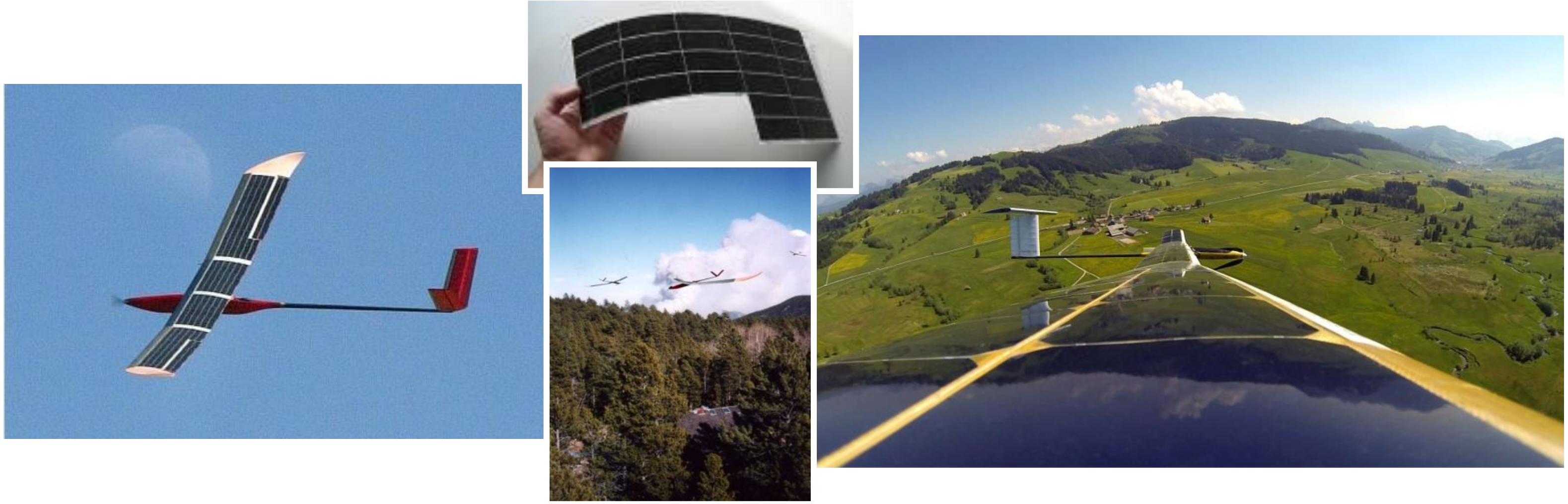
Case Studies:
Solar Powered Airplanes



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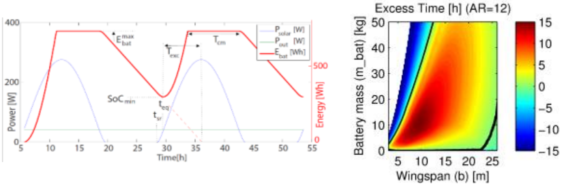
Topics in this case study

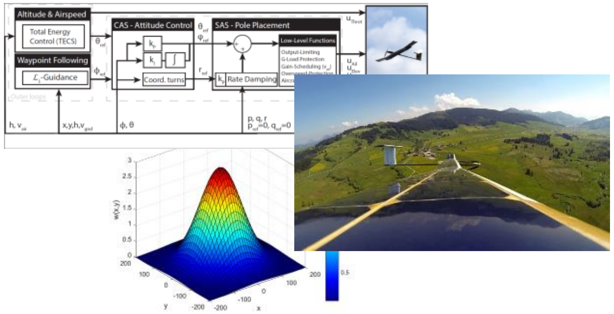
- ***Overview***
  History and state-of-the-art of solar-powered (unmanned) aircrafts

- ***Concept Design***
  Energetic modeling for sustained solar powered flight*

  (*Or: How can we reach world-record endurance on/for a small Unmanned Aerial Vehicle)



- ***Flight Autonomy***
  Autonomous flight and Kalman filtering approaches for the autonomous tracking of thermal updrafts



Part 1: Overview

History and State-of-the-art

Why Solar Powered Flight now?

- **Motivation**
  Today, realization of solar airplanes for continuous flight is possible
  - efficient and flexible solar cells
  - High energy density batteries
  - Miniaturized sensors and processors
  - Lightweight construction techniques

Possible Solar UAS Applications

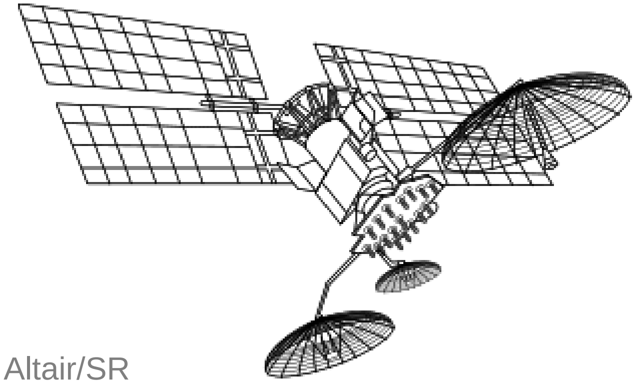
www.telegraph.co.uk
Yingxiu, May 15th 2008

