Design of Solar Powered Airplanes for Continuous Flight

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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
History of Solar Flight

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

Introduction
- Motivations
- History of Solar Flight
- State of the Art
- Contributions

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

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PhD Defense
Autonomous Systems Lab
ETH Zürich, 24.09.08

- Sunrise (1974)
  1st solar powered flight
- Gossamer Penguin (1980)
  1st manned solar powered flight
- Sunseeker (1990)
  manned, crossed the USA in 21 flight
- Solar Riser (1979)
  manned, battery solar charged for short flights
- Solar Challenger (1981)
  manned, channel crossing
- Helios (1999)
  unmanned, flew at > 29'000 m
- Solong (2005)
  1st continuous flight, used thermals
- Zephyr (2005)
  unmanned, flew 83h
Many solar airplanes in History

- ... but no clear design methodologies explained
- anyway useful practical papers on case studies
  
  [BOUCHER79, MACCREADY83, COLELLA94]

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 unrealistic designs
  
  [RIZZO08, ROMEO04]
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

Introduction

Design Methodology
- Required Energy
- Solar Energy
- Weight Models
- Resolution

Sky-Sailor Design

Sky-Sailor Prototype

Scaling

Conclusion
Energy balance

![Energy balance diagram](image)

Weight balance

![Weight balance diagram](image)
Methodology

- Sizing the airplane: hen & egg problem

- This loop can be solved:
  - **Iteratively** (trying existing components, refining the design)
  - **Analytically** (using mathematic models of the components)

  ➔ Allows to establish some general design principles
Required Energy

- Equilibrium at steady level flight

\[ L = mg = C_L \frac{\rho}{2} S v^2 \]
\[ D = T = C_D \frac{\rho}{2} S v^2 \]

\[ P_{\text{level}} = D v = \frac{C_D}{C_L^{3/2}} \left( \frac{mg}{S} \right)^{3/2} \sqrt{\frac{2}{\rho}} \]

- Power required

\[ P_{\text{elec tot}} = \frac{1}{\eta_{\text{ctrl}} \eta_{\text{mot}} \eta_{\text{grb}} \eta_{\text{plc}}} \left( P_{\text{level}} \right) \]
\[ + \frac{1}{\eta_{\text{bec}}} (P_{\text{av}} + P_{\text{pld}}) \]

- Daily energy required

\[ E_{\text{elec tot}} = P_{\text{elec tot}} \left( T_{\text{day}} + \frac{T_{\text{night}}}{\eta_{\text{chrg}} \eta_{\text{dechrg}}} \right) \]
Required Energy

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Solar Energy

- Daily average solar irradiance
  - Irradiance ~ cosine
    \[ E_{\text{day density}} = \frac{I_{\text{max}} T_{\text{day}}}{\pi/2} \eta_{\text{wthr}} \]
    - \( I_{\text{max}} \ T_{\text{day}} = f(\text{date, location, weather}) \)

- Daily energy obtained
  \[ E_{\text{electo}} = E_{\text{day density}} A_{\text{sc}} \eta_{\text{sc}} \eta_{\text{cbr}} \eta_{\text{mppt}} \]

- Daily energy required = Daily energy obtained
  => We compute \( A_{\text{sc}} \)
Required Energy

Introduction

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Sky-Sailor Design

Sky-Sailor Prototype

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Weight Prediction Models

- **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 [RIZZ004] 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
    \[ \Rightarrow \] 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:
    \[ W_{af} = 0.44 b^{3.10} \cdot AR^{-0.25} \]
Weight Prediction Models

Biologists already studied flying in nature to extract tendencies

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

Our model is // to Tennekes curve

[STENDER69,RIZZO04] seem incoherent

Keywords: Wing weight to area, wing area as a function of structural weight, great flight diagram, Tennekes, wing mass to area, mass to surface, area to mass, surface to mass.
Required Energy

