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Solar Cells' Characteristics of Unmanned Aerial Vehicle Under the Coupling Influence of Flight and Environmental Factors

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Abstract: This paper investigates the power generation characteristics of solar cells mounted on unmanned aerial vehicles (UAVs) under the coupled influence of flight conditions and the surrounding environment. Firstly, the study reveals that the voltage, current, and power output of the solar cells undergo consistent temporal variations throughout the day, primarily driven by voltage fluctuations, with a peak occurring around noon. Secondly, it is observed that the cells' performance is significantly more influenced by temporal variations in external light intensity than by temperature changes resulting from variations in flight speed. Finally, the study finds that the impact of flight altitude on the cells' performance is slightly more pronounced than the influence of temporal variations in external light intensity.

Keywords: unmanned aerial vehicle (UAV); solar cell; performance; flight altitude; flight speed

1 Introduction

With the continuous advancement of technology, solar-powered unmanned aerial vehicles (UAVs) have found a wide range of application scenarios in fields such as reconnaissance, mapping, firefighting, rescue, and communication [1–2]. One of the key challenges faced by solar aircraft applications is meeting the energy demands for long-endurance missions. Consequently, researchers are continually seeking methods to enhance flight efficiency and duration [3–4]. The power generation capability of solar cells in UAVs is influenced by various factors, including flight strategy [5–6], flight time and altitude [7–8], as well as meteorological conditions [9], etc. Research suggests that UAVs can increase the solar power captured by their wings by adjusting their flight attitude, thereby enhancing solar cell power generation [10–11]. Since power generation peaks around noon, UAVs prioritize using solar cell output power for climbing and charging, storing solar energy in the form of gravitational potential energy; at night, they glide at a maintenance power level to maximize continuous flight duration [12–14]. Compared to high-altitude flight, which is less affected by atmospheric drag and cloud cover, low-altitude flight has a more complex impact on solar cell performance [15]. The challenging meteorological phenomena at low altitudes, such as clouds and wind, pose significant obstacles to understanding their impact on solar cell power generation in UAVs [16]. Early research indicated that solar radiation intensity and the temperature of photovoltaic

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components are factors affecting solar cell performance on aircraft [17]. Further research found that as ambient temperature increases, the nonlinear rise in cell temperature leads to a decrease in cell efficiency [18]. Additionally, research has shown that solar cell efficiency is directly proportional to environmental wind speed and inversely proportional to the angle of incidence of environmental wind [19]. Existing research predominantly focuses on the impact of individual factors on the performance of solar cells, often overlooking the coupling effects among these factors. However, in practical flight scenarios of solar-powered UAVs, factors such as light intensity, altitude, and speed frequently change simultaneously and interact in complex ways. For example, variations in flight altitude can affect atmospheric transmittance, thereby altering the amount of solar radiation received by the solar cells. Simultaneously, changes in flight speed can influence the temperature of the cells through air friction, which in turn affects their performance. As a result, studies that consider only a single factor fail to comprehensively capture the performance variations of solar cells under actual flight conditions. Such studies are inadequate for informing the optimization of solar-powered UAVs' flight strategies. Therefore, a thorough investigation into the coupling effects of these factors is crucial for optimizing solar cell performance and enhancing flight endurance.

To this end, this paper studies the power generation characteristics of solar cells mounted on UVAs under the combined influences of flight conditions and the environmental factors. The investigation encompasses the following parameters: the temporal dynamics of the relationship between the voltage, current, and power of a cell throughout a diurnal cycle, as well as the patterns of variation in cellular voltage, current, and power when subjected to concurrent alterations in time and flight velocity, or time and flight altitude. This study not only addresses the research gap regarding the coupling effects of multiple factors but also provides significant theoretical support and optimization strategies for the practical flight operations of solar-powered UAVs. By rationally adjusting the combination of flight altitude and speed under different environmental conditions, the charging efficiency of the batteries can be effectively improved, thereby extending flight duration. These findings demonstrate substantial practical value for real-world applications.