Disaster Scenario / Search and Rescue

Agricultural and industrial inspection

Wildfires in California October 2007

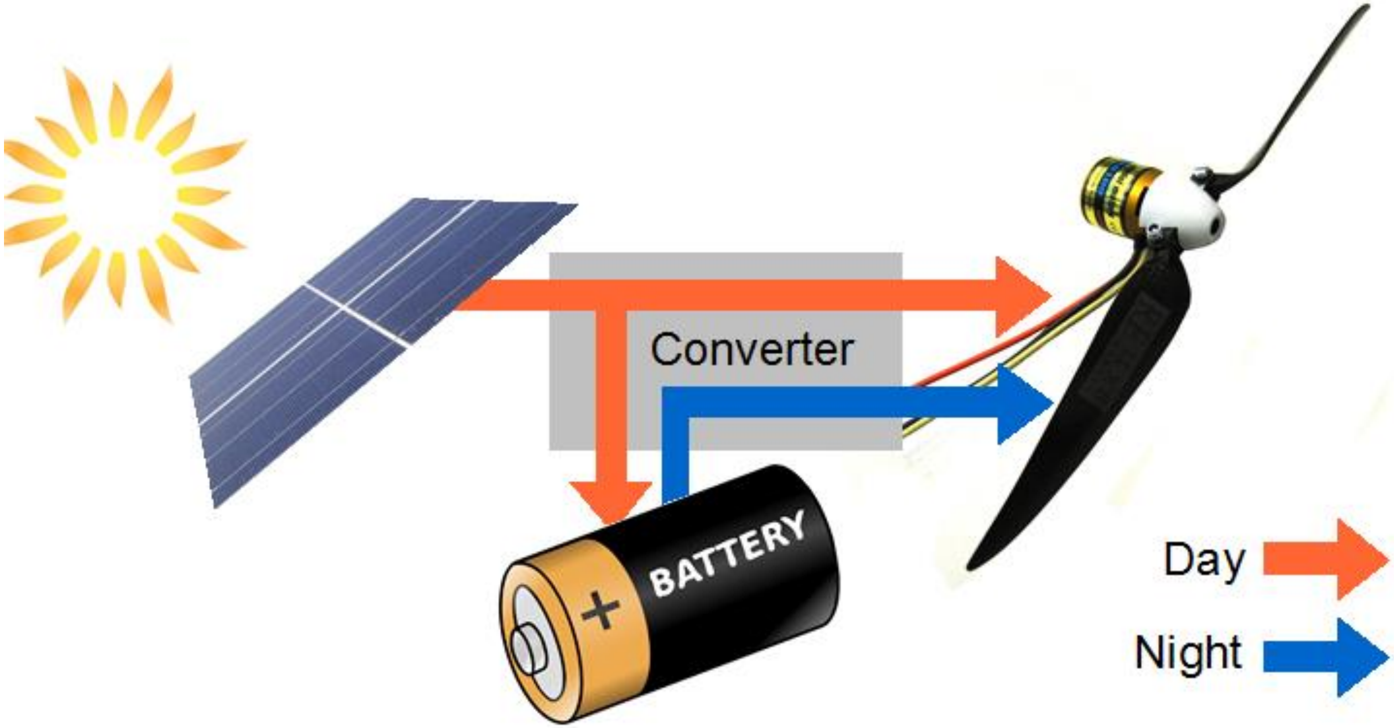
Early Wildfire Detection



Altair/SR

High-Altitude Long Endurance (HALE)

Working Principle of Solar-Electric Airplanes



Introduction – History of Solar Flight

- ***Premises of solar aviation with model airplanes***
  - first flight of a solar-powered airplane:
    4th Nov. 1974, Sunrise I & II (Boucher, US)

    Wingspan 9.76 m

    Mass 12.25 kg

    4480 solar cells ➔ 600 W; Max duration: 3 hours
  - In Europe, H. Bruss & F. Militky with Solaris in 1975
  - Since then, this hobby became „affordable“

MikroSol, PiciSol, NanoSol 1995-1998

Sunrise II, 1975

Solaris, 1976

Solar Excel, 1990

Introduction – History of Solar Flight

- ***The dream of manned solar flight***
  - first attempts : battery charged on the ground with solar power ➔ then flights of some minutes
    (*Solar One* of Fred To (UK) in 1978 and *Solar Riser* from Larry Mauro (US) in 1979)
  - 1st solar manned flight without energy storage:
    Gossamer Penguin of Dr. MacCready (US) in 1979.
  - Next version: *Solar Challenger* crossed the English channel in 1981

Solar Riser, 1979

Gossamer Penguin, 1980

Solar Challenger, 1981

Introduction – History of Solar Flight

- ***The dream of manned solar flight***
  - In 1983, Günter Rochelt (D) flies *Solair I* during 5 hours 41 minutes
  - In 1986, Eric Raymond (US) starts building Sunseeker. In 1990, he crossed the USA in 21 solar-powered flights with 121 hours in the air
  - In 1996, *Icare 2* wins the "Berblinger Contest" in Ulm (D).
  - In 2010, **SolarImpulse A** flies through the night (26h fully sustained flight)
  - In 2015, **SolarImpulse B** flies for 117h 52min (World Endurance and Range record for solar-powered manned airplanes)

Solair I, 1981

Sunseeker, 1990

Icare 2, 1996

SolarImpulse, 2010

Introduction – History of Solar Flight

- ***The way to High Altitude Long Endurance (HALE) platforms***
  - 1st continuous flight: Alan Cocconi of AcPropulsion built SoLong in 2005

    ➔ Use of Solar Power and Thermals
    22nd of April 2005 : 24 hours 11 min
    3rd of June 2005 : 48 hours 16 min

  - Qinetiq (UK) built *Zephyr* in 2005
    - December 2005 : 6 hours at 7’925 m
    - July 2006 : 18 hours flight (7 during night)
    - Sept 2007 : 53 hours
    - August 2008 : 83 hours
    - July 2010: 336 hours (world flight endurance record)

