

A solar-powered hand-launchable UAV for low-altitude multi-day continuous flight

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Abstract—Abstract. Idea for this paper:

- Conceptual design, realization/integration, development of onboard systems, flight testing and verification of conceptual/preliminary design = Complete cycle including all steps can be shown here. - Demonstrations - rather basic control approaches chosen, i.e. this platform will be the basis for further research in control, guidance & navigation, mapping and will go towards the applications of XXX - solar-powered, hand-launchable 5m-class Unmanned Aerial Vehicle with multi-day continuous flight capability combined with payload capacity for long-endurance SAR and inspection missions. Questions: - This paper = engineering paper, rest is then BASING upon this paper (use it as a ref). Is this OK? Is the chance that this will be accepted big enough? - Yes, focus on “complete cycle” here, with more details in papers XXX to YYY

- We were special : mission applications possible, long endurance, combination

I. INTRODUCTION

A. Solar-powered UAVs for perpetual flight endurance

When carefully designed, solar-electrically powered fixed-wing Unmanned Aerial Vehicles (UAVs) exhibit significantly increased flight endurance over purely-electrically or even gas-powered aerial vehicles. Given certain environmental conditions, a solar-powered UAV creates surplus energy when observed over a full day-night cycle, i.e. it will fully recharge its batteries during the day to continue flight through the night and potentially subsequent day-night cycles. Long endurance - and especially this multi-day continuous flight capability termed “perpetual endurance” - is of significant interest for large-scale mapping, observation or telecommunications relay applications as they occur in Search-And-Rescue (SAR) missions, industrial or agricultural inspection, meteorological surveys, border patrol and more [1].

Recently, interest in employing solar-powered large-scale (wing span above 20m) High-Altitude Long-Endurance (HALE) UAVs as “atmospheric satellites” - i.e. stationary/loitering platforms e.g. for telecommunications relay - has peaked. Notable examples of this trend are Solara [2] and Zephyr, the latter of which has already demonstrated a continuous flight of 14 days[3]. In contrast, smaller scale solar-powered UAVs are mostly designed for Low-Altitude Long Endurance (LALE) applications. While they have to

cope with the more challenging meteorological phenomena of the lower atmosphere (clouds, rain, wind gusts or thermals), they generally have the advantage of lower complexity and cost as well as easier and faster handling (e.g. through hand-launchability) as beneficial in First-Aid SAR scenarios. However, research in small-scale solar UAVs targeting perpetual endurance has been relatively sparse, with most research including [4] focussing on conceptual design studies without extensive flight experience. However, in 2005, Cocconi’s SoLong [5] performed a continuous 48 hours flight using solar power and thermal-updraft hunting, though with limited airplane autonomy. Noth[6] presents the conceptual design methods, realization and experimental flight results of the 3.2m wing span “SkySailor”, which demonstrated a 27 hours solar-powered continuous flight without the use of thermals in 2008.



Fig. 1. The AtlantikSolar solar-powered UAV developed at ETH Zurich

B. Contributions of this paper

This paper aims to extend the work of [5], [6] by presenting AtlantikSolar, a solar-powered LALE-UAV with a wing span of 5.6m designed towards more robust multi-day autonomous operation capabilities while providing the option to use an advanced optical&infrared sensor system together with on-board computation resources developed at ETH Zurich. The contribution of the paper lies in presenting the complete development cycle from conceptual UAV design to actual testing and missions, or more specifically

- 1) The application and extension of the conceptual design approach in [6], [7] towards more robust multi-day flight under sub-optimal meteorological conditions
- 2) The realization of the conceptual design in UAV hardware, i.e. structure, low-level electronics & avionics

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*This work was supported by a number of project partners and generous individuals, see <http://www.atlantiksolar.ethz.ch/>

- 3) The development of onboard EKF state estimation algorithms and flight control methods based on PID control with non-linear guidance
- 4) The discussion of flight test results including long-endurance flight (up to 12h) and mapping results during exemplary Search-And-Rescue missions.