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Weight Prediction Models

- **Solar Cells**
  - Surface = \( f(\text{cells properties, required energy}) \)
  - 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 \( P_{\text{max}} \)
    \[
    m_{\text{mppt}} = k_{\text{mppt}} P_{\text{sol max}} = k_{\text{mppt}} I_{\text{max}} \eta_{sc} \eta_{\text{cbr}} \eta_{\text{mppt}} A_{sc}
    \]

- **Batterie**
  - Weight proportionnal to capacity
    \[
    m_{\text{bat}} = \frac{T_{\text{night}}}{\eta_{\text{dchrg}} k_{\text{bat}}} P_{\text{elec tot}}
    \]
Required Energy

**Introduction**

**Design Methodology**
- Required Energy
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- Resolution

**Sky-Sailor Design**

**Sky-Sailor Prototype**

**Scaling**

**Conclusion**
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

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.
Introduction

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Sky-Sailor Design

Sky-Sailor Prototype

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Mission parameters
Airplane’s shape variables
Others: Technological parameters

⇒ Search $b$ and $AR$ for which the loop has a solution
Methodology application

- Mission parameters
  - Solar flight possible 3 months in summer ($T_{\text{day}}=13.2\text{h}$)
  - 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)
Real-Time Simulation

Objectives

– Validate the design
– Analyze energy flows on the airplane each second
– Rapidly see influence of parameters change
Real-Time Simulation

Simulation of a 48 h flight

– On the 21\textsuperscript{st} of June
– On the 4\textsuperscript{th} of August (+1.5 month)
**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
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
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%
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
Goals

- Tune controller parameters
- Test Navigation algorithms
- Evaluate airplane capabilities

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

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

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

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

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

\[ M_i = C_{mi} \frac{\rho}{2} S_i v^2 \cdot \text{chord}_i \]

\[
\begin{bmatrix}
C_{11} & C_{13} & C_{1m} \\
C_{21} & C_{23} & C_{2m} \\
C_{31} & C_{33} & C_{3m} \\
C_{41} & C_{43} & C_{4m} \\
C_{51} & C_{53} & C_{5m} \\
C_{61} & C_{63} & C_{6m} \\
C_{71} & C_{73} & C_{7m}
\end{bmatrix}
= f(AoA_i, U_2) \]

\[ \begin{bmatrix}
C_{i1} & C_{i3} & C_{im} \\
\end{bmatrix}
= f(AoA_i) \quad \text{for } i=2,3,4 \]

\[ \begin{bmatrix}
C_{i5} & C_{i3} & C_{im} \\
\end{bmatrix}
= f(AoA_i, U_3) \]

\[ \begin{bmatrix}
C_{i6} & C_{i3} & C_{im} \\
\end{bmatrix}
= f(AoA_i, U_4) \]

\[ \begin{bmatrix}
C_{i7} & C_{i3} & C_{im} \\
\end{bmatrix}
= f(AoA_i, U_5) \]
Experiments

- **Several tests with subgroups**
  - Efficiencies increase
  - Weight reduction
  - Adding functionalities
  - 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](http://www.sky-sailor.ethz.ch/videos.htm)
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
- $E_{\text{used}}$: 675 Wh
- $E_{\text{obtained}}$: 768 Wh

⇒ Continuous flight proved to be feasible without thermic or altitude gain
Scaling & Other considerations

Introduction
Design Methodology
Sky-Sailor Design
Sky-Sailor Prototype
Scaling
- Down: MAV
- Up: Manned & Hale
- Epot & Thermal

Conclusion
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 $E_{\text{density}}$ 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 ➔ $(V_{\text{diode loss}} / V_{\text{MPPT}})$

➔ No 24h solar flight at MAV size, but day flight possible
Up Scaling

Drawback

- Structure weight $\sim b^3$
- Theory said it should be $\sim b^2$
  ➔ 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
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
Conclusion

• **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
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
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 $E_{\text{solar}}$ on the ground $\rightarrow$ 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 Energy

Solar Spectrum

Direct, diffused and reflected light

Angle of incidence variation
Variation of $T_{\text{day}}$ and $I_{\text{max}}$ along year
Solar Cell
MPPT

![Graph showing MPPT performance over day time]

- Battery voltage [V]
- Power [W]

