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Simulation Model of Solar Powered UAV

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Abstract. This article presents the results of work of power supply system of an unmanned aerial vehicle (UAV) powered by solar cells. The goal of work was to develop simulation model which allow us to calculate the flight time for the input assumptions. The UAV power supply system main elements are photovoltaic cells and batteries. In the model we also included energy consumption devices (electric motors, servos, steering and measuring devices) and electricity converters. Adapting the model to the proposed technical system required detailed identification tests of the components used in the project. For this purpose, identification tests were carried out on test stands, in particular, on photovoltaic cells and battery cells. The proposed simulation model combines knowledge in the field of aerodynamics, flight mechanics, electrical engineering, electronics, avionics and photovoltaic and astronomy supplemented with the characteristics of individual components identified in laboratory tests. This data allow us to prepare more accurate and real simulation model. The irradiation charts allowed for the analysis of how long the UAV will be able to flight for a given location and time and simulate different scenarios of flights. The case study UAV is TwinStratos (TS) – High Altitude Long Endurance Unmanned Aerial Vehicle (HALE UAV) designed by the team we are members of. TS is able to achieve 20 km and flight in the stratosphere.

Keywords. Model-Based Design, Solar energy, Energy harvesting, UAV, HALE

Introduction

Unmanned aerial vehicles (UAVs) are vehicles that perform a remotely piloted or autonomous flight. UAVs are currently used by more and more industries, mainly by the armed forces for observation and reconnaissance, which is why they are usually equipped with observation equipment [1-3]. The range of the UAV is usually limited. An important issue is the integration of electric motors and batteries [4]. The correct selection of drives and the type of battery allows for the extension operation of the UAV, but it is still not energy independent. Obtaining energy from the outside allows for energy autonomy, however, it is closely related to the location and time of flight [5]. The use of solar cells allow for increasing the flight duration but it also has a numerous limitations which have to be taken into account during designing the power supply systems [6-9]. Renewable energy technologies are certainly the direction in which UAVs will follow.

UAV’s power supply system can be built using many different storage sources. The current predominant battery energy storage technology for UAVs is the Li-ion battery [10]. The choice of batteries should take into account the numerous limitations of different types of battery cells. For UAV we have to take into account energy density, temperature range, performance, lifespan. Some types of battery cells will not be

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efficient for UAVs. Second thing which have to be consider during designing the power supply system for UAV is shape of the battery cell. We have 3 main shape of cells: prismatic, cylindrical and pouch. Cylindrical cell has good mechanical strength, specific energy, and energy density. Disadvantage of cylindrical cell is bad heat management. Prismatic cell has good mechanical strength, heat management, specific energy, and energy density but they have heavy shell, which leads to certain restrictions on the energy density of the battery pack. Pouch cells has good heat management, energy density, and specific energy. Disadvantage is low mechanical strength [11]. To improve the lifespan of the battery, increase safety, and control storage system, Li-Ion batteries have a battery management system (BMS). BMS control charging and discharging currents, uniform voltage of cells, and overall temperature of the system [12].

In order to analyze whether a given object is able to obtain energy autonomy, it is necessary to develop energy balance equations. The Model-Based Design (MBD) method allows to analyze the power supply systems, drive system, and control system, ensure energy surplus, reduce the weight of the system, and increase the payload. The complexity of the model should be adjusted to obtain satisfactory results [13]. The simulation model allows for quick and efficient introduction of changes [14,15].

The goal of our work is to develop simulation model of power supply system for solar powered High-Altitude Long Endurance (HALE) UAV. Our UAV - TwinStratos (TS) is two-fuselage airframe. TS is able to flight in the stratosphere and reach a ceiling of 20km (Fig.1) [16,17].