Solong, 2005

Zephyr, 2005

High Altitude Long Endurance platforms today

Airbus - Zephyr

Facebook - Aquila

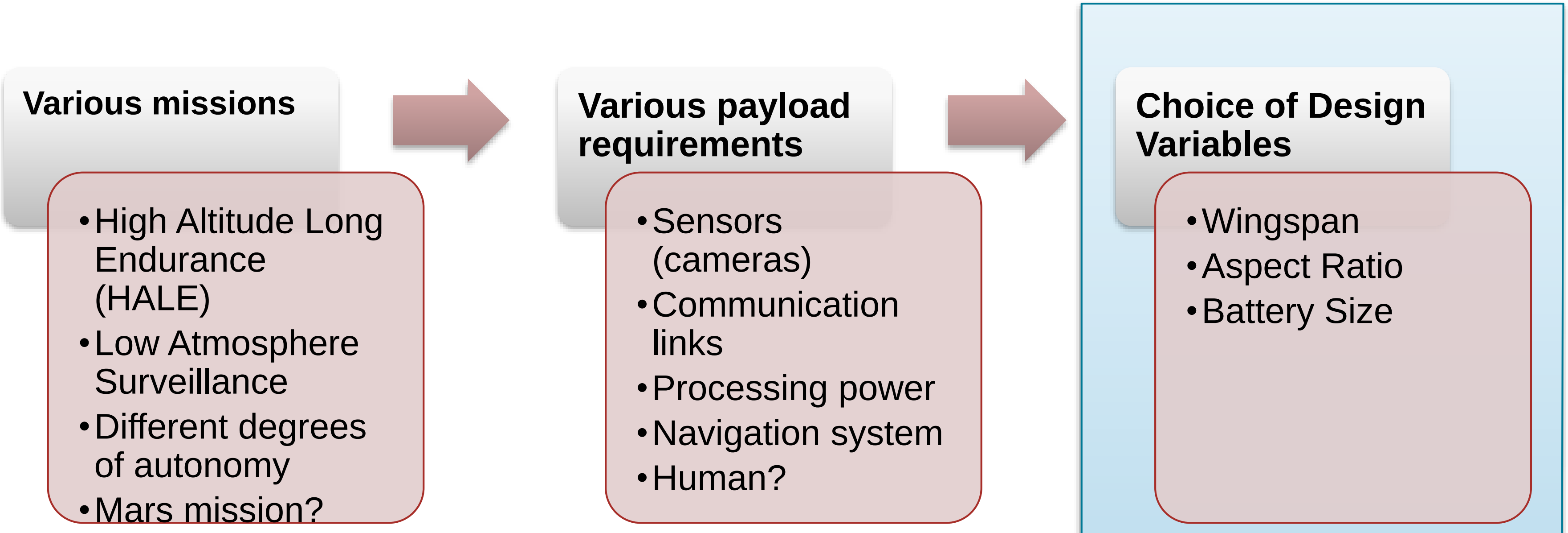
Google - Titan

	Airbus - Zephyr	Facebook - Aquila	Google - Titan
↔	22.86 m	42 m	50 m
kg	50 kg	400 kg	160 kg
↕	19.8 km	18-28 km	19 km

Part 2: Concept Design

Energetic modeling for sustained solar powered flight

Solar-Electric Airplane Conceptual Design



Various missions

- High Altitude Long Endurance (HALE)
- Low Atmosphere Surveillance
- Different degrees of autonomy
- Mars mission?

Various payload requirements

- Sensors (cameras)
- Communication links
- Processing power
- Navigation system
- Human?

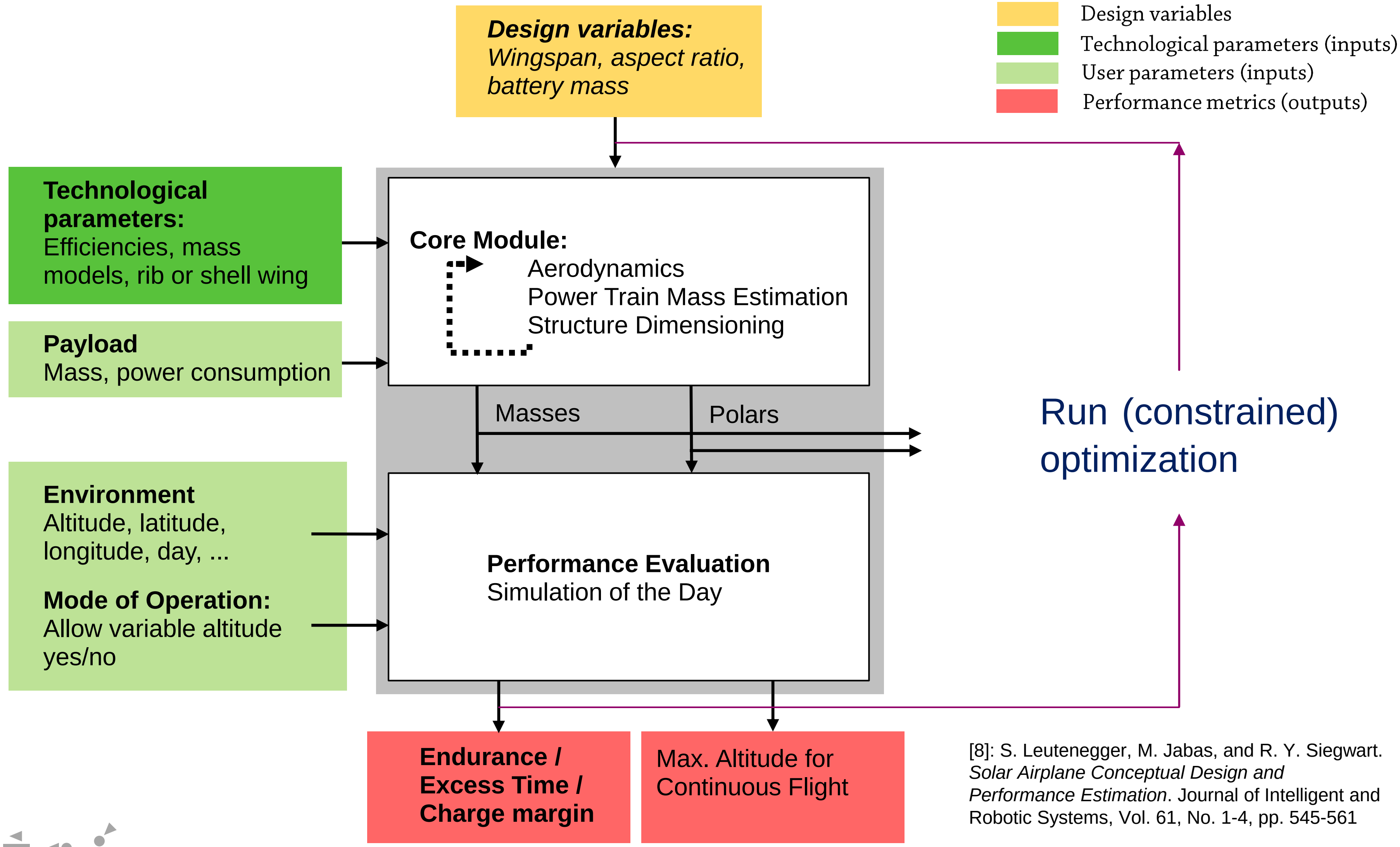
Choice of Design Variables

- Wingspan
- Aspect Ratio
- Battery Size

How do I do this?

What performance can I expect?

Solar-powered UAV Conceptual Design: A Tool



🟨 Design variables
🟩 Technological parameters (inputs)
🟩 User parameters (inputs)
🟥 Performance metrics (outputs)

Design variables:
Wingspan, aspect ratio, battery mass

Technological parameters:
Efficiencies, mass models, rib or shell wing

Payload
Mass, power consumption

Environment
Altitude, latitude, longitude, day, ...

