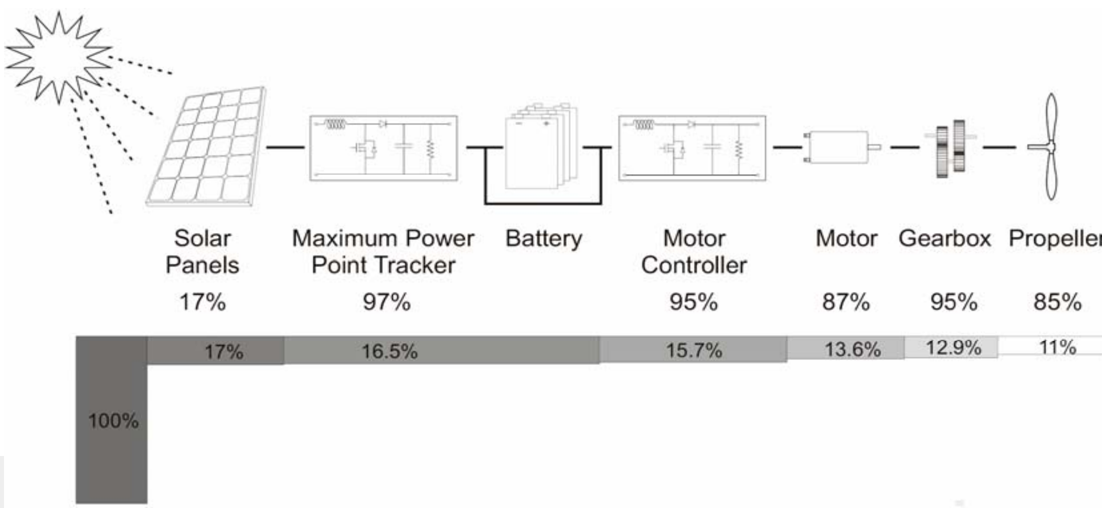


- **Methodology developed**
  - Simple and versatile
  - Valid on a large range
  - Solid weight & efficiency models
  - Allows fast feasibility studies
  - Allows to identify bottle necks
- **Prototype built**
  - Validation of the design
  - Continuous flight proven
  - Very good know-how acquired







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Conclusion

- **Scaling problems**
  - Down: efficiencies and aerodynamics
  - Up: large wing structure
- **Outlook**
  - Increase # parameters (efficiency = f(power))
  - Flight algorithm learning energy saving
  - Thermal soaring
  - Building: improve costs, time & robustness

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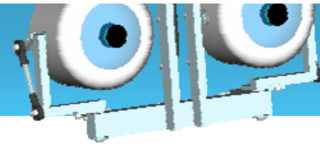
Future of solar aviation

- **MAV size**
  - Needs still many improvements (eff, aerodynamics, batteries)
- **At 2-10 meters**
  - Forest fire monitoring
  - Pipeline surveillance
  - ...
  - ➔ In 10 years with tech. improvements (batteries, solar cell)
- **HALE**
  - Act as mobile phone antenna
  - Real need to stay airborne
  - ➔ Will require many improvements (structure,batteries)
- **Manned airplane (transportation)**
  - High fragility, risks and long trips
  - Even with a 100% eff. airplane, problem is the sun!
  - ➔ A better idea would be to:
    - ➔ Transform E_{solar} on the ground → H2
    - ➔ Use H2 in flight (fuel cell & electrical motor)



Thank you for your attention

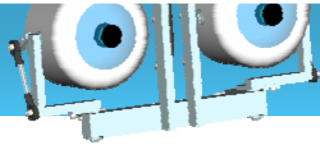
Questions ?

Special Thanks to:

- **Prof. Siegwart and the entire ASL**
- **Walter Engel & all the people who worked on the project**
- **Doctoral comity**

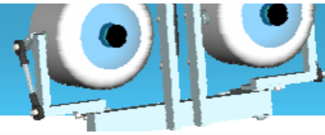
Appendices

- **Solar Generator**
  - Spectrum, Albedo, Sun angle
  - T_{day} & I_{max}
  - Best research cell efficiencies
  - I-V curve
  - MPPT
  - Integration in the wing
- **Energy Storage**
  - All solutions
  - Energy density of fuel
  - Lithium-Ion battery evolution
- **Propulsion Group**
  - Motors
  - Propeller
  - Weight prediction models
- **Autopilot**
  - Schematic
  - Telemetry
  - Power consumption
  - Placement
  - GUI (thermals)
  - Simulation & modeling
- **Overall**
  - Energy Chain
  - Solar Airplane: light and slow
  - Weight-Power-Autonomy
  - Methodology Resolution
  - 30 Parameters
  - Weight distribution
- **Applications**
  - Potential applications
  - Sky-Sailor
  - MAV
  - Manned
  - HALE
  - Mars
- **Other**
  - Using thermals
  - Sun Surfer
  - Design phases
  - Airframe model
  - 27 hours flight

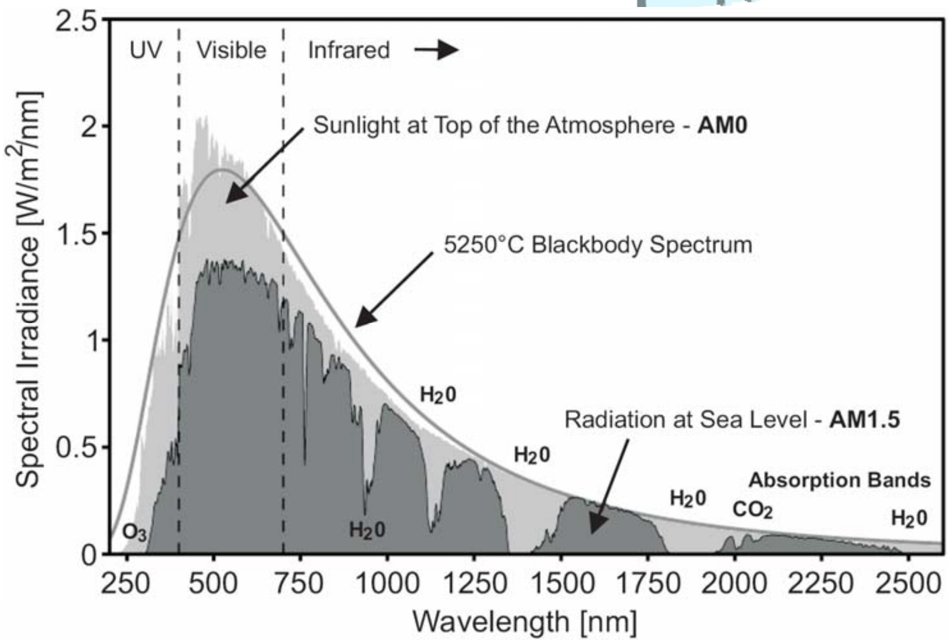


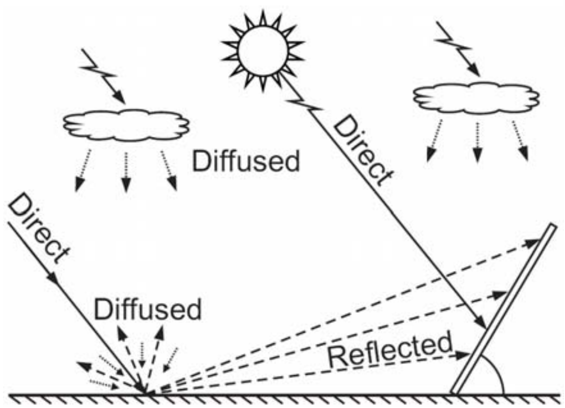
Solar Generator

Solar Energy



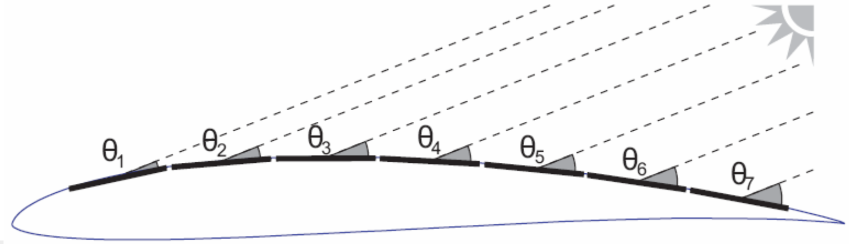
Solar Spectrum





Direct, diffused and reflected light

Angle of incidence variation



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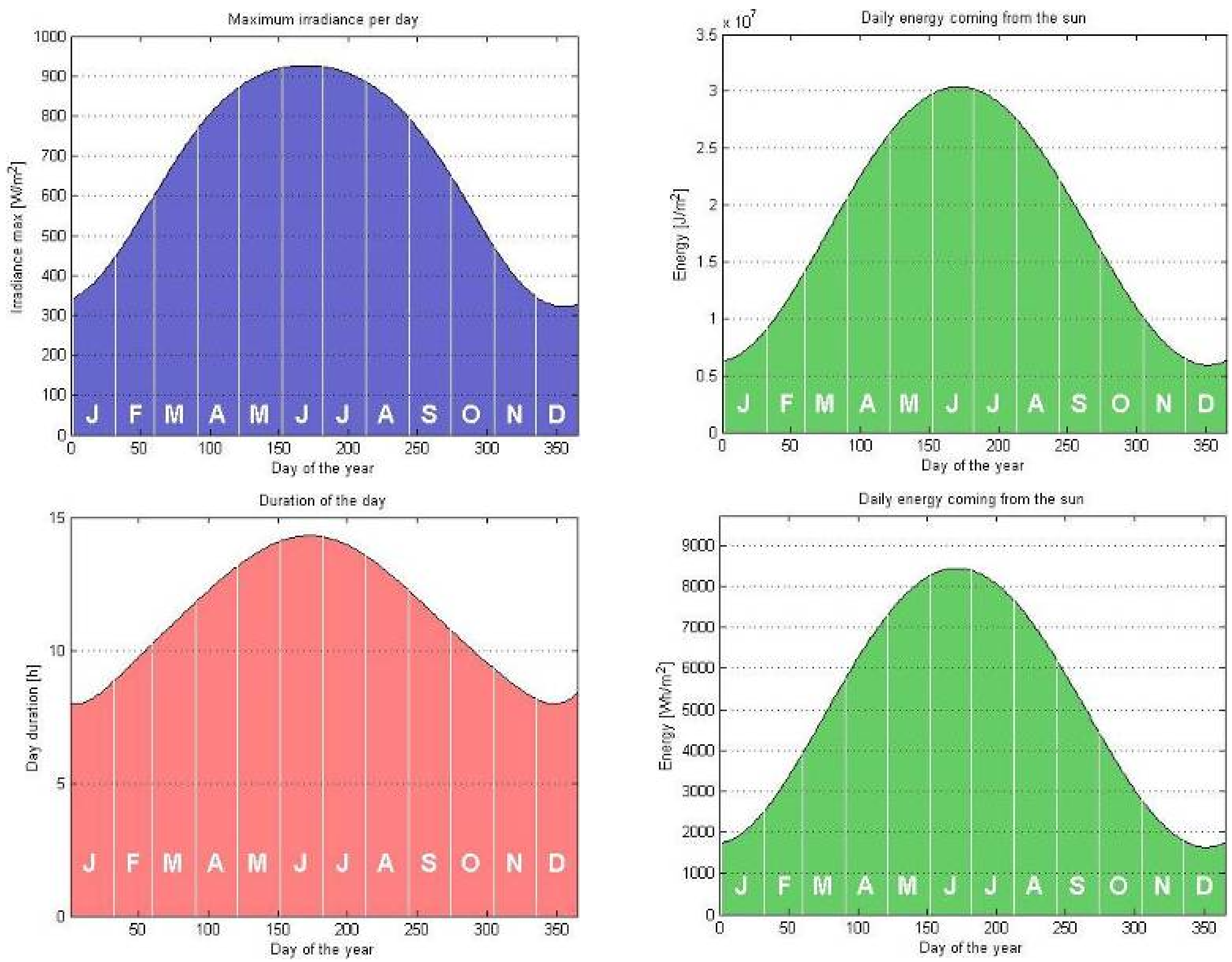
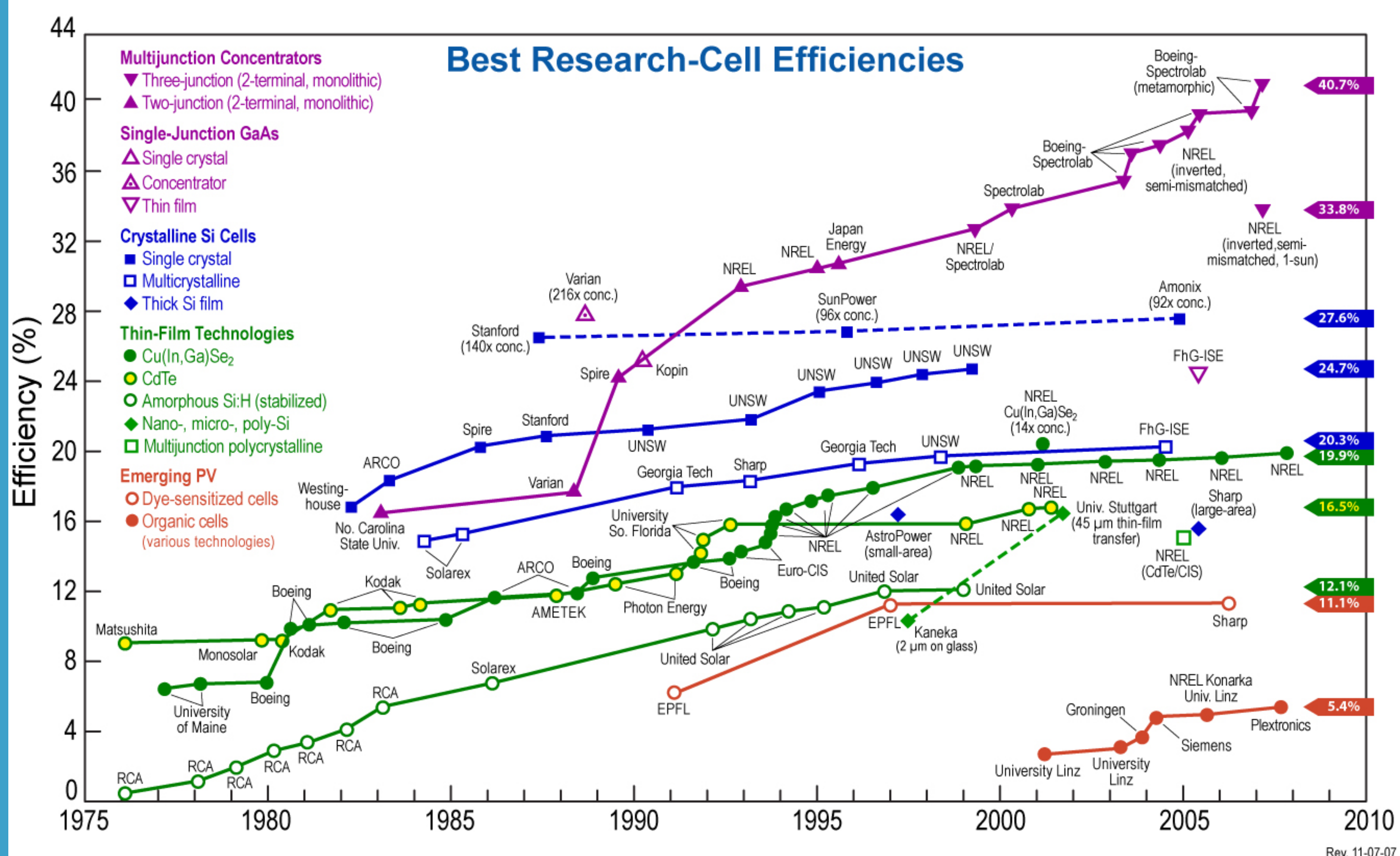
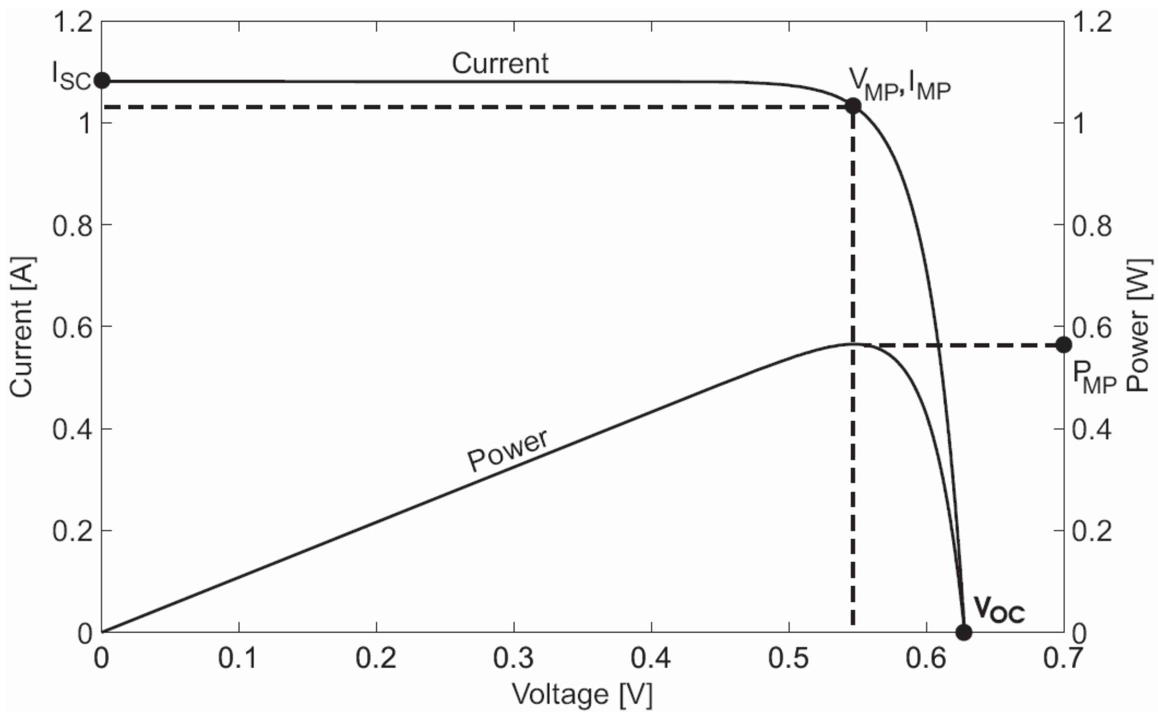
Variation of T_{day} and I_{max} along year