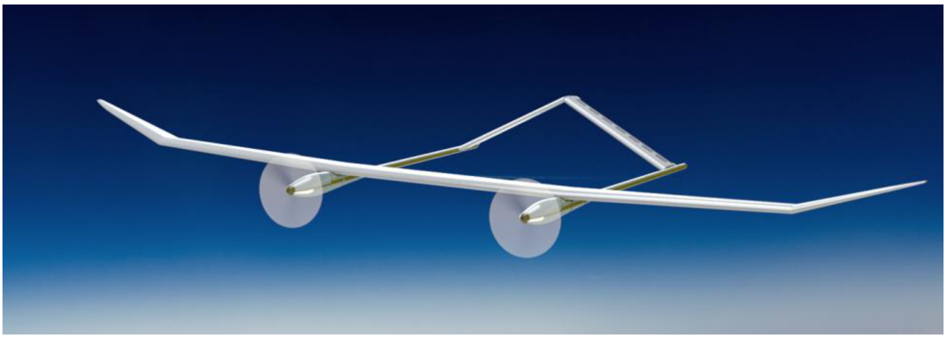

Figure 1. Designed TwinStratos.

1. Concept of power supply system

We want to based our power supply system on the flexible solar cells which allow us to place solar cells on the curved wing of UAV. During the work we have to take into account energy balance which allow us to calculate whether we have surplus or insufficiency of energy. The aim of energy efficiency analysis is to maximize flight duration and even ensure full energy autonomy. The solar powered power supply system consists of 4 main elements: solar cells, MPPT, BMS, and battery cells. Solar cells and batteries are sources of energy. MPPT and BMS act as energy converter and control function for the system.

The value of the power obtained from solar cells depends on several factors:

- Location and season – responsible for sun rays angle
- Flight altitude

- Atmospheric conditions: cloud cover, fog
- Air pollution, solar cell pollutants: smog, dust

In the initial phase, it is essential to read the information that limits the access of sunlight. The information is directly related to the location and seasons, due to which the duration of day and night is constantly changing (the exception is the equator). This input data allow us to obtain output data like time of insolation, produced energy, State of Charge (SOC) of battery cells (Fig. 2).

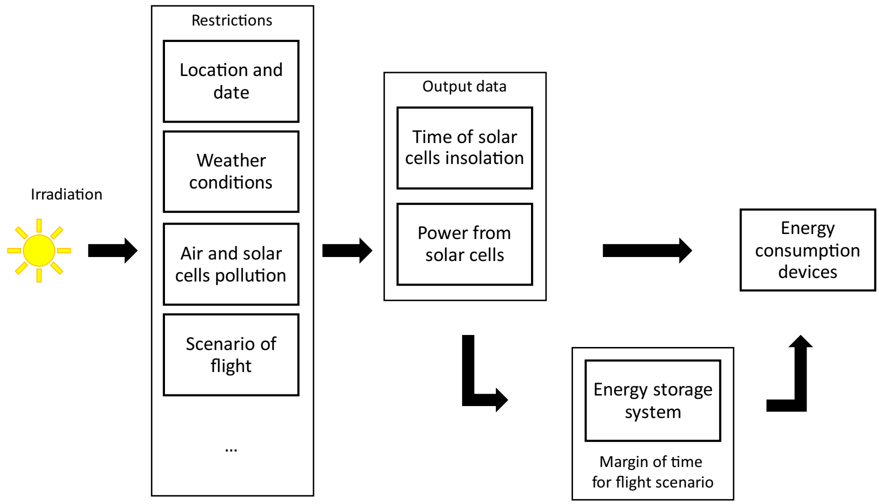

Figure 2. General diagram of operation of the power supply system.

The analyzed object – TwinStratos is powered by solar cells. Based on the construction data and flight parameters, the elements of the power supply system and the propulsion system were selected. The most important parameters of TwinStratos:

- Mass: 30 kg
- Wingspan: 12.6 m
- Area of the wings: 8.5 m^2
- Area of tail-plane: 2.2 m^2
- Area of the solar cells: 5.5 m^2 (350 pcs.)

UAV parameters allow us to plan how much space we have for solar cells, batteries and additional equipment. This data is also related with the weight of the power supply system and payload. Concept model take into account all this restrictions and allow for prepare the simulation model.

2. Simulation model

Developed simulation model can be divided into two parts. First one is related with outside parameters (location, weather, season of the year) which affect on energy produced by solar cells and energy storage by battery cells. Second part is related with energy consumption devices. Energy consumption devices are electric motors, servos, and all control and measurement systems (Fig.3).

