SÉRIE “Nauki techniczne”

[https://doi.org/10.52058/2695-1592-2021-1\(1\)-200-213](https://doi.org/10.52058/2695-1592-2021-1(1)-200-213)

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MULTI-OBJECTIVE OPTIMIZATION OF HYBRID ENERGY SYSTEM OF SOLAR RECHARGEABLE AIRCRAFT

Abstract. This article aims on the development of structural models of structural elements of the UAVs that incorporates solar energy system with the usage of hybrid energy systems using the multi-objective optimization approach. Proposed models taking into account the parameters of the optimization procedure. Simulation environment is built to check the behavior of a given UAV structure obtained during multi-objective optimization stage for objectives validation. Results of the article are obtained by using the proposed UAV design procedure with a verification based on the Simulink environment.

Keywords: hybrid energy system, solar power system, rechargeable aircraft, UAV.

Introduction. The availability of an alternative energy source in the form of solar panels can significantly increase the flight time compared to unmanned aerial vehicles (UAV), which use only batteries or fuel systems as the main source of energy. Solar-powered UAVs use solar panels to collect solar energy during daylight hours, which after conversion can be used to maintain flight and onboard systems.

In the case of an optimal aircraft design and appropriate environmental conditions, it is possible that there will be enough solar energy to charge the onboard energy storage system, in order to then use the stored energy during the night flight cycle and then enter the daytime phase. This is the so-called continuous

flight capability, in which the energy stored in the energy system is cycled during the night period and recharged during the daytime period.

UAVs using solar energy can be divided into three main types according to the nature of the choice of flight altitude [1, 2]:

- UAVs are designed for long-term high-altitude flight (HALE, High-Altitude Long-endurance). These include large-scale aircraft with a large wingspan (most often used as mobile telecommunications platforms);

- UAVs are designed for long-term flight at low altitude (LALE, Low-Altitude Long-endurance). This includes UAVs with a small wingspan (most often used for monitoring and collecting information);

- UAV with continuous flight capability. A special class of UAV that can perform continuous flight under specified restrictions (flight altitude, horizontal flight, aircraft size etc.).

The main differences between high-altitude flight and low-altitude flight are different weather conditions (rain, wind, cloud cover) and meteorological phenomena (thermal processes).

Analysis of recent research and publications and problem statement. UAVs with solar energy systems (SES) have been the subject of research for quite a long time [3, 4]. To date, many light UAVs have been developed, the main researchers in this field are the laboratory at ETHZ, Switzerland and the group of works [1, 2, 3]. In these works, the tasks of determining the possibility of continuous flight using solar energy are set, taking into account the features of the operating environment (height, width, date and time of flight, meteorological conditions), as well as the tasks of determining the main geometric parameters of the aircraft structure, the area of solar panels, in order to ensure the maximum duration of the flight, taking into account the user-specified parameters (payload, technological parameters, design parameters of the UAV structure).

One of the fundamental works on the topic of designing solar UAVs is [3]. In which the main goal is to design a solar UAV that will perform continuous flight using solar energy under the conditions of a given operating environment, time of year and place, as well as structural and technological parameters of the UAV. The paper focuses on three main models: UAV aerodynamics in steady-state horizontal flight, the UAV energy model with subsystems and payload taken into account, and approximating mass models. At the stage of conceptual design, only the search for solutions for three parameters of the aircraft layout is carried out: span, wing extension and weight of the UAV.

At the same time, the conceptual design is built around one criterion: that there is a sufficient energy reserve (energy balance), so that the aircraft can carry out continuous flight. Accordingly, an accessible solution is sought for it by iterating through or solving the inequality that will satisfy the energy balance for the implementation of steady-state horizontal flight.

Also, the paper [3] does not set a multi-criteria optimization problem, only one criterion is introduced, the search for the optimal configuration of the aircraft layout is not carried out, the UAV power consumption is not optimized (except for

the introduction of MPPT), as well as its performance indicators for the tasks set.