II. CONCEPTUAL DESIGN

A. Methodology

The conceptual design methodology for solar-powered UAVs used in this paper was developed at ETH Zurich by [6], [7] and is briefly summarized below. To analyze flight performance and a potential perpetual flight capability, the energy input/output-balance needs to be modeled. The total required nominal electrical output power

$$P_{out}^{nom} = \frac{P_{level}}{\eta_{prop}} + P_{av} + P_{pld} \quad (1)$$

consists of the required electrical propulsion power for level-flight $\frac{P_{level}}{\eta_{prop}}$, where η_{prop} includes propeller, gearbox, motor, and motor-controller efficiency, and the necessary avionics and payload power P_{av} and P_{pld} . The aircraft is assumed to fly at the airspeed of minimum aerodynamic level-flight power

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

Here, $m_{tot} = m_{bat} + m_{struct} + m_{prop} + m_{sm} + m_{av} + m_{pld}$ is the total airplane mass, where structure, propulsion and solar module masses m_{struct} , m_{prop} , m_{sm} are automatically sized according to [6], [7] and m_{av} , m_{pld} are given in table I. The local earth gravity is designated by g , A_{wing} is the wing area, and ρ is air density. The airplane lift and drag coefficients C_L and C_D are retrieved from 2-D airfoil simulations using XFOIL [8], with C_D being combined with parasitic drag from the airplane fuselage and stabilizers and the induced drag

$$C_{D,ind} = \frac{c_L^2}{\pi \cdot e_0 \cdot \lambda} \quad (3)$$

Here, $e_0 \approx 0.92$ is the Oswald efficiency and λ the wing aspect ratio. On the input side, the nominal solar input power

$$P_{solar}^{nom} = I \cdot A_{sm} \cdot \eta_{sm} \cdot \eta_{mppt} \quad (4)$$

considers the solar module area $A_{sm} = f_{sm} \cdot A_{wing}$ with relative fill-factor f_{sm} , module efficiency η_{sm} , and Maximum Power Point Tracker (MPPT) efficiency η_{mppt} . The solar radiation $I = I(\varphi, h, t)$ is assumed to be a function of the geographical latitude φ , the altitude h , and the current date and local time t , and is modeled as in [9]. The state equation can now be formulated in a simplified form as

$$\begin{aligned} \frac{dE_{bat}}{dt} &= P_{solar}(\varphi, h, t) - u - P_{av} - P_{pld}, \\ \frac{dh}{dt} &= \frac{\eta_{prop} \cdot u - P_{level}(h)}{m_{tot}g}. \end{aligned} \quad (5)$$

Here, u is the actual electrical power sent to the propulsion system. Simple forward integration of the state equation (5) gives the battery state of charge (SoC) over time and thus determines the perpetual flight capability.

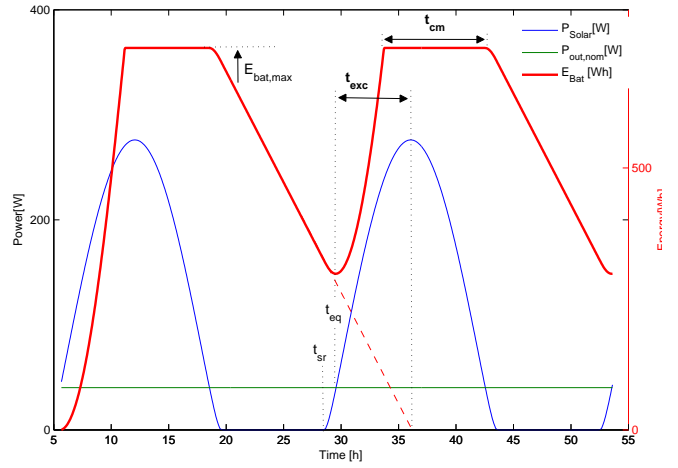


Fig. 2. Energetic simulation of the AtlantikSolar UAV configuration ($b = 5.6m$, $\lambda = 18.5$, $m_{bat} = 3.5kg$), showing input and output power, battery capacity, and performance metrics excess time t_{exc} and charge margin t_{cm} during a 2-day flight.