Solar Cells Research

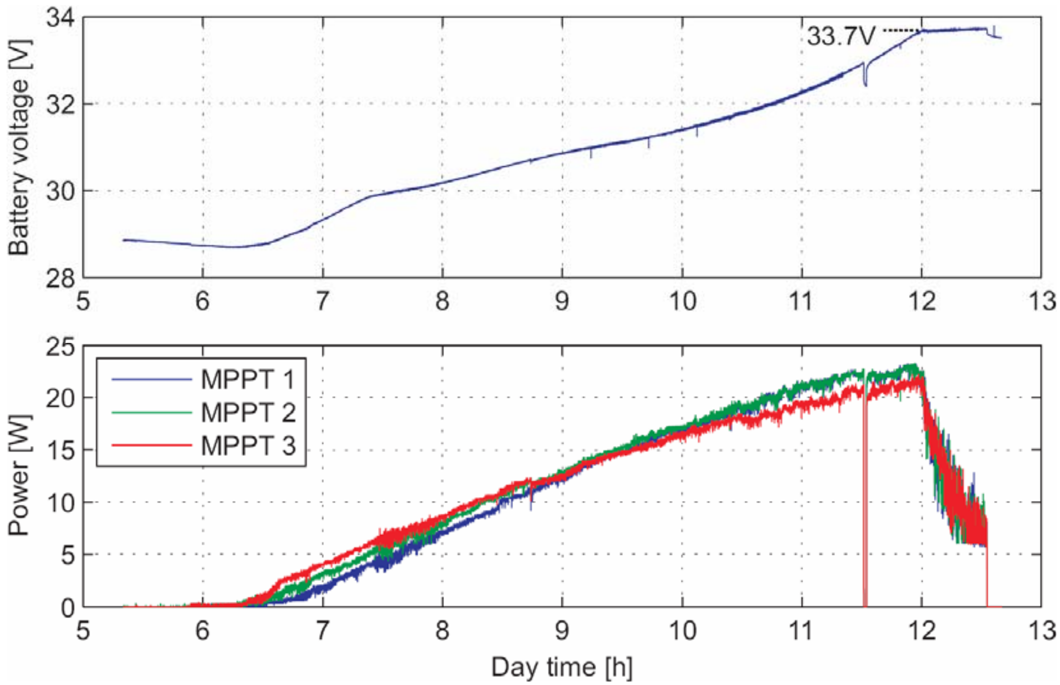


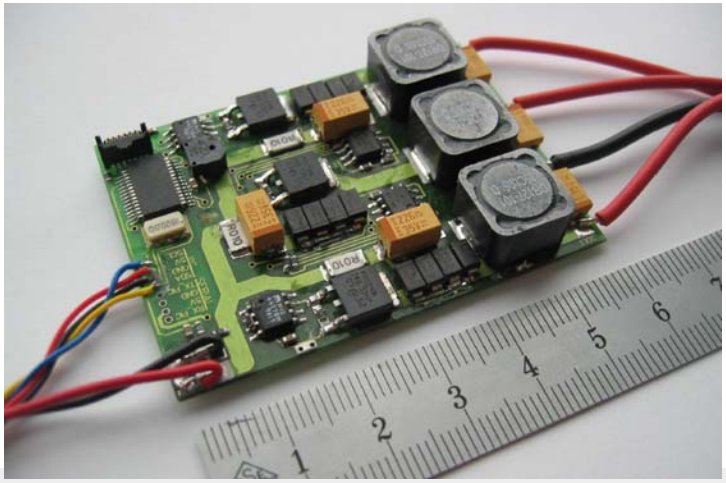
Solar Cell



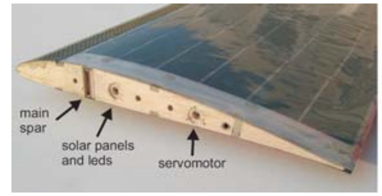
Current
Power
Current [A]
Power [W]
Voltage [V]
I_{SC}
V_{MP}, I_{MP}
P_{MP}
V_{OC}
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

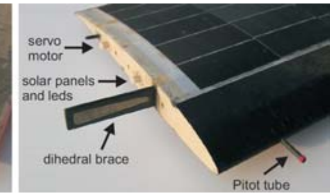
MPPT

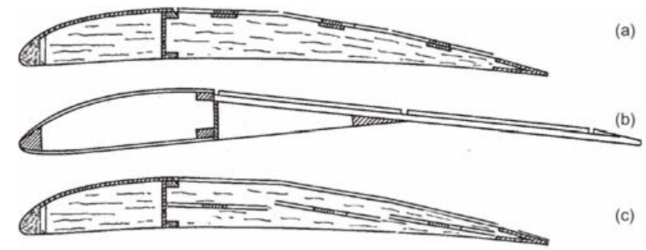

Battery voltage [V]
34
32
30
28
5 6 7 8 9 10 11 12 13
33.7V
Power [W]
25
20
15
10
5
0
MPPT 1
MPPT 2
MPPT 3
Day time [h]

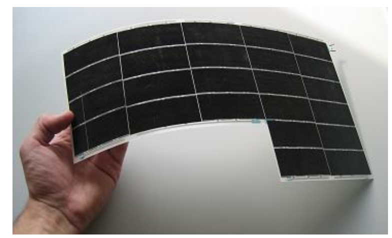


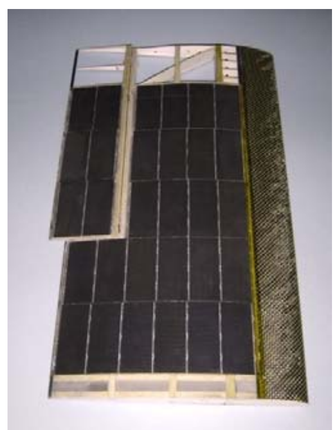
Structure


main
spar
solar panels
and leds
servomotor


servo
motor
solar panels
and leds
dihedral brace
Pitot tube

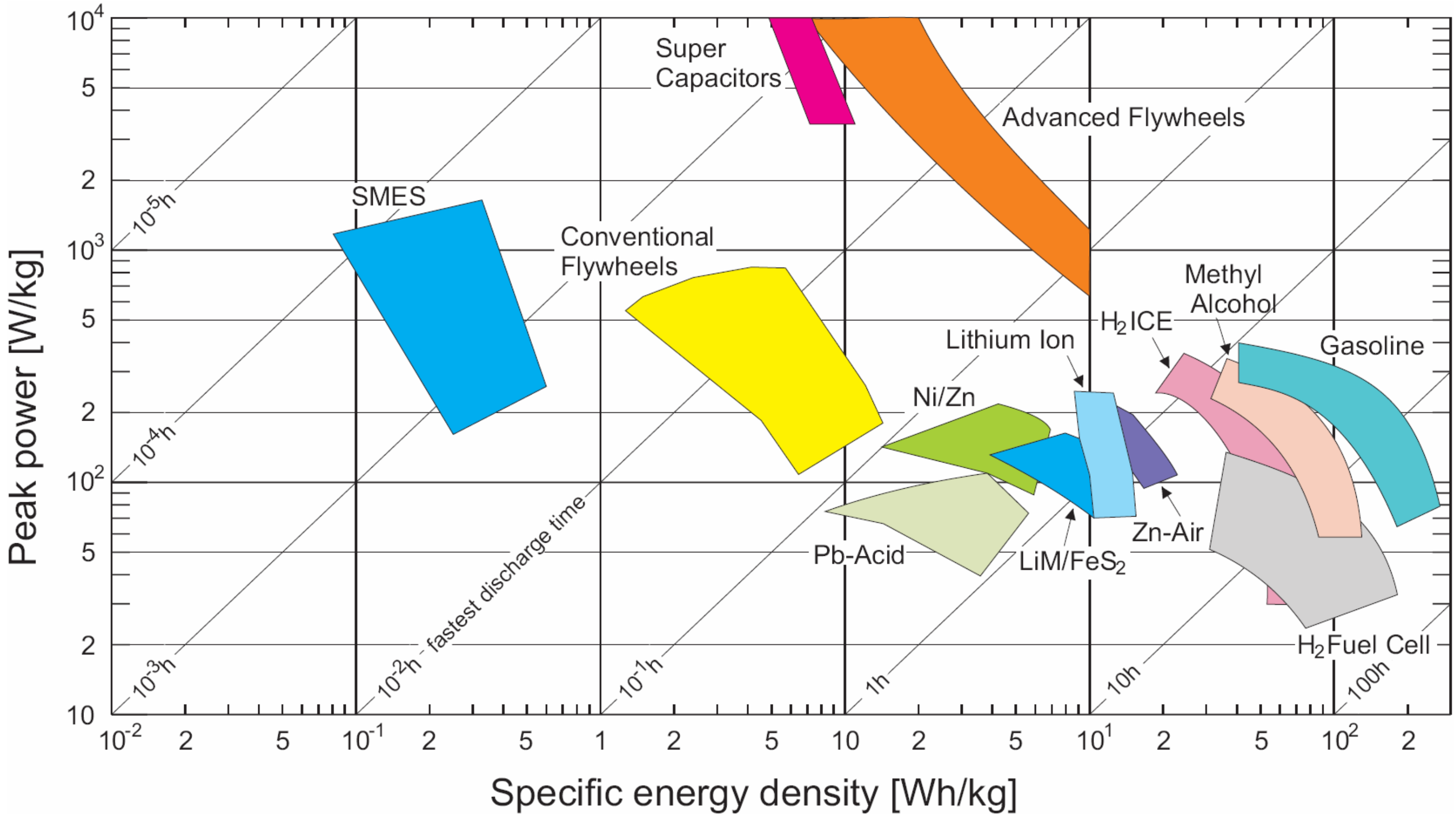

(a)
(b)
(c)





Energy Storage

Energy storage solutions



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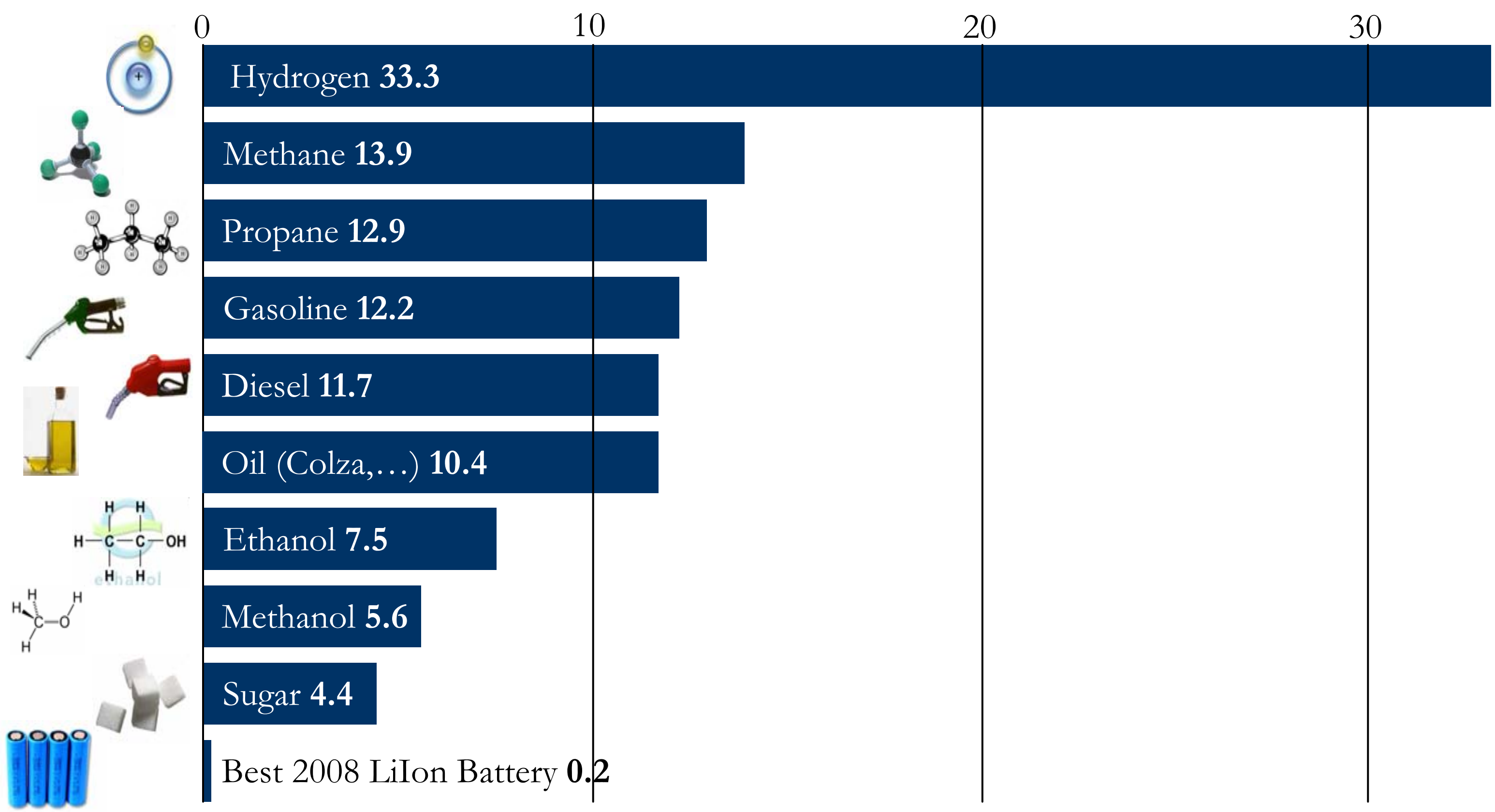
Energy Storage

Energy density of some reactants **[kWh/kg]**
(LHV Lower heating value)



➔ Important to keep in mind Availability / Efficiency of converters

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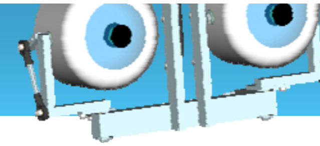
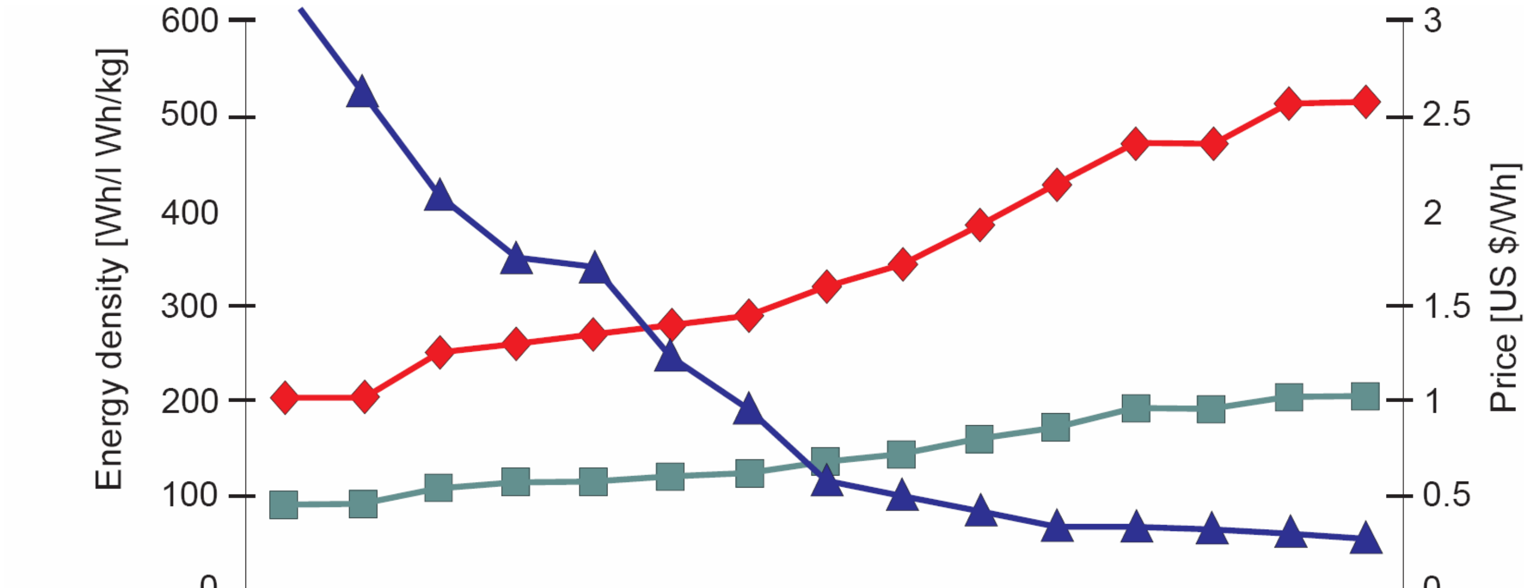
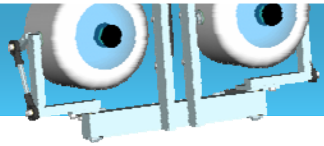
Lithium-Ion battery evolution