2 Experimental Principle and Setup

The equipmental setup includes a self-made unmanned aerial vehicle, semi-flexible solar cells, a high-precision high-speed voltmeter and ammeter, lithium batteries, and a portable charger, as shown in Fig. 1(a). The UAV is constructed with a wooden airframe and frame, a flight control system, motors, and electronic speed controllers. It features a twin-engine twin-vertical tail conventional layout, and the wing section is a flat-camber design. The solar cells are mono-crystalline silicon cells produced by SunPower of the United States, with the model number GEN5. They have a conversion efficiency of 23.2%, a rated voltage of 0.59 V, a power output of 6W, and an area of 261.5 cm^2. The voltmeter and ammeter are the iMetr T3 produced by Italy's IME company. The lithium battery is produced by Shenzhen Zhongli Energy Technology Co., Ltd. with a capacity of 5600 mAh. The portable charger is the HT-DX151 model produced by Shenzhen Qiaowei Power Co., Ltd.

Fig. 1(b) illustrates the experimental schematic. Six series-connected solar cells are installed on the wings of the UAV; the voltmeter and ammeter measure the output voltage, current, and power of the cells; the signals are stored on a memory card; the portable charger supplies power to the voltmeter and ammeter; the generated electricity from the solar cells is stored in the lithium battery. The assembled solar-powered UAV is shown in Fig. 1(c).

Fig. 1(d) depicts a schematic diagram of a UAV flying a complete circle along a predetermined trajectory (1→…→7→1), while the entire loop taking approximately 60 s to complete. The phase transitioning from point 4 to 5 is controlled by the flight control system, which maintains the UAV at a preset altitude and speed. Conversely the remaining phases are manually operated by the pilot resulting in fluctuations in altitude and speed. During the experiment, the relationships between the voltage, current, and power generated by the solar cells were recorded and analyzed, taking into account factors such as flight altitude and flight speed.

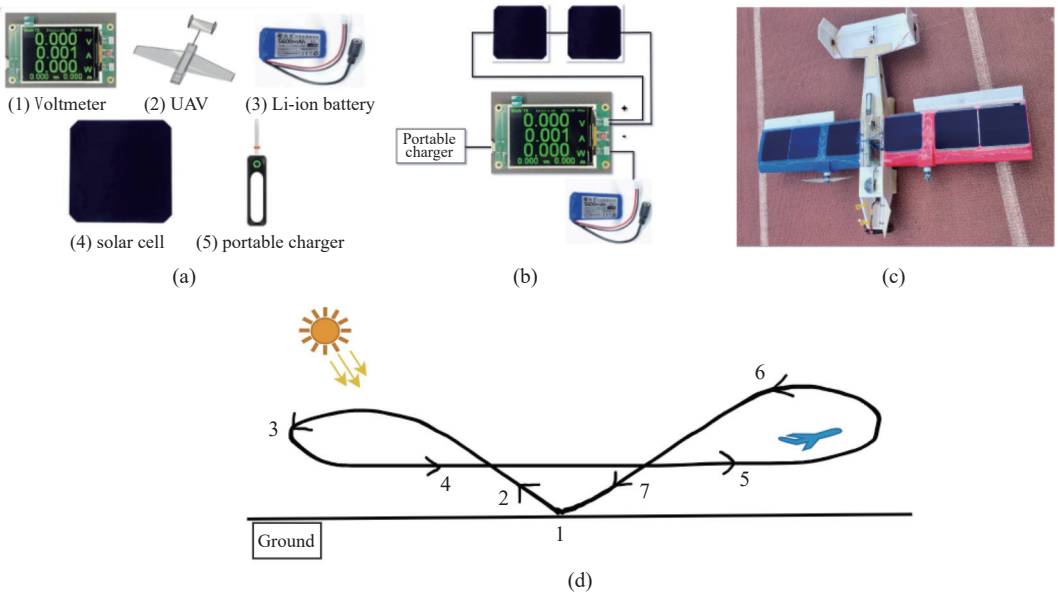

Fig. 1 Schematic of experimental setup and flight process: (a) experimental setup; (b) experimental schematic; (c) experimental aircraft; (d) flight trajectory

3 Experimental Results and Analysis

3.1 Data Analysis for a Full Day

On August 24, 2024, an experiment was conducted in Gongqing City, Jiujiang, Jiangxi Province, to investigate the impact of flight time (t) on the performance of photovoltaic components. The weather conditions during the experiment included a highest temperature of 36℃, a lowest temperature of 27℃, a southeast wind with a force of 2, an air humidity of 62%, and an air quality index of 34. Measurements were taken at various times throughout the day: 9 AM, 10 AM, 11 AM, 12 PM, 13 PM, 14 PM, and 15 PM. At each of these starting times, eight consecutive measurements were recorded. During the flight segments ranging from 27 s to 41 s, the UAV, controlled by the flight control system, maintained a preset flight altitude of 28 m and a speed of 17 m/s.

Fig. 2 depicts the solar cell's voltage, current, and power during a complete flight circle at 9:00 AM. The inset shows the data during the flight control phase. Firstly, it can be observed that the overall trends in voltage, current, and

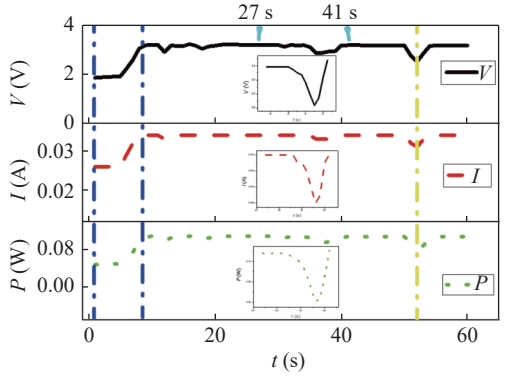

Fig. 2 Solar cell's voltage, current, and power during a complete flight circle at 9:00 AM (the inset shows the data during the flight control phase)

power are generally consistent. Initially, between 0-8 s (corresponding to the time period of the blue line), there is an upward trend as the solar-powered aircraft moves from the shade into sunlight, leading to an increase in light intensity and consequently an increase in voltage, current, and power. During the subsequent 9 to 60 s, the three parameters tend to stabilize with some fluctuations. The voltage is approximately 3.2 V, the current is around 0.034 A, and the power is about 0.1 W. Their respective fluctuation ranges relative to the maximum values are approximately 22% for voltage, 9% for current, and 26% for power. Among them, the power is the most affected by these fluctuations, followed by voltage, with current being the least affected. The fluctuations are attributed to shadows from clouds during the flight [20], unstable temperatures [21] and other factors. The magnitude of the fluctuations indicates that the current is the least affected while the voltage is the most. This is because light intensity has a decisive effect on current, whereas voltage is primarily influenced by temperature [22–23]. Towards the end, a significant drop is observed in all parameters around 51 s (indicated by the yellow line). This is likely due to the aircraft being in the 5→6 section of its flight path where the angle of sunlight incidence decreases during the turn, resulting in reduced light intensity hitting the solar panels. The inset shows that even during the flight control phase, with consistent altitude and speed, the cell's voltage, current, and power still exhibit fluctuations.

Tab. 1 presents the average values, error bars, and relative errors of the cell's voltage, current, and power from eight measurements taken at 13 PM on the 24 th under the altitude and speed conditions set by the flight control system. It can be observed that the average voltage is approximately 3.6 V, the average current is around 0.33 A, and the average power is about 0.12 W; the relative errors are all within 9%, indicating a high repeatability of the measured data. Additionally, it is noted that the fluctuations in current are smaller than those in voltage, and the fluctuations in power generally align with those in voltage, as previously described.

Fig. 3 illustrates the relationship between the average of cell's voltage, current, and power throughout the day on the 24 th versus time (T). It can be seen that the voltage, current, and power all gradually increase, reaching a peak before starting to decline. The peak occurs around noon, due to the direct sunlight at this time, the minimal solar incidence angle, and the maximum irradiance received by the solar cells. Consequently, the conversion of electrical energy reaches its highest point, leading to maximum voltage, current, and power. Upon performing Gaussian fitting, the peak is found to be at 11:58 AM, which is generally consistent with the literature's conclusion that the highest peak occurs at 12 PM [8]. The deviations from the maximum values for voltage, current, and power are 16.6%, 9.0%, and 20.3%, respectively.

Tab. 1 Average values, error bars, and relative errors of the cell's voltage, current, and power measured during the 8 measurements at 13 PM

Number	V(V) ±error	Error ratio (%)	I(A) ±error	Error ratio (%)	P(W) ±error	Error ratio (%)
1	3.5537±0.2849	8.02	0.0332±0.0010	3.01	0.1181±0.0098	8.3
2	3.7041±0.0894	2.41	0.0339±0.0004	1.18	0.1243±0.0032	2.57
3	3.6167±0.2571	7.1	0.0337±0.0006	1.78	0.121±0.0093	7.69
4	3.6789±0.1801	4.9	0.0339±0.0004	1.18	0.1237±0.0066	5.22
5	3.7611±0.0776	2.06	0.0339±0.0002	0.59	0.1263±0.0026	2.06
6	3.7759±0.0589	1.56	0.0335±0.0005	1.49	0.1265±0.0021	1.66
7	3.6964±0.1657	4.48	0.0329±0.0003	0.91	0.1230±0.0060	4.88
8	3.6887±0.1522	4.12	0.0334±0.0003	0.9	0.1261±0.0068	5.39

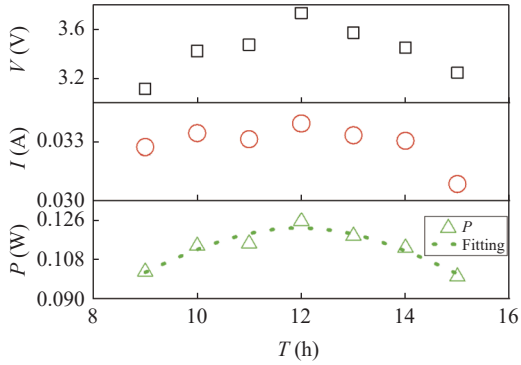

Fig. 3 Relationship between the variations of cell's voltage, current, and power over time during the day

Notably, the current demonstrates the least variation, whereas the power exhibits the most substantial fluctuation.

3.2 The Impact of Flight and Environmental Coupling on Cell's Performance

From August 16 th to 24 th, 2024, experiments were conducted in Gongqing City, Jiangxi Province, to study the coupling effects of time-related factors (specifically, light intensity) with flight speed, and of time-related factors (again, specifically, light intensity) with flight altitude, on the generation characteristics of cells in UAVs. During this period, the average maximum temperature was around 33°C, the minimum was about 26°C, the average wind force was a level 2.3 easterly wind, the air humidity was approximately 66%, and the air quality index was about 35.

In the experiment investigating the coupling effects of time and flight speed, the flight altitude was maintained at 28 m. The time period spanned from 1:00 PM to 4:30 PM, with a half-hour interval between measurements. The flight speed varied from 17 to 23 m/s, with an increment of 1 m/s. Fig. 4 shows the correlation heatmap of average voltage, current, and power with respect to time and flight speed.

From Fig. 4 (a), it can first be observed that the correlation coefficient between voltage and current is 0.969 99, the correlation coefficient between voltage and power is 0.999 5, and the correlation coefficient between current and power is 0.97556. This indicates that the correlation coefficients are all above 0.96, demonstrating a very strong positive correlation among them. The strong positive correlation among voltage, current, and power is primarily due to their physical relationship. According to the basic electrical formula, power is the product of voltage and current. Therefore, changes in voltage and current directly affect the power output. It can also be seen that the correlation coefficient between power and voltage is greater than that between power and current. This is consistent with the previously obtained conclusions about the volatility of voltage, current and power. The fluctuations in power are primarily effected by voltage.

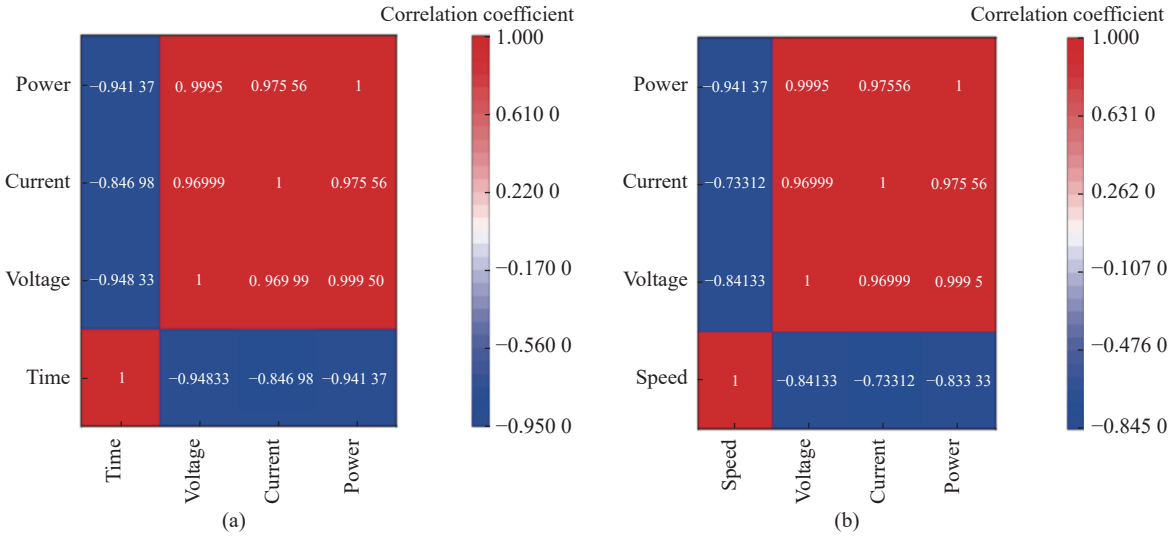

Fig. 4 Correlation heatmap of average voltage, current, and power with respect to: (a) time; (b) flight speed

The reason is that the voltage of the cell is primarily determined by the intensity of light and the photoelectric properties of the material, while the current is closely related to the load of the cell, internal resistance, and external circuit conditions. Secondly, it can be observed that the correlation coefficients of voltage, current and power with respect to time are all negative. This indicates that as time increases, voltage, current and power are all decreasing, which is consistent with the weakening of light intensity. Finally, the absolute values of the correlation coefficients of voltage, current and power with respect to time are 0.948 33, 0.846 98, and 0.941 37, respectively. This indicates that the correlation between voltage and time is the strongest, while the correlation between current and time is the weakest. Given the earlier conclusion that power fluctuations are primarily influenced by voltage, the trend of power changes aligns closely with that of voltage, thus establishing a strong correlation between power and time as well.

From Fig. 4(b), it can first be observed that the correlation coefficients of voltage, current, and power with respect to flight speed are all negative, indicating that as flight speed increases, voltage, current, and power decrease instead. This is because, as the flight speed increases, the friction between the drone and the air significantly intensifies. This friction generates a substantial amount of heat, causing the temperature of the solar cells to rise. The efficiency of solar cells is highly sensitive to temperature, typically decreasing as the temperature rises. Additionally, high temperatures increase the internal resistance of the cells, further reducing the current output. Secondly, the absolute values of the correlation coefficients of voltage, current, and power with respect to flight speed are 0.841 33, 0.733 12, and 0.833 33, respectively, which is consistent with the conclusion that wind speed has the greatest effect on voltage [19].

When comparing Fig. 4(a) with Fig. 4(b), it is found that the absolute values of the correlation coefficients of voltage, current and power with respect to time are greater than those with respect to flight speed. This indicates that time, or more specifically, light intensity has a greater impact on voltage, current, and power than flight speed. This is because light intensity is the primary driving force behind the energy conversion of solar cells. The variation in flight speed mainly affects the cell's temperature through air friction and aerodynamic effects. Although high-speed flight leads to an increase in cell's temperature, which in turn impacts cell's performance, this effect is relatively limited compared to the changes in light intensity. Particularly under conditions of high light intensity, the positive impact of light on cell's performance far outweighs the negative effects caused by the temperature rise. The effect of light intensity on cell's performance is direct and significant, while the impact of temperature is relatively indirect and limited. Therefore, in practical flight scenarios, light intensity is the primary factor influencing the performance of solar cells, while the temperature changes caused by variations in flight speed have a relatively smaller effect.

In the experiment on the coupled effects of time and flight altitude, the flight speed was fixed at 17 m/s. The time spanned from 1:00 PM to 4:30 PM, with an interval of half an hour. The flight altitude ranged from 13 to 31 m, with an intervals of 3 m. Fig. 5 shows the correlation heatmap of average voltage, current and power with respect to time and flight altitude.

From Fig. 5(a), it can be observed that the correlation coefficient between voltage and current is 0.978 16, the correlation coefficient between voltage and power is 0.999 3, and the correlation coefficient between current and power is 0.985 05. This indicates that the correlation coefficients are all above 0.97, suggesting a very strong positive correlation among them. Moreover, it can be observed that the correlation coefficient between power and voltage is greater than that between power and current, which is consis-

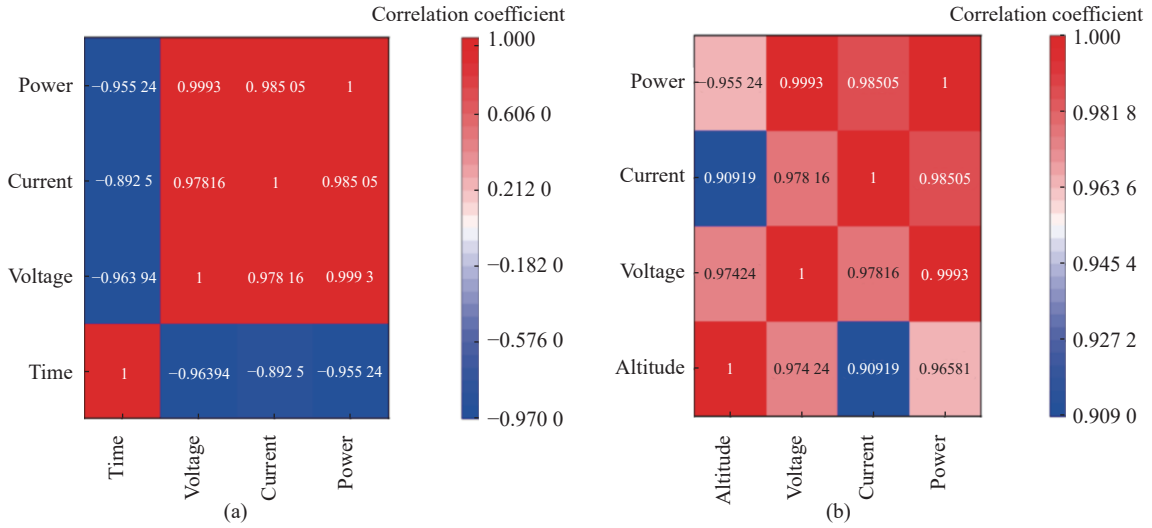

Fig. 5 Correlation heatmap of average voltage, current, and power with respect to: (a) time; (b) flight altitude

tent with the conclusion obtained earlier. Secondly, it can be observed that the correlation coefficients of voltage, current, and power with respect to time are all negative. This indicates that as time increases (i.e., as light intensity decreases), voltage, current, and power are all decreasing. Finally, the absolute values of the correlation coefficients of voltage, current, and power with respect to time are 0.963 94, 0.892 5, and 0.955 24, respectively. This indicates that the correlation between voltage and time is the strongest, meaning that light intensity has the greatest impact on voltage and the least impact on current, which is consistent with the previous conclusion.

From Fig. 5(b), it can first be observed that the correlation coefficients of voltage, current, and power with flight altitude are all positive, indicating that as flight altitude increases, voltage, current, and power also increase. This is because, at high altitudes, the atmosphere is thinner and the air density is lower, resulting in reduced absorption and scattering of solar radiation by the atmosphere. As a result, more solar radiation reaches the surface of the solar cell. Additionally, as altitude increases, the ambient temperature decreases, and the improved cooling conditions help maintain the cell within its optimal temperature range, preventing performance degradation caused by overheating. It can also be observed that the absolute values of the correlation coefficients of voltage, current, and power with flight altitude are 0.974 24, 0.909 19, and 0.965 81, respectively. This indicates that the correlation between voltage and flight altitude is the strongest, meaning that flight altitude has the greatest impact on voltage, while the least impact is on current. In line with the previous findings, it is evident that light intensity has the most pronounced impact on voltage, while its effect on current is relatively minor.

Comparing Fig. 5(a) with Fig. 5(b), it is found that the absolute values of the correlation coefficients of voltage, current and power with respect to time are slightly smaller than those with respect to flight altitude. This indicates that, in a relatively stable flying environment, flight altitude has a greater impact on cell's performance. In contrast, variations in flight altitude can rapidly and significantly alter the amount of solar irradiance received by the solar cells, thereby exerting a greater impact on cell's performance. Thus, changes in flight altitude can more noticeably influence the performance of solar cells. However, this does not mean that the time factor (i.e., light intensity) is unimportant, as their correlations strengths are essentially of the same magnitude.

4 Conclusion

In order to clarify solar cells' characteristics of unmanned aircraft vehicle under the coupling influence of flight and environmental factors, this study investigated the relationship between the voltage, current, and power of solar cells on the aircraft throughout the day, as well as the impact of coupling factors on cells performance.

1) Firstly, the variation trends of voltage, current, and power of the solar cells on the aircraft throughout the day are generally consistent. However, power is affected the most, followed by voltage, while current is impacted the least. Additionally, the cell's peak power occurs around noon at approximately 12 PM.

2) Secondly, a very strong positive correlation is found among the cell's voltage, current and power with respect to time, with correlation coefficients all above 0.96. The correlation between power and voltage is higher than that with current, indicating that voltage fluctuations are the main factor affecting power fluctuations. Voltage has the strongest correlation with time, while current has the least correlation with time. Additionally, it was observed that an increase in flight speed leads to a decrease in voltage, current, and power, possibly due to increased air friction raising the cell's temperature. However, the impact of light intensity on cell's performance is greater than that of flight speed. The results demonstrate that under strong light intensity conditions, reducing flight speed can significantly enhance the power output of solar cells. This finding provides a practical optimization strategy for solar-powered UAV operations during midday periods: adjusting flight speed allows for a balance between energy consumption and energy generation, thereby extending flight duration. Furthermore, these results establish a scientific foundation for refining flight strategies and improving mission execution efficiency in solar-powered UAVs. They also contribute theoretical insights to support future applications in long-duration monitoring, communication relay, and related fields.

3) Finally, it was observed that an increase in flight altitude results in increased cell's voltage, current, and power. This is because at higher altitudes, atmospheric transmittance is greater, allowing the cells to receive more solar irradiance. Compared to cell's current, the voltage has a greater correlation with flight altitude. This indicates that the impact of flight altitude on cells' performance is greater than that of the time factor. In conditions of weak light intensity, such as during cloudy or twilight periods, appropriately adjusting flight altitude and speed can significantly enhance the power output of solar cells, thereby extending flight duration. Specifically, increasing flight altitude can maximize the efficiency of solar cells by improving atmospheric transmittance and increasing the amount of solar radiation received. This finding provides a valuable optimization strategy for UAV operations in such conditions and offers significant guidance for optimizing flight strategies in complex environments. Ultimately, this approach is of great significance for improving the endurance and mission execution efficiency of solar-powered UAVs.

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