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CONCEPTUAL DESIGN OF SOLAR UNMANNED AERIAL VEHICLE

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***Abstract**—In this paper, emphasis was placed on the fact that a solar unmanned aerial vehicle, should be used in the context of certain missions, taking into account this, the general structure of the aircraft's internal systems was presented. The criterion for continuous flight during the day is analyzed. Based on this, an approach is presented for calculating and modeling the characteristics of a unmanned aerial vehicle, with the possibility of recharging during a daylight solar cycle. The main parameters of the aircraft were the wingspan and aspect ratio of the wing and the capacity of the batteries.*

Index Terms—Conceptual design; unmanned aerial vehicle; solar rechargeable airplane; solar power plant; solar cells; solar power.

I. INTRODUCTION

The flight of unmanned aerial vehicles (UAVs) using solar energy is not a new concept, its development begins in the early 1970s. The history of the creation is described in the work of Noth [1], he developed UAV that confirms the possibility of a flight exceeding the earth's day.

Unmanned aerial vehicle with the use of solar energy has a significantly increased flight time compared to aircraft that is using fuel systems including those which only using batteries as power source. UAV on solar energy uses excess sun energy after conversion to electrical energy collected during the day to charge batteries.

Considering the proper design and suitable environmental conditions, the stored energy may even be enough to continuously keep the UAV in the air during the night and possibly the subsequent day cycles. This so-called perpetual flight capability makes UAVs on solar panels excellent candidates for applications in which observable data must be collected or distributed.

Unmanned aerial vehicles using solar energy can be divided into two main types by the nature of the choice of flight altitude [3]:

– UAVs intended for *long-endurance high-altitude flight* (HALE, High-Altitude Long-endurance). These include aircraft on a large scale with a large wingspan. Most often used as moving communications platforms;

– UAVs designed for *long-endurance at low altitude* (LALE, Low-Altitude Long-endurance). This includes UAVs with a small wingspan. They are used most often for observation and information gathering.

The main differences between high altitude flight and low altitude are various meteorological phenomena, such as thermal processes and different weather conditions, such as rain, wind and the presence of clouds.

II. PROBLEM STATEMENT

The task of developing UAVs on solar panels captures many areas of development and design:

– aircraft design (aircraft structure, aerodynamics, flight mechanics);

– designing of onboard power systems (power electronics, power supply, solar power plant);

– development of autopilot navigation software.

In addition, UAVs can be involved in certain usage scenarios:

– remote sensing of terrain, both on land and in airspace;

– surveillance of the terrain, in order to identify natural disasters, perimeter control, etc .;

– the atmospheric platform (high-altitude flight), as a certain replacement for satellites.

To implement a continuous UAV flight within a calendar day, the maximum flight time should be considered. Accordingly, continuous flight is not possible if the maximum flight time T_{endur} < 24 h, and is possible if T_{endur} > 24 h. Also not unimportant criterion is the available energy of the aircraft when you leave the calendar day, using which the aircraft also can have additional time in flight T_{excess}, without the possibility of recharging.

The total power consumption and capacity of the onboard battery, as well as the availability of solar energy, have direct influence on T_{endur}.

III. STRUCTURE OF SOLAR UAV

The solar UAV is structurally composed of (Fig. 1):

– airframe (aerodynamics);

– solar subsystem (solar panels, battery, DC-DC MPPT converters);

– propulsion group (propeller, electric motor);

– on-board equipment of the autopilot (flight controller, INS);

– on-board radio electronic equipment (communication system);

– on-board equipment for the chosen scenario (payload).