We decided to chose the spring time as the moment to prepare the simulation. The reason is that spring time “give us” the 12 hours of the day and 12 hours of night. If we do not receive the surplus of energy we can change time of mission more to summer time. As location we choose Gliwice in Poland.

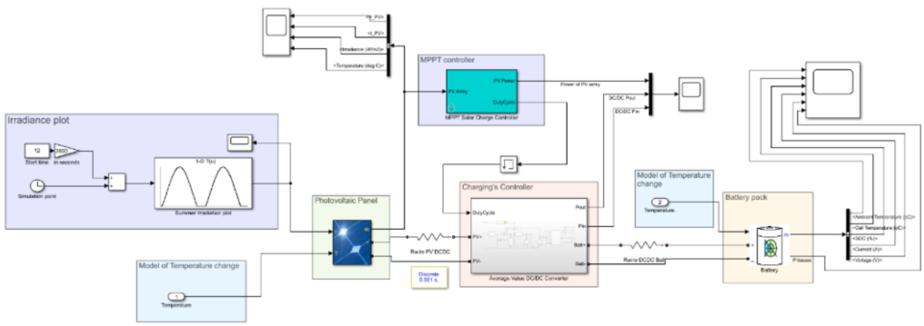

Figure 3. Simulation model of power supply system powered by solar cell.

To develop a complete simulation model of UAV power supply system, we need cooperation and knowledge in the field of astronomy and geography (to calculate the level of irradiation), metrology (to study the level of cloud cover), mechanics, aeroelasticity, electrical engineering, chemistry (chemical processes occurring in battery cells).

2.1. Solar cell

In our UAV we decided to use the SunPower MAXEON Ne3 solar cells. These solar cells generates 3,77 watts of power and ensure the 24,3% of efficiency. SunPower cells are flexible and provide the ability to assembly the solar cells on the UAV parts e.g. wings, center wing, tail-plane. To check if the solar cells efficiency is over 24% we prepared test stand which allow us to test solar cells in the STC (Standard Test Conditions) - irradiate with the power 1000W/m^2 in the temperature 25^{o}C (Fig.4).

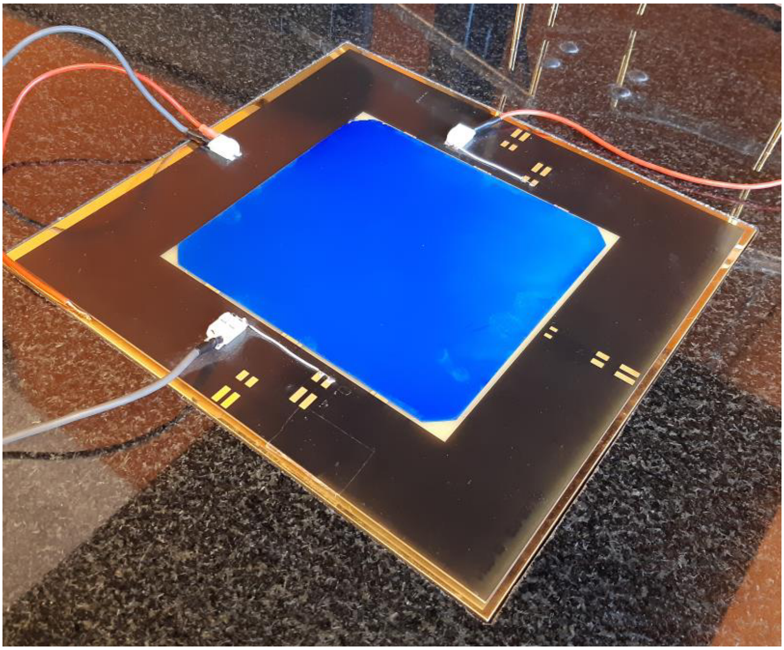

Figure 4. Test stand of solar cell.

I-V characteristic of solar cells allow us to know the exact parameters MAXEON Ne3 (Fig.5). On the test stand we have tested 25 pcs. of solar cells. All data was very similar. The difference between the tested solar cells was three tenths of a percent. In the Table 1 are data that we used in our simulation model. This values are the average value of the data obtained during the research.

