ELAHA – ELASTIC AIRCRAFT FOR HIGH ALTITUDES

CONCEPT AND CURRENT DEVELOPMENT STATE OF AN UNCONVENTIONAL STRATOSPHERIC UAV

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NOMENCLATURE

DLR	German Aerospace Center
ELAHA	Elastic Aircraft for High Altitudes
ELHASPA	Electric High Altitude Solar Powered Aircraft
HABLEG	High Altitude Balloon Launched Experimental Glider
HAP	High Altitude Platform
HAPS	High Altitude Pseudo-Satellite
IMU	Inertial Measurement Unit
UAV	Unmanned Aerial Vehicle

ABSTRACT

The group *Flying Robots* at the *DLR Institute of Robotics and Mechatronics* in Oberpfaffenhofen conducts research on solar powered high altitude aircraft. Due to the high altitude and the almost infinite mission duration, these platforms are also denoted as High Altitude Pseudo-Satellites (HAPS) or High Altitude Platforms (HAP).

After the successful flight of HABLEG [1], which was presented at ESA PAC 2015 [2], work continued with the goal to reach the stratosphere under own power with a reasonable sized platform.

In order to achieve continuous flying, the overall goal with HAP designs is to obtain a very high battery-to-structure mass ratio. This leads to very fragile aircraft which greatly influences operational availability due to the dependence on calm weather conditions. In fact, thermals and wind have led to several catastrophic failures in the past.

(a) Helios [NASA]

(b) Helios break-up [NASA]

(c) Zephyr [Airbus]

(d) ELHASPA [DLR]

(e) Solara 50 [Titan/Google]

(f) Aquila [Facebook]

Figure 1: Current HAP Designs

This overview paper proposes a new way of building high altitude platforms. The idea behind ELAHA (Elastic Aircraft for High Altitudes) is to build a segmented airplane with an extremely elastic wing, only elevators as control surfaces and appropriate control algorithms that allow it to survive in turbulent weather conditions.

To date, a proof-of-concept has already been flown successfully and the construction of a larger 10m wingspan version is ongoing. This paper discusses the concept, what has already been achieved and the current status of the development.

1. PROBLEMS OF CURRENT HAP DESIGNS

Fig. 1 shows a few examples of HAP designs. Of those, only the upper row, Fig. 1 (a) – (c), have actually flown in the stratosphere whereas the others only did low level flight testing so far.

Current HAP designs are built using modern fiber compound materials. The mandatory weight reduction as a key design driver currently leads to lightweight but also extremely fragile platforms. Carbon fiber, which is commonly used, has a very high tensile strength and stiffness, but is only capable of small amounts of compression before failing. This geometrically limits the achievable bending radius of a wing with a given thickness. In combination with high wingspans and low wing loadings, these fragile structures lead to tight flight envelopes in which an overspeed condition is reached rather easily. It can be stated that there were several incidents involving structural failure of existing HAP designs.

The airplanes in the lower row of Fig. 1, ELHASPA, Solara 50 [3], and Aquila [4], all encountered structural failure in consequence of piloting or autopiloting shortcomings which caused a violation of flight envelopes. We assume that a more deformable and thus forgiving wing structure in combination with high local control authority to cope with reduced stiffness can help to extend the operation boundaries and avoid getting into undesired situations.

A non-sufficient local control authority of a high aspect-ratio wing also played a role in the Helios breakup. Here, the aircraft morphed into a high dihedral state. The “procedure to reduce dihedral was to increase airspeed” [5]. This approach failed and the wing disintegrated after a successional occurrence of deficient longitudinal control stability.

Furthermore, some of the existing designs don’t scale well in size. The increase in size comes with the need for an over-proportionally heavier structure diminishing the potential gain of a bigger platform. This can only be adverted by truly span-loading platforms.

2. THE CONCEPT

We propose to approach these problems with a highly elastic wing and a segmented aircraft.

By highly elastic, we mean a wing that is able to bend up to 90° from wingtip to wingtip. If, as shown in Fig. 2, a thermal updraft catches a part of the aircraft, the wing bends all the way up until the projected surface against the updraft is reduced to almost zero and thereby has no further harming influence. We refer to this, as passive safety.

