NUMERICAL MODELING OF AN ENERGY MANAGEMENT SYSTEM FOR A UAV DESIGN POWERED BY PHOTOVOLTAIC CELLS

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Abstract: *UAVs are increasingly used for tasks such as surveillance, monitoring, and inspection, but their effectiveness is limited by their energy storage and generation capacity. Therefore, optimizing the energy system of a solar-powered UAV is crucial to extend its range and duration, and numerical modeling can help achieve this goal.*

In this particular study, researchers focused on a solar-powered UAV with a 151 cm wingspan. They used three different energy sources to power the UAV, and then simulated its performance using numerical modeling. The aim was to find the optimal energy source for each stage of flight and ensure a steady and efficient power supply throughout the entire mission.

The findings of this study have important implications for the development of new UAVs with exceptional performance.

Keywords: *numerical modeling, algorithm, photovoltaic cells, fuel cell, UAV, drone, battery*

1. INTRODUCTION

Over the past decade, the use of unmanned aerial vehicles (UAVs) in military operations has revolutionized the way we think about warfare. These innovative aircrafts, equipped with complex power systems fueled by photovoltaic cells, have proven to be highly effective tools for conducting operations in a more efficient and less risky manner [4]. As technology continues to develop, the civilian world is taking notice and exploring new uses for these versatile machines [3].

With the ability to fly missions at higher altitudes and greater distances than ever before, UAVs have expanded beyond their initial military application [1]. They are now being used in a wide range of civil and commercial industries, from real-time traffic monitoring and wireless coverage to precision agriculture and civil infrastructure inspections [5].

Conventionally, the energy required to power all the electrical consumers on board a UAV is provided by a battery. The limitations of a flight mission are determined by the amount of energy stored or produced on board the aircraft prior to takeoff [2]. Increasing the number of battery cells can extend the duration of electric power supply, but the added weight significantly limits the flight range.

A constructive solution to mitigate these operational limitations is the implementation of a photovoltaic system on the surfaces of the UAV. This way, solar radiation absorbed by the photovoltaic cells is converted into electric energy and transmitted to both consumers and the battery, enabling sustained flight throughout the day [6].

This paper outlines the way in which the energy system of a UAV, whose main energy source is photovoltaic cells, provides the necessary power for all consumers . In this regard, an analysis was conducted by simulating a long-term aerial monitoring mission lasting 24 hours. The numerical modeling presented was generated using the MATLAB/SIMULINK computational tool, in which the initial settings considered were the technical characteristics of the UAV developed in ing. Buzdugan Andrei's doctoral thesis [9].

2. THE MATHEMATICAL MODEL OF THE ENERGY MANAGEMENT SYSTEM

The theoretical developments made during this research are directly used in the development of the software integrated in the energy management unit. Therefore, on-board the UAV, the supply of electrical consumers is controlled through the energy management system. The C++ code was developed based on (1)-(8) and (9)-(14), and was implemented in the PIC microcontroller using the mikroC PRO for PIC application [10]. The resulting files were loaded onto the PIC16F887 microcontroller using a PICKit 3 programmer [8].

$$\frac{d_v}{d_t} = \frac{T\cos\alpha}{m} - \frac{D}{m} - g \cdot \sin\gamma \tag{1}$$

$$\frac{d_\gamma}{d_t} = \frac{T\sin\alpha}{mv} + \frac{L}{mv} \cdot \cos\psi - \frac{g}{v} \cdot \cos\gamma \tag{2}$$

$$\frac{d_\varphi}{d_t} = \frac{L}{m \cdot v\cos\gamma} \cdot \sin\psi \tag{3}$$

$$\frac{d_x}{d_t} = v \cdot \cos\gamma \cdot \cos_\varphi \tag{4}$$

$$\frac{d_y}{d_t} = v \cdot \cos\gamma \cdot \sin_\varphi \tag{5}$$

$$\frac{d_h}{d_t} = v \cdot \sin\gamma \tag{6}$$

$$L = \frac{1}{2} \cdot \rho \cdot v^2 \tag{7}$$

$$D = \frac{1}{2} \rho \cdot v^2 \cdot S_w \cdot C_D \tag{8}$$

in which:

- x, y and h represent the position of the UAV (N, E and height), relative to the terrestrial axis system;
- v - speed of the UAV;
- m - total mass of the UAV;
- g - gravitational acceleration;
- angles: Ψ - roll angle, φ - yaw angle and γ - pitch angle;
- forces: T - traction force, L - lift force and D - drag force.