For the design optimization, we assume that a solar-powered UAV configuration is designed for missions at and around a specific date of the year (DoY) and geographical latitude φ , and thus φ and DoY are fixed parameters. The three design parameters to be optimized are

- The wingspan b and wing aspect ratio λ , which specify wing geometry and thus influence the level-power in (2) and the solar input power in (4).
- The battery mass m_{bat} contained in m_{tot} in (2)

B. Extension of conceptual design optimization criteria

The conceptual design tool developed in [6], [7] has been extended in two ways: First, it now provides the capability to perform energetic simulations of multi-day solar-powered flight, whereas before only one day-night cycle was considered. Fig. 2 shows the results for incoming solar power P_{solar} , required power P_{out} , and remaining battery charge E_{bat} obtained for a two day/night cycle flight. Clearly, the initial charge condition E_{bat} at time of sunrise $t_{sr} = \min(t(P_{solar} > 0))$ for the second day is different than on the first day, which significantly reduces the required charge time until $E_{bat} = E_{bat}^{max}$ and leads to increased charge margins with respect to the pure one day/night-cycle simulation. Second, and more importantly, the optimization criteria are extended with respect to [6], [7] to achieve more robust multi-day flight. In general, a necessary and sufficient condition for perpetual flight is that the excess time $t_{exc} > 0$, where

$$t_{exc} = \frac{E_{bat}(t = t_{eq})}{P_{out}^{nom}} \Big| P_{solar}(t > t_{sr}) = 0 \quad (6)$$

with “power-equality time” $t_{eq} = t(P_{solar}^{nom} = P_{out}^{nom})$ in the morning. This means that at $t = t_{eq}$ there has to exist remaining battery capacity to continue flight e.g. in case of cloud coverage in the morning. This is why [6], [7] focus on maximizing t_{exc} . However, a large t_{exc} does not provide direct robustness against disturbances in P_{solar}

during the charging process(e.g. due to clouds). In contrast, when optimizing purely for t_{exc} , the methodology in Sec. II-A will select the largest battery size (due to the scaling of P_{level} with m_{bat}) which can still be fully charged under optimal conditions, but every reduction in P_{solar} will directly decrease t_{exc} due to only partially charged batteries. We thus introduce the charge margin t_{cm} as the time margin between achieving the full charge $E_{bat} = E_{bat}^{max}$ and restart of the discharge in the evening. In case of decreased solar power income, $t_{cm} > 0$ will provide an additional margin before a decrease in excess time occurs.

The overall approach for increasing robustness with respect to local disturbances in the power income and output is thus to determine the lowest acceptable t_{exc} satisfying the UAV application requirements, and to then optimize the configuration for t_{cm} . The exact procedure applied here is:

- 1) Choose the nominal operating latitude φ and Day-of-Operation DoY^{nom} , and the outermost days where perpetual UAV endurance is required $DoY^{min,max}$
- 2) Obtain t_{night}^{min} and t_{night}^{max} for the range of $DoY = [DoY^{min}, DoY^{max}]$ from [9].
- 3) The required excess time $t_{exc,req}$ is now the sum of
 - $t_{exc,DoY} = t_{night}^{max} - t_{night}^{min}$
 - $t_{exc,clouds}$, to allow a margin for clouds in the morning or evening
 - $t_{exc,P_{level}}$, to allow a margin for increased power consumption e.g. caused by downdrafts or uncertainties in estimating P_{level}
- 4) Perform the design analysis given the methodology in sec. II-A for $DoY(t_{night} = t_{night}^{min})$. Pre-select the subset \mathcal{S} of configurations satisfying $t_{exc} > t_{exc,req}$.
- 5) Within \mathcal{S} , allow for a set of intermediate configurations \mathcal{S}_i to take into account UAV-specific constraints on b , λ , or m_{bat} . Then choose the final configuration \mathcal{S}_f from \mathcal{S}_i to obtain the largest charge margin t_{cm} .

This conceptual design methodology is applied below. An alternative conceptual design approach utilizing a weighed version of t_{exc} and t_{cm} is proposed in [4].

C. Application of Conceptual Design methodology

AtlantikSolar operate at a nominal latitude of $\varphi = 45N$ and shall provide perpetual endurance within a +/-2 month window around DoY_{nom} =June 21st (April 21st-August 21st). From [9], we find $t_{night}^{min} = 8.7h$ (June 21st), $t_{night}^{max} = 10.5h$ (April 21st), and thus $t_{exc,DoY} = 1.80h$. We choose $t_{exc,clouds} = 3.0h$ to account for three hours of full cloud coverage either on the evening or the morning and choose $t_{exc,P_{level}} = 0.2 \cdot t_{night,max} = 2.1h$ to cover increased power consumption due to modelling errors, downdrafts or headwinds. Using $t_{exc,req} = t_{exc,DoY} + t_{exc,clouds} + t_{exc,P_{level}}$, we retrieve $t_{exc,req} = 6.9h$ as the minimum required excess time for robust perpetual-flight at the given dates and locations.