- MPPT 1
- MPPT 2
- MPPT 3

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Solar cells integration

Structure
Energy Storage
Energy storage solutions
### Energy Storage

#### Energy density of some reactants \([\text{kWh/kg}]\)

(LHV Lower heating value)

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Energy Density [kWh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>33.3</td>
</tr>
<tr>
<td>Methane</td>
<td>13.9</td>
</tr>
<tr>
<td>Propane</td>
<td>12.9</td>
</tr>
<tr>
<td>Gasoline</td>
<td>12.2</td>
</tr>
<tr>
<td>Diesel</td>
<td>11.7</td>
</tr>
<tr>
<td>Oil (Colza,…)</td>
<td>10.4</td>
</tr>
<tr>
<td>Ethanol</td>
<td>7.5</td>
</tr>
<tr>
<td>Methanol</td>
<td>5.6</td>
</tr>
<tr>
<td>Sugar</td>
<td>4.4</td>
</tr>
<tr>
<td>Best 2008 Li-Ion Battery</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Important to keep in mind**: Availability / Efficiency of converters
Lithium-Ion battery evolution

Energy density + 6.6%/year
Price - 17%/year
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
  - Gewicht 156 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

5V DC/DC

Li-Po Accu
6x8 cells 7200mAh, 28.8 V

~30V 2.88A max

MPPT 1
MPPT 2
MPPT 3

~20V 1.44A max

3 x
2 x 36 Si Solar Cells

5V

RC Receiver Sexta

Altimeter MS5534

Airspeed sensor DSDX

GPS NB1041

I2C

RS232

I2C ↔ RS232

Motor Board

Servo Board

Motor

Servos

Radio Modem (or GPRS)
XStream OEM module

X-board

IMU Xsens MTX

USB

Camera OV7649FB
Telemetry

Autopilot V2
Electric Schematic & Registers v 7.0

Power
- Ground
- Battery V+ [34-33.7V]
- Bec V+ [5.5V]
- Digital Electronics
- Ground
- 5V regulated
- 3.3V regulated
- I²C clock line (SCL)
- I²C data line (SDA)
- Other data line (PPM, RS232)

Autopilot Board
Multi Purpose Pic module
Radio-Modem 900 Mhz

Module address (0x30 in PPM/Wak)
0x60
- 0x22 r Pressure lsb [Internal Unit]
- 0x23 r Pressure msb [IntU]
- 0x24 r Raw pressure lsb [IntU]
- 0x25 r Raw pressure msb [IntU]
- 0x26 r Pressure offset lsb [IntU]
- 0x27 r Pressure offset msb [IntU]
- 0x28 r Speed lsb [1/100 m/s]
- 0x29 r Speed msb [1/100 m/s]
- 0x2A r/w Melody
  - 1 - waiting gap
  - 2 - gps fix
  - 3 - Do-Nothing
  - 4 - Music
  - 11:19 Warning (r:1-9)
- 0x2B r/w Reset Pressure 1 - reset 0 - else
- 0x2C r/w Sensor Type
  - 10 - DSDX (0x0A)
  - 11 - CSBX (0x0B)

Module address (24Hz in PPM/Wak)
0x80
- 0x22 r Voltage bat lsb [1/1000 V]
- 0x23 r Voltage bat msb [1/1000 V]
- 0x24 r Voltage bec lsb [1/1000 V]
- 0x25 r Voltage bec msb [1/1000 V]
- 0x26 r Current motor lsb [1/1000 A]
- 0x27 r Current motor msb [1/1000 A]
- 0x28 r Current servo lsb [1/1000 A]
- 0x29 r Current servo msb [1/1000 A]