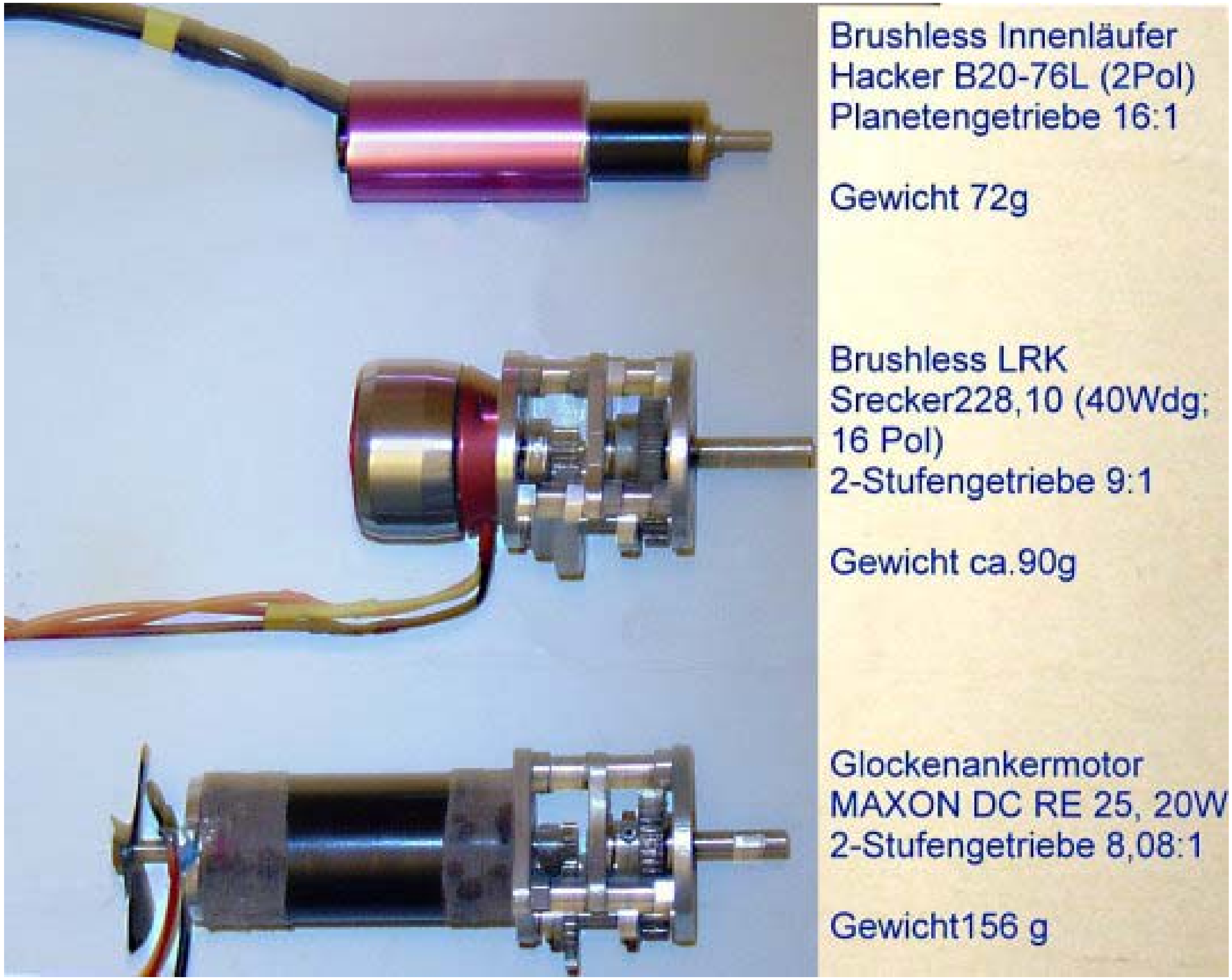
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
[Wh/l]	204	208	250	260	271	281	292	321	343	386	428	471	471	514	514
[Wh/kg]	88	90	108	113	114	119	123	135	143	159	172	189	189	202	202
[US$/Wh]	3.17	2.63	2.09	1.75	1.71	1.24	0.95	0.59	0.51	0.42	0.35	0.35	0.33	0.31	0.28

Energy density + 6.6%/year
Price - 17%/year

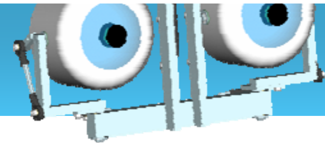


Propulsion Group

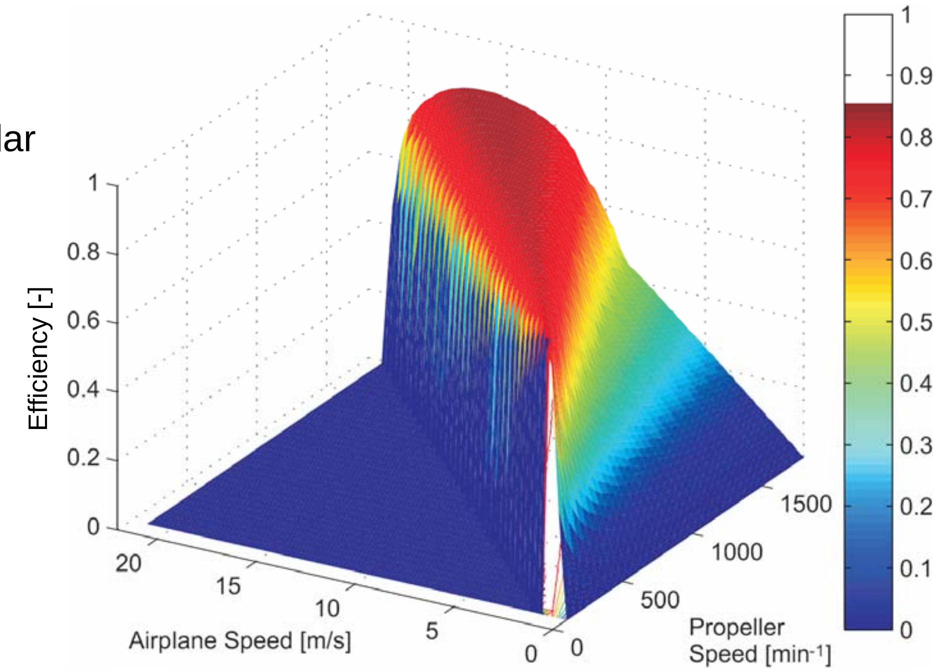
Motors

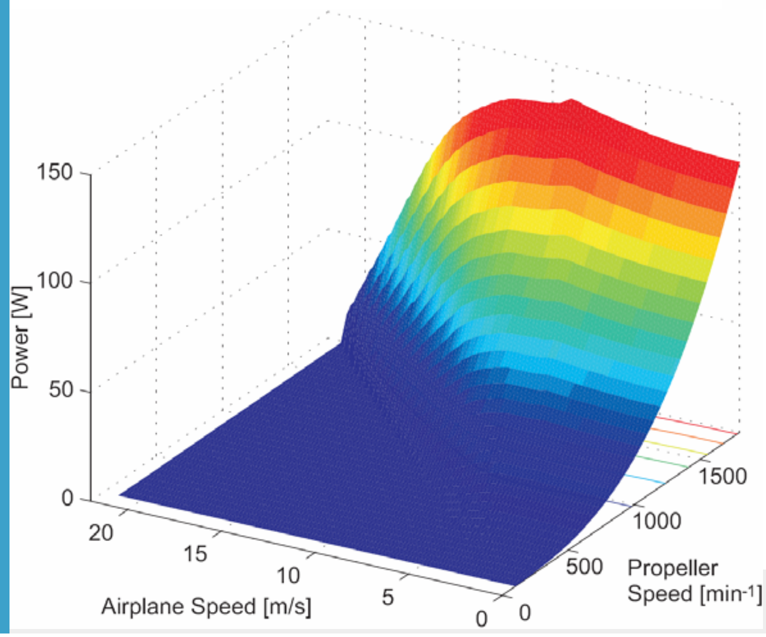

Brushless Innenläufer
Hacker B20-76L (2Pol)
Planetengetriebe 16:1
Gewicht 72g
Brushless LRK
Srecker228,10 (40Wdg;
16 Pol)
2-Stufengetriebe 9:1
Gewicht ca.90g
Glockenankermotor
MAXON DC RE 25, 20W
2-Stufengetriebe 8,08:1
Gewicht156 g

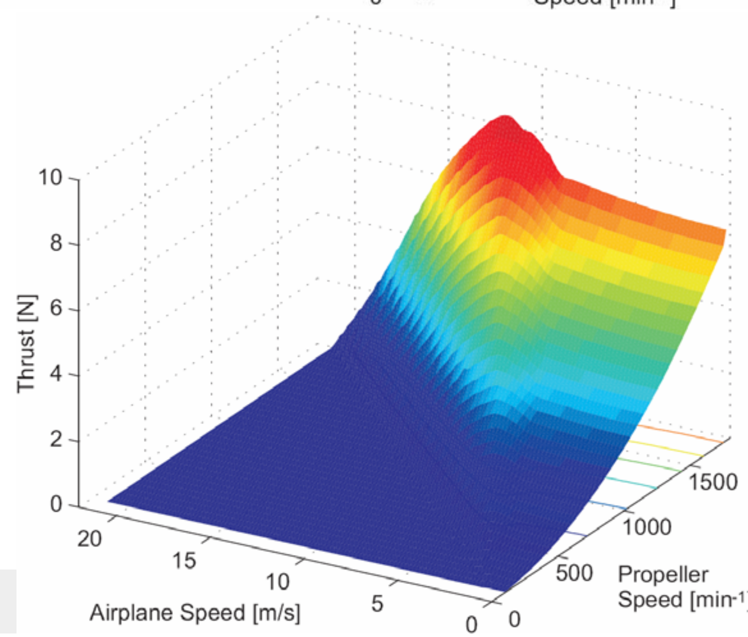
Propeller



Designed by E. Schöberl
- « Master of Prop »
- Also worked on Icaré and other solar airplanes

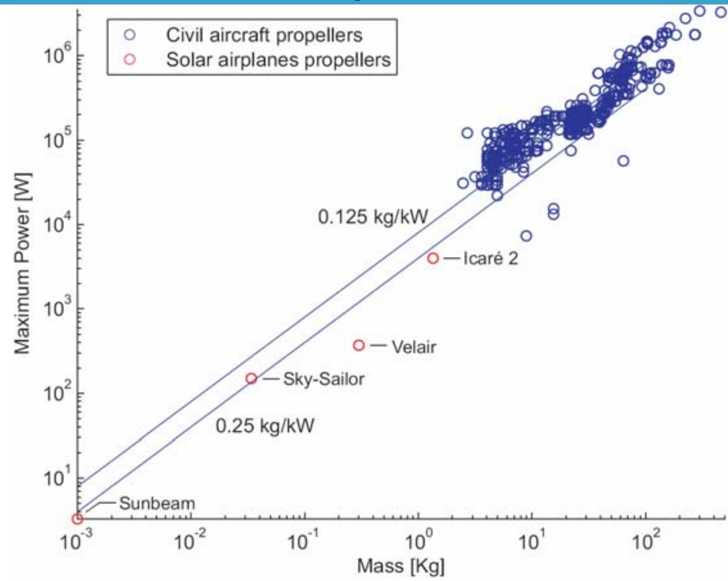




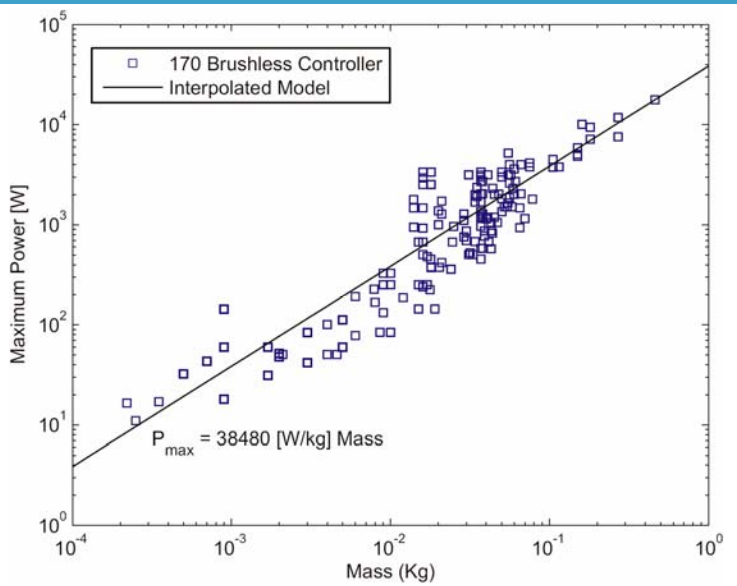


Weight prediction models

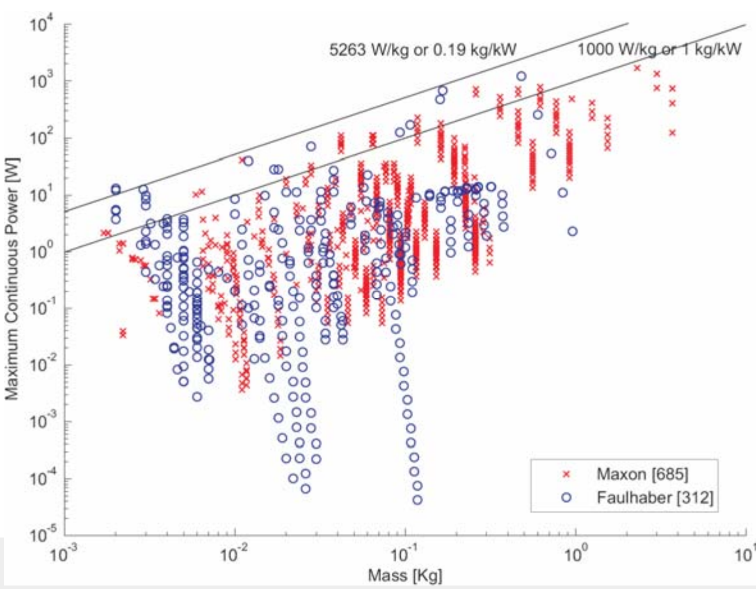
Propellers

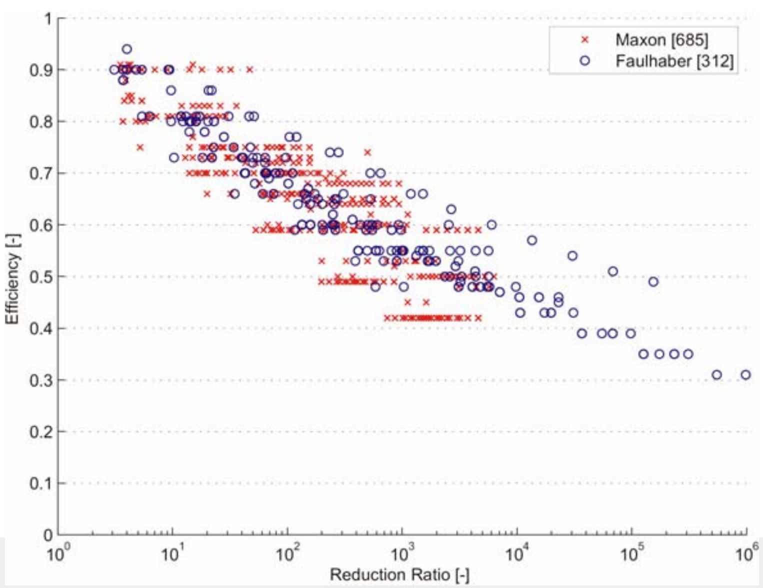


Brushless controllers



Gearboxes





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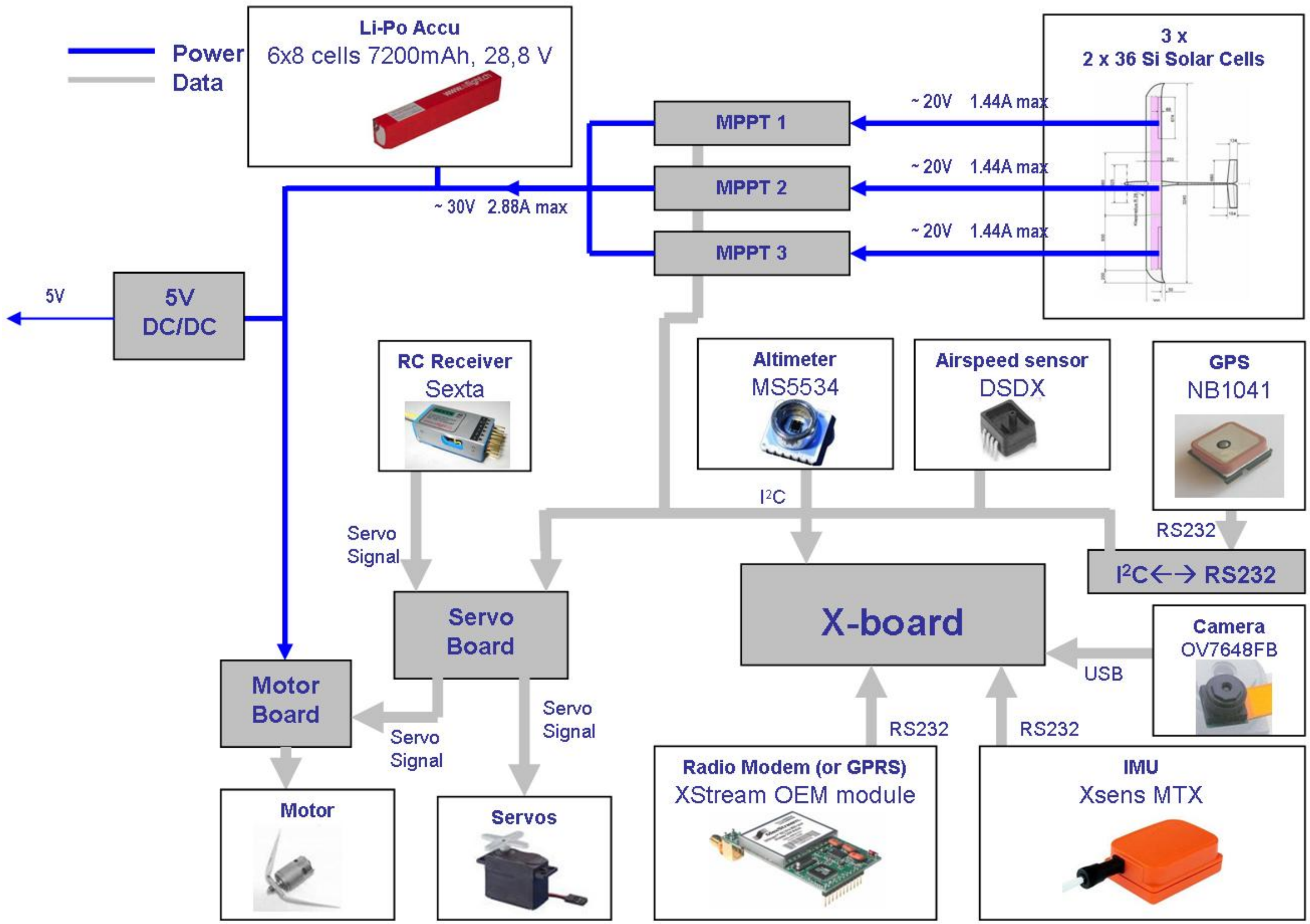
Autopilot