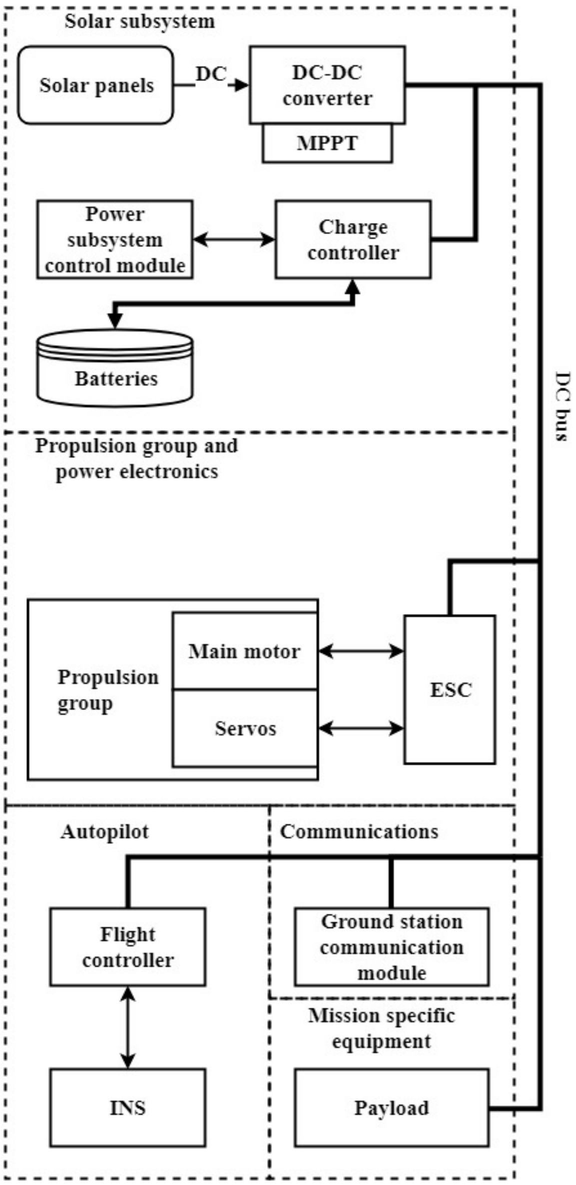

Fig. 1. Structure of Solar UAV

Solar subsystem provides the conversion of solar energy for the on-board UAV power network and provides the proper energy levels for the continuous operation of electrical equipment, as well as the connected additional load of the use scenario.

Propulsion group and power electronics with autopilot flight controller are just fixed on-board devices that required to proper operation of solar UAV.

Communication module another fixed on-board device provides ability to work with airplane remotely, where mission specific equipment could be configured as set of sensors, cameras.

IV. CONCEPTUAL DESIGN

The development of a solar UAV begins with the stage of the specification of the usage scenario and the parameters of the operating environment. Then basic parameters such as the swing and aspect ratio of the wings, mass of the battery, should be determined to match the usage scenario and its primary limitations.

Approaches to this task were developed in Noth [2]. In this paper, UAV models for all structural parts of the aircraft were presented. Also, a lot of solar planes were analyzed. Started from planes that were able to fly a couple of hours, such as Sunrise 1 to Helios NASA with a wingspan of 75 m, which was able to fly 75 h. As a result of the work, Sky-Sailor was presented with a swing of 3.2 m, which overcame 27 h of continuous flight.

Task of conceptual design consists in multi-criterion optimization of UAV parameters, in order to increase the flight time. Main structure of conceptual design is shown at Fig. 2.

The main idea of the design is the possibility of a continuous flight using solar energy, taking into account the operating environment (altitude, latitude, date and time of flight, meteorological conditions), as well as user-defined restrictions (payload, technological parameters, UAV airframe design parameters).

Well-known that weight of airplane must be compensated by the life force of the wings and the drag force must be compensated by the propeller thrust to acquire much power for level flight.

Here we can calculate *power for level flight*:

$$P_{\text{level}} = Tv = \frac{C_D}{C_L^{\frac{3}{2}}} \sqrt{\frac{(mg)^3}{S}} \sqrt{\frac{2}{\rho(h)}} = \frac{C_D}{C_L^{\frac{3}{2}}} \sqrt{\frac{2ARg^3m^3}{\rho(h)b}},$$

where C_D is the drag coefficient; C_L is the lift coefficient; AR is the aspect ration; ρ is the air density; m is the mass; b is the wingspan; g is the gravitation acceleration.