Radio-Modem 900 Mhz

Module address (0x30 in PPM/Wak)
0x40
- 0x22 r Pressure lsb [1/10 mbar]
- 0x23 r Pressure msb [1/10 mbar]
- 0x24 r Temperature lsb [1/10 °C]
- 0x25 r Temperature msb [1/10 °C]
- 0x26 r Altitude lsb [1/10 m]
- 0x27 r Altitude msb [1/10 m]
- 0x28 r Error
- 0x29 r Time hour [hr]
- 0x2A r Time minute [min]
- 0x2B r Time second [sec]
- 0x2C r Altitude degree [deg]
- 0x2D r Altitude minute [min]
- 0x2E r Altitude 10000ths lsb [1/10000 min]
- 0x2F r Altitude 10000ths msb [1/10000 min]
- 0x30 r Altitude direction [N/S]
- 0x31 r Longitude degree [deg]
- 0x32 r Longitude minute [min]
- 0x33 r Longitude 10000ths lsb [1/10000 min]
- 0x34 r Longitude 10000ths msb [1/10000 min]
- 0x35 r Longitude direction [E/W]
- 0x36 r Satellite fix 1=ok, no fix=0
- 0x37 r Number of satellite
- 0x38 r Altitude GPS lsb [1/10 m]
- 0x39 r Altitude GPS msb [1/10 m]
- 0x3A r Speed lsb [1/100 m/s]
- 0x3B r Speed msb [1/100 m/s]
- 0x3C r Heading lsb [1/100000 rad ➔ North]
- 0x3D r Heading msb [1/100000 rad ➔ North]
- 0x3E r/w New data ready 1=new data, okd=0

MPPT 100 kHz
Sky-Regler 100 kHz
Energy Board
BEC
StepDown 3.3V
ServoBoard
Li-Po Battery
RC Receiver 35 MHz

Sky-Sailor Project, A. Noth, Jan 2007
### Autopilot power consumption

**Table 5.2: Power consumption of the avionics subsystems**

<table>
<thead>
<tr>
<th>Device</th>
<th>Voltage [V]</th>
<th>Current [mA]</th>
<th>Power [mW]</th>
<th>$\eta_{conv}$</th>
<th>Power @ BEC [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Modem (XStream)</td>
<td>5</td>
<td>80</td>
<td>400</td>
<td>89%</td>
<td>449</td>
</tr>
<tr>
<td>IMU (Xsens MTX)</td>
<td>5</td>
<td>70</td>
<td>360</td>
<td>89%</td>
<td>404</td>
</tr>
<tr>
<td>CSDX (Sensortechnics)</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>89%</td>
<td>39</td>
</tr>
<tr>
<td>Pic16F876-Autopilot</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>89%</td>
<td>39</td>
</tr>
<tr>
<td>Pic16F876-Energy Board</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>89%</td>
<td>39</td>
</tr>
<tr>
<td>MS5534 (Intersema)</td>
<td>3.3</td>
<td>1</td>
<td>33</td>
<td>92%</td>
<td>36</td>
</tr>
<tr>
<td>GPS (Nemerix NB1043)</td>
<td>3.3</td>
<td>20</td>
<td>66</td>
<td>92%</td>
<td>72</td>
</tr>
<tr>
<td>DsPic33-Autopilot</td>
<td>3.3</td>
<td>27</td>
<td>99</td>
<td>92%</td>
<td>108</td>
</tr>
<tr>
<td>DsPic33-Servoboard</td>
<td>3.3</td>
<td>27</td>
<td>99</td>
<td>92%</td>
<td>108</td>
</tr>
<tr>
<td>Pic16LF877-Autopilot</td>
<td>3.3</td>
<td>5</td>
<td>17</td>
<td>92%</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>1.179</strong></td>
<td></td>
<td><strong>1.313</strong></td>
</tr>
</tbody>
</table>
Element placement in fuselage
GUI (thermals)
Modeling & Simulation

Controller Implemented Under Matlab

Real Control and Navigation System

Commands given to the actuators

Mathematical Representation

Matlab Aerospace Blockset

X-Plane Flight Simulator

State variables of the airplane
Overall
Energy chain

A succession of losses....