Autopilot overview



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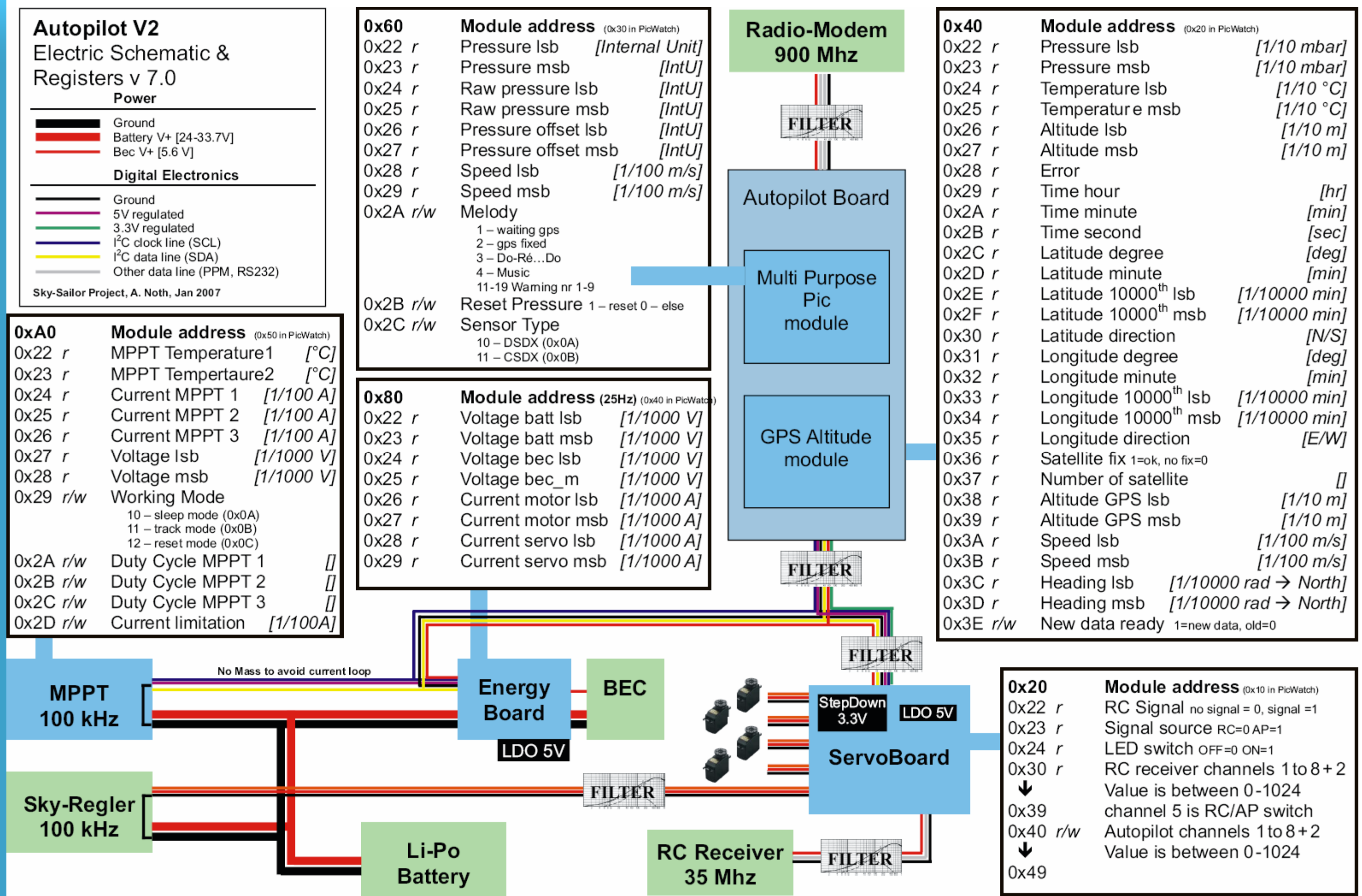
Telemetry



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Autopilot power consumption

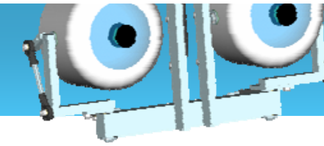
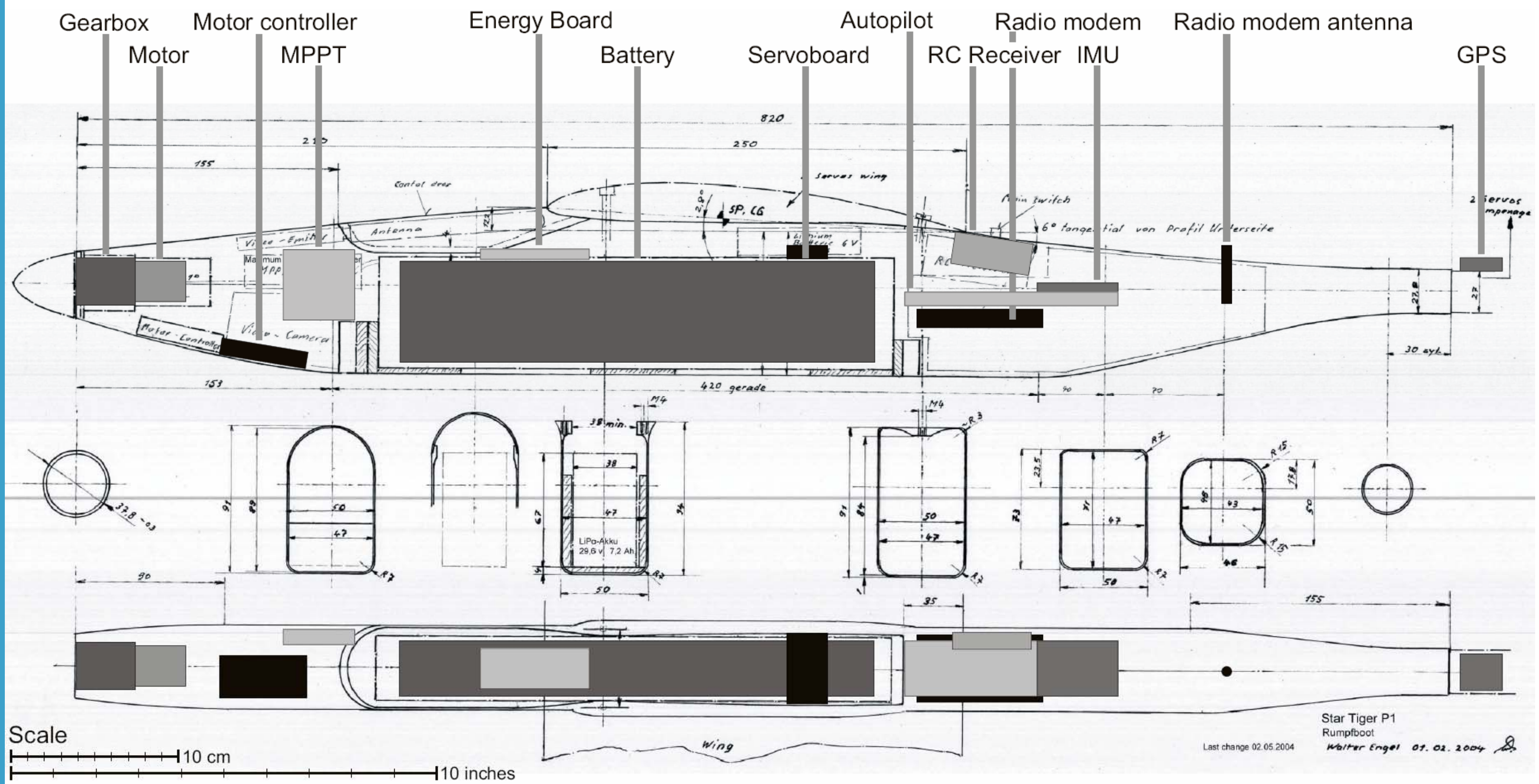


Table 5.2: Power consumption of the avionics subsystems

Device	Voltage [V]	Current [mA]	Power [mW]	η_{conv} from 5.6V [-]	Power @ BEC [mW]
Radio Modem (XStream)	5	80	400	89%	449
IMU (Xsens MTX)	5	70	360	89%	404
CSDX (Sensortechnics)	5	7	35	89%	39
Pic16F876-Autopilot	5	7	35	89%	39
Pic16F876-Energy Board	5	7	35	89%	39
MS5534 (Intersema)	3.3	1	33	92%	36
GPS (Nemerix NB1043)	3.3	20	66	92%	72
DsPic33-Autopilot	3.3	27	99	92%	108
DsPic33-Servoboard	3.3	27	99	92%	108
Pic16LF877-Autopilot	3.3	5	17	92%	18
Total			**1.179**		**1.313**

Element placement in fuselage



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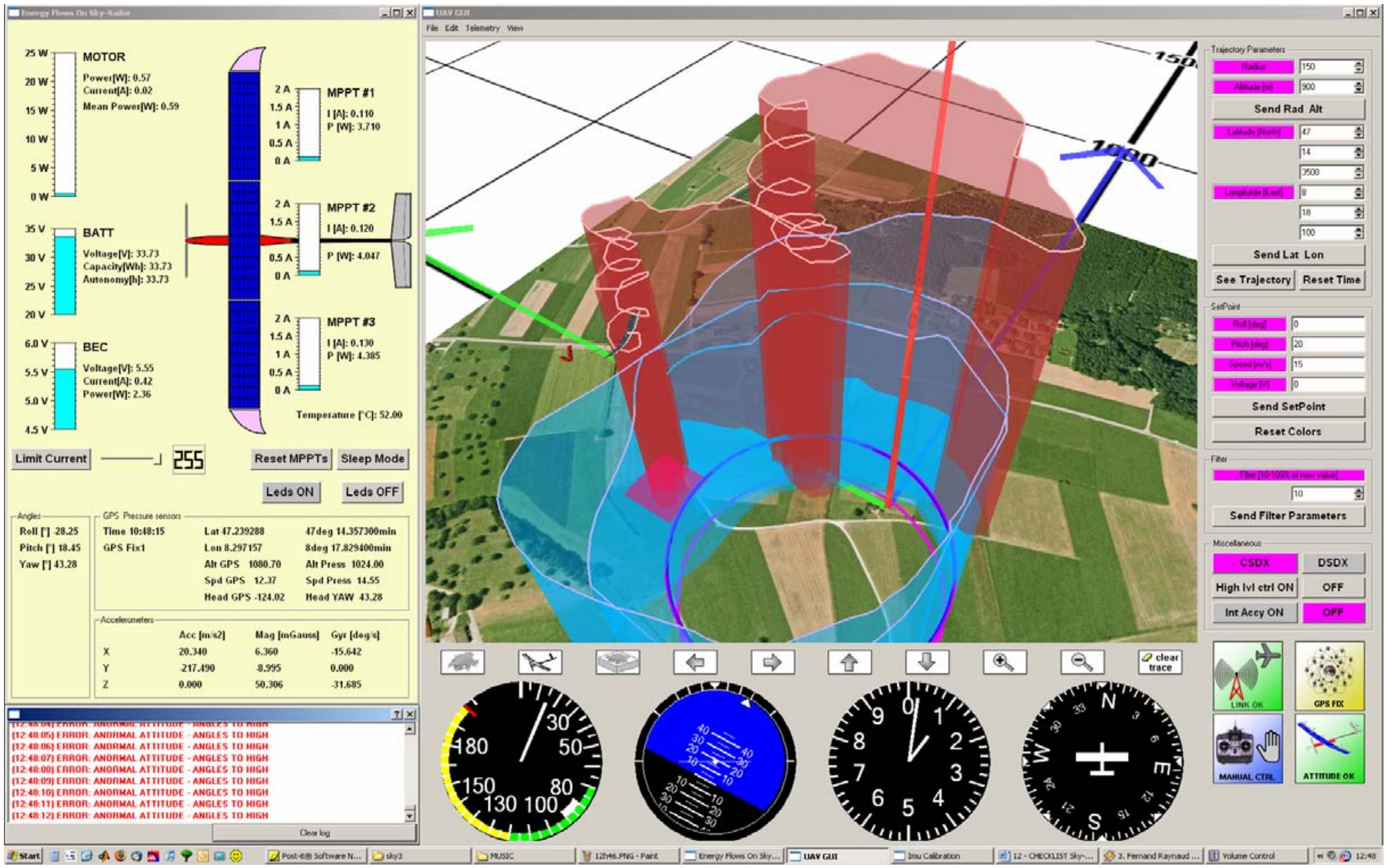
GUI (thermals)



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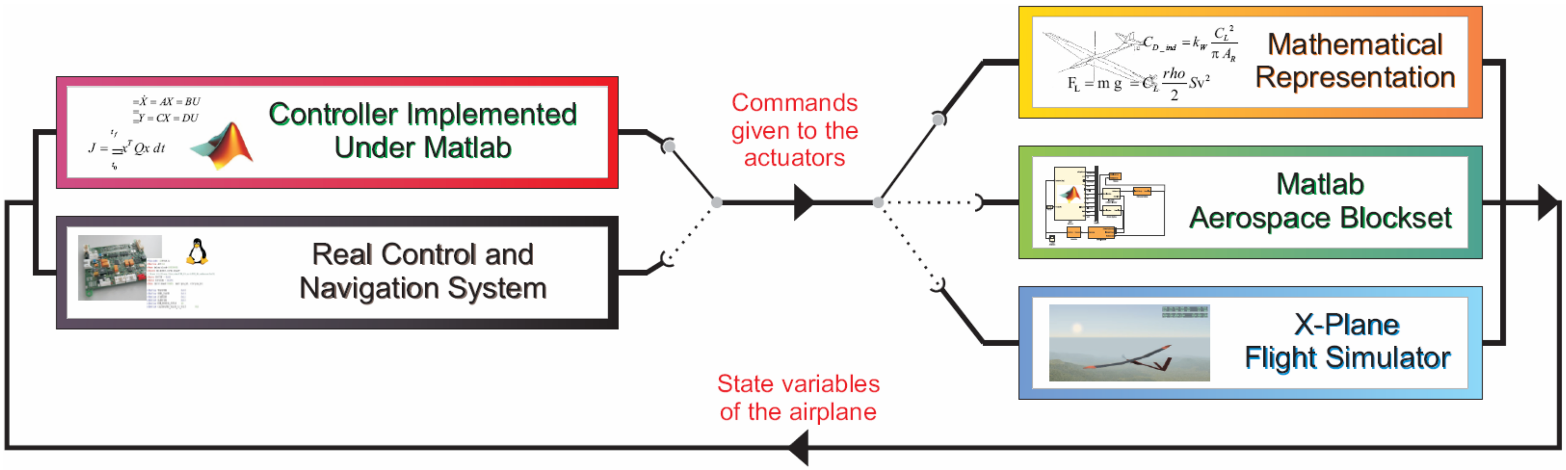
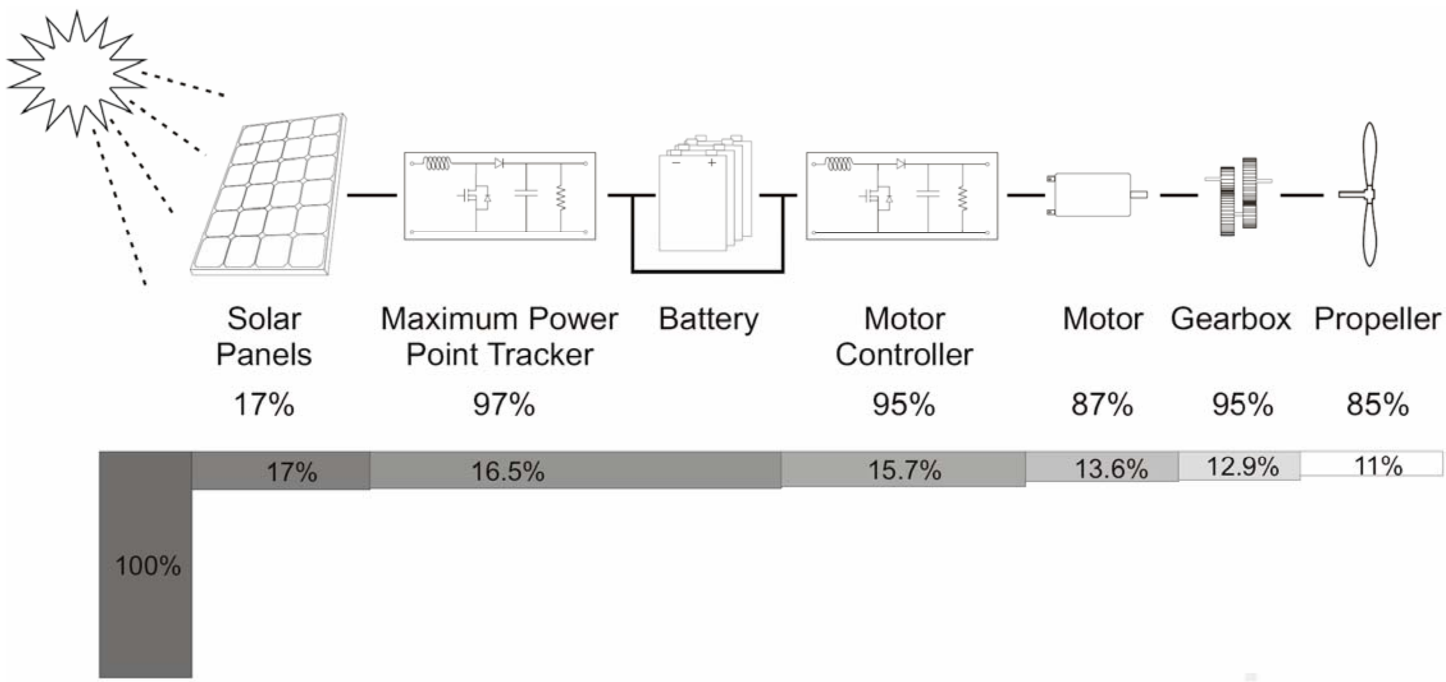
Modeling & Simulation



Overall

Energy chain

A succession of losses....