Figure 2: Thermal bending wing upwards

The airplane is made up of segments that can be joined together as needed, which can be seen in Fig. 3 and following. We distinguish between payload and propulsion segments:

<u>Payload segment</u>

- Build like a conventional aircraft
- Stiff enough to distribute the forces of a payload point mass over the segment wingspan
- Receives power to counter its drag, either in electrical form from the propulsion segments if it has an own engine or in form of an interface force from the neighboring propulsion segments

<u>Propulsion segment</u>

- Highly elastic wing
- Spanwise distribution of batteries
- High battery-to-structure weight ratio

This aircraft is controlled by wing torsion which is induced by several all-moving horizontal stabilizers. A deflection of such a horizontal stabilizer leads to a force that, with the tail boom as lever, generates a moment at the wing structure. This local change in attitude, results in a change of the local angle of attack, which changes the local generated lift and thereby makes it possible to move a segment of the wing upwards or downwards. An appropriate control law is used to keep the wing level and locally counteract disturbances. Differential thrust is used to control heading. This setup allows for a high control authority in various conditions which we refer to, as active safety.

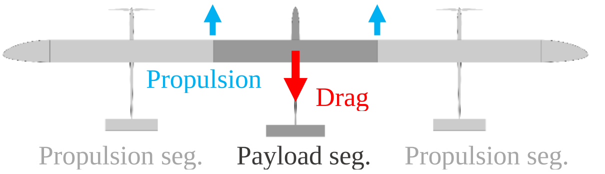

Figure 3: Segmented aircraft – propulsion forces on payload segment

The segmented approach allows the plane to be reconfigured depending on the mission. So, if for example a heavier payload segment needs more propulsive power, additional propulsion segments can be added as shown in Fig. 4. This even improves the systems overall efficiency, due to the increased aspect ratio of the wing. Here, the central property of the concept that every segment basically flies for itself plays a major role. Adding segments doesn't over-proportionally add structural weight like adding wingspan to a conventional aircraft design would.

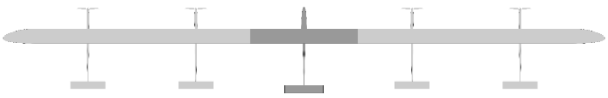

Figure 4: Aircraft with single payload and four propulsion segments

Since only two segments are needed to provide controllability, even an in-flight separation is possible, as shown in Fig. 5. This allows for a landing of separate segment groups in unfavorable weather conditions, due to the smaller wingspan. Operational-wise this makes a lot of sense, where you have better control over the launch conditions than the landing conditions, especially considering long duration missions.

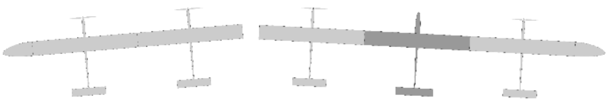

Figure 5: In-flight separation

Separation would also allow for a staged ascent. In order to lift heavy payloads to stratospheric altitudes, first, power would be drawn from batteries of two neighboring outer segments and then, upon depletion, they would be detached and returned to base while the remaining segments with the payload would continue their ascent.

An additional benefit of an elastic wing with high control authority is the possibility to morph it into different shapes. For example, it might be beneficial to partly bend the wing upwards to catch shallow sunlight that would otherwise not be captured by the solar cells due to the unfavorable angle of incidence, as it has been described by Parks [6].

Finally, since every segment flies at its own angle of attack needed to generate the necessary lift at a given common speed, the lift distribution over the entire wing, can be influenced to some degree by distributing the masses over the segments accordingly. For example, with five or seven segments, the outer left and right segment could be loaded with less batteries, thereby favorably influencing the lift distribution and subsequently the efficiency of the whole wing.

A more exotic example for benefits regarding mission flexibility arose from discussions with our friends from T-minus Engineering. A small sounding rocket with 10kg total mass and 2kg payload capability would reach an altitude of only 6km from sea level, due to a great amount of air friction losses in the dense lower part of the atmosphere. However, if launched vertically in 20km altitude, the apogee would increase drastically to 122km.

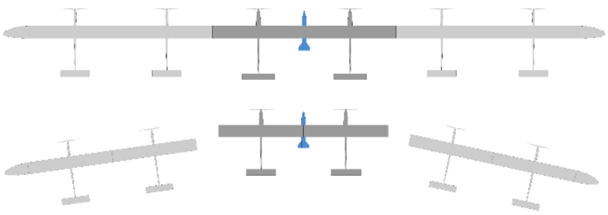

Figure 6: Air-launch of a small sounding rocket

To make this possible, the aircraft could be configured as shown in Fig. 6. Two relatively stiff built payload segments with own electric engines are joined together rigidly. Upon reaching launch altitude, the outer propulsion segments would detach. The payload segments with the rocket would then perform a dive and pull-up manoeuver, during which the rocked is fired.

It needs to be noted that there are other concepts that share some of the features just described.

One is the X-HALE project [7]. Their goal was to create a test platform to research the behavior of flexible slender wings for high altitude platforms. They also use wing torsion for control. Though their wings are quite elastic they don't bend as far as we intend ours to do.