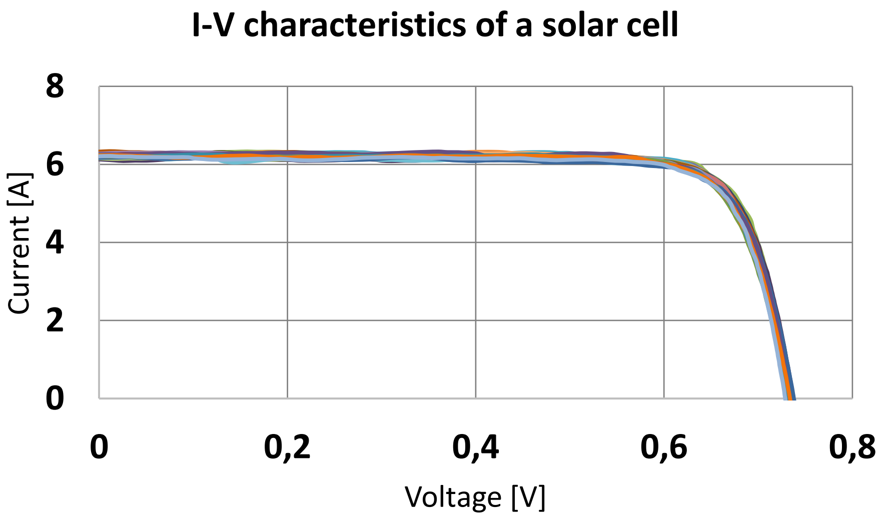

Figure 5. I-V characteristics of 25 pcs. of solar cells

Table 1. Data of solar cell used in the simulation model

Data	Value
V_{oc}	0.7332 V
I_{sc}	6.3304 A
V_{mp}	0.6265 V
I_{mp}	5.92 A
Series connections	70
Parallel connections	5
Efficiency	24.29 %

2.2. Battery cell

Initial parameters of the power supply system were determined on the basis of simplified analytical calculations. Thanks to them, the number of solar cells and batteries has been preselected. The power supply system is based on a voltage of 12S Li-Ion battery cells (44,4V). The battery capacity was initially determined as 63[Ah]. We decided to use the Samsung INR18650-35E (3500 mAh) battery cells. The main advantage of this battery cell is high energy density. Our battery pack 12S18P should allow us to complete our mission and flight for 24h.

Temperature range of Samsung INR18650-35E is from 0 to +50ºC for charging and from -20 to +75ºC for discharging. For TwinStratos outside temperature can be even in range of -55ºC if TS will rise to the stratosphere. To avoid dropping below the operating temperature, we have developed a special battery pack heating system and a housing of insulating material.

3. Power consumption

Developed UAV flight scenario took into account the basic operations – take-off, climbing, gliding. The scenario helps to define the UAV energy demand so that it is possible to determine the power needed for each stage of flight.

We received data connected with the power consumption from the detailed specification and aeronautical calculation results. The power consumption depends on: velocity of UAV, angle of attack, direction and velocity of wind. Aviation designers chose the best parameters, which allow us the most efficient conditions to realize the mission (Fig.6).