→ Important to ↗ efficiencies

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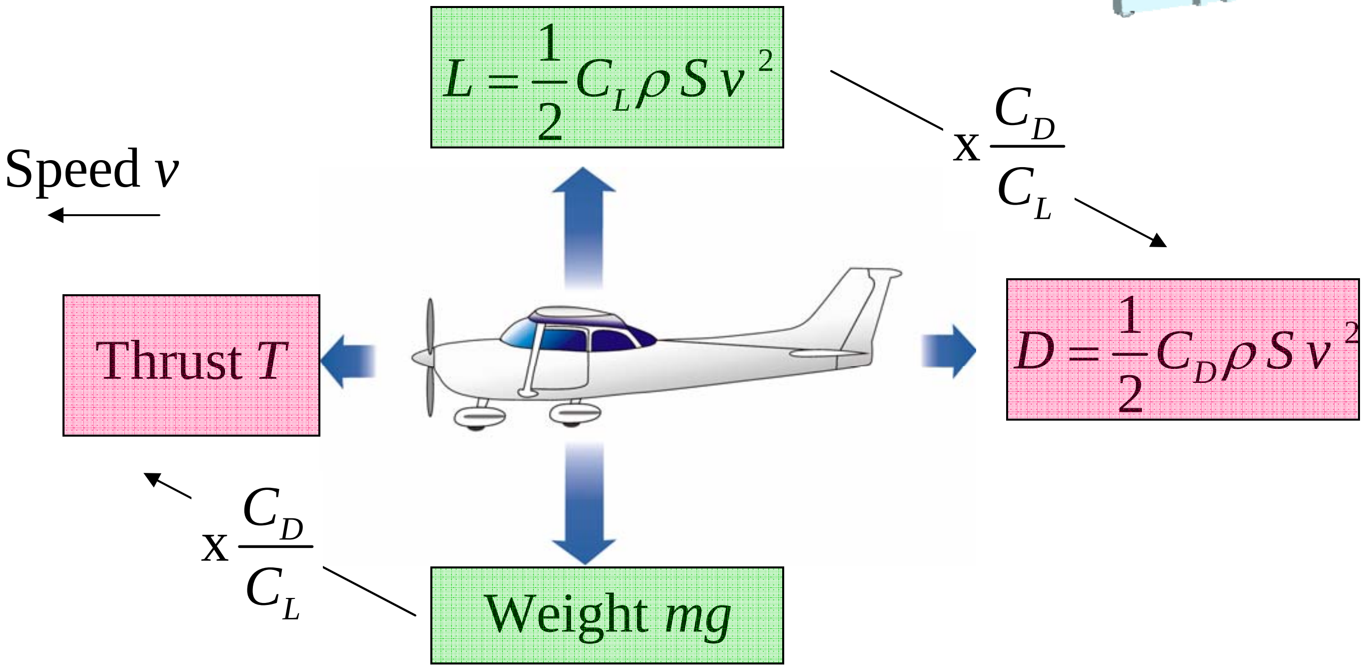
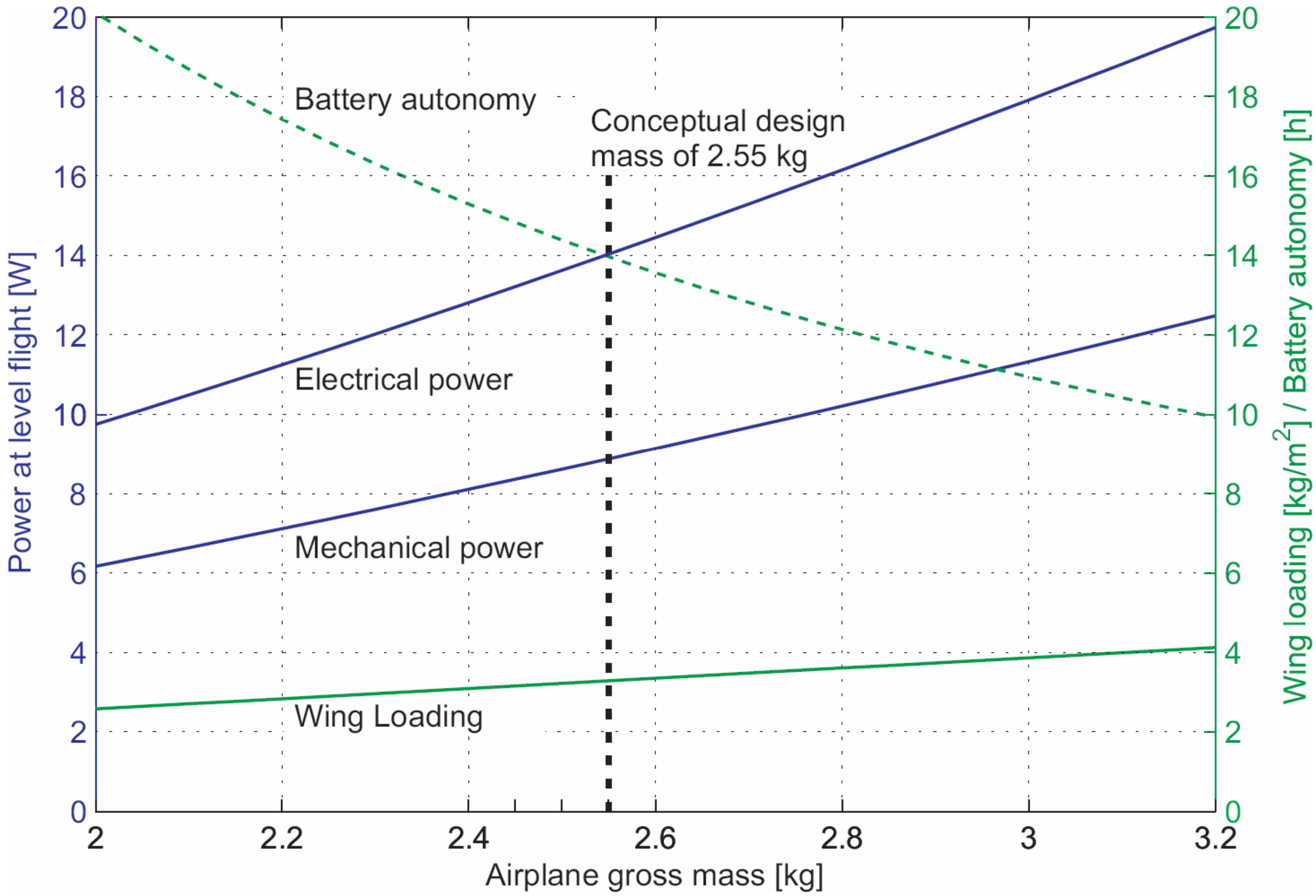
Why are solar airplanes large and slow ?



1. Equilibrium of forces
2. Ratio between L and D is equal to CL/CD
   ➔ the same ratio occurs between thrust and weight
   ➔ independent of *v*, it only requires Sv^2 constant
3. Power for level flight is thus $P_{required} = T \cdot v = (mg \cdot C_D / C_L) \cdot v$
4. A way to reduce the power is to lower the speed *v*
   ➔ in order to keep the lift (Sv^2 constant), S needs to be increased

➔ Solar airplanes generally have large wings and a low speed

Weight – Power - Autonomy



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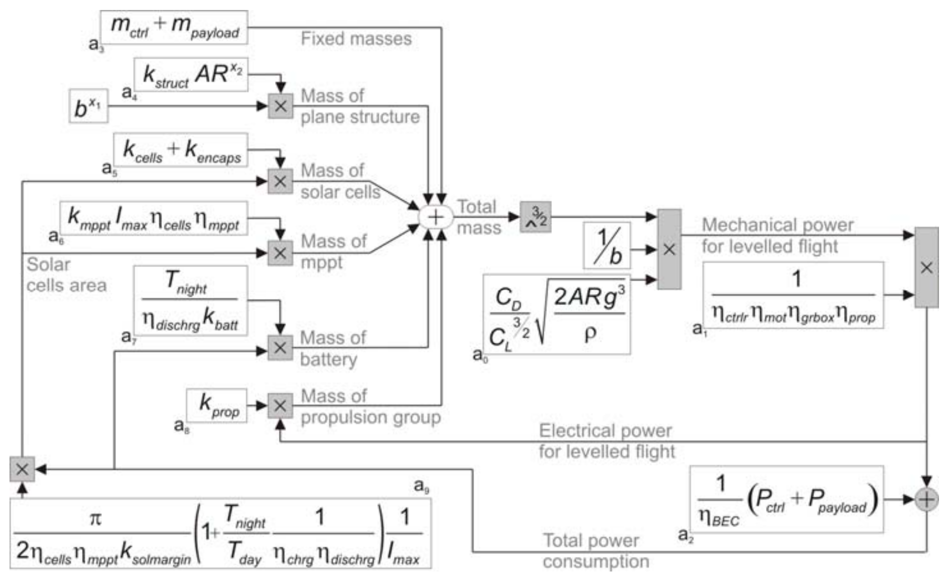
Methodology Resolution



$$m = m_{ctrl} + m_{payload} + m_{struct} + m_{solar} + m_{batt} + m_{mppt} + m_{prop}$$

$$m - \underbrace{a_0 a_1 \left(a_7 + a_8 + a_9 \left(a_5 + a_6\right)\right) \frac{1}{b}}_{a_{10}} m^{\frac{3}{2}} = \underbrace{a_2 \left(a_7 + a_9 \left(a_5 + a_6\right)\right) + a_3}_{a_{11}} + a_4 b^{x_1}$$

The equation of the total mass is

$$m - \underbrace{a_{10} \frac{1}{b}}_{a_{12}} m^{\frac{3}{2}} = \underbrace{a_{11} + a_4 b^{x_1}}_{a_{13}}$$

It can be shown that it has a solution if:

$$a_{12}^2 \, a_{13} \leq \frac{4}{27}$$

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30 Parameters

Table 1 Parameters that are constant or assumed constant

Parameter	Value	Unit	Description
C_L	0.8	-	Airfoil lift coefficient
C_{Da}	0.013	-	Airfoil drag coefficient
e	0.9	-	Oswald's efficiency factor
I_{max}	950	[W/m^2]	Maximum irradiance
k_{batt}	190·3600	[J/kg]	Energy density of battery
k_{cells}	0.32	[kg/m^2]	Mass density of solar cells
k_{encaps}	0.22	[kg/m^2]	Mass density of encapsulation
k_{mppt}	0.00047	[kg/W]	Mass to power ratio of mppt
k_{prop}	0.013	[kg/W]	Mass to power ratio of propulsion unit
k_{struct}	0.44/9.81	[kg/m^3]	Structural mass constant
m_{elec}	0.25	[kg]	Mass of navigation & control system
η_{bec}	0.7	-	Efficiency of step-down converter
η_{cells}	0.169	-	Efficiency of solar cells
η_{chrg}	0.98	-	Efficiency of battery charge
η_{ctrlr}	0.95	-	Efficiency of motor controller
$\eta_{dischrg}$	0.98	-	Efficiency of battery discharge
η_{grbox}	0.95	-	Efficiency of gearbox
η_{mot}	0.85	-	Efficiency of motor
η_{mppt}	0.97	-	Efficiency of mppt
η_{prop}	0.85	-	Efficiency of propeller
P_{ctrl}	1	[W]	Power of navigation & control system
x_1	3.1	-	Structural mass area exponent
x_2	-0.25	-	Structural mass aspect ratio exponent

Table 2 Parameters determined by the mission

Parameter	Value	Unit	Description
$k_{solmargin}$	0.7	-	Irradiance margin factor
$m_{payload}$	0.25	[kg]	Payload mass
$P_{payload}$	0.5	[W]	Payload power consumption
ρ	1.1655	[kg/m^3]	Air density (500 m)
T_{day}	14·3600	[s]	Day duration

Table 3 Variables linked to the airplane shape

Parameter	Value	Unit	Description
AR	12.9	-	Aspect ratio
b	3.2	[m]	Wingspan
m	2.6	[kg]	Total mass

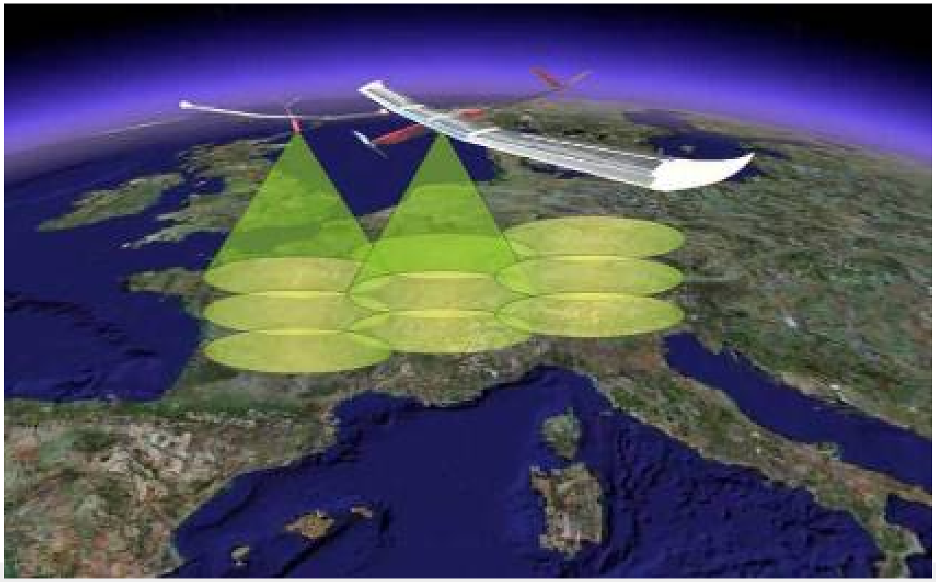
Sky-Sailor weight distributions

Part	Dimensions [mm]	Mass [g]
Motor Controller	52 x 25 x 10	20
Brushless motor (Strecker)	⌀30 x 25	55.3
Gearbox	⌀33 x 29	29.7
Solariane Propeller & mounting piece	600	34.05
Lipo-Akku	283 x 60 x 33	1056.00
MPPT + Shielding	42 x 42.5 x 9	25.86
Energy board (Incl. BEC & Shield)	65 x 24 x 6	17.70
Autopilot sensor board	127 x 33 x 8	8.37
IMU	48 x 33 x 13.5	15.00
GPS & patch antenna	25 x 22 x 8	10.96
Servoboard	42 x 24 x 8	6.51
RC Receiver	47 x 19 x 10	9.80
RC Receiver Antenna	1000	1.30
Radio Modem & Antenna	75 x 40 x 11	26.48
On/Off Switch	23 x 14 x 13	4.85
Wing part middle (complete)	980 x 250 x 25	302
Wing part left (complete)	1130 x 300 x 25	266
Wing part right (complete)	1130 x 300 x 25	270
3 Wing Screw M4		0.95
Fuselage with tail boom	1720 x 94 x 54	168.85
2 V-Tails	41.5 x 15.5 x 1.2	54
Cables		To be def.
Total take-off mass(21.06.2008)	3240 x 1818 x 295	2444.00

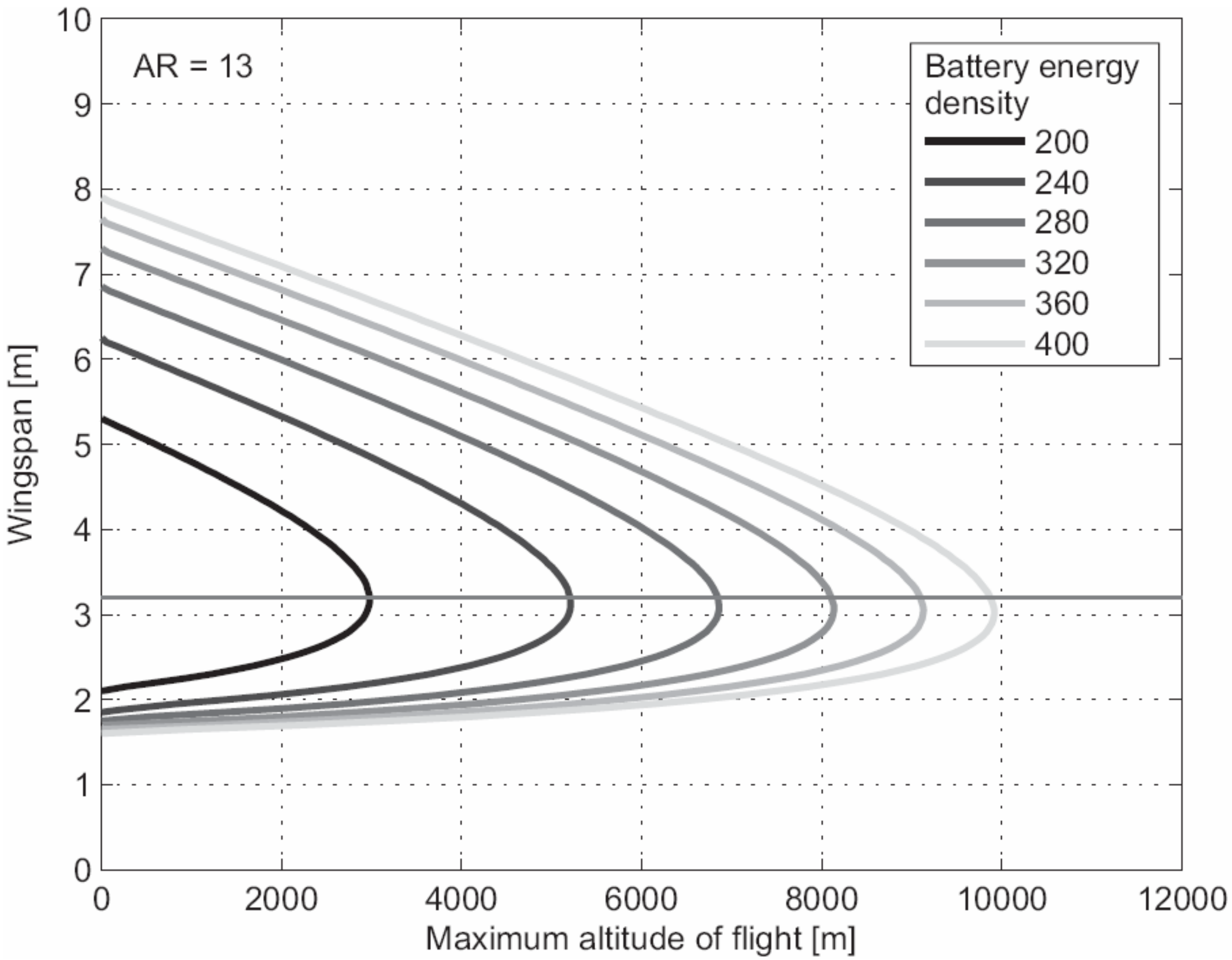
Applications

Potential Applications

- high altitude communication platform
- law enforcement
- border surveillance
- forest fire fighting
- power line inspection
- ...