In (7) and (8) Sw is the area of the wings, CD and CL are the drag and lift coefficients, and ρ is the air density coefficient.

The solar radiation for a terrestrial system, marked by P_s and expressed in W/m^2, is calculated using (9).

$$P_s = I_{SC} \cdot \tau \cdot \sin(H_s) \tag{9}$$

in which:

- I_{SC} - current intensity generated by photovoltaic cells;
- τ -transmission factor.

A detailed form of solar radiation is obtained by describing the intensity of the current generated by the photovoltaic cells and the elevation angle of the sun in the form of (10) and (11).

$$I_{SC} = I_0 \cdot \left(\frac{1 + \varepsilon \cdot \cos(2\pi(n-4)/365}{1-\varepsilon^2}\right)^2 \tag{10}$$

$$\sin(H_s) = \sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\delta \cdot \cos(\pi - \pi \cdot t/12) \tag{11}$$

In (10) and (11) the following notations were used:

- I_0 - constant value of solar radiation (1367W/m^2);
- ε - represents the earth's eccentricity ratio (≈0.01671);
- n - represents the number of the day of the year;
- Φ- represents the latitude of a location;
- t - solar time of a location;
- δ- the declination angle of the sun.

A first step in this process consists in representing the solar radiation P_s in all three directions IXb, IYb and IZb, in the positive and negative sense. Depending on the azimuth angle and the elevation angle of the sun, the intensity of solar radiation in the three directions is represented in the form of (12), (13) and (14).

$$I_{Xg} = P_S \cdot \cos H_s \cdot \cos A_s \tag{12}$$

$$I_{Yg} = P_S \cdot \cos H_s \cdot \sin A_s \tag{13}$$

$$I_{Xg} = P_S \cdot \cos H_s \cdot \cos A_s \tag{14}$$

3. EXPERIMENTAL DETERMINATIONS

To corroborate the accuracy of the mathematical model of the energy management system, a sequence of experiments were conducted on an electric-powered UAV using photovoltaic cells. To ensure comparable operational circumstances throughout various flight phases, a parameter-recording test rig was utilized.

The examination of the data obtained from ten samples collected during the experiment facilitates the identification of an approach to optimize and streamline the energy system of a solar-powered UAV utilized for aerial surveillance missions. As depicted in Fig. 1, the configuration comprising the UAV, the testing platform, and the evaluation apparatus is presented.

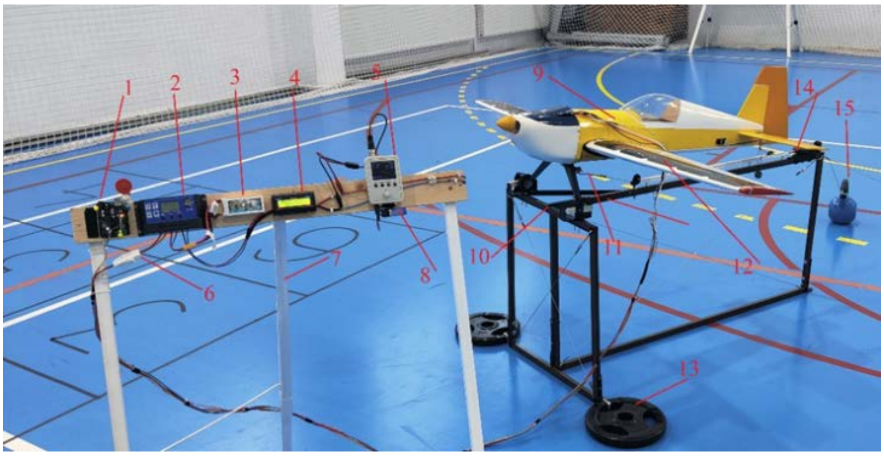

FIG. 1 The experimental setup for determining the functional parameters of a solar UAV

The main components used in the experiment are numbered from 1 to 15 and represent the following:

1 – Ardnuio UNO R3 [7]; **2** – MPPT device with microcontroller PIC16F887 [8]; **3** – battery pack; **4** – device for measuring the consumed power; **5** – oscilloscope; **6** – electrical circuit switch photovoltaic system; **7** – test bench; **8** – battery power oscilloscope; **9** – UAV; **10** – stand for testing UAV; **11** – thrust thrust; **12** – photovoltaic cells; **13** – holding weight in fixed position; **14** – traction force measuring device; **15** – anchor weight.