The task of developing a solar-powered UAV covers many areas of design and development [5]:

- aircraft design (aircraft structure, aerodynamics, flight mechanics);
- design of on-board power systems (power electronics, power supply, solar power plant);
- development of autopilot navigation software.

Problems that arise when designing a UAV:

– low energy reserves low energy reserves do not provide resilience to worse weather conditions (such as clouds or downdraft), nor do they allow night-time flights with payloads

– actual absence of payload;

– the high complexity of operation, low power consumption and significant weight of the UAV leads to sluggish flight dynamics, which requires advanced autopilot algorithms.;

– limited autonomy without environmental awareness. UAVs, and in particular solar UAVs, are affected by the environment. In addition to the terrain, local weather effects can quickly damage the aircraft (for example, due to wind gusts, precipitation, or thunderstorms) or reduce its performance (for example, through clouds).

The development of a solar UAV begins with the stage of specification of the use scenario and operating environment parameters, as well as available technological parameters, based on which the main structural parameters of the UAV are determined.

The result of the design will be the design parameters of the UAV, as well as the structure of the onboard systems.

Purpose and objectives of the study. The goal of the project is to develop an approach to designing a solar-powered UAV using solar panels based on hybrid energy system (HES), applying multi-criteria optimization methods and building a CAD system using a hybrid energy storage system. It is based on mathematical models and the conceptual design approach developed in [3] with the improvement of mathematical models of the energy system.

To achieve this goal, it is required to solve the following tasks:

– to develop models of structural elements of UAVs on the SES with the use of HES, taking into account the parameters of the optimization procedure, simulation models that allow to check the behavior of a given UAV structure, as well as formalize a set of criteria;

– perform a search for the optimal configuration of the UAV using multi-criteria optimization using genetic algorithms, using mathematical models of elements.

Results of research

4.1. Development of UAV structural elements models

Structurally, the UAV (Fig. 1), like a conventional aircraft, consists of a fuselage, wings and tail, which is also equipped with a SES, and also has a

certain layout scheme.

Fig. 1. *Layout of a glider aircraft*

According to the structure of the solar UAV consists of:

- UAV housing with taking into account its layout and wing profile;
- solar power system (solar panels, batteries, set of converters, MPPT), representing the energy part of the power complex;
- propulsion group (propeller, electric motor), which is part of the power complex to create thrust;
- flight and navigation equipment (flight controller, INS);
- radio and telemetry equipment;
- payload equipment for operating scenario.

Solar panels cover the upper part of the wing of the aircraft, which accordingly forms many different angles of incidence of sunlight on the solar modules.

When designing an unmanned aerial vehicle, an adapted version of the SES is used in terms of weight and size. Communication and integration of UAV subsystems with SEM subsystems is shown on the Fig. 2.

The SES provides solar energy conversion for the on-board network of the unmanned aerial vehicle and provides appropriate energy levels for the continuous operation of electrical equipment, including battery charging, as well as controlled energy support for the payload.

Fig. 2. Solar UAV structure

CAD is a system that contains a set of blocks, where each block represents a set of models, configurations, software and algorithmic software for solving the problem of conceptual design, as well as the ability to check the results.

Fig. 3. Structure of a solar UAV

The CAD structure and block relationships are shown in Fig. 3. Let's look at each block in more detail:

The mission subsystem. This block represents user input of the flight configuration, targets that will be set in front of the UAV to guide the design process for solving application problems. Parameters that this device uses: payload mass, power consumption, mission type, as well as the expected route type and critical points (flight from point A to point B, flight with or without return, circular flight, circular flight along waypoints, etc.).

Environment subsystem. This block is an input of information expected by the user about the environmental conditions in which the UAV will fly. Parameters that the device works with: the time of year, as well as the range of working dates for expected weather conditions (alternatively, use a historical database that will be used to make assumptions about weather conditions).