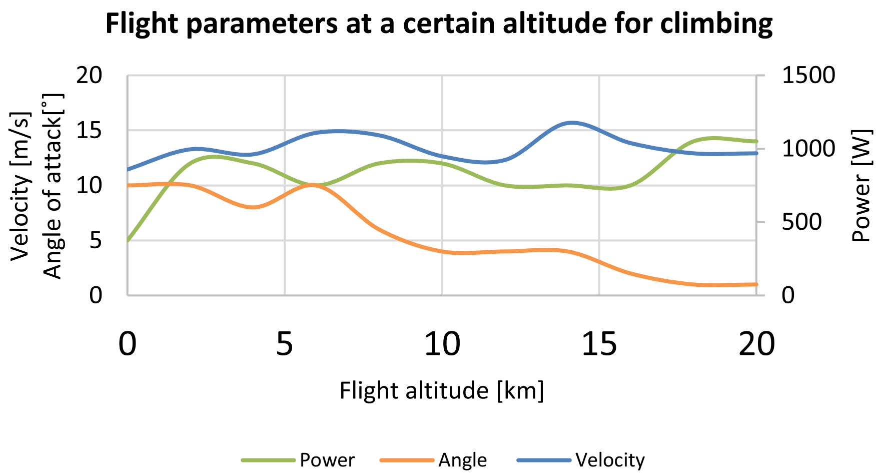

Figure 6. Flight parameters of climbing for TwinStratos

Power consumption devices were divided into two groups. First group is electric motors. BLDC motors need most power from power supply system. Depend on the scenario and stage of the mission electric motors need from 850W to 1200W. When UAV is gliding electric motor do not consume power. Second group of power consumption devices are all electronic devices on the UAV board e.g. navigation, steering, controlling, sensors. This devices works all the time. Our calculations let us know the value of power consumption. Average power needed by these devices is 50W. It is small part of this what motors need. Total value of power needed in scenarios is a sum of electric motors power and constant value of power needed by electronics. These data were use in the simulation model. Thanks to them we could check if the chosen capacity of the battery cells and the number of solar cells were appropriate. We have to receive the surplus of energy at day to charge the batteries and use this storage energy at night. Simulation model allow us to know if the results are similar to analytical calculation.

Developed calculations show that power supply system will be discharged with a low C-rated(C) currents of a 0.2 – 0.5C. This discharge range will not cause excessive heating of the battery cells and sudden voltage drops. Depending on the flight scenario and power consumption we can calculate that the time range of discharge without the solar energy will be between range from 2 to 5 hours (not including gliding).

4. Results

We prepared three simulations which are the most efficient in case of flying up to 24 hours. Initial assumptions was that we are taking-off in the sunny day at sunrise. Temperature at ground level is 15°C. Battery is charged to 100% SOC. Three scenarios which were prepared was based on 3 main steps:

1. Take-off and climb
2. Reach the altitude of:

a. 10km
b. 15km
c. 20km

and if necessary, flight at this height to finish gliding (next step) in the 24 hours form take-off.

3. After reaching the previous altitude start gliding to 1km height

All 3 scenarios are showing on the below Figures (Fig. 7-9). Flight speed, angle of attack and power consumption data are these same data like in the Figure 6. Descent speed varies with the height of gliding. Due to the slight differences between range of descent speed we took approximation of sink rate equal ~0.2m/s.