What is the influence of battery technology on the maximal flying altitude ?



MAV

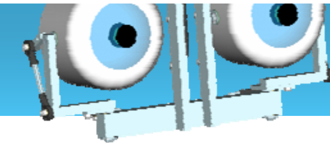
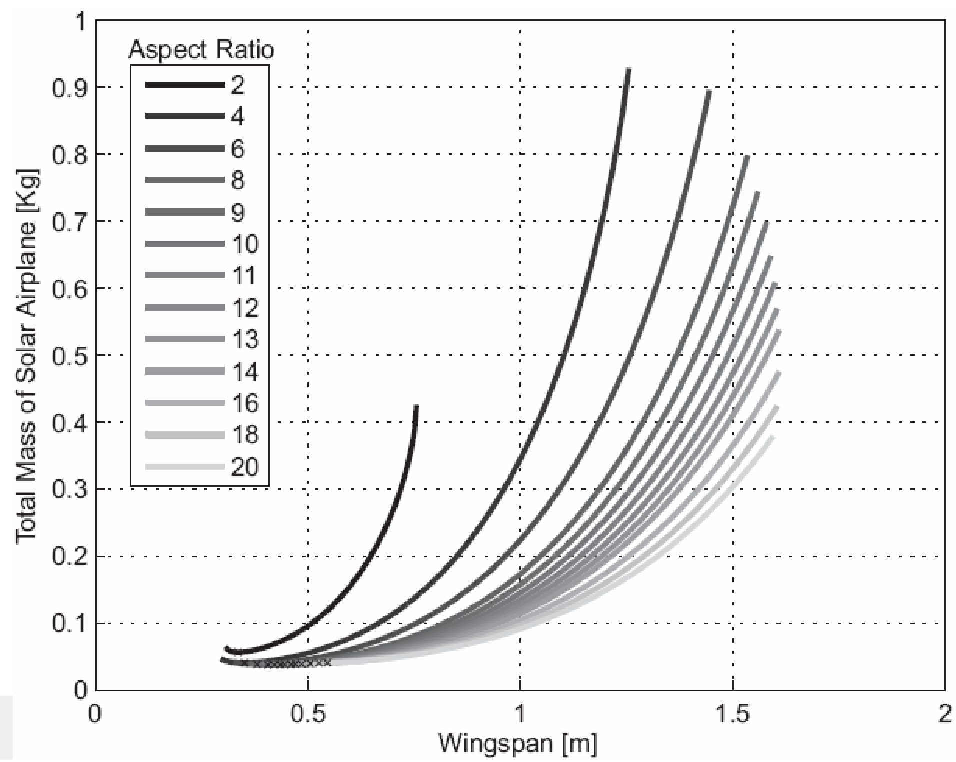


Table 6.1: Parameters changes at the MAV size

Parameter	Value	Unit	Description
C_L	0.5	-	Airfoil lift coefficient
$C_{D\,afl}$	0.05	-	Airfoil drag coefficient
e	0.6	-	Oswald's efficiency factor
k_{af}	5.58/9.81	$[kg/m^3]$	Structural mass constant
m_{av}	0.005	$[kg]$	Mass of autopilot system
η_{grb}	0.81	-	Efficiency of gearbox
η_{mot}	0.62	-	Efficiency of motor
η_{plr}	0.80	-	Efficiency of propeller
P_{av}	0.1	$[W]$	Power of autopilot system
x_1	3.18	-	Airframe mass area exponent
x_2	-0.88	-	Airframe mass aspect ratio exponent
m_{pld}	0.01	$[kg]$	Payload mass
P_{pld}	0.00	$[W]$	Payload power consumption



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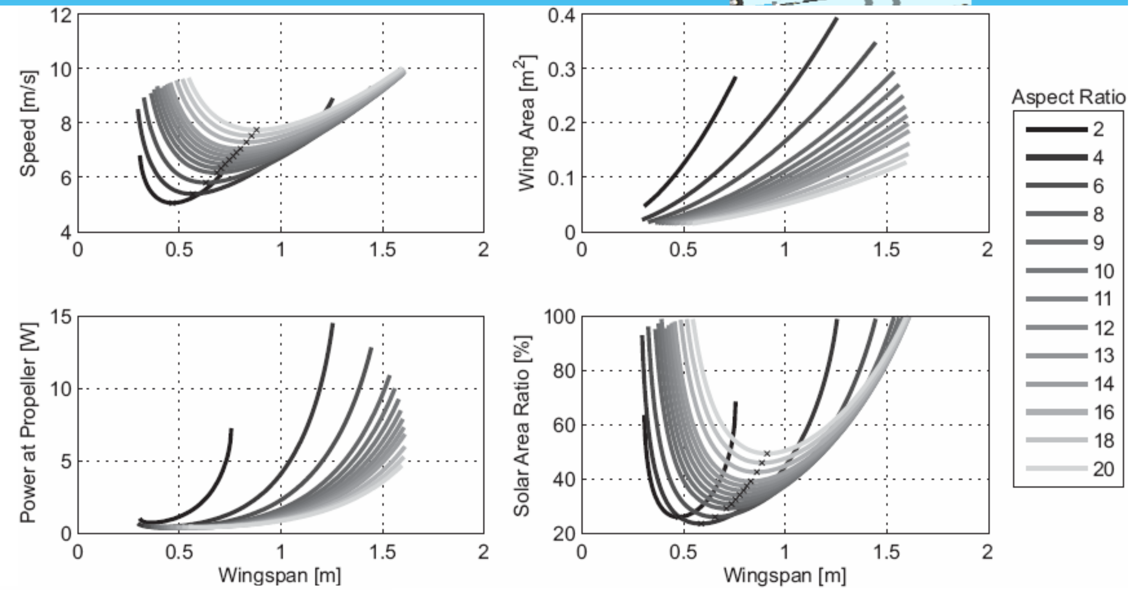
MAV



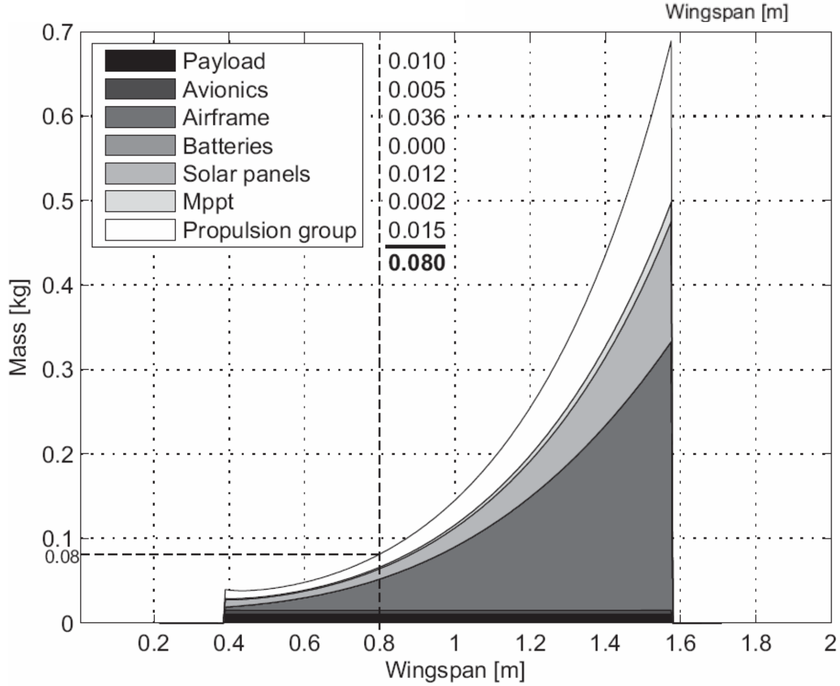


Figure 6.4: Mass distribution for $AR = 10$

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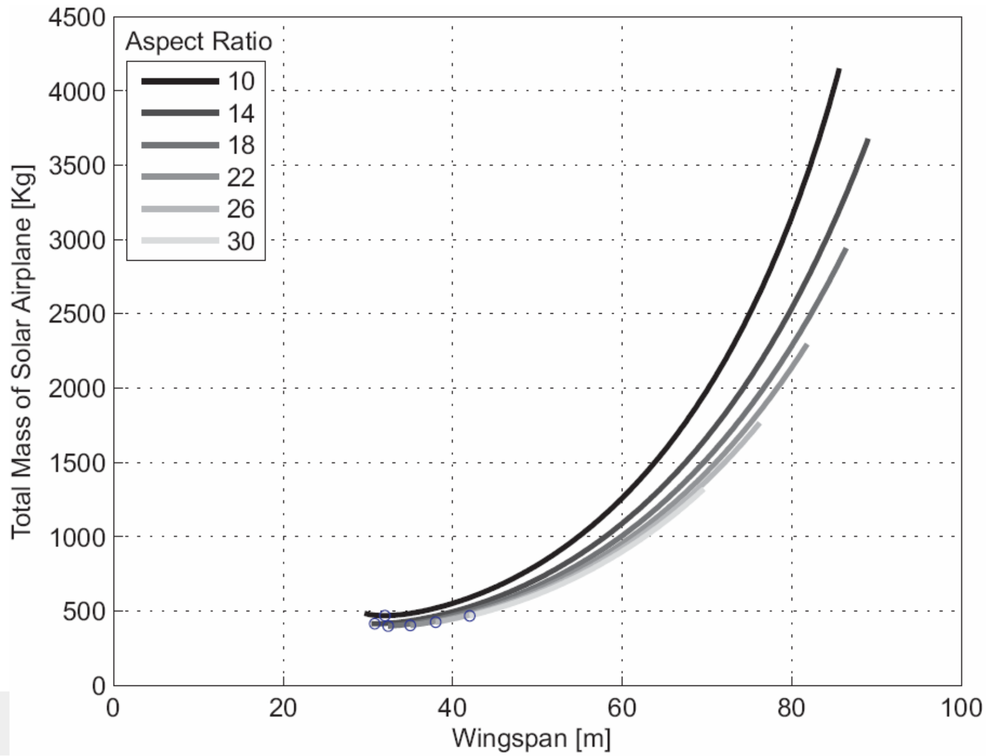
Manned

Table 6.2: Parameters changes at the manned airplane size

Parameter	Value	Unit	Description
C_L	1	-	Airfoil lift coefficient
k_{prop}	0.00121	$[kg/W]$	Mass to power ratio of prop. group
k_{af}	0.44/9.81/15	$[kg/m^3]$	Structural mass constant
m_{av}	20	$[kg]$	Mass of autopilot system
η_{sc}	0.19	-	Efficiency of solar cells
η_{ctrl}	0.98	-	Efficiency of motor controller
η_{mot}	0.88	-	Efficiency of motor
η_{plr}	0.87	-	Efficiency of propeller
P_{av}	100	$[W]$	Power of autopilot system
m_{pld}	120	$[kg]$	Payload mass
P_{pld}	0	$[W]$	Payload power consumption



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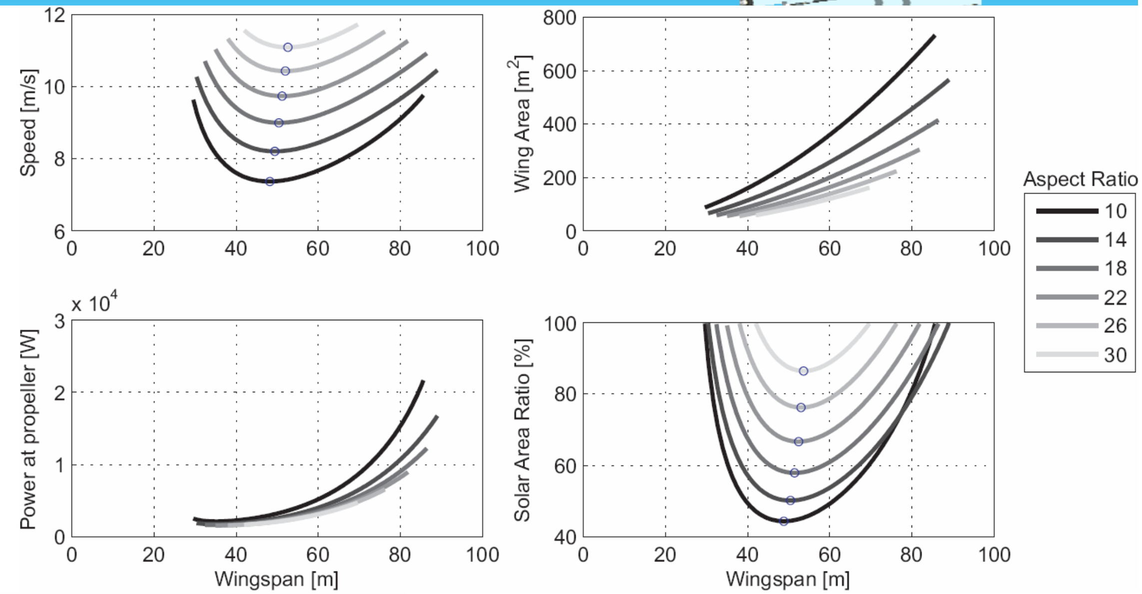
Manned



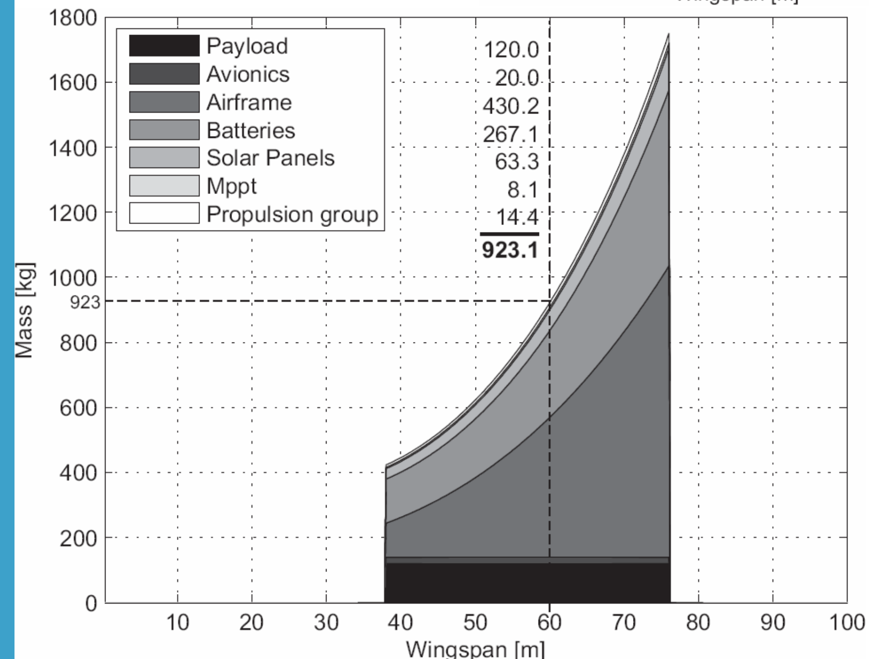


Figure 6.7: Mass distribution for $AR = 10$

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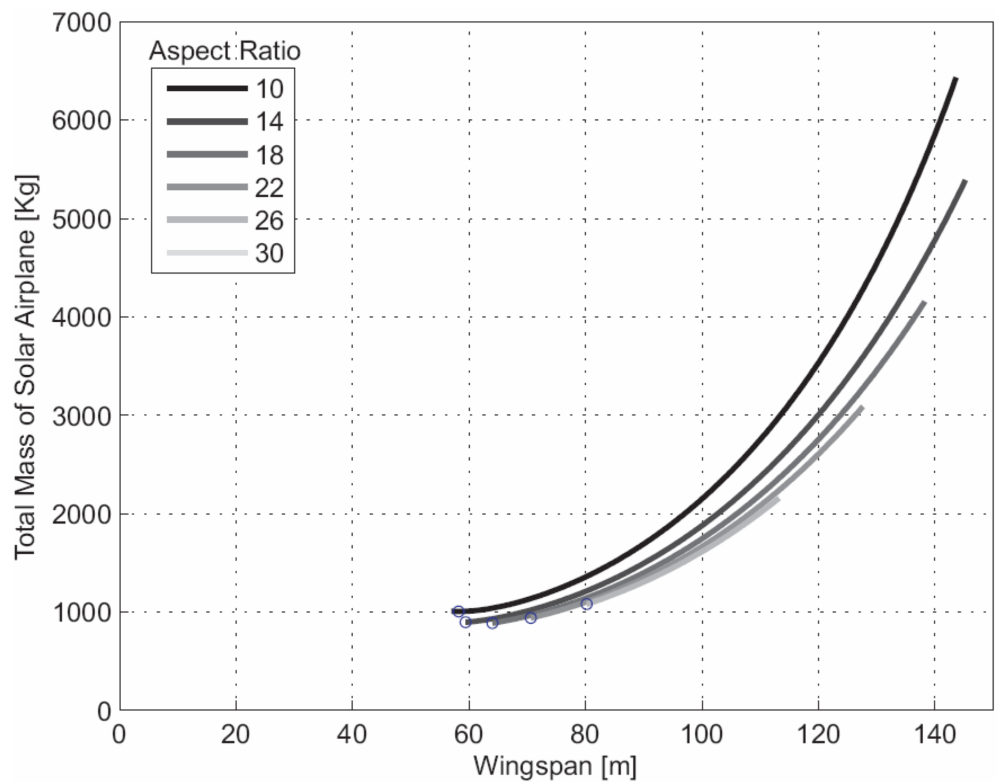
HALE Platform