Total power required for proper operation of solar aircraft could be calculated by using efficiencies of propulsion group with combination of efficiencies used by payload and avionics:

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

where η_{ctrl} is the motor controller efficiency; η_{mot} is the motor efficiency; η_{plr} is the propeller efficiency; η_{bec} is the battery eliminator circuit efficiency; P_{level} is the power of level flight; P_{av} is the power of avionics; P_{pld} is the power of payload.

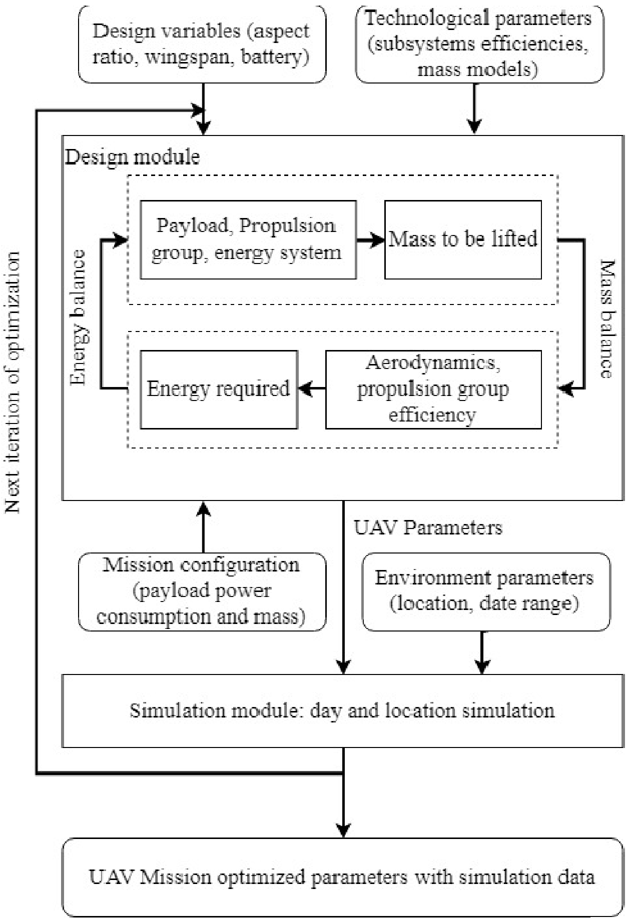

Fig. 2. Conceptual Design Structure of Solar UAV

Calculation of *total daily energy required* energy could be performed through taking charge and discharge efficiency of system at night period and day period during which we charge the battery by excess energy:

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

where η_{chrg} is the charge efficiency; η_{dchrg} is the discharge efficiency; T_{night} is the night time; T_{day} is the day time.

Daily average solar irradiance depends on irradiance models that take weather conditions, location and day of the year. Generally irradiance model was defined by Duffie & Beckman at Fig. 3.

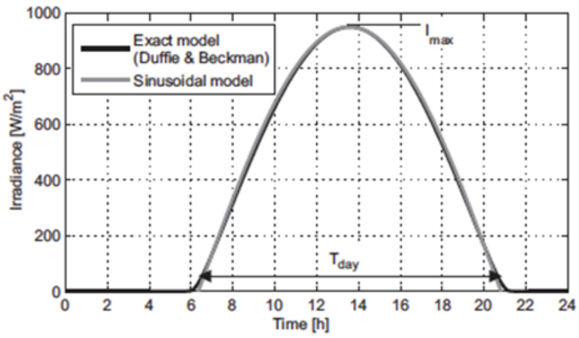

Fig. 3. Irradiance model

Solar energy that could be obtained from the surface of aircraft is below the curve and could be described in the following equation, with taking in mind simplification that model irradiation model is very similar to sinusoidal curve:

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

where η_{wthr} is the weather efficiency; $I_{\max}$ is the maximum current; T_{day} is the day time.

To calculate total *daily energy obtained* which could be obtained with solar cells on the wing, we could introduce to equitation such relations like cells efficiency and the efficiency of MPPT.

Daily energy obtained depends on performance and efficiency of solar power subsystem:

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

where A_{sc} is the solar cells; η_{sc} is the solar cells efficiency; η_{cbr} is the camber efficiency; η_{mppt} is the MPPT efficiency.