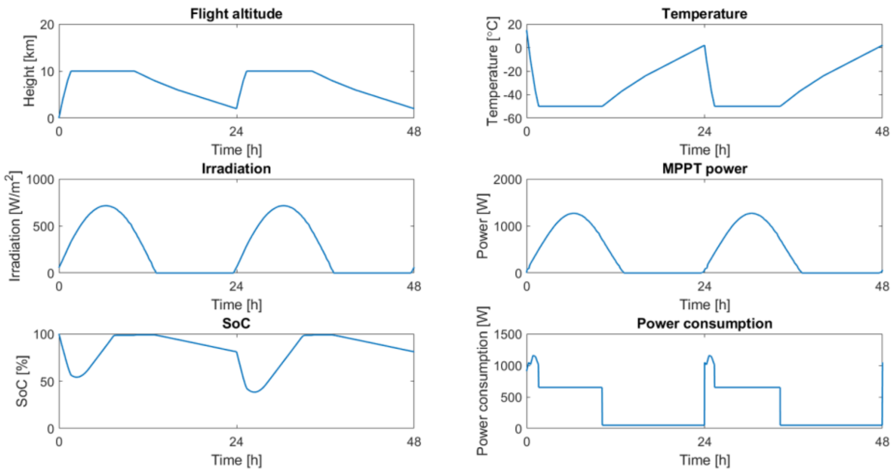

Figure 7. Scenario taking into account maximum altitude equal 10 km

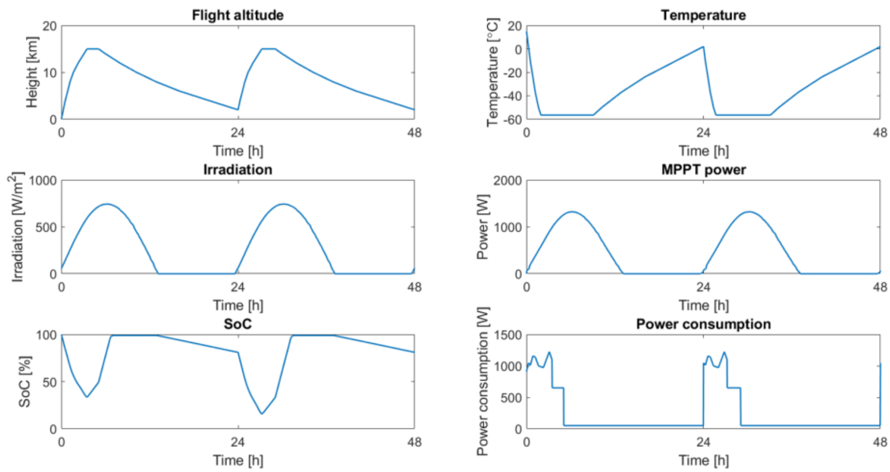

Figure 8. Scenario taking into account maximum altitude equal 15 km

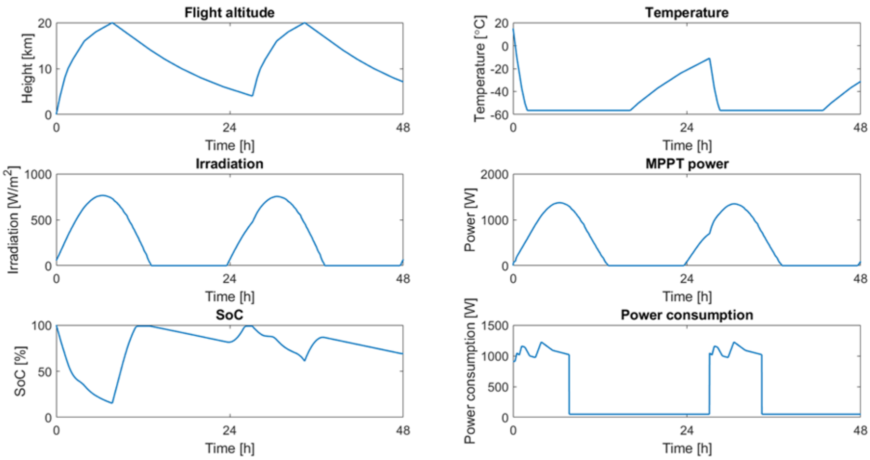

Figure 9. Scenario taking into account maximum altitude equal 20 km

5. Conclusions

Solar powered UAV is a transdisciplinary issue. The integration of all components, their selection and initial calculations requires the cooperation of many engineers from various industries. Collaboration in the R&D field will allow for the manufacturing of a solar powered UAV in the future.

Simulations allow us to show that continuous flight of TwinStratos is possible. Energy from solar cells in sunny spring day provide enough surplus of energy to flight over 24 hours. In our simulations the lowest SOC was around 20%. This value was achieved when the UAV was climbing to the highest altitudes. During gliding power supply system was able to charge the battery to full capacity. Simulation showed that for location of Gliwice in the spring equinox UAV will be able to flight 24 hours in perfect conditions. More advanced simulation model has to take into account cloudy weather and air pollutions. In march weather is not always sunny. Further works should included restrictions connected with the actual state of the weather.

Depend on the scenario, SOC is changed because of different power consumption. It is planned to develop more advanced flight scenarios and the most optimal flight trajectories using e.g. neural networks. Flight missions should take into account wind direction and power for flight path planning. Further actions are planned to develop a detailed simulation model. Using calculations connected with the geographical coordinates and time we will be able to know the irradiation for a specific day and place. We want to know the efficiency of the solar cells by develop research taking into account different type of lamination solar cells. Lamination of solar cells has two main purposes. Firstly improving the aerodynamics of the wing. Secondly protection and enhancement of the solar cells. Disadvantage of lamination is a reduction of the efficiency of solar cells. Tested laminated solar cells will enable us to obtain more accurate data for simulation model.

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