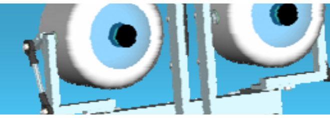
Payload: 300 Kg

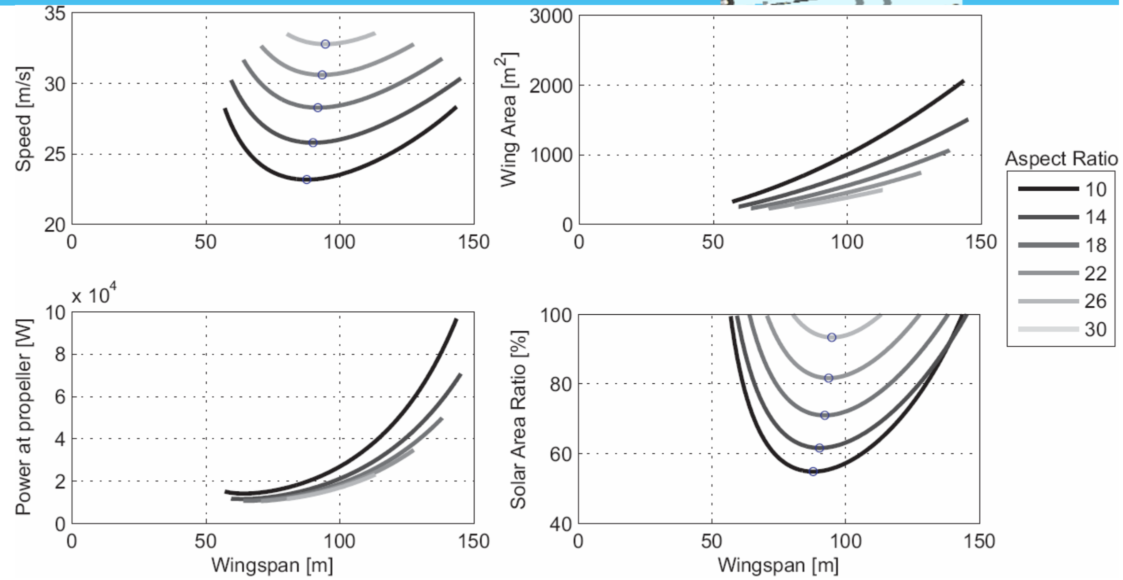
Altitude: 21’000 m

Mission time: 3 months in summer



HALE Platform





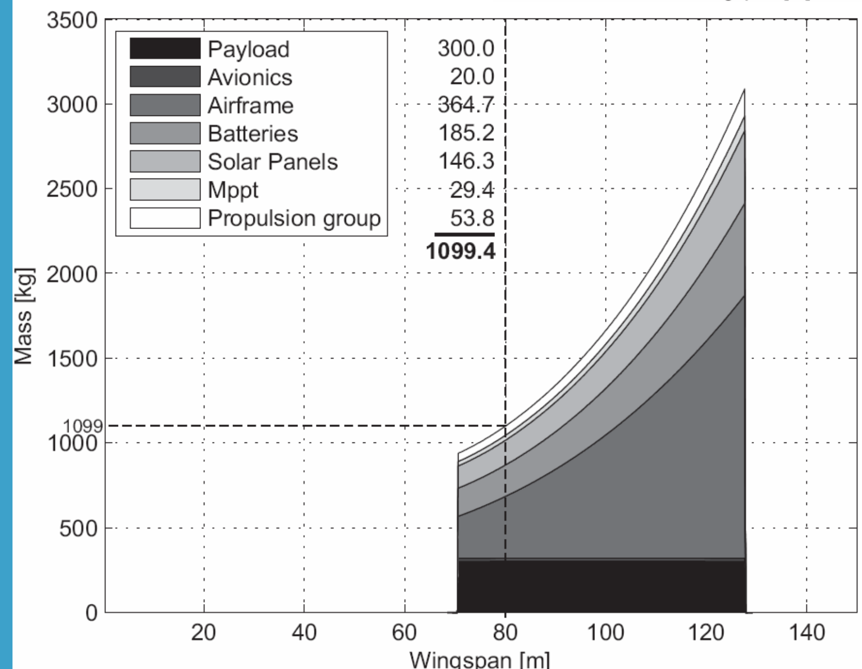


Figure 6.12: Mass distribution for $AR = 22$

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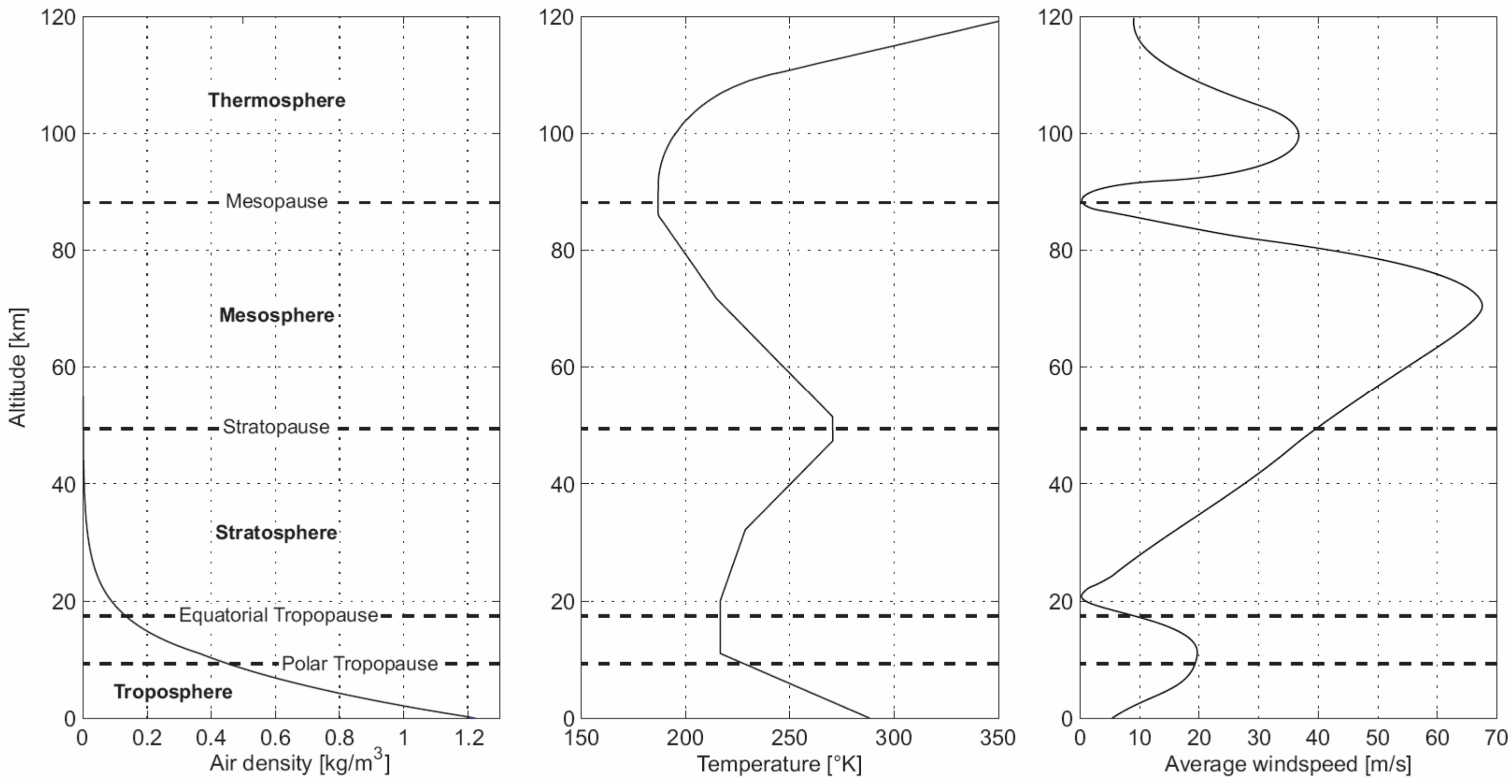
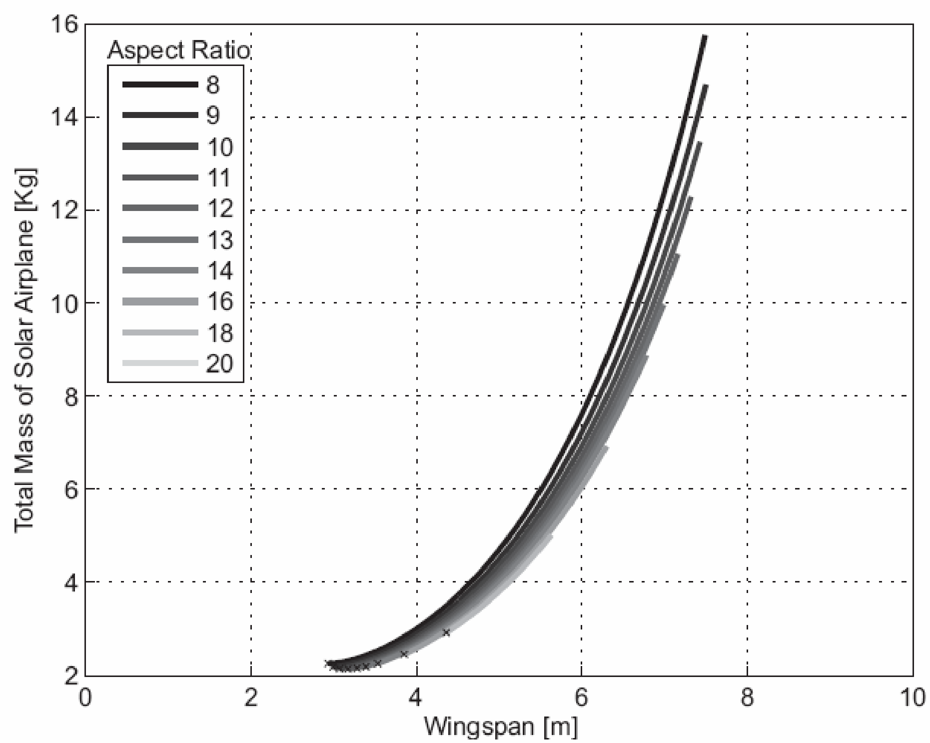
HALE Platform



Mars design

Parameter	Value	Unit	Description
I_{max}	589	$[W/m^2]$	Maximum Irradiance
k_{bat}	1000·3600	$[J/kg]$	Energy density of energy storage
k_{af}	0.44/9.81/2	$[kg/m^3]$	Structural mass constant
m_{av}	0.15	$[kg]$	Mass of autopilot system
m_{pld}	0.5	$[kg]$	Payload mass
η_{wthr}	1	-	Irradiance margin factor
P_{pld}	0.5	$[W]$	Payload power consumption
ρ	0.015	$[kg/m^3]$	Air density (500 m)



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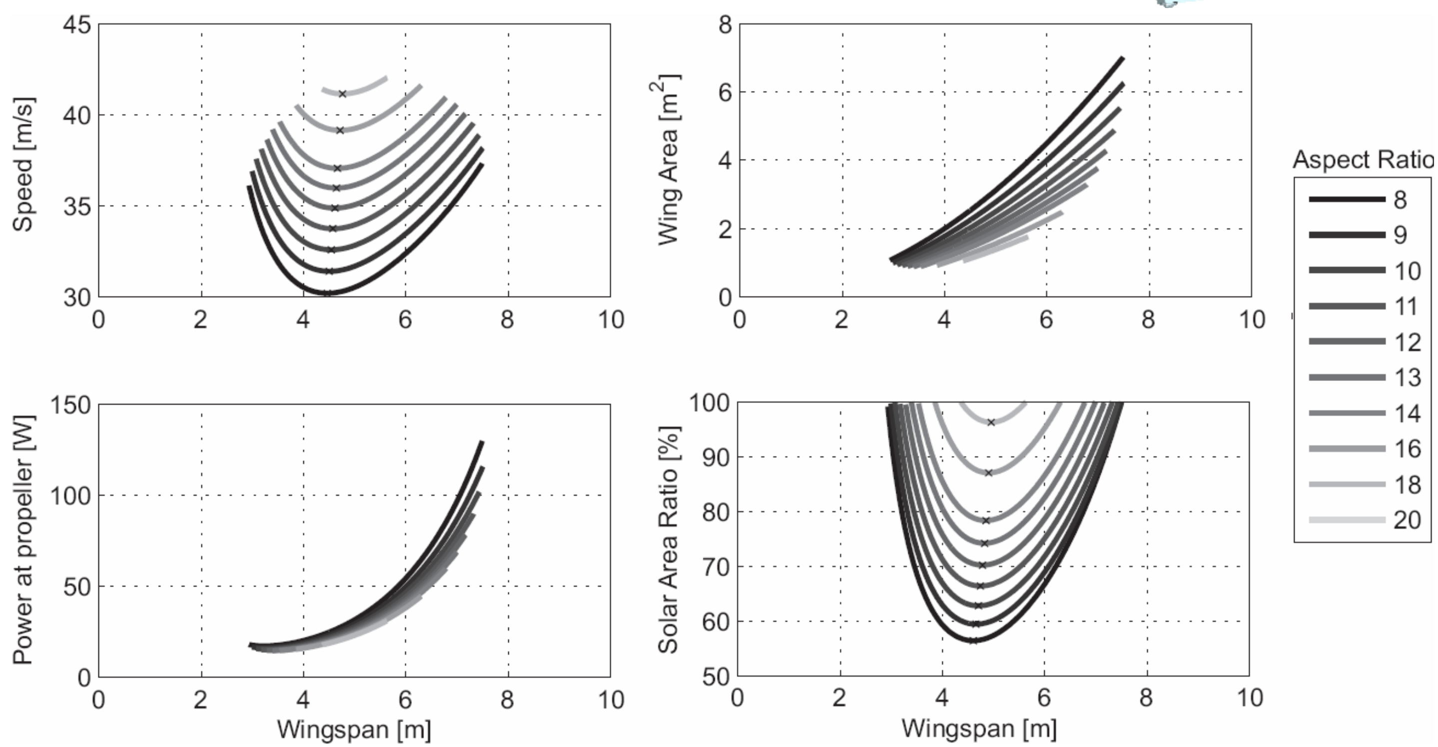
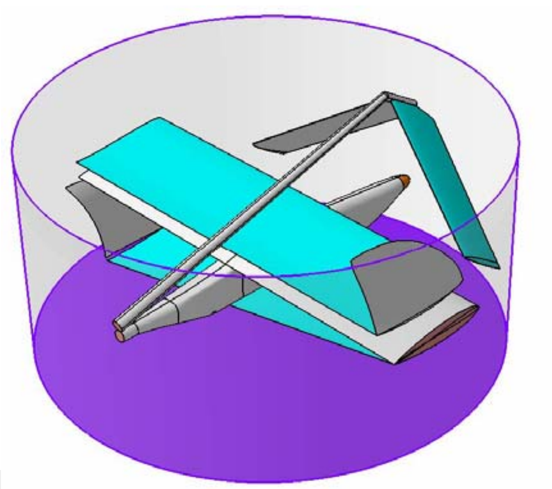
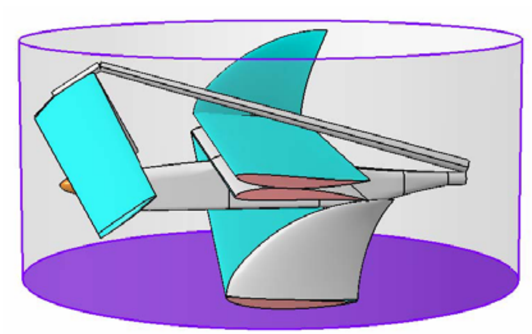
Mars design