Mode of Operation:
Allow variable altitude yes/no

Core Module:
Aerodynamics
Power Train Mass Estimation
Structure Dimensioning

Masses

Polars

Performance Evaluation
Simulation of the Day

Run (constrained) optimization

Endurance / Excess Time / Charge margin

Max. Altitude for Continuous Flight

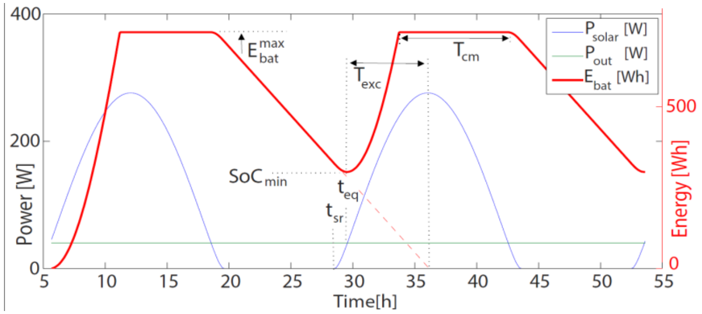
[8]: S. Leutenegger, M. Jabas, and R. Y. Siegwart. *Solar Airplane Conceptual Design and Performance Estimation*. Journal of Intelligent and Robotic Systems, Vol. 61, No. 1-4, pp. 545-561

Basic System Modeling (1/2)

- Forward-integration of state equations:

$$\frac{dE_{bat}}{dt} = P_{solar} - P_{out}$$

$$\frac{dh}{dt} = \frac{1}{m_{tot}g} \cdot (\eta_{prop} \cdot P_{prop} - P_{level})$$



- Power modeling

$$P_{solar}^{nom} = \boxed{I} \cdot A_{sm} \cdot \eta_{sm} \cdot \eta_{mppt}$$

I = I (day,t,lat,h)

$$P_{out} = P_{prop} + P_{av} + P_{pld}$$

$$P_{prop} = P_{level} / \eta_{prop}$$

I	Solar irradiance [W/m²]
A_{sm}	Solar module area [m²]
η_{sm}, η_{mppt}	Solar module and maximum power point tracker efficiency [-]
P_{av}, P_{pld}	Avionics and payload power [W]
η_{prop}	Propulsion system efficiency
m_{tot}	Total airplane mass

Basic System Modeling (2/2)

To derive the level flight power (constant altitude flight), we combine

$$P_{level} = F_D \cdot v$$

with

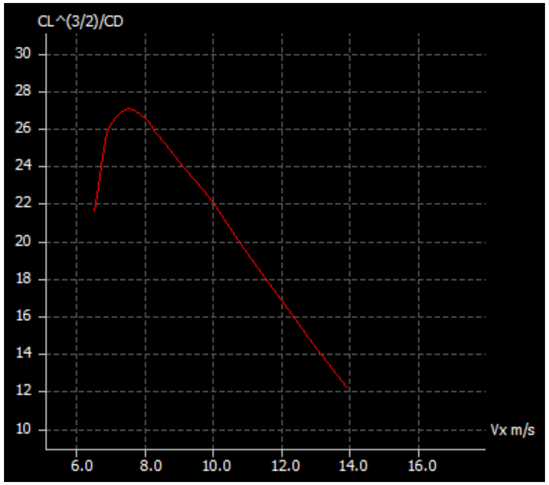
$$F_D = {}^1\!/_2 \cdot \rho \cdot c_D \cdot A_{wing} \cdot v^2$$
$$F_L = {}^1\!/_2 \cdot \rho \cdot c_L \cdot A_{wing} \cdot v^2 = m_{tot} \cdot g$$

v	Airspeed [m/s]
A_{wing}	Wing area [m²]
C_D, C_L	Drag / Lift coefficients [-]
ρ	Local air density [kg/m³]

and minimize the resulting expression w.r.t. the airspeed to yield

$$P_{level} = \left(\frac{C_D(v)}{C_L^{\frac{3}{2}}(v)}\right)_{min} \sqrt{\frac{2(m_{tot}g)^3}{\rho \cdot A_{wing}}}$$

C_D and C_L are functions of the airspeed v! They are retrieved from airplane and airfoil analysis tools such as XFOIL or XFLR5.



Example (see image): AtlantikSolar UAV, MH139 airfoil, m_{tot}=6.9kg, A_{wing}=1.7m², v_{opt}=7.6m/s, P_{level}=21W.

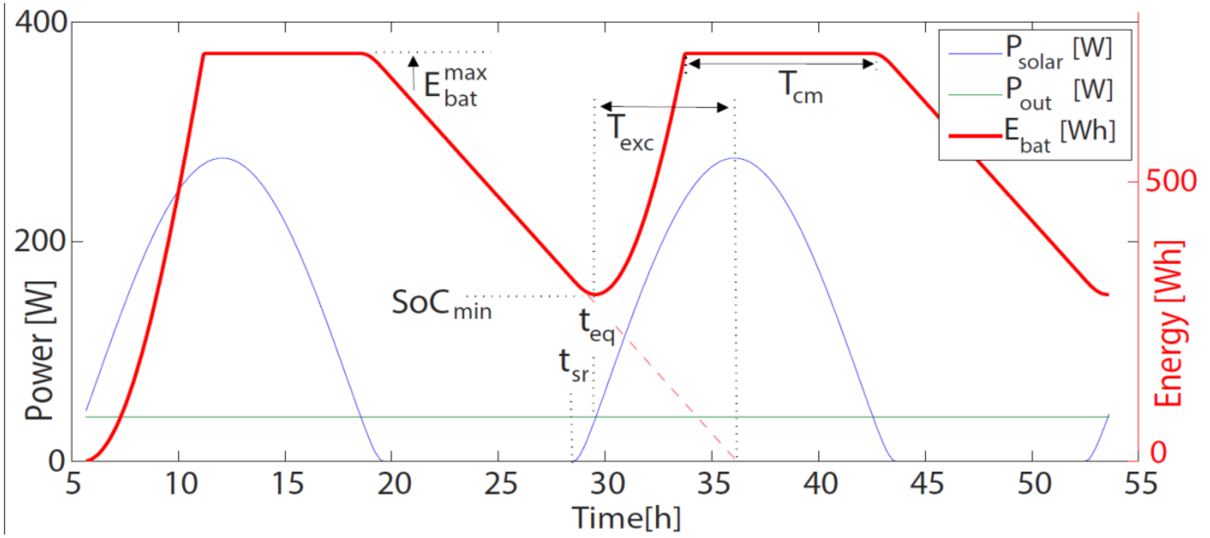
Performance Metrics

E_{bat}	Battery energy [J]
SoC	Battery state of charge [%]
P_{out}^{nom}	Nominal required output power [W]

If perpetual flight is not possible, the main performance metric is the maximum endurance T_{end}.