The design methodology tool of section II-A is now applied assuming the fixed component performance parameters in Tab. I. Fig. 3 shows the resulting plot for t_{exc} versus the

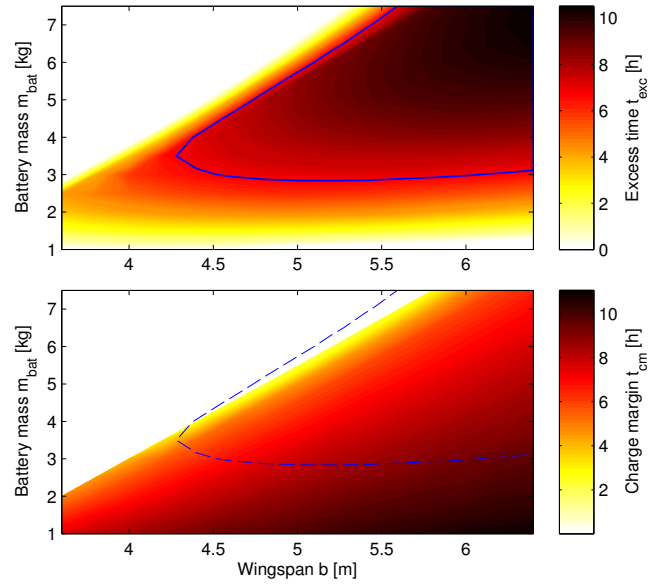


Fig. 3. Excess time t_{exc} (top) and charge margin t_{cm} (bottom) vs. optimization parameters b and m_{bat} , all at $\lambda = 18.5$. The configuration subset \mathcal{S} satisfying $t_{exc} > t_{exc,req}$ under our design requirements lies inside the blue contour line.

optimization variables b , m_{bat} and $\lambda = 18.5$. The subset \mathcal{S} of configurations satisfying $t_{exc} > t_{exc,req}$ is the region within the blue contour-line. The optimum clearly occurs at large wing spans, however, considering an external size constraint (each of the three wing pieces of AtlantikSolar shall be $< 2m$ in wing span to allow proper handling and transport), we choose $b = 5.6m$. The aspect ratio $\lambda = 18.5$ is found to provide an optimum in t_{exc} and also allows to seamlessly integrate the solar cells (see Sec. III-A.1) inside the wing chord. The last design choice is now m_{bat} , for which we seek to optimize t_{cm} within the previously selected set $\mathcal{S}_i = (\mathcal{S} | b = 5.6m, \lambda = 18.5)$. As visible in Fig. 3, $m_{bat} = 3.0 \dots 7.5kg$ lie within \mathcal{S}_i . We choose $m_{bat} = 3.5kg$ to optimize t_{cm} and due to practical battery sizing constraints described in Sec. III-A.1. The selected final configuration $\mathcal{S}_f = (\mathcal{S} | m_{bat} = 3.5kg, b = 5.6m, \lambda = 18.5)$ has an overall estimated mass of $m_{tot} = 7.22kg$ and yields a predicted $t_{exc} = 7.89h$ and $t_{cm} = 8.38h$ for the nominal operating date and latitude.

TABLE I
FIXED PARAMETERS FOR THE CONCEPTUAL DESIGN

Parameter	Value	Description
η_{asm}	0.20	Solar module efficiency
η_{MPPT}	0.97	MPPT efficiency
η_{prop}	0.58	Propulsion system efficiency
e_{bat}	874800Wh/kg	Battery specific energy
f_{sm}	0.94	Solar module fill factor
k_{sm}	0.59kg/m	Solar module areal density
m_{av}	0.6kg	Avionics mass (including all cabling)
m_{pld}	0.1kg	Payload mass
P_{av}	4.5W	Avionics power consumption
P_{pld}	0.0W	Payload power consumption