Solar energy subsystem. This block is a model of a solar power plant, including its own CAD system for calculating and designing adapted SES for the usage scenario. Input parameters: specification of requirements for the main nodes and subsystems of the SES (solar panels, MPPT or PWM, storage, load requirements, etc.). Output parameters: specification of the adapted SES (type and capacity of solar panels, connection configuration, expected node specifications, operating voltage range, and generating capacity).

Multi-purpose optimization subsystem. This block is a subsystem of multi-criteria optimization, in which the optimization process of many objective functions is started under specified constraints. Accordingly, the problem of finding the optimal UAV configuration is solved taking into account many factors, such as: flight specifics, environmental features and flight time, as well as additional user restrictions on weight, size, etc.

The aerodynamics subsystem. This block is a subsystem for calculating the UAV's aerodynamic component, such as drag and lift coefficients.

Flight dynamics subsystem. This block is a subsystem of the solar aircraft flight dynamics, which will be used to configure the validation system and calculate the flight mechanics parameters.

Aircraft layout subsystem. This block is used as a subsystem for calculating the layout.

Energy balance subsystem. This unit is a subsystem for calculating and evaluating UAV energy requirements in the context of available solar energy generated by SES.

Validation subsystem (simulation modeling). This is a set of UAV simulation models, including the aircraft's aerodynamic model, the navigation system configured for flight, the aircraft's energy model, layout, environment model, and available solar radiation model. Performs simulations and analyzes several days of flight of a configured UAV to generate a report on all onboard subsystems, including the power one.

Fig. 4. UAV design cycle with multi-objective optimization

The reference point is the concept of continuous flight, on this basis, the concept of energy balance, mass balance and energy balance: weight balance provides that the lifting force needs to compensate for the total weight of the aircraft and must be balanced; the energy balance represents some of the values of the available solar energy during the day that is going solar panels placed onboard, which should equal or exceed the value of the energy consumed at all power components of the aircraft.

A methodology for conceptual design is proposed in [3] is the following form:

1. an expression of the required UAV power is formed under the condition of continuous horizontal flight;
2. an expression of available solar energy is constructed during the day;
3. we have developed weight models that allow us to close the cycle of searching for an analytical solution to the design problem.

An extension of the concept of UAV design with SES is that the SES is complemented by a hybrid energy storage and storage system (HESS).

The UAV mass model, which takes into account all the main subsystems of the UAV, proposed in [3] has the following form:

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

where: m_{av} - avionics mass; m_{pld} - payload mass, m_{af} - aircraft body mass, m_{sc} , - solar panel mass, m_{mppt} - MPPT controller mass, m_{hes} - battery mass, m_{prop} - mass of the engine group.

HESS is introduced using rechargeable batteries and supercapacitors:

$$m_{storage} = N_{sc}m_{sc}k_{storage} + N_{bat}m_{bat}(1 - k_{storage})$$

where $k_{storage}$ is the mass distribution coefficient between the supercapacitors and the battery.

5.2. Multi-objective optimization and validation of rechargeable solar aircraft with hybrid energy storage

The task of determining the size of HES elements is to find the optimal number of HES elements, namely batteries (N_{bat}) and supercapacitors (N_{sc}), provided that the weight of HESS is minimized, as well as the requirements of the load, available power and limitations of system elements are met.

There are many studies of the size of the storage system, including on the basis of a bunch of batteries and supercapacitors [6, 7].

The HESS size optimization problem is to find the optimal combination of (N_{bat}, N_{sc})

Minimize $f(N_{bat}, N_{sc})$
under restrictions

$$\begin{aligned} N_{bat}P_{bat}^{max} &\geq P_{bat}(t) \\ N_{sc}P_{sc}^{max} &\geq P_{sc}(t) \\ N_{bat}P_{bat,one} &\geq P_{load} \\ N_{bat}P_{bat,one} + N_{sc}P_{sc,one} &\geq P_{load}^{max} \\ N_{bat}E_{bat,one} + N_{sc}E_{sc,one} &\geq E_{load}^{max} \\ P_{sc}^{min} &\leq P_{sc}(t) \leq P_{sc}^{max} \\ P_{bat}^{min} &\leq P_{bat}(t) \leq P_{bat}^{max} \\ SOC_{bat}^{min} &\leq SOC_{bat}(t) \leq SOC_{bat}^{max} \\ SOC_{sc}^{min} &\leq SOC_{sc}(t) \leq SOC_{sc}^{max} \end{aligned}$$