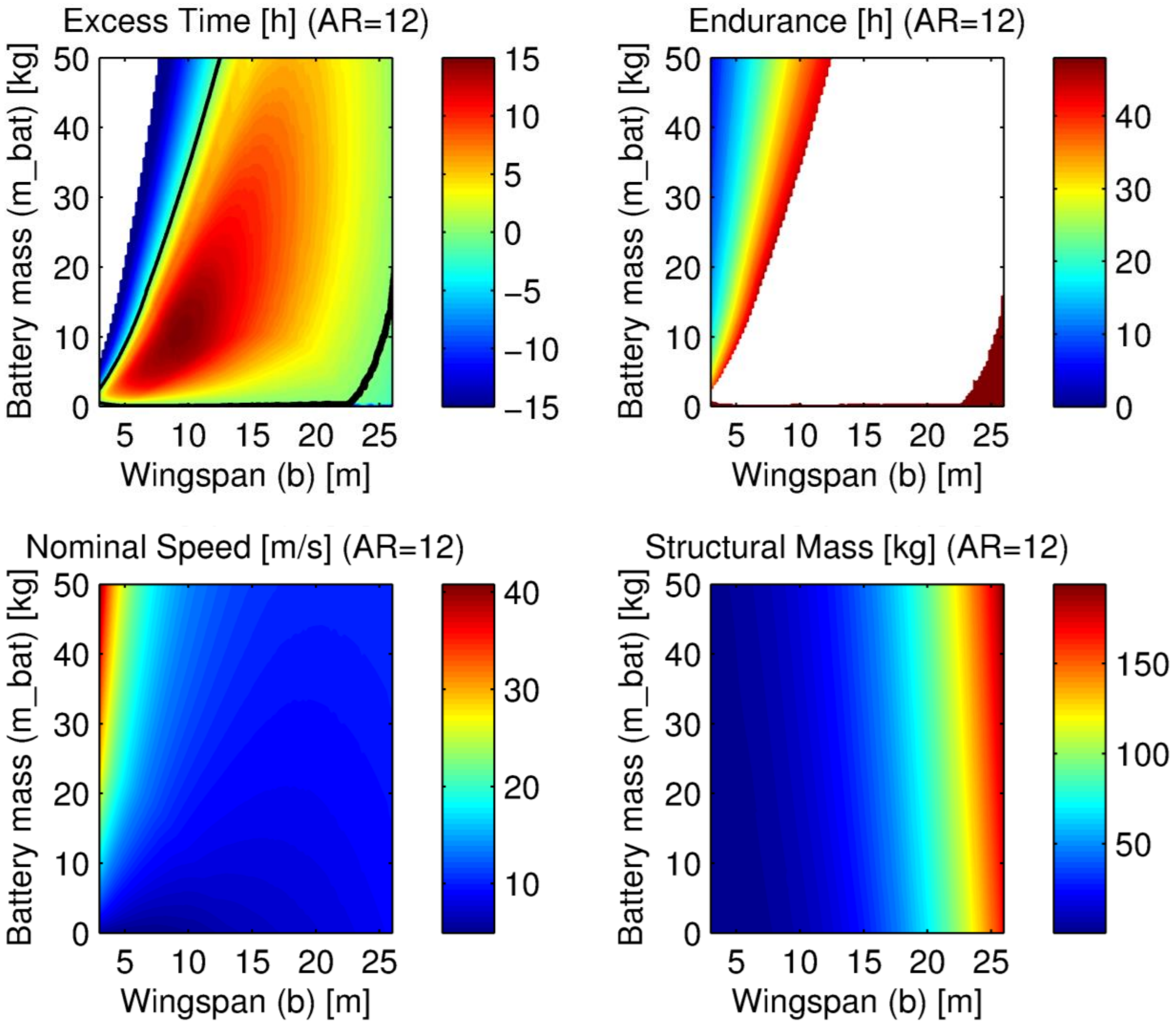
If perpetual flight is possible, we define:

$$T_{exc} = \frac{E_{bat}(t = t_{eq})}{P_{out}^{nom}}\Bigg|_{P_{solar}(t>t_{sr})=0} \qquad T_{cm} = T(E_{bat} = E_{bat}^{max})$$



In the conceptual design phase, we optimize both T_{exc} and T_{cm} to generate sufficient safety margins for perpetual flight!

Conceptual Design Results


Excess Time [h] (AR=12)

Endurance [h] (AR=12)

Nominal Speed [m/s] (AR=12)

Structural Mass [kg] (AR=12)

- Low-altitude perpetual flight (700m AMSL)
- Current technology
- Aspect ratio 12
- Minimal payload: 0.6kg, 7W
- Latitude 37.34°N
- June 21
- Clear sky

Example: Solar Powered Airliner?

- Payload 100 passengers, 12000 kg
- Speed: 600 km/h
- Height: 12 km: $\rho = 0.31$ kg/m^3
- Wing area and mass for AR=10:

$$C_L \approx 0.5 \Rightarrow A = \frac{b^2}{AR} = \frac{2mg}{\rho V^2 C_L}$$

$$m = m_{pld} + m_{propulsion} + m_{struct}$$

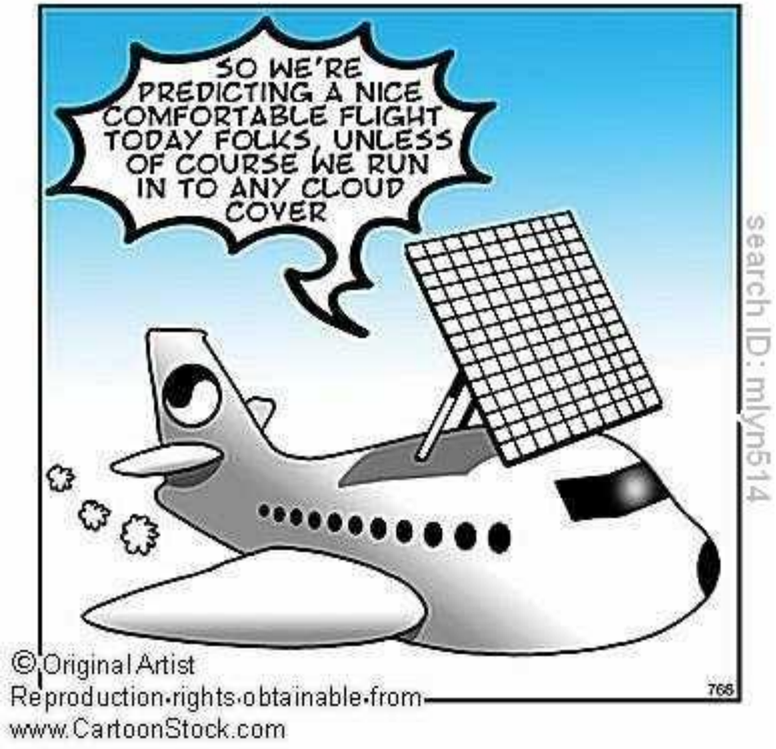
$$\approx m_{pld} + 0.043\left(\frac{b}{\mathrm{m}}\right)^{3.1} AR^{-0.25}\,\mathrm{kg}$$