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Storing Potential Energy

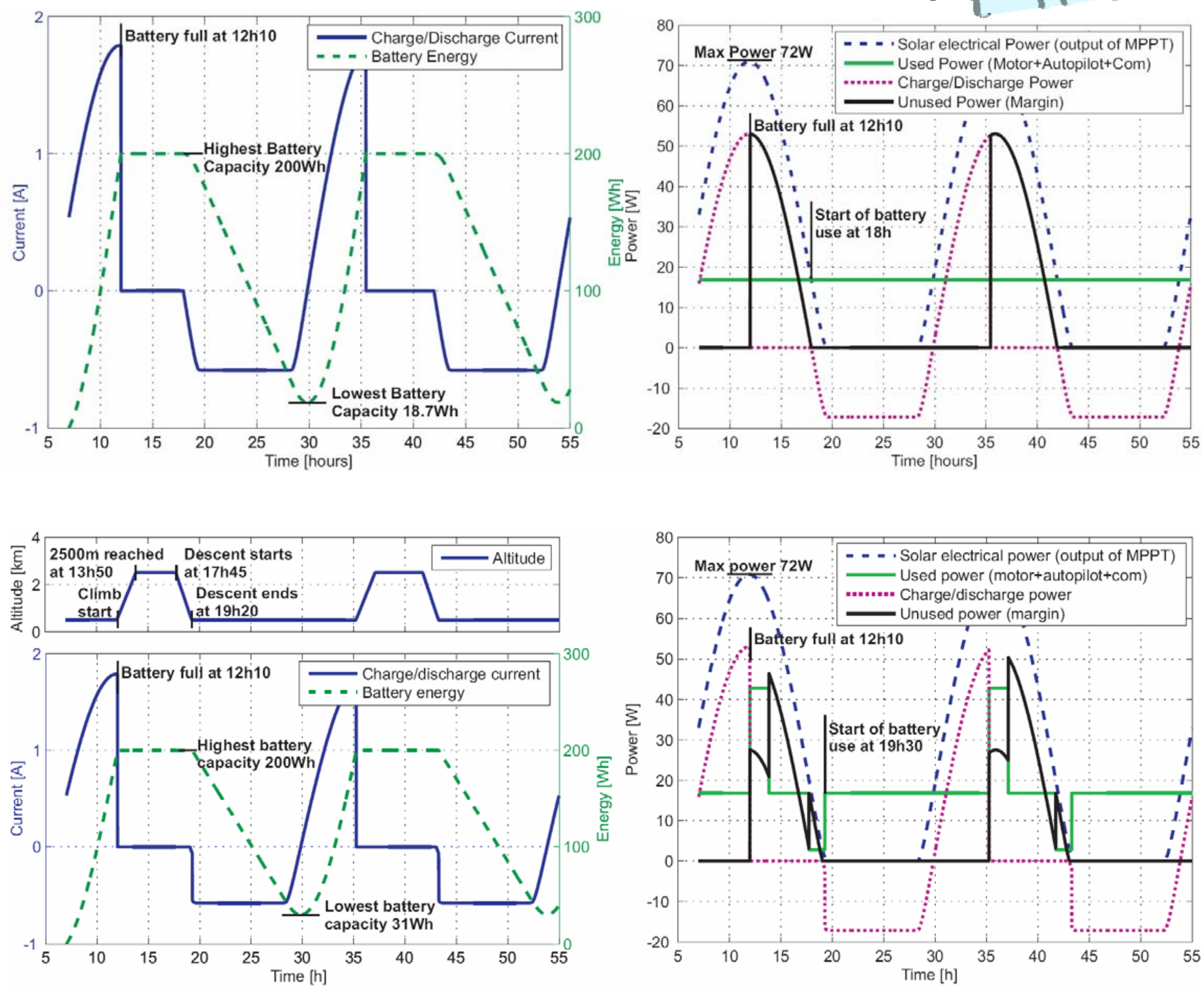

Figure 6.13: Continuous flight simulation on the 21^{st} of June

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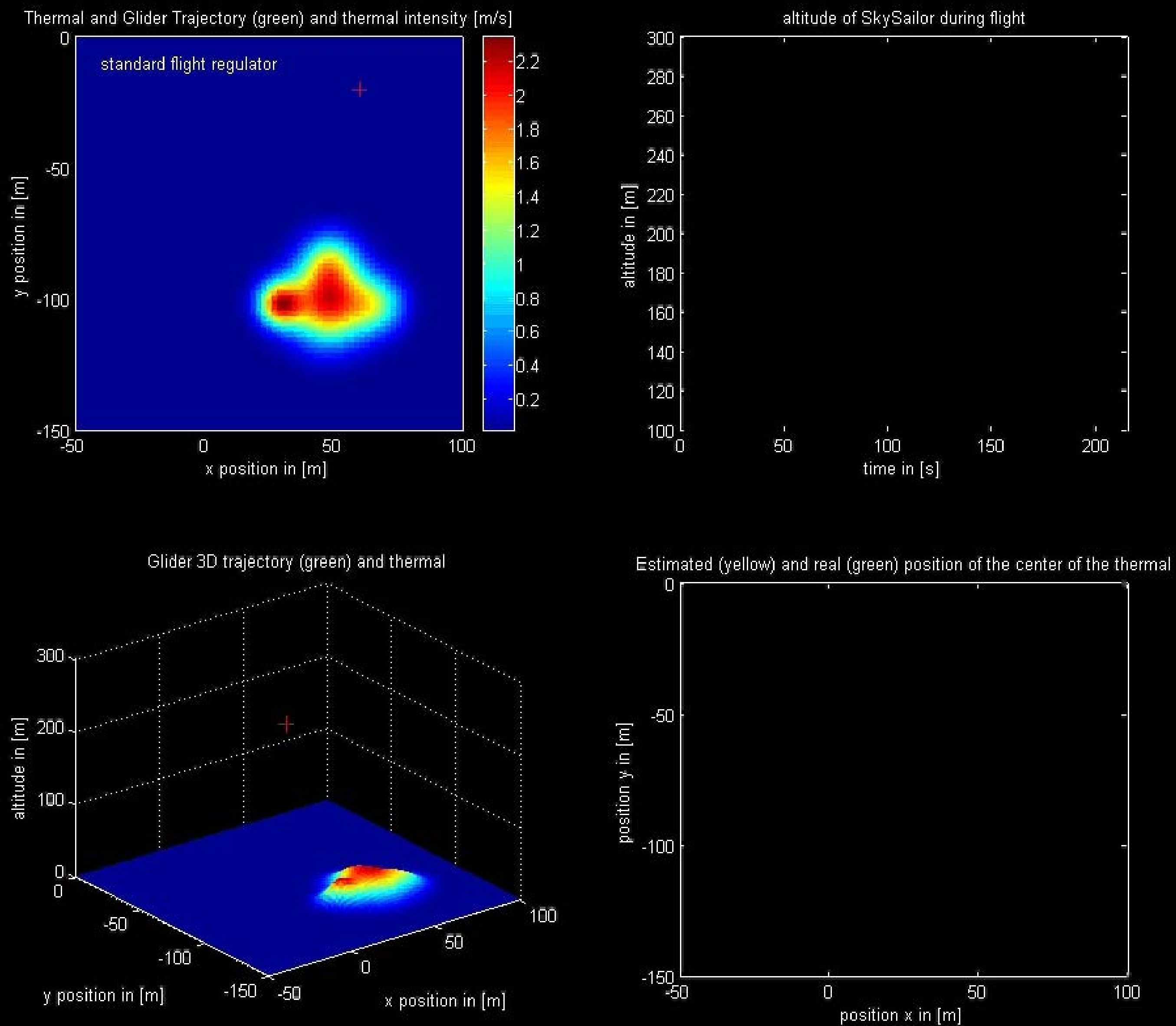
Using Thermals



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Link to videos:
http://www.sky-sailor.ethz.ch/videos.htm

Sun-Surfer

Objective:

- ➔ **reduce the scale and cost**
- ➔ **develop low-cost solar MAVs with payload capacity of ~40 gr**

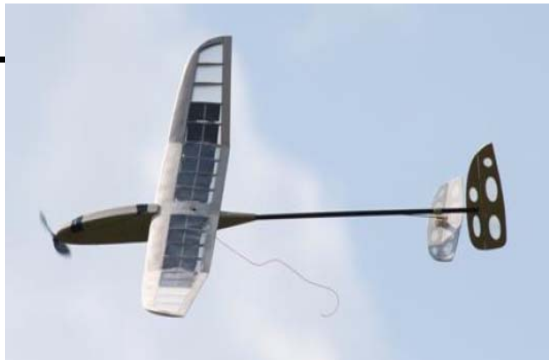
Sun-Surfer I

Wingspan: 0.77 meters

Weight: 115 g

P level flight: 1 W

P solar : 3 W



Sun-Surfer II

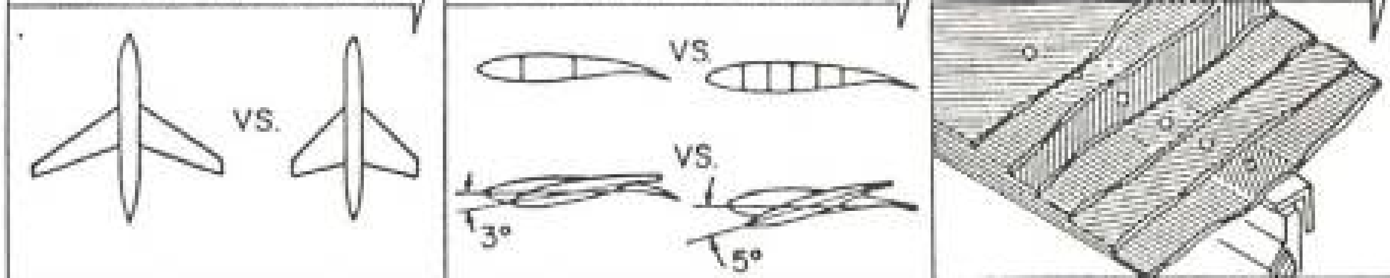
Wingspan: 0.78 meters

Weight: 190 g

P level flight: 2.4 W

P solar : 8 W

Design Phases



	PHASE I CONCEPTUAL DESIGN	PHASE II PRELIMINARY DESIGN	PHASE III DETAIL DESIGN
KNOWN	• BASIC MISSION REQMTS. • RANGE • ALTITUDE • SPEED • BASIC MATERIAL PROPERTIES σ/ρ E/ρ \$/LB	• AEROELASTIC REQMTS. • FATIGUE REQUIREMENTS • FLUTTER REQUIREMENTS • OVERALL STRENGTH REQMTS.	• LOCAL STRENGTH REQUIREMENTS • PRODUCIBILITY • FUNCTIONAL REQMTS
RESULTS	GEOMETRY • AIRFOIL TYPE • AR • t/c • λ • Λ DESIGN OBJECTIVES • DRAG LEVEL • WEIGHT GOALS • COST GOALS	• BASIC INTERNAL ARRGMT. • COMPLETE EXTERNAL CONFIG. • CAMBER, TWIST DISTRIBUTIONS • LOCAL FLOW PROBLEMS SOLVED • MAJOR LOADS, STRESSES, DEFLECTIONS	• DETAIL DESIGN • MECHANISMS • JOINTS, FITTING, & ATTACHMENTS • DESIGN REFINEMENTS AS RESULTS OF TEST & OPER

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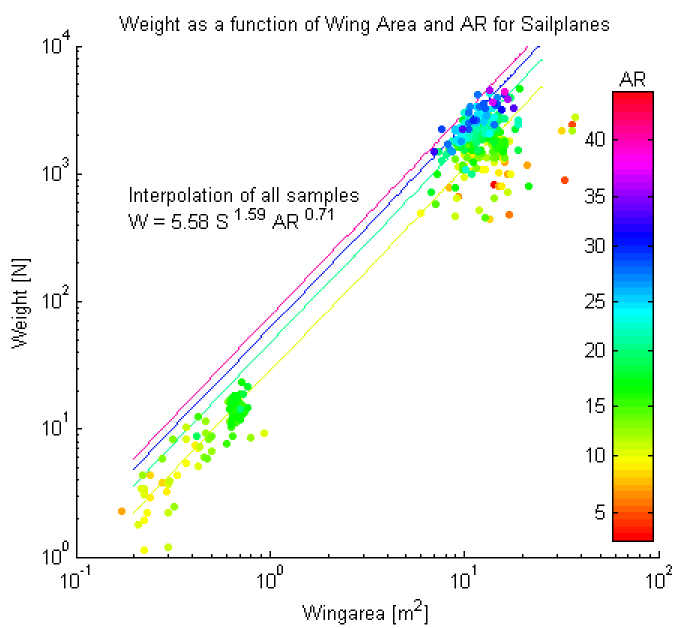
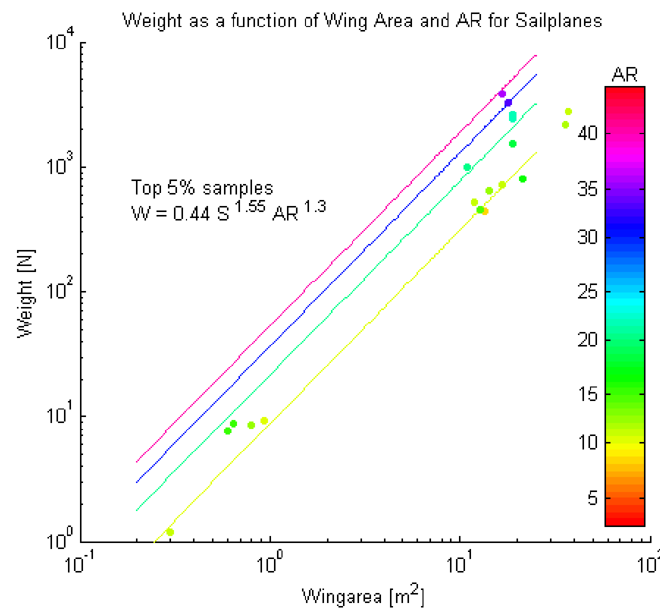
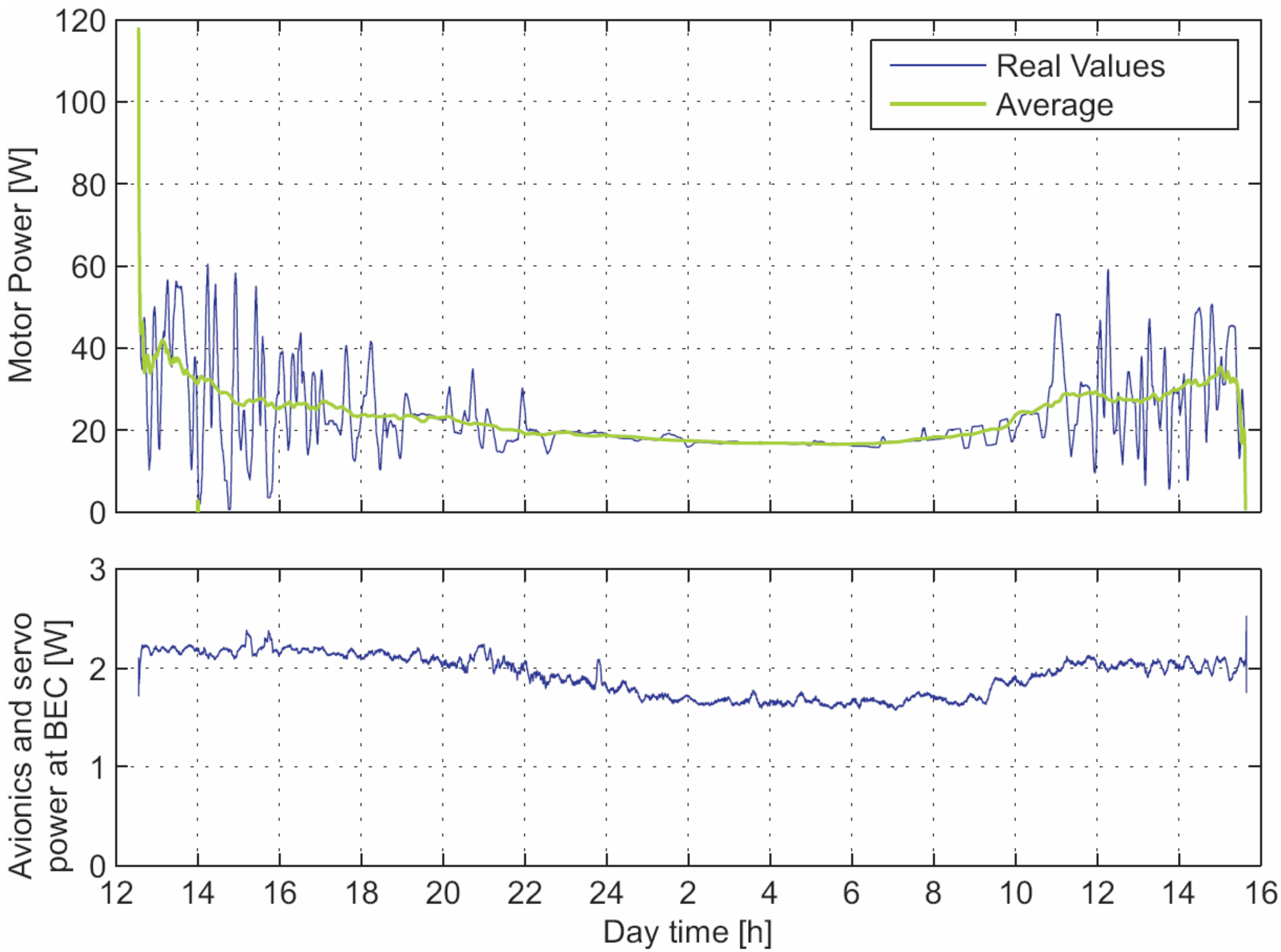
Airframe model

Samples	$W_{af} = f(S, AR)$	$W_{af} = f(b, AR)$	$W_{af}/S = f(W_{af}, AR)$
415	$5.58\ S^{1.59}\ AR^{0.71}$	$5.58\ b^{3.18}\ AR^{-0.88}$	$2.94\ W_{af}^{0.37}\ AR^{0.45}$
260	$2.31\ S^{1.58}\ AR^{0.94}$	$2.31\ b^{3.16}\ AR^{-0.64}$	$1.70\ W_{af}^{0.37}\ AR^{0.59}$
143	$1.15\ S^{1.57}\ AR^{1.13}$	$1.15\ b^{3.14}\ AR^{-0.44}$	$1.09\ W_{af}^{0.36}\ AR^{0.72}$
73	$0.78\ S^{1.55}\ AR^{1.21}$	$0.78\ b^{3.10}\ AR^{-0.34}$	$0.85\ W_{af}^{0.35}\ AR^{0.78}$
40	$0.56\ S^{1.55}\ AR^{1.27}$	$0.56\ b^{3.10}\ AR^{-0.28}$	$0.69\ W_{af}^{0.35}\ AR^{0.82}$
19	$0.44\ S^{1.55}\ AR^{1.30}$	$0.44\ b^{3.10}\ AR^{-0.25}$	$0.59\ W_{af}^{0.35}\ AR^{0.84}$





27 hours flight



27 hours flight