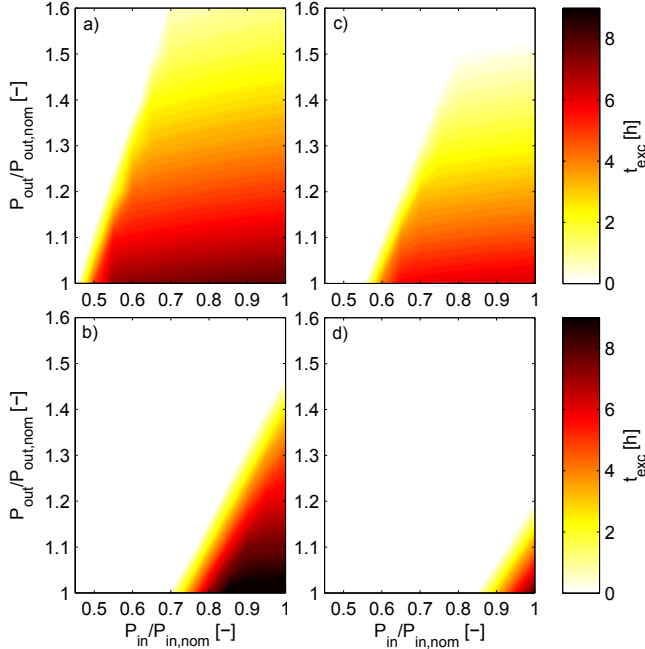


Fig. 4. Excess time t_{exc} under disturbed power input and output for the developed $b = 5.6m$, $\lambda = 18.5$ configuration: a) $m_{bat}=3.5kg$ on June 21st b) $m_{bat} = 6.0kg$ on June 21st c) $m_{bat}=3.5kg$ on April 21st d) $m_{bat} = 6.0kg$ on April 21st

D. Robustness analysis

To verify the multi-day flight robustness of the developed UAV configuration \mathcal{S}_f , we analyze its performance considering a set of local disturbances in UAV power input and output, namely

- The disturbed solar power income P_{solar}^{dist} , as caused by clouds or fog. Lacking knowledge of the exact spatial and temporal disturbance distribution, we assume the simple scaling

$$P_{solar}^{dist}(t) = P_{solar}^{nom}(t) \cdot k_{CCF}. \quad (7)$$

Here, $k_{CCF} = [0, 1]$ represents the current cloud cover factor [10], i.e. the clearness of the atmosphere.

- The disturbed electrical power output P_{out}^{dist} . Wind downdrafts, head wind, or gusts may require increased propulsion or actuation power. Again, we assume

$$P_{out}^{dist}(t) = P_{out}^{nom}(t) \cdot k_{OPF}, \quad (8)$$

with k_{OPF} representing the Output Power Factor.

Fig. 4 shows the remaining excess time with respect to these disturbances. The UAV configuration developed in section II-C (with $m_{bat} = 3.5kg$) still provides perpetual endurance with less than 50% of the solar power income or if more than 60% surplus power are required e.g. to compensate for downdrafts on June 21st (Fig.4a). In contrast, a configuration purely optimized towards excess time with $m_{bat} = 6.0kg$ (Fig.4b) will yield a higher maximum t_{exc} of 9.5h, however, the robustness with respect to clouds or higher required level power is greatly decreased. On April 21st, the UAV configuration of section II-C still provides solid robustness

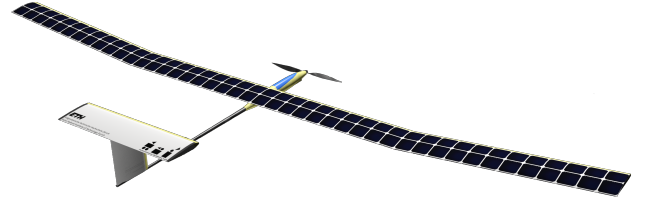


Fig. 5. The AtlantikSolar UAV features a conventional T-tail configuration with 1 motor, two ailerons, an all-moving elevator and a rudder for actuation.

TABLE II
ATLANTIKSOLAR DESIGN CHARACTERISTICS

Wing span	5.65m
Wing chord	0.305m
Length	
Height	
Mass	7.36kg
Battery mass	3.52kg
Wing loading	4.28kg/m ²
Stall speed	8.1m/s TBD

(Fig.4c), which verifies the $DoY^{nom} \pm 2$ months perpetual endurance requirement. In contrast, the $m_{bat} = 6.0kg$ configuration (Fig.4d) can not provide reliable perpetual endurance anymore. Overall, the configuration developed using the extended optimization criteria from Sec. II-B thus shows significantly improved multi-day flight robustness in comparison with configurations that are purely optimized for maximum excess time t_{exc} .