At the aerospace fair LIMA 2017, the company UAVOS displayed an UAV named APUS that has many common features to our concept. It is also meant for high altitude flying and also relies on control by wing torsion induced by elevators. They claim that they can save 25% of structural weight by building the aircraft this way [8]. To this date we however don't know to which extent their wings are capable of bending up- and downwards. Also they don't pursue a segmented approach.

3. PROOF OF CONCEPT

To prove the concept, we built several foam demonstrators to test the general idea of an extremely elastic wing with control by wing torsion. In several iterations different configurations were tested and basic flight control algorithms developed. Each fuselage has an IMU allowing to capture the local attitudes and use them for control. As presented during the talk, it is possible to fly this 3.6m wingspan aircraft in extremely turbulent weather conditions which shows the general validity of our approach. These demonstrators, which we refer to as ELAHA_dev, will also be in further use to develop the avionics and software for the bigger, all-composite, versions ELAHA 10 and 15.

Figure 7: ELAHA_dev flying in turbulent air conditions

4. CURRENT DEVELOPMENT

Aside from afore mentioned demonstrators, work has already begun on the 10m wingspan version, ELAHA 10, which is pictured in Fig. 8 as work-in-progress.

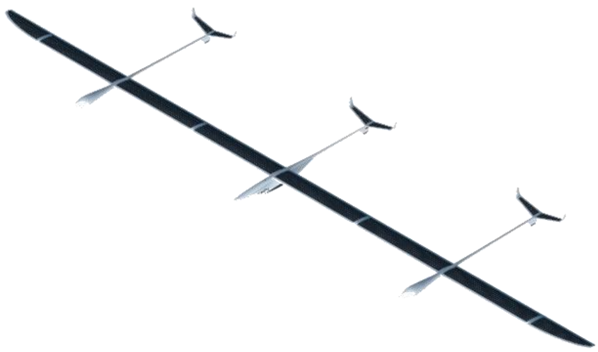

Figure 8: ELAHA 10 (Work in Progress)

The aerodynamic design of the wing segments is finished. Here, a batch analysis comprising a set of over 1500 airfoils has been conducted. The top 100 candidates of this analysis were used for another batch analysis with the goal to optimize an actual three-dimensional wing for different altitude regimes using these airfoil candidates. Then the top five candidates were individually compared for their performance at 0km, 10km and 20km altitude. The final airfoil is an optimized blend of two airfoils to improve the average performance over a broader altitude range. The base airfoils are Mark Drela's Dae51 and Dae41, originally developed for the human powered aircraft project Daedalus [9].

Based on this outer shape, the wing structure was designed [10] and molds were built, as pictured in Fig. 9. With the goal to reach the desired bending capabilities of the wing, material tests with different composite sandwich materials were made. This is necessary due to the, for aircraft structural parts, uncommonly thin laminates. Furthermore, an analysis toolchain was implemented to predict the mechanical properties of the wing structure. This toolchain was verified with several structural tests, including those of a full wing segment with an inter-segment joint, as shown in Fig. 10. The current focus lies on further refining the structure and start building the first wing segments meant for flying.

Figure 9: Mold with first finished ELAHA 10 wing-segment used for structural testing

Another focus is the development of a distributed control system. Each segment will have a microcontroller performing low-level control. The segments communicate over a bus system and will receive commands of a mission control computer running all higher control loops. Here, also the implementation of different control approaches is a strong topic. Also the in-flight reconfiguration into two individual aircraft has to be kept in mind.

Overall, the goal is to conduct a first flight with ELAHA 10 in 2018 and shortly after begin with modifications to make it high altitude capable.

If successful, the next update would integrate solar cells into the wing structure and extend the aircraft with two additional segments, resulting in a total wingspan of 15.6m. In this configuration it should already be possible to lift payloads of up to 5kg to an altitude of 20km or conduct continuous day-night cycles with a minimalist payload.

Figure 10: Structural test of ELAHA 10 wing segment

5. CONCLUSION

As we have shown in section 1, there are a number of reasons for pursuing the concept of an elastic and segmented aircraft, the most relevant reason being the paradigm “what bends doesn’t break”.

The concept also offers a great flexibility to reconfigure the airframe for different mission requirements while using a majority of identical parts.

So far, we have demonstrated the general validity of our approach by flying several demonstrators under difficult weather conditions.

The development of the larger 10m wingspan version ELAHA 10 is ongoing with the goal of a first flight in 2018.

We strongly want to encourage everyone to contact us in regard of collaborations regarding scientific or other applications that would benefit from the capabilities of a stratospheric UAV.

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