Important to efficiencies
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 $P_{\text{required}} = T \cdot v = (mg \cdot C_D / C_L) \cdot v$
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

![Graph showing Weight, Power, and Autonomy as functions of Airplane gross mass (kg).](image)

- **Battery autonomy**
- **Conceptual design mass of 2.55 kg**
- **Electrical power**
- **Mechanical power**
- **Wing Loading**

The graph plots the relationship between Power at level flight [W], Wing loading [kg/m²], Battery autonomy [h], and Airplane gross mass [kg].
The equation of the total mass is

\[ m = m_{ctrl} + m_{payload} + m_{struct} + m_{solar} + m_{batt} + m_{mppt} + m_{prop} \]

\[ m - a_{10} \left( a_7 + a_8 + a_9 \left( a_5 + a_6 \right) \right) \frac{1}{b} m^2 = a_2 \left( a_7 + a_9 \left( a_5 + a_6 \right) \right) + a_3 + a_4 b^x \]

It can be shown that it has a solution if:

\[ a_{12}^2 a_{13} \leq \frac{4}{27} \]
### Table 1 Parameters that are constant or assumed constant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L$</td>
<td>0.8</td>
<td>-</td>
<td>Airfoil lift coefficient</td>
</tr>
<tr>
<td>$C_{Da}$</td>
<td>0.013</td>
<td>-</td>
<td>Airfoil drag coefficient</td>
</tr>
<tr>
<td>$e$</td>
<td>0.9</td>
<td>-</td>
<td>Oswald’s efficiency factor</td>
</tr>
<tr>
<td>$I_{max}$</td>
<td>950</td>
<td>[W/m²]</td>
<td>Maximum irradiance</td>
</tr>
<tr>
<td>$k_{batt}$</td>
<td>190-3600</td>
<td>[J/kg]</td>
<td>Energy density of battery</td>
</tr>
<tr>
<td>$k_{cells}$</td>
<td>0.32</td>
<td>[kg/m³]</td>
<td>Mass density of solar cells</td>
</tr>
<tr>
<td>$k_{encaps}$</td>
<td>0.22</td>
<td>[kg/m³]</td>
<td>Mass density of encapsulation</td>
</tr>
<tr>
<td>$k_{mppt}$</td>
<td>0.00047</td>
<td>[kg/W]</td>
<td>Mass to power ratio of mppt</td>
</tr>
<tr>
<td>$k_{prop}$</td>
<td>0.013</td>
<td>[kg/W]</td>
<td>Mass to power ratio of propulsion unit</td>
</tr>
<tr>
<td>$k_{struct}$</td>
<td>0.44/9.81</td>
<td>[kg/m³]</td>
<td>Structural mass constant</td>
</tr>
<tr>
<td>$m_{elec}$</td>
<td>0.25</td>
<td>[kg]</td>
<td>Mass of navigation &amp; control system</td>
</tr>
<tr>
<td>$\eta_{occ}$</td>
<td>0.7</td>
<td>-</td>
<td>Efficiency of step-down converter</td>
</tr>
<tr>
<td>$\eta_{cells}$</td>
<td>0.169</td>
<td>-</td>
<td>Efficiency of solar cells</td>
</tr>
<tr>
<td>$\eta_{chrg}$</td>
<td>0.98</td>
<td>-</td>
<td>Efficiency of battery charge</td>
</tr>
<tr>
<td>$\eta_{trv}$</td>
<td>0.95</td>
<td>-</td>
<td>Efficiency of motor controller</td>
</tr>
<tr>
<td>$\eta_{dscd}$</td>
<td>0.98</td>
<td>-</td>
<td>Efficiency of battery discharge</td>
</tr>
<tr>
<td>$\eta_{gbcx}$</td>
<td>0.95</td>
<td>-</td>
<td>Efficiency of gearbox</td>
</tr>
<tr>
<td>$\eta_{mot}$</td>
<td>0.85</td>
<td>-</td>
<td>Efficiency of motor</td>
</tr>
<tr>
<td>$\eta_{mppt}$</td>
<td>0.97</td>
<td>-</td>
<td>Efficiency of mppt</td>
</tr>
<tr>
<td>$\eta_{prop}$</td>
<td>0.85</td>
<td>-</td>
<td>Efficiency of propeller</td>
</tr>
<tr>
<td>$P_{ctl}$</td>
<td>1</td>
<td>[W]</td>
<td>Power of navigation &amp; control system</td>
</tr>
<tr>
<td>$x_1$</td>
<td>3.1</td>
<td>-</td>
<td>Structural mass area exponent</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-0.25</td>
<td>-</td>
<td>Structural mass aspect ratio exponent</td>
</tr>
</tbody>
</table>