At each time step of the load model, $P_{load}(t)$ is the sum of the instantaneous power of the battery (P_{bat}) and the supercapacitor (P_{cs}) equal to the load power consumption:

$$P_{load}(t) = P_{bat}(t) + P_{sc}(t)$$

In turn, the instantaneous power can be expressed in terms of energy for a moment in time:

$$P_{sc} = \frac{E_{sc}(t) - E_{sc}(k-1)}{\Delta T}$$

Connection of energy with voltage:

$$\begin{aligned} E_{sc}(t) &= \frac{CV_{sc}^2(t)}{2} \\ E_{sc}^{min} &\leq E_{sc}(t) \leq E_{sc}^{max} \\ P_{sc}^{min}(t) &\leq P_{sc}(t) \leq P_{sc}^{max}(t) \end{aligned}$$

The maximum discharge/charge power can be expressed as follows (the maximum discharge/charge currents are determined by the characteristics of):

$$\begin{aligned} P_{sc}^{min} &= V_{sc} I_{sc}^{min} \\ P_{sc}^{max} &= V_{sc} I_{sc}^{max} \end{aligned}$$

To solve the optimization problem and synthesize a multi-criteria optimization subsystem for an automated design system, we used the method of the advanced Pareto evolution algorithm (SPEA2 [8]). This method has proven itself for solving this type of problem and is an improved version of the method with the same name.

The main goal of the SPEA2 algorithm is to support and search for solutions in the form of a pareto-optimal set.

The main differences between SPEA2 and SPEA are:

- an improved fitness assignment scheme is used, which takes into account for each person how much a person dominates and what they dominate over;
- included is a method for estimating the density of nearest neighbors, which allows you to navigate more accurately during the search process;
- new methods of archive reduction guarantee the preservation of marginal solutions.

Multi-criteria optimization was performed for the input parameters, which are presented in Table 1 with a reduced set of critical parameters.

Table 1

Design parameters

Start Time	1/August/2019
End Time	1/Sep/2019
Location	Kiev, Ukraine
Target height	100 m
Solar cell efficiency	0.18
Solar MPPT efficiency	0.98
SoC	Full
Charge/discharge Efficiency	0.98
Power Payload	0.5W

Solutions that were found using multi-criteria optimization of the subsystem are shown in Table 2.

Table 2

Aircraft parameters

Total weight	2.8 kg
Wingspan	3.4 m ²
Endurance	25h
Cruise power	17W
Solar Cells area	0.75 m ²
Battery capacity	150Wh
Speed (climb)	0.1 m / sec
Power (climb)	20W
Avionics Power	2.5 W
Payload power	0.5 W

The analysis tool developed in Simulink is used as input parameters for the characteristics of the flight environment, launch time, and UAV parameters. Modeling is performed using three basic subsystems:

- a model of solar radiation intensity, which is a model of the available energy provided by the sun;
- model of the power system that is used to calculate the current power distribution;
- UAV model that is used to calculate and track the actual flight parameters of the UAV.

The analysis tool is shown in Fig. 5. It represents the following types of blocks: input parameters and simulation models;

Analysis Tool Inputs:

- day of the year (start the simulation);
- placement parameters, such as longitude and latitude;
- parameters of the area of solar cells that are associated with the conversion of power from solar to electric energy;
- the battery bank parameters that are responsible for storing and providing additional energy, if required, can be configured with different battery charge states;
- UAV flight parameters, which represent the parameters of the designed aircraft, such as the required power for horizontal flight, the parameters of the UAV structure, the expected ascent speed and additional power required for climb, and the initial take-off height;
- a block of UAV power requirements that describes the required additional power for the system.