$\Rightarrow$ m ≈ 13 t (unrealistically light),
b ≈ 24 m, A ≈ 57 m^2

- Power for level flight / Drag:
  Assume glide ratio 1:30 $\Rightarrow C_D = C_L/30$

$$P_{level} = \frac{\rho}{2} A C_D V^3 \approx 680\,\mathrm{kW}$$

- Solar Power Irradiance: max. 1.4 kW/m^2



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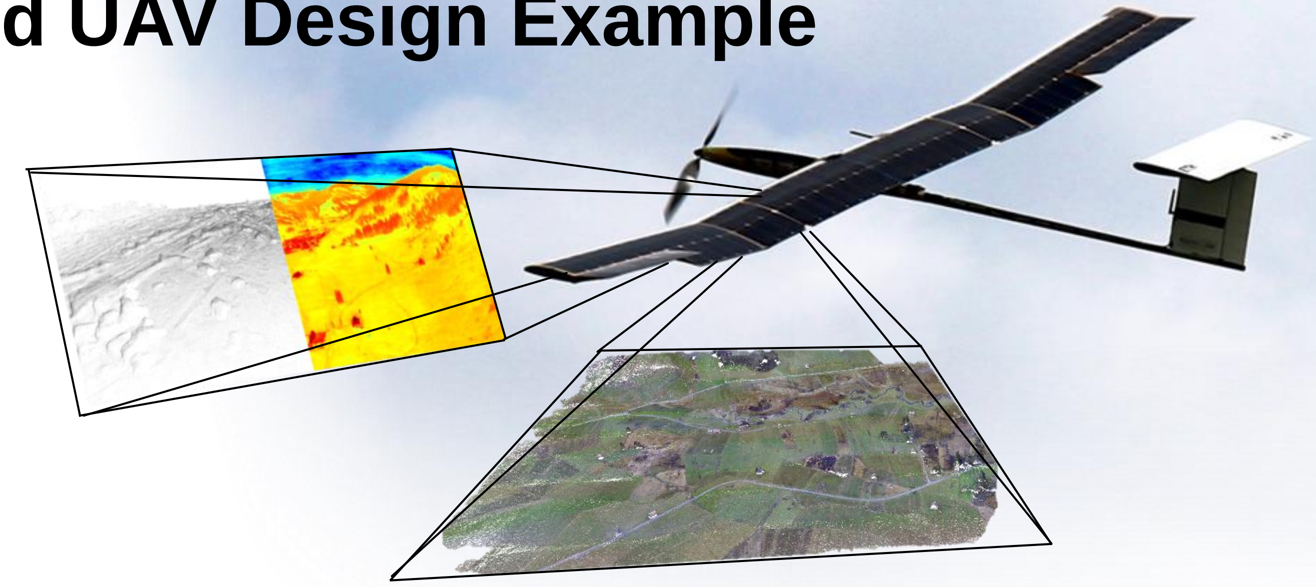
It is – **unfortunately** – far from being realistic…

Solar-powered UAV Design Example



Atlantik Solar

- Hand-launchable and rapidly deployable
- Fully autonomous, minimal supervisory requirements
- Versatile sensor payload

AtlantikSolar UAV	
Wingspan	5.65 m
Mass	6.9 kg
Nominal cruise speed	10 m/s
Minimum endurance[a]	13 hrs
Record endurance	81.5 hrs
Max. solar power	280 W
Power consumption	43 W

a – full battery with no solar charging

For student projects, please contact us!
(e.g. philipp.oettershagen@mavt.ethz.ch)

Avionics

Perception

Communication

Primary: 3DR radio

Long-Range: Iridium SATCOM

Radio control: Spektrum

First person view goggles

Autopilot and Sensors

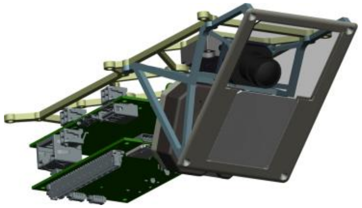
Pixhawk PX4 Autopilot

IMU: ADIS16448

Airspeed Sensing: Sensirion SDP600

GPS: U-Blox Lea-6H uBlox

Sensorpod



Optical cameras:
Aptina MT9V034,
IDS UI-3251LE

Thermal camera:
FLIR Tau 2

External cameras

GoPro Hero 3 silver

Sony HDR AS100V

Robust EKF-based State estimation

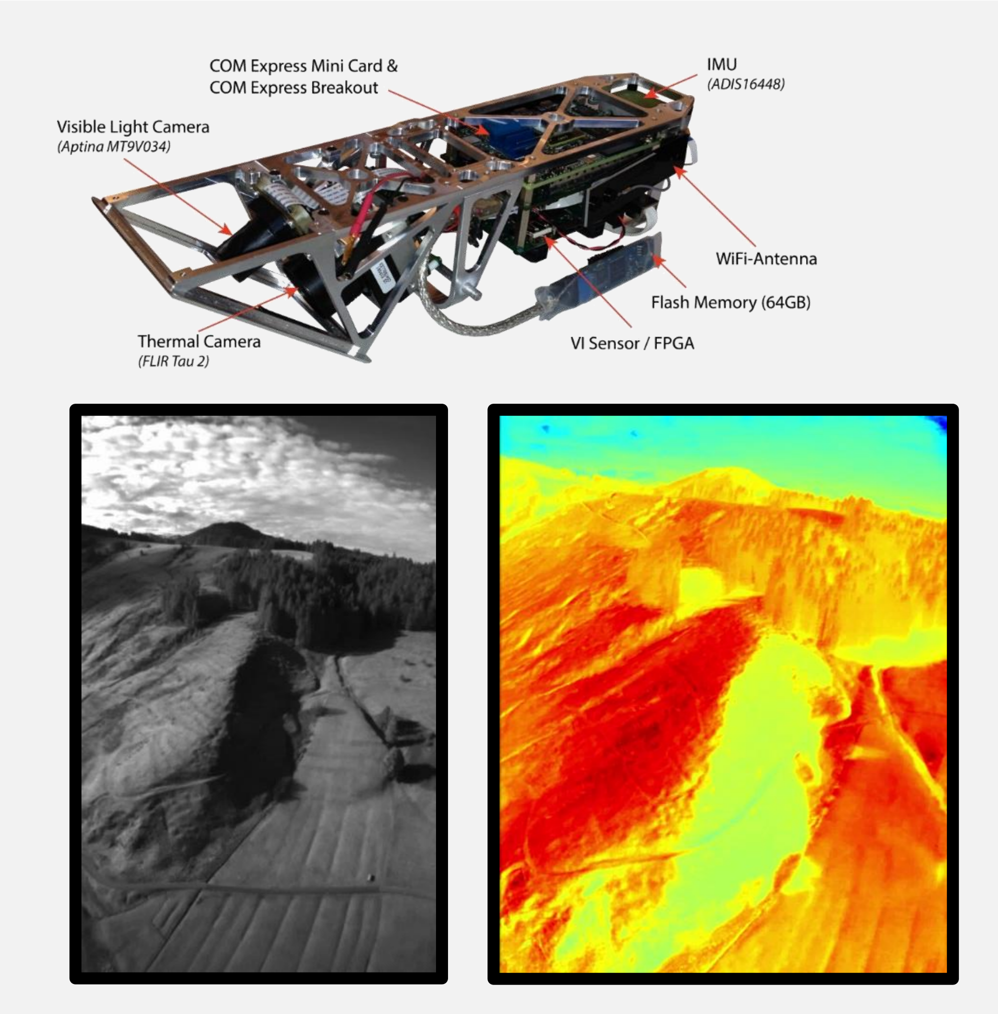
Leutenegger, S.; Melzer, A.; Alexis, K.; Siegwart, R., "**Robust state estimation for small unmanned airplanes**," in Control Applications (CCA), 2014