As result area of solar cells could be calculated:

$$A_{\text{sc}} = \frac{\pi}{2\eta_{\text{sc}}\eta_{\text{cbr}}\eta_{\text{mppt}}\eta_{\text{wthr}} I_{\max}} \cdot \left(1 + \frac{T_{\text{nigt}}}{T_{\text{day}}} \frac{1}{\eta_{\text{chrg}}\eta_{\text{dchrg}}}\right) P_{\text{elec, tot}},$$

Mass models. Airplane consists of several set of subsystems that was described previously on structure of UAV. Each subsystem has its own mass model.

Airframe mass:

$$m_{\text{af}} = k_{\text{af}} AR^{x2} b^{x1},$$

where AR is the aspect ratio; b is the wingspan; k_{af} is the scaling coefficient of airframe; X is the input vector of parameters.

Solar cell surface mass:

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

where k_{sc} is the scaling factor of solar cells; k_{enc} is the scaling of solar cells encapsulation.

The MPPT has a relation between maximum power out of the solar modules and its area. And its efficiency could be described as a relation between efficiency of DC / DC convert and the efficiency of the tracking algorithm implementation.

$$m_{mppt} = k_{mppt}P_{solmax} = k_{mppt}I_{max}\eta_{sc}\eta_{cbr}\eta_{mppt}A_{sc} = \left(k_{sc} + k_{enc}\right)A_{sc},$$

$$\eta_{mppt} = \eta_{mppt\ dcdc}\eta_{mppt\ algo}.$$

Batteries mass is directly proportional to the energy they store and relates on the product between power consumption and night time duration.

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

Mass of the propulsion group

$$m_{prop} = k_{prop}P_{level}.$$

Total mass

$$m = m_{av} + m_{pld} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}.$$

Design stage assume that solar UAV would be developed for specific mission or application parameters with definition of date of the year, location with usage of main design parameters as wingspan, aspect ration and battery mass.

Validation stage could be performed for any day of the year in following way:

1) Define day of the year and location with flight height.
2) Calculate day and night cycle time.
3) Correct with weather conditions
4) Perform day analysis by using irradiance model.

V. CONCLUSION

First stage of conceptual design that was shown for solar airplane, it will introduce to user overall metrics and performances where user could select best mission specific design with considering overall efficiencies of each submodule.

Next stage will be framework to simulate and analyze performance of the aircraft at simulated flight during the day and at different location with changeable weather conditions. It will provide theoretical validation of design.

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Д. П. Карабецький. Проектування сонячних безпілотних літальних апаратів

У даній роботі, зроблено акцент на тому, що сонячний безпілотний літальний апарат, повинен використовуватися в контексті певних завдань (місії), з урахуванням цього була представлена загальна структура внутрішніх систем літака. Проаналізовано критерій при якому можливий безперервних політ на протязі доби. Виходячи з цього представлений підхід для розрахунку і моделювання характеристик безпілотного літального апарата, з можливість перезарядки під час денного сонячного циклу. Основними параметрами літака були виділені розмах і подовження крила і ємність батарей.

Ключові слова: проектування; безпілотний літальний апарат; сонячний перезаряджувальний літак; сонячна енергетична установка; сонячні панелі; сонячна енергія.

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Д. П. Карабецкий. Проектирование солнечных беспилотных летательных аппаратов
В данной работе, сделан акцент на том, что солнечный беспилотный летательный аппарат, должен использоваться в контексте определенных задач (миссии), с учетом этого была представлена общая структура внутренних систем самолета. Проанализирован критерий при котором возможен непрерывных полет в течении суток. Исходя из этого, представлен подход для расчета и моделирования характеристик беспилотного летательного аппарата, с возможность перезарядки во время дневного солнечного цикл. Основными параметрами самолета были рассмотрены размах и удлинение крыла и емкость батарей.
Ключевые слова: проектирование; беспилотный летательный аппарат; солнечный перезаряжаемый самолет; солнечная энергетическая установка; солнечные панели; солнечная энергия.

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