During the experimental testing of the UAV on the designated test stand, a simulated aerial monitoring mission was conducted, during which ten measurements were taken to determine the performance characteristics of the propulsion system and energy consumption. For each level of rotation speed, varying values of current intensity and voltage were recorded using a power measurement device. The measurement of the traction force of the UAV entailed the monitoring of propeller speed and weight exerted on the digital scale. Upon the completion of the experiment illustrated in Fig. 1, an array of parameters was acquired, providing a comprehensive depiction of the energy system's operation. These data are presented in Table 1.

Table 1. Experimental parameters determined during UAV testing on the stand

Sample no.	RPM	I	V	Thrust (g)
1.	1293	0.22	11.29	71
2.	2253	0.49	11.28	110
3.	3278	1.13	11.26	165
4.	3925	2.03	11.23	212
5.	4569	3.24	11.19	405
6.	5459	5.67	11.12	518
7.	5924	7.23	11.05	590
8.	6364	9.3	10.97	620
9.	6912	11.95	10.88	1018
10.	7204	13.81	10.82	1210

Upon examination of the data provided in Table 1, several key findings have been uncovered. Firstly, it has been determined that the voltage supplied to consumers remains constant throughout the entirety of the operation. Additionally, it has been observed that the electric current intensity and thrust force increase simultaneously with the propeller speed.

Based on the aforementioned findings, the graph displayed in Fig. 2 has been created to demonstrate the relationship between power consumption and electric motor speed. As the propulsion system speed increases, there is a concurrent increase in traction force.

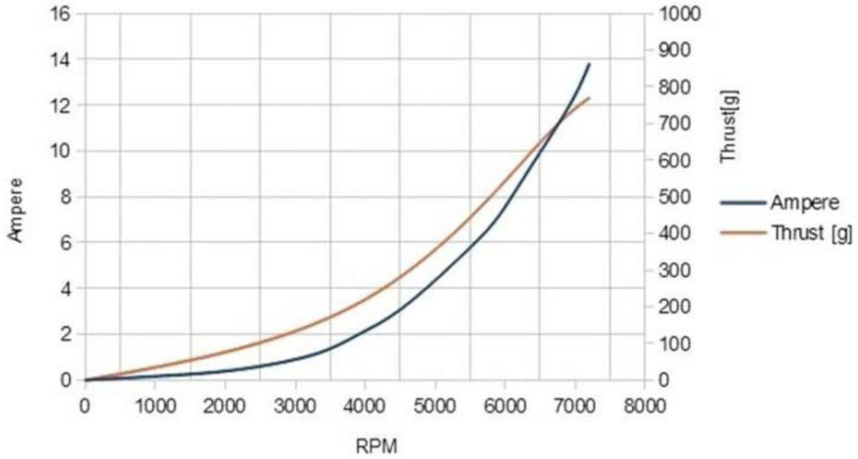

FIG. 2 The graphical representation of the experimentally obtained parameters in the testing phase

The obtained experimental data play a pivotal role in commencing the numerical modeling stage, wherein the operation of the energy system and its efficacy in furnishing power to electrical consumers to fulfill the mission objectives are scrutinized.

4. NUMERICAL MODELING OF THE ENERGY MANAGEMENT SYSTEM

The numerical model, formulated based on equations (1)-(14), proves to be versatile, enabling its use in both constant altitude flight missions and those with variable ceilings across different stages. In order to generate a set of reference data for the actual operation of the UAV, the MATLAB computational tool [9] was used. Two distinct scenarios were considered, corresponding to the UAV's power supply being furnished by varying numbers of electrical sources. Subsequent simulations were conducted, focused on a 24-hour flight mission profile, whose stages are illustrated in the schematic presented in Fig. 3.

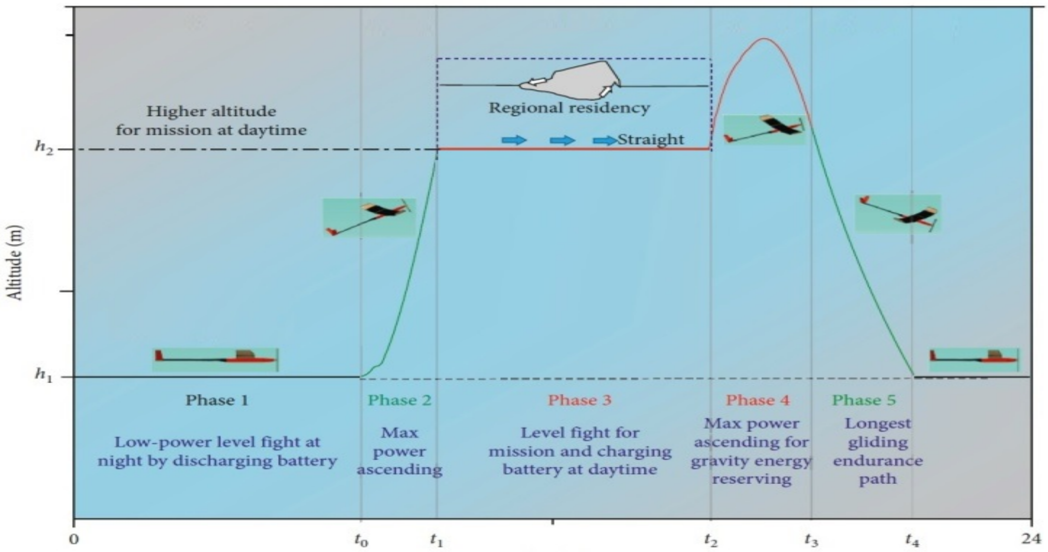

FIG. 3 Flight diagram for a UAV powered through photovoltaic cells

The difference between the two cases represents the number of electrical sources used to power the consumers. The selected options are:

- Photovoltaic cells, battery pack, and fuel cell;
- Photovoltaic cells and battery pack.

The numerical model was implemented in the MATLAB application, which has been widely used for various terrestrial or aerial simulations. The source code is a personal contribution and not a commercially purchased product.

Thus, there is the possibility of modification/adaptation for different types of photovoltaic-powered UAV's. The program is not limited to a restricted set of cases as is the case with many commercial programs.

4.1. Case 1 (photovoltaic cells and battery pack)

The solar UAV performs an aerial monitoring mission, in which the electrical consumers are powered by a battery and a photovoltaic system.

Flight mission data:

- Maximum flight altitude: 3000 m;
- Aerial monitoring altitude: 2100 m;
- Cruise altitude: 1600 m;
- Time period: 24h - July 15, 2022;
- Flight stages: 5;
- Weather conditions: normal for this period (clear sky);
- Solar radiation interval: 06:17-19:50.

Technical data on the UAV:

- Maximum power generated by the photovoltaic system: 180 W;
- Maximum power generated by the battery: 200 W.

Drawing on its own management system's numerical model, the solar UAV reached a maximum altitude of 3000 m, as shown in Fig. 4. During the ascent, the electrical consumers were supplied with power from the two energy sources in a differentiated manner determined by the calculation algorithm.

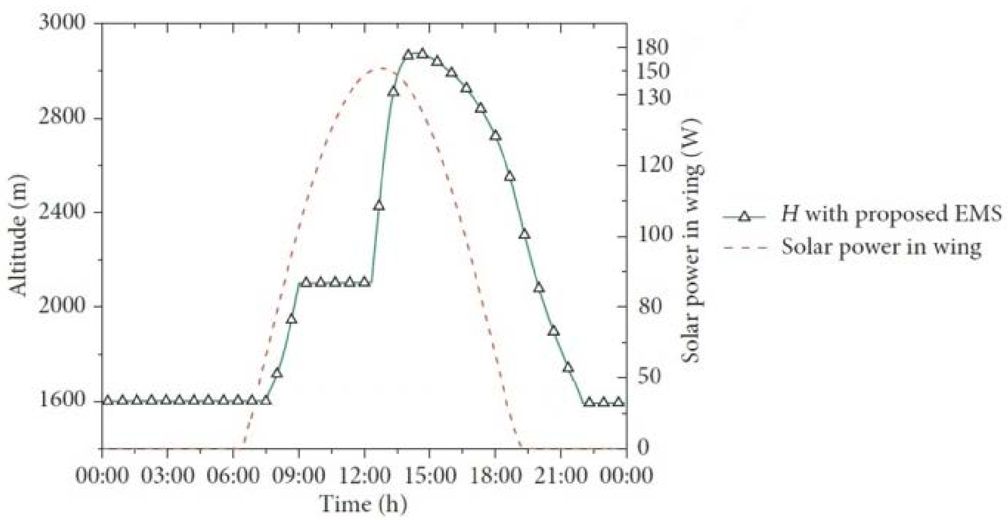

FIG. 4 Determination of the maximum flight altitude in the case of using only two energy sources

The graph depicted in Fig. 4 reveals a clear correlation between the performance of the photovoltaic system and the ascending flight of the UAV. As the sun rises and the photovoltaic cells start generating electricity, the propulsion system experiences an additional power consumption.

However, the energy required to power the system is simultaneously supplied by the two energy sources. The photovoltaic system needs to generate a maximum of 56 W while the ascending flight to a height of 2930 m requires 180 W.

The energy management system ensures the power difference by utilizing the accumulator battery. Throughout this time interval, the energy transfer to the consumers is maintained by both electrical sources.

4.2. Case 2 (photovoltaic cells, battery pack, and fuel cell)

The flight mission in the second case is conducted under the same conditions as in the first scenario, with the exception that the electrical consumers are powered by three energy sources: a photovoltaic system, an accumulator battery, and a fuel cell with a total power generation capacity of 120 W.

Moreover, Fig. 5 displays a constant power output by the fuel cell during the entire operation period. The accumulator battery supplies power to the electric consumers between 00:00-01:30, after which the fuel cell takes over to assist with energy transfer until the photovoltaic system is able to provide the required power.

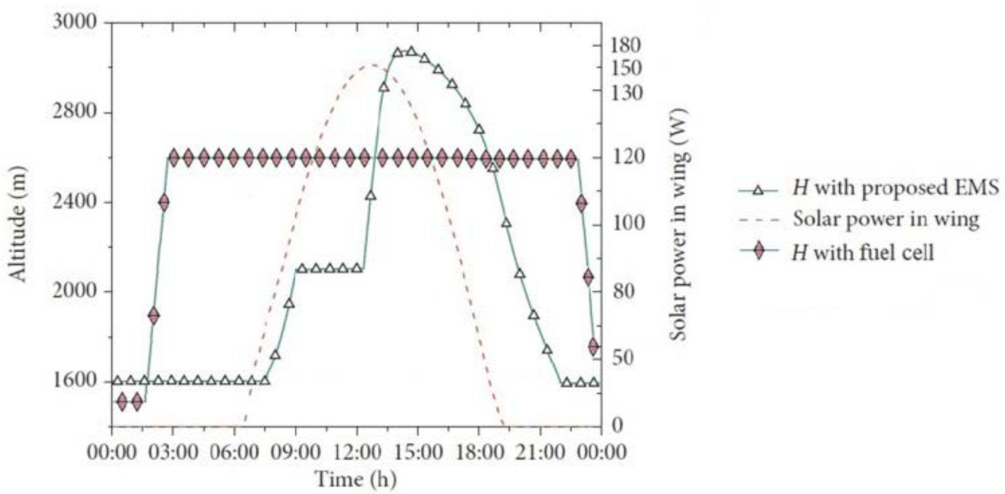

FIG. 5 Graphical representation of the power supply system using three electrical sources

The graph presented in Fig. 5 demonstrates that the fuel cell operates steadily at maximum capacity, and the following observations can be made:

- the fuel cell provides 75 % of the power required by the propulsion system.
- over the entire flight mission, the fuel cell generates 93.75 % of the total electrical energy.

By analyzing the graphs in Fig. 4 and 5, it is clear that using three electrical sources leads to a high efficiency in powering the electric consumers.

The importance of incorporating a fuel cell into the power system is particularly evident when the solar radiation is low and cannot provide sufficient power for the propulsion system. In this scenario, the accumulator battery may become depleted after prolonged use.

CONCLUSIONS

In order to achieve a solar UAV capable of high-altitude and long-distance missions, it is necessary to power the electrical consumers through multiple energy sources. An energy management system, such as the active command system (APM), can switch between energy sources to ensure a constant power supply to the electrical consumers throughout the flight duration. By combining photovoltaic cells with a battery and a fuel cell, the UAV can be powered for longer periods of time and at various times of the day. The power supply is provided in a mixed or individual mode from the three sources depending on flight conditions and propulsion system requirements.

A proposed technical solution involves developing an energy management system with an integrated MPPT function that selects the optimal energy source and supplies all electrical consumers in the most efficient way possible. The mathematical algorithm takes into account solar radiation levels, battery charging capacity, and fuel cell status to determine the best energy source for powering the consumers. Energy source switching is controlled by the algorithm to ensure uninterrupted and efficient power supply.

During the flight mission, energy consumption and battery charging vary depending on the altitude and propulsion system requirements. Flying at a constant altitude involves a uniform power consumption, with energy generated by the photovoltaic system used to power the electrical consumers and charge the battery. If the UAV maintains a constant flight altitude below 2000 m and the maximum power consumption of the propulsion system does not exceed 50 W under normal solar radiation conditions, then the propulsion system can be powered exclusively by energy generated by the photovoltaic cells.

During the ascent, all the power generated by the photovoltaic system is transmitted to the propulsion system without charging the battery. During the descent, energy consumption is minimal and the power generated by the photovoltaic system is used to power the electrical consumers and charge the battery.

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