Fig. 5. Simulink UAV Analysis Tool (Simulink)

Location Irradiance - An illumination model that uses the Duffie & Beckman model, which can provide an estimated level of illumination depending on the time of year and current geographical location;

Irradiance to Power, which provides the ability to convert the actual light level using a solar cell array with certain parameters (the efficiency of solar cells and its configuration efficiency) and the efficiency of the MPPT block;

The **Battery Bank Power System**, which is an energy storage system, simulates a power management system that can make a decision based on the state of charge of the batteries to charge or not. Because the inputs control parameters like available power and required power for flight, and can provide a difference in power during the discharge phase. Because the internal state provides the current state of charge and excess energy;

The **Flight Controller** is the most complex unit, it is configured with flight parameters and provides the logic for using the ascent strategy (keeping altitude or increasing energy as potential energy), taking into account the current charging status. Provides both current altitude and power.

Time simulations are performed using a 48-hour time scale to test possible continuous flight capability, with a detailed view of all internal states of subsystems at a selected location in Kiev, Ukraine.

The simulation parameters were chosen for an average UAV that could provide a theoretical continuous flight, the location in Kiev, and the date was used as not the best day duration, but during the summer. The full set of parameters is shown in Table 4.4 below.

Table 3

Modeling input parameters

Start time	1/Aug/2019 10:00
Location	Kyiv, Ukraine
Simulated Altitude	100m
Solar cells area	0.6 m ²
Solar cells efficiency	0.18
MPPT efficiency	0.98
Battery initial SoC	168Wh
Battery Capacity	168Wh
Charge/Discharge efficiency	0.98
Level flight power	12W
Velocity (climbing)	0.1 m/s
Power (climbing)	14W
Power Avionics	2.5 W
Power Payload	0.5 W

From the simulation results, we could achieve that continuous flight is possible for these parameters. In Fig. 4.10 compares the available power (represents the power received from the solar cells after conversion to electric), used with power (the power required for all aircraft systems connected to the grid, such as avionics and payload) and power charge (which represent the power flow from and to the battery). Fig. 5 shows the state of charge of the battery, which shows the current capacity.

Fig. 0.**Error! Bookmark not defined.** – Comparison of available and used battery charge energy

This simulated flight over time could be divided into several stages:

Phase 1: Initial launch and daylight flight.

At this stage, the simulation started with a battery with full capacity, it is shown in both Fig. 4-5, charging power and SoC battery, there are straight lines here. This means that for this simulated day and for this start time, it is possible to start with a less initial SoC, where we could additionally recharge the battery at full capacity at night.

Phase 2: Fly at night.

Night flight time is due to the fact that it is not possible to charge the battery, this type of flight is completely dependent on the availability of energy from the battery. After simulating the time at this stage, we could analyze the available power reserve after the night end.

Stage 3: Continuous flight.

The next step is the ability to provide continuous flight, at this stage there may be few indicators to achieve this. First of all, this is not a preliminary stage, but a second one, at this stage in daylight, the battery should be charged enough for the upcoming night flight. In the current simulation, it is shown as a straight horizontal line between 21h and 28h flight. In this case, the battery can be charged quickly enough, even to the maximum solar radiation.

As a result, this simulation tool could create a "real" picture of flight efficiency, with some ideas where we could improve some design parameters or how we can use excess power, for example, as shown between 21 and 28 hours of flight, is excess power. This power can be saved by increasing the altitude, or it can be used by additional payload functions.

Conclusions. The structure of solar-powered solar power plants for UAVs (which includes a hybrid energy storage system based on rechargeable batteries and supercapacitors) has been developed, the parameters of which are determined as a result of solving an optimization problem, which makes it possible to increase reliability, increase flight time, and increase the peak maximum power of the UAV power system.

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