III. DETAILED DESIGN AND REALIZATION

AtlantikSolar (Figs. 1 and 5) is a solar-powered Low-Altitude Long-Endurance(LALE) Unmanned Aerial Vehicle designed for perpetual flight at $\varphi = 45$ geographical latitude from April 21st to August 21st. It was designed and built at ETH Zurich as a lightweight high aspect ratio airplane to achieve minimum sink rate. Although its design is mostly dictated by the requirement for low power consumption, it does provide the option to use visual&infrared sensor systems and on-board computation resources in an autonomous operation mode for use in search and rescue or industrial inspection applications. The airplane design is summarized in table II. Figure 7 presents an overview over the aircraft components topology.

A. UAV Platform Design

1) *Airframe and hardware*: The structure of AtlantikSolar is built in a traditional rib-spar construction method. The wing (Fig. 6) consists of an inner cylindrical carbon-fibre spar to resist torsional wing loads. Four carbon-fibre belts of trapezoidal and laterally-varying cross-section are located around the spar to optimally resist bending loads and to provide maximum wing stiffness to protect the solar cells on the wings. Equally-spaced balsa-wood ribs and the kevlar-reinforced wing leading edge provide structural support for

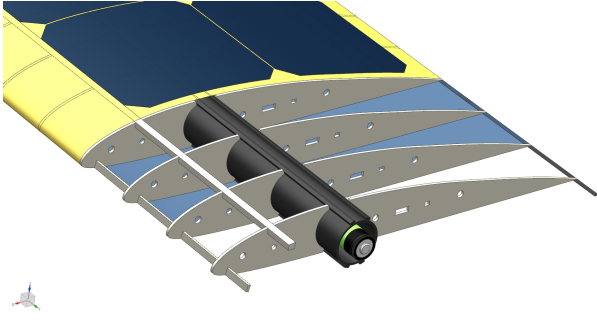


Fig. 6. AtlantikSolar's wing structure, integrated batteries and solar cells.

the non-load-carrying outer wing surface. The horizontal and vertical tail planes are constructed in a similar fashion.

The cylindrical wing spar contains a total of 60 cylindrical Lithium-Ion battery cells to optimally distribute the battery mass in a “span loader” concept. An additional 12 batteries can be added inside the outer wings to optimize the aircraft for a specific application. The Li-Ion cells are Panasonic NCR18650b high energy density (243Wh/kg) industrial cells. They are connected in a 6S (22.2V) configuration and provide $E_{bat,max} = 850Wh$ at $m_{bat} = 3.5kg$. The solar modules are seamlessly embedded into the upper wing surface to avoid premature flow separation. They feature a total of 88 SunPower C60 cells with a measured module-level efficiency of $\eta_{sm} = 0.20$, an areal density of $k_{sm} = 590g/m^2$ and a maximum power output of 275W at $\varphi = 45$ on June 21st. Modules featuring SunPower E60 cells with a verified module-level efficiency of $\eta_{asm} = 0.23$ are currently being integrated.

The propulsion system features a foldable carbon-fibre propeller with $D = 66cm$ and 60cm pitch that was specifically developed to achieve $\eta_{propeller} = 82\%$ at the nominal operating point of $F_{propeller} = 2.4N$ at $v = 8.5m/s$. The propeller is driven by a 5:1 reduction-ratio planetary gearbox, a RS-E Strecker 260.20 brushless DC motor with $k_V = 570RPM/V$ and a Kontronik Koby 55 LV motor controller. The propulsion system delivers a maximum electrical power of $P_{prop,max} = 450W$. The actuation system consists of four Volz DA-15N servos that drive the two ailerons, the all-moving elevator and the rudder. To guarantee reliable multi-day flight, the Volz actuators were successfully bench-tested throughout a simulated continuous 30-day flight [11].

2) *Avionics*: The AtlantikSolar avionics topology is shown in Fig. 7 and an integration snapshot is presented in Fig. 8. Multiple sensors are centered around a Pixhawk PX4 Autopilot - an open source and open hardware project initiated at ETH Zurich - with a Cortex M4F microprocessor running at 168Mhz and featuring 192kB RAM. For state estimation (section XXX), an ADIS 16448 10-axis Inertial Measurement Unit (IMU), a u-Blox LEA-6H GPS receiver, and a Sensirion SDP600 differential pressure (i.e. airspeed) sensor are used. The SDP600 airspeed sensor has been chosen due to its low relative error of less than 5% at airspeeds of 8m/s, which is necessary to closely control the airspeed to