### Table 2 Parameters determined by the mission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{solem}$</td>
<td>0.7</td>
<td>-</td>
<td>Irradiance margin factor</td>
</tr>
<tr>
<td>$m_{payload}$</td>
<td>0.25</td>
<td>[kg]</td>
<td>Payload mass</td>
</tr>
<tr>
<td>$P_{payload}$</td>
<td>0.5</td>
<td>[W]</td>
<td>Payload power consumption</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.1655</td>
<td>[kg/m³]</td>
<td>Air density (500 m)</td>
</tr>
<tr>
<td>$T_{day}$</td>
<td>14:3600</td>
<td>[s]</td>
<td>Day duration</td>
</tr>
</tbody>
</table>

### Table 3 Variables linked to the airplane shape

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AR$</td>
<td>12.9</td>
<td>-</td>
<td>Aspect ratio</td>
</tr>
<tr>
<td>$b$</td>
<td>3.2</td>
<td>[m]</td>
<td>Wingspan</td>
</tr>
<tr>
<td>$m$</td>
<td>2.6</td>
<td>[kg]</td>
<td>Total mass</td>
</tr>
</tbody>
</table>
Sky-Sailor weight distributions

<table>
<thead>
<tr>
<th>Part</th>
<th>Dimensions [mm]</th>
<th>Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Controller</td>
<td>52 x 25 x 10</td>
<td>20</td>
</tr>
<tr>
<td>Brushless motor (Strecker)</td>
<td>φ30 x 25</td>
<td>55.3</td>
</tr>
<tr>
<td>Gearbox</td>
<td>φ33 x 29</td>
<td>29.7</td>
</tr>
<tr>
<td>Solariane Propeller &amp; mounting piece</td>
<td>600</td>
<td>34.05</td>
</tr>
<tr>
<td>Lipo-Akku</td>
<td>283 x 60 x 33</td>
<td>1056.00</td>
</tr>
<tr>
<td>MPPT + Shielding</td>
<td>42 x 42.5 x 9</td>
<td>25.86</td>
</tr>
<tr>
<td>Energy board (Incl. BEC &amp; Shield)</td>
<td>65 x 24 x 6</td>
<td>17.70</td>
</tr>
<tr>
<td>Autopilot sensor board</td>
<td>127 x 33 x 8</td>
<td>8.37</td>
</tr>
<tr>
<td>IMU</td>
<td>48 x 33 x 13.5</td>
<td>15.00</td>
</tr>
<tr>
<td>GPS &amp; patch antenna</td>
<td>25 x 22 x 8</td>
<td>10.96</td>
</tr>
<tr>
<td>Srccboard</td>
<td>42 x 24 x 8</td>
<td>6.51</td>
</tr>
<tr>
<td>RC Receiver</td>
<td>47 x 19 x 10</td>
<td>9.80</td>
</tr>
<tr>
<td>RC Receiver Antenna</td>
<td>1000</td>
<td>1.30</td>
</tr>
<tr>
<td>Radio Modem &amp; Antenna</td>
<td>75 x 40 x 11</td>
<td>26.48</td>
</tr>
<tr>
<td>On/Off Switch</td>
<td>23 x 14 x 13</td>
<td>4.85</td>
</tr>
<tr>
<td>Wing part middle (complete)</td>
<td>980 x 250 x 25</td>
<td>302</td>
</tr>
<tr>
<td>Wing part left (complete)</td>
<td>1130 x 300 x 25</td>
<td>266</td>
</tr>
<tr>
<td>Wing part right (complete)</td>
<td>1130 x 300 x 25</td>
<td>270</td>
</tr>
<tr>
<td>3 Wing Screw M4</td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>Fuselage with tail boom</td>
<td>1720 x 94 x 54</td>
<td>168.85</td>
</tr>
<tr>
<td>2 V-Tails</td>
<td>41.5 x 15.5 x 1.2</td>
<td>54</td>
</tr>
<tr>
<td>Cables</td>
<td></td>
<td>To be def.</td>
</tr>
<tr>
<td><strong>Total take-off mass</strong> (21.06.2008)</td>
<td>3240 x 1818 x 295</td>
<td>2444.00</td>
</tr>
</tbody>
</table>
Applications
Potential Applications

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

André Noth
Phd Defense
Autonomous Systems Lab
ETH Zürich, 24.09.08
What is the influence of battery technology on the maximal flying altitude?
Table 6.1: Parameters changes at the MAV size

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L$</td>
<td>0.5</td>
<td>-</td>
<td>Airfoil lift coefficient</td>
</tr>
<tr>
<td>$C_{D,aft}$</td>
<td>0.05</td>
<td>-</td>
<td>Airfoil drag coefficient</td>
</tr>
<tr>
<td>$e$</td>
<td>0.6</td>
<td>-</td>
<td>Oswald’s efficiency factor</td>
</tr>
<tr>
<td>$k_{af}$</td>
<td>5.58/9.81</td>
<td>[kg/m³]</td>
<td>Structural mass constant</td>
</tr>
<tr>
<td>$m_{av}$</td>
<td>0.005</td>
<td>[kg]</td>
<td>Mass of autopilot system</td>
</tr>
<tr>
<td>$\eta_{grb}$</td>
<td>0.81</td>
<td>-</td>
<td>Efficiency of gearbox</td>
</tr>
<tr>
<td>$\eta_{mot}$</td>
<td>0.62</td>
<td>-</td>
<td>Efficiency of motor</td>
</tr>
<tr>
<td>$\eta_{plr}$</td>
<td>0.80</td>
<td>-</td>
<td>Efficiency of propeller</td>
</tr>
<tr>
<td>$P_{av}$</td>
<td>0.1</td>
<td>[W]</td>
<td>Power of autopilot system</td>
</tr>
<tr>
<td>$x_1$</td>
<td>3.18</td>
<td>-</td>
<td>Airframe mass area exponent</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-0.88</td>
<td>-</td>
<td>Airframe mass aspect ratio exponent</td>
</tr>
<tr>
<td>$m_{pld}$</td>
<td>0.01</td>
<td>[kg]</td>
<td>Payload mass</td>
</tr>
<tr>
<td>$P_{pld}$</td>
<td>0.00</td>
<td>[W]</td>
<td>Payload power consumption</td>
</tr>
</tbody>
</table>
Figure 6.4: Mass distribution for $AR = 10$
Table 6.2: Parameters changes at the manned airplane size

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L$</td>
<td>1</td>
<td>-</td>
<td>Airfoil lift coefficient</td>
</tr>
<tr>
<td>$k_{prop}$</td>
<td>0.00121</td>
<td>[kg/W]</td>
<td>Mass to power ratio of prop. group</td>
</tr>
<tr>
<td>$k_{af}$</td>
<td>0.44/9.81/15</td>
<td>[kg/m^3]</td>
<td>Structural mass constant</td>
</tr>
<tr>
<td>$m_{av}$</td>
<td>20</td>
<td>[kg]</td>
<td>Mass of autopilot system</td>
</tr>
<tr>
<td>$\eta_{sc}$</td>
<td>0.19</td>
<td>-</td>
<td>Efficiency of solar cells</td>
</tr>
<tr>
<td>$\eta_{ctrl}$</td>
<td>0.98</td>
<td>-</td>
<td>Efficiency of motor controller</td>
</tr>
<tr>
<td>$\eta_{mot}$</td>
<td>0.88</td>
<td>-</td>
<td>Efficiency of motor</td>
</tr>
<tr>
<td>$\eta_{plr}$</td>
<td>0.87</td>
<td>-</td>
<td>Efficiency of propeller</td>
</tr>
<tr>
<td>$P_{av}$</td>
<td>100</td>
<td>[W]</td>
<td>Power of autopilot system</td>
</tr>
<tr>
<td>$m_{pld}$</td>
<td>120</td>
<td>[kg]</td>
<td>Payload mass</td>
</tr>
<tr>
<td>$P_{pld}$</td>
<td>0</td>
<td>[W]</td>
<td>Payload power consumption</td>
</tr>
</tbody>
</table>
Figure 6.7: Mass distribution for $AR = 10$
HALE Platform

Payload: 300 Kg
Altitude: 21’000 m
Mission time: 3 months in summer
Figure 6.12: Mass distribution for $AR = 22$
Mars design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{max}}$</td>
<td>589</td>
<td>$[W/m^2]$</td>
<td>Maximum Irradiance</td>
</tr>
<tr>
<td>$k_{\text{bat}}$</td>
<td>1000-3600</td>
<td>$[J/kg]$</td>
<td>Energy density of energy storage</td>
</tr>
<tr>
<td>$k_{\text{af}}$</td>
<td>0.44/9.81/2</td>
<td>$[kg/m^3]$</td>
<td>Structural mass constant</td>
</tr>
<tr>
<td>$m_{\text{av}}$</td>
<td>0.15</td>
<td>$[kg]$</td>
<td>Mass of autopilot system</td>
</tr>
<tr>
<td>$m_{\text{pld}}$</td>
<td>0.5</td>
<td>$[kg]$</td>
<td>Payload mass</td>
</tr>
<tr>
<td>$\eta_{\text{wthhr}}$</td>
<td>1</td>
<td>-</td>
<td>Irradiance margin factor</td>
</tr>
<tr>
<td>$P_{\text{pld}}$</td>
<td>0.5</td>
<td>$[W]$</td>
<td>Payload power consumption</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.015</td>
<td>$[kg/m^3]$</td>
<td>Air density (500 m)</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between aspect ratio and wingspan for total mass of solar airplane]
Mars design

![Graphs showing performance metrics vs. wing span and aspect ratio for Mars design.](image)

**Aspect Ratio**
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 16
- 18
- 20

---

**André Noth**  
PhD Defense  
Autonomous Systems Lab  
ETH Zürich, 24.09.08
Figure 6.13: Continuous flight simulation on the 21\textsuperscript{st} of June
Using Thermals

[Diagrams showing thermal data with coordinates and thermal intensity measurements.]

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

VS.

PHASE II
PRELIMINARY DESIGN

VS.

PHASE III
DETAIL DESIGN

KNOWN

- BASIC MISSION REQMTS.
- RANGE
- ALTITUDE
- SPEED
- BASIC MATERIAL PROPERTIES
  \( \sigma / \rho \), \( E / \rho \), \$/LB

RESULTS

- GEOMETRY
  - AIRFOIL TYPE
  - AR
  - \( \lambda / c \)
  - \( \lambda \)

- DESIGN OBJECTIVES
  - DRAG LEVEL
  - WEIGHT GOALS
  - COST GOALS

- BASIC INTERNAL ARRNGMT.
- COMPLETE EXTERNAL CONFIG
  - CAMBER, TWIST DISTRIBUTIONS
  - LOCAL FLOW PROBLEMS SOLVED
  - MAJOR LOADS, STRESSES, DEFLECTIONS

- LOCAL STRENGTH REQUIREMENTS
- PRODUCIBILITY
- FUNCTIONAL REQMTS.

- DETAIL DESIGN
  - MECHANISMS
  - JOINTS, FITTING, & ATTACHMENTS
  - DESIGN REFINEMENTS AS RESULTS OF TEST & OPER.
### Airframe model

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

**Weight as a function of Wing Area and AR for Sailplanes**

- **Interpolation of all samples**
  
  $W = 5.58 S^{1.59} AR^{0.71}$

- **Top 5% samples**
  
  $W = 0.44 S^{1.55} AR^{1.3}$
27 hours flight

![Graph showing motor power and avionics and servo power over day time.](image-url)
27 hours flight