Simultaneous Localization and Mapping (SLAM)

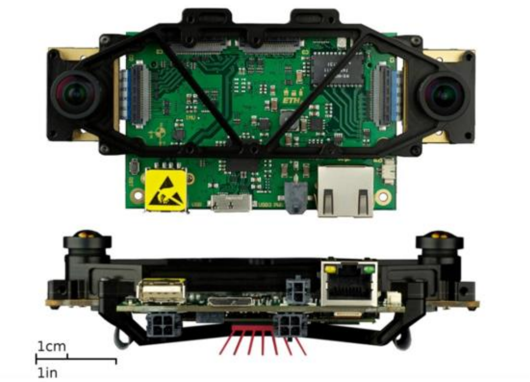
Human detection

Agricultural inspection

Sensorpod: Sensor and Processing Unit



Visual-inertial SLAM sensor

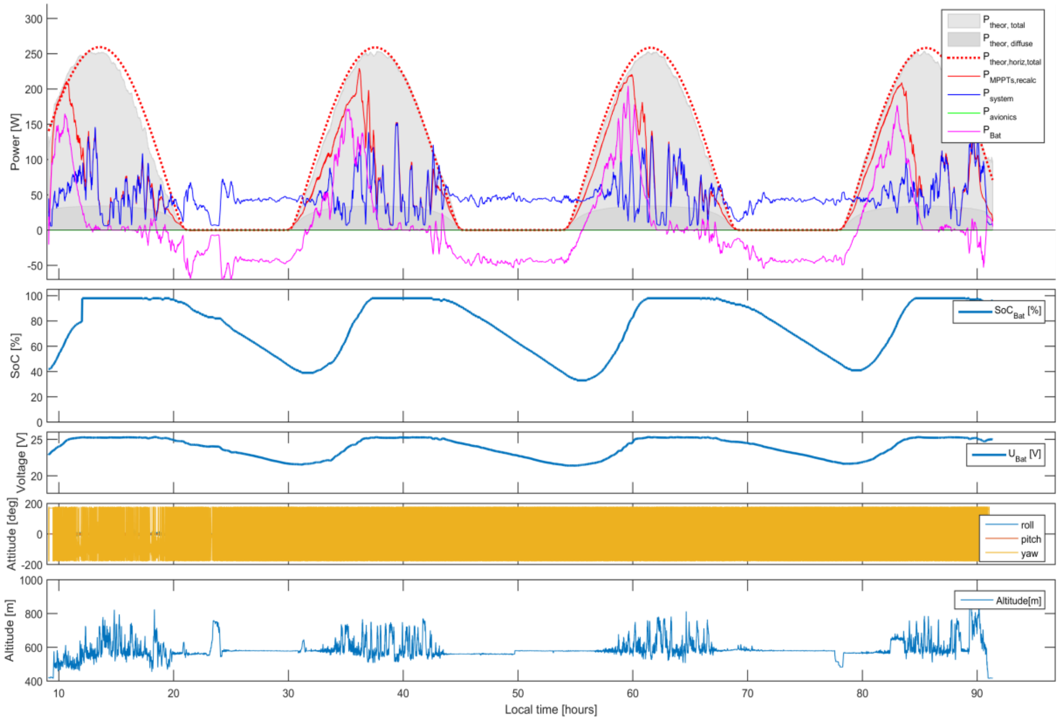


- Developed at ETH Zurich
- FPGA board for visual-inertial odometry
- Hardware synchronized IMU and camera data
- Up to four cameras

Janosch Nikolic, Joern Rehder, Michael Burri, Pascal Gohl, Stefan Leutenegger, Paul T Furgale, Roland Siegwart, **A synchronized visual-inertial sensor system with FPGA pre-processing for accurate real-time SLAM**, Robotics and Automation (ICRA), 2014 IEEE International Conference on, pp.431–437, 2014

Flight-endurance record: 81h flight (14.07.15)

- Conditions
    - Excellent irradiance
    - Significant thermals during the day
- Achievements
    - Duration: 81h23m
    - Distance: 2316km
    - Av. airspeed: 8.6 m/s
    - P_mean: 43W
    - SoC_{min}: 39%
    - World record in flight endurance for all aircrafts with m_{tot}<50kg



➔ Continuous flight proven to be feasible with good energetic margins and without using thermals or potential energy storage

AtlantikSolar

AtlantikSolar 2 UAV
Flight Endurance Record Attempt

Test Flight #5
July 14th-17th 2015
Rafz, Switzerland

Note: Video sequences that are marked with an asterisk (*) were not recorded during this record flight but during previous test flights.

Autonomous Systems Lab

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Part 3: Flight Autonomy

Autonomous flight and recursive filtering approaches for the autonomous tracking of thermal updrafts

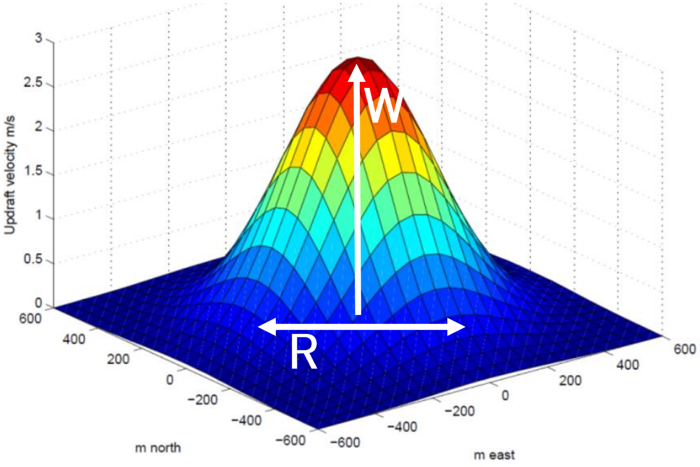
Flight Autonomy:

Example: Autonomous Thermal Updraft Tracking

Flight Autonomy:

Example: Autonomous Thermal Updraft Tracking

Attempt tracking of
- a single thermal updraft represented as
- a Gaussian updraft speed distribution
- with an Extended Kalman Filter (EKF)

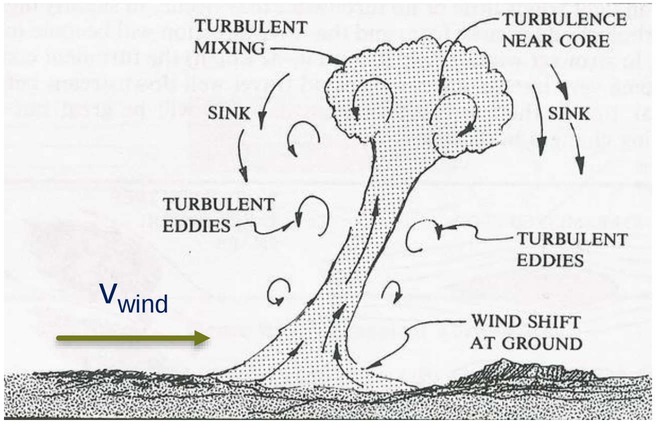


Use simple 4-state EKF:

State
$$X = \begin{bmatrix} W \\ R \\ x \\ y \end{bmatrix} = \begin{bmatrix} Max.\,updraft\ strength \\ Radius \\ Distance\ north\ of\ A/C \\ Distance\ east\ of\ A/C \end{bmatrix}$$

System model
$$X_{k+1} = f(X_k) = X_k + \begin{bmatrix} 0 \\ 0 \\ -v_{wind,north} \cdot {}^{\Delta h}/_{v_c} \\ -v_{wind,east} \cdot {}^{\Delta h}/_{v_c} \end{bmatrix}$$

Measurement
$$z_1 = w(W, R, x, y) = W \cdot e^{-\frac{x^2+y^2}{R^2}}$$



Flight Autonomy:

Example: Autonomous Thermal Updraft Tracking

Goal: Map (1) location and (2) orientation in thermal to an expected roll angle tracking error while in attitude stabilized mode.

$$\boxed{z_2} = c \cdot \boxed{\frac{r \cdot W}{R^2} \cdot e^{-\frac{r^2}{R^2}}} \cdot \boxed{\sin\zeta \cdot \cos\phi}$$

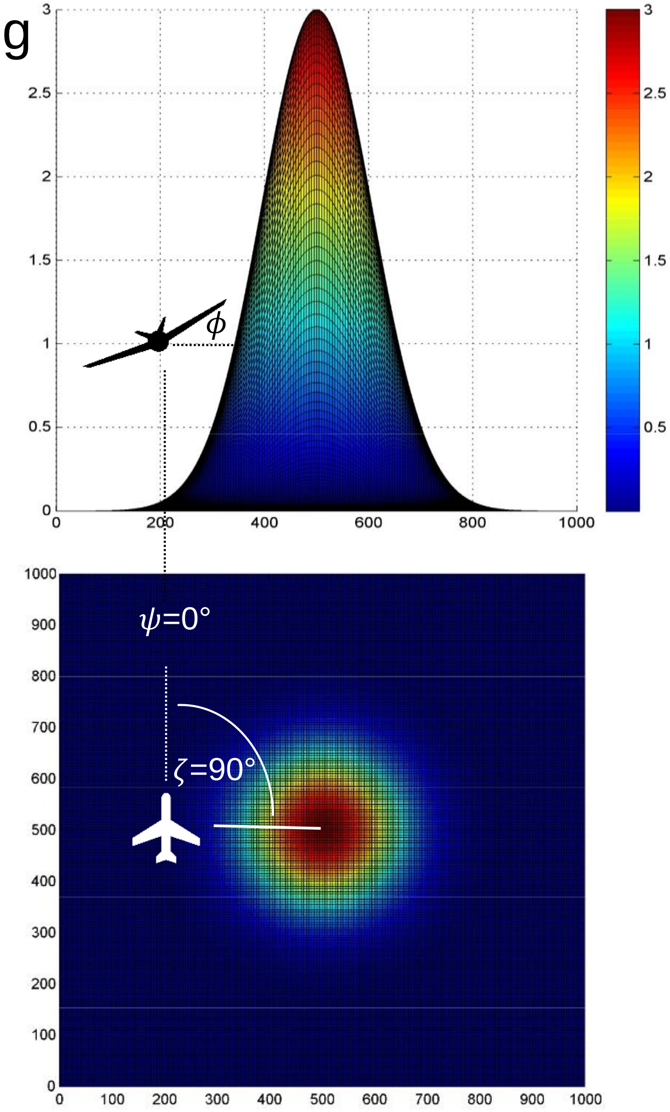
Roll Angle Tracking Error

Updraft gradient at current position

(Lateral) orientation of A/C w.r.t thermal core

ϕ = Roll angle. ψ = Yaw Angle. ζ = Direction of. thermal center

$$r = \sqrt{x^2 + y^2} \qquad sin\zeta = \frac{\cos\psi \cdot y - \sin\psi \cdot x}{r}$$



Future improvements / work:

- Unscented Kalman Filter (UKF)
- Particle Filter (PF)
- Non-gaussian updraft distribution (parabolic, …)
- Infrared-camera based detection of ground hotspots

AtlantikSolar

SolAIR

SolAIR Project:
Solar-powered Automated Aerial Imaging and Reconnaissance Using Infrared Cameras

AtlantikSolar 3 UAV
Fully autonomous solar-powered 26-hour day/night flight with RGB+IR camera payloads and victim detection

Test Flight #7
July 19th-20th 2016
Hinwil, Switzerland

Note: Video sequences that are marked with an asterisk (*) were not recorded during this flight but during previous test flights. They are used mainly for visualization purposes.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für Verteidigung,
Bevölkerungsschutz und Sport VBS
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Autonomous Systems Lab

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Thanks for your attention! Questions?

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