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Energy-Efficient Hybrid Solar UAV Design for Prolonged Flight Operations nce

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Abstract:

This work presents the design and development of a hybrid solar-assisted Unmanned Aerial Vehicle (UAV) aimed at extending flight endurance and improving energy efficiency. The proposed system integrates photovoltaic panels with a rechargeable battery to provide supplementary power during flight operations. An intelligent energy management strategy is employed to optimize power utilization between the solar source and onboard energy storage. The UAV structure and propulsion system are designed to maximize aerodynamic efficiency while minimizing energy consumption. Performance evaluation demonstrates a significant improvement in flight duration compared to conventional battery-powered UAVs. The proposed hybrid architecture offers a sustainable and reliable solution for long-endurance surveillance, monitoring, and remote sensing applications.

Keywords: solar-powered; UAV; endurance extension; flight experiments.

1. Introduction

Energy Unmanned Aerial Vehicles (UAVs), commonly known as drones, have gained significant attention in recent years due to their wide range of applications in both civilian and military domains. UAVs are used in areas such as aerial surveillance, environmental monitoring, disaster management, agriculture, mapping, and communication systems. Their ability to operate without human intervention, access remote locations, and provide real-time data makes them highly valuable in modern technological systems. Despite their advantages, one of the major limitations of conventional UAVs is their limited flight endurance. Most UAVs rely solely on batteries, particularly lithium-polymer (Li-Po) batteries, which have limited energy storage capacity. This restricts flight time to typically a few minutes to an hour depending on the design and payload. Frequent battery replacement or recharging interrupts continuous operation and reduces efficiency, especially in long-duration mission. To overcome this limitation, researchers have explored the integration of renewable energy sources, particularly solar energy, into UAV systems. Solar energy is abundant, clean, and sustainable, making it an ideal candidate for enhancing UAV endurance. By integrating solar panels onto the UAV structure, it is possible to harvest energy during flight and supplement the on board battery power. This project focuses on the design and development of a hybrid solar-assisted UAV for extended flight endurance. The proposed system combines solar photovoltaic (PV) panels with a rechargeable battery system to create a hybrid energy solution. Additionally, efficient power management techniques such as Maximum Power Point Tracking (MPPT) are required to extract maximum energy from the solar panels under varying environmental conditions.

2. Methods and Material

The proposed hybrid UAV system consists of photovoltaic (PV) solar panels, lithium-polymer (Li-Po) batteries, brushless DC motors, electronic speed controllers (ESCs), a flight controller, a power distribution unit (PDU), and a charge controller P integrated with Maximum Power Point Tracking (MPPT). A lightweight UAV frame made of carbon fiber or composite material is used to ensure structural strength and reduced weight. A hybrid energy approach is adopted by integrating solar panels with a battery storage system. The solar panels generate electrical energy during flight, which is either directly supplied to the propulsion system or stored in the battery through a charge controller. The flight controller processes sensor inputs to maintain stability and control. Power distribution is managed to ensure efficient energy utilization. The system is designed, implemented, and experimentally tested under real-time conditions to evaluate flight endurance, stability, and overall performance.

3. Results and Discussion

The developed hybrid solar-assisted UAV demonstrated improved flight endurance and stable performance under test conditions. The integration of solar panels reduced battery discharge rate and increased flight time compared to the conventional system. The UAV achieved stable flight with efficient control response and no major power fluctuations. However, the performance of the solar system depended on sunlight intensity, and the additional weight of the panels slightly affected thrust efficiency. Overall, the hybrid system proved effective in enhancing energy efficiency and extending flight duration.

3.1 Overview of Hybrid Solar UAV System:

The hybrid solar-assisted UAV system is designed to improve flight endurance by combining solar energy with conventional battery power. This system utilizes photovoltaic (PV) panels mounted on the UAV to capture solar energy during flight and convert it into electrical energy. The generated solar energy is regulated using a charge controller or Maximum Power Point Tracking (MPPT) system to ensure efficient energy conversion. This energy is then either directly supplied to the UAV components or stored in a lithium-polymer (Li-Po) battery for later use. The battery acts as a backup power source when solar energy is insufficient.

Time of day	Sunlight Intensity	Voltage per panel(V)	Total voltage	Total power output(W)
(6-8 AM)	20%	5.5	22.0	2.4W
(8-10 AM)	50%	6.0	24.0	6.0W
(10-12 PM)	75%	6.2	24.8	9.0W
(12-2 AM)	100%	6.5	26.8	12.0W
(2-4 PM)	70%	6.2	24.8	8.4W
(4-6 PM)	40%	5.8	23.0	4.8W
(After 6 PM)	10%	5.0	20.0	1.2W

total thurst > total weight

3.2 Working principle of Hybrid Power System

The hybrid solar assisted UAV operates by combining energy from solar panels and a battery system to achieve extended flight duration. The working principle involves the conversion of solar energy into electrical energy, which is used to power the propulsion system and on board electronics. Initially, solar panels mounted on the UAV wings capture sunlight and convert it into direct current (DC) electricity using photovoltaic cells. This generated power is either directly supplied to the motors or stored in a rechargeable battery through a charge controller. The battery acts as a secondary power source, ensuring continuous operation when solar energy is insufficient, such as during cloudy conditions or night time. The power management system intelligently distributes energy between the solar panels, battery, and motors to maintain optimal performance. The propulsion system consists of brushless DC motors.

COMPONENTS	QUANTITY	WEIGHT PER UNIT(g)	TOTAL WEIGHT(g)
Frame	1	50	50
Brushless motor	4	75	75
Propellers	4	40	40
ESC	4	40	40
Battery(Li-Po)	2	2	100
Solar Panel	4	150	150
Flight Control	1	20	20
Wiring & connection	-	-	25
Total	-	-	500g