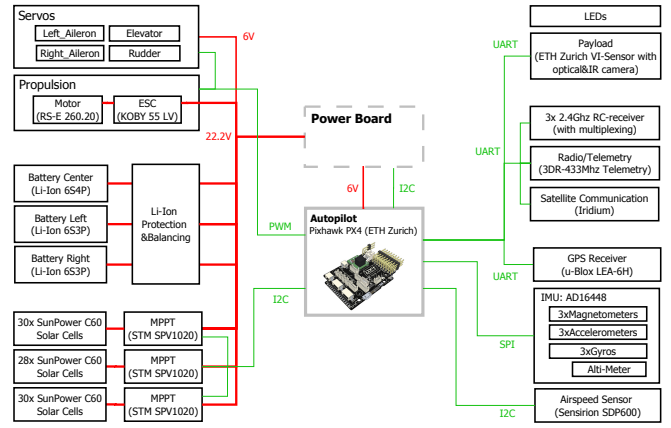


Fig. 7. AtlantikSolar system overview. For clarity, voltage lines from the autopilot to connected devices (5.0V and 3.3V) are omitted.

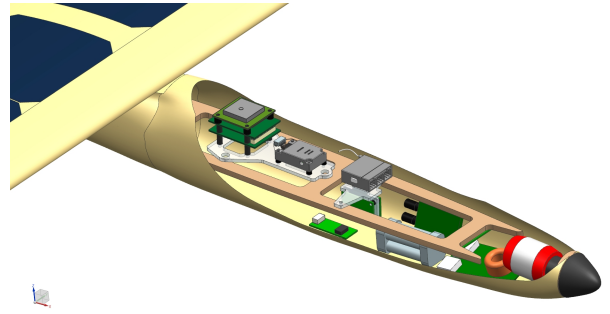


Fig. 8. Avionics components and their placement inside AtlantikSolar.

the airspeed with minimum required power P_{out} . Commands are received through a 433Mhz telemetry link for medium ranges, or through a long-range IRIDIUM-based satellite communication link that also serves as a backup in case of primary telemetry link failure. The airplane implements a fully manual RC-command fallback mode in case of a severe autopilot failure. Night operations are possible due to four on-board high-power LEDs.

3) *Payload*: - VI Sensor [ref to VI-sensor paper; ref to Leutenegger thesis?] - 5 sentences + 1 picture

B. State Estimation and Control Design

Onboard state estimation & control

1) *State estimation*: - brief (5 sentence) description of SE type/principle - one verification plot (e.g. gps position “ground truth” vs. estimated position) then REF to stefan&Amir paper

2) *System Identification*: - System Identification & Modelling

3) *Control*: - Control using PID, outer loops TECS & L1 (Ref to OMLAS MED paper, also saying that there is future technologies which are being developed). - Full pre-flight verification in HIL

C. Preliminary Results

- control: - SE&Control: PID performance over various trim points. PID computational requirements (low!) - state

estimation - solar system functioning - power efficiency curves. P_level from Test flights. - potentially comparison to conceptual design - power (why not optimal: e.g. because optimal CD/CL^{1.5} assumed, but this has a) to be met in average and b) even then fluctuations as seen in flight tests are on the order of 2-3 degrees in AOA or +/- 1m/s, so this will never be met perfectly. - actual mass vs. mass models?

IV. EXPERIMENTAL RESULTS

- mention Total flight hours, total flights. Mention that 2 AtlantikSolars have already been built & flown. Range of weather conditions?

A. Subsystem level results

- power efficiency curves. P_level from Test flights. - solar power system and recharging of batteries? - control results? [if not already shown before]. - control: - SE&Control: PID performance over various trim points. PID computational requirements (low!)

B. Continuous 12hour Flight

C. Mapping Flights in Search and Rescue scenarios

- mapping missions in ICARUS. - REF to Separate paper??? Yes, but only once both are accepted. - some cool pics/reconstructed maps

V. CONCLUSIONS

Mention: - Main lessons learned / summarize main points of paper - Future work

APPENDIX

Appendixes should appear before the acknowledgment.

ACKNOWLEDGMENT

The preferred spelling of the word acknowledgment in America is without an e after the g. Avoid the stilted expression, One of us (R. B. G.) thanks . . . Instead, try R. B. G. thanks. Put sponsor acknowledgments in the unnumbered footnote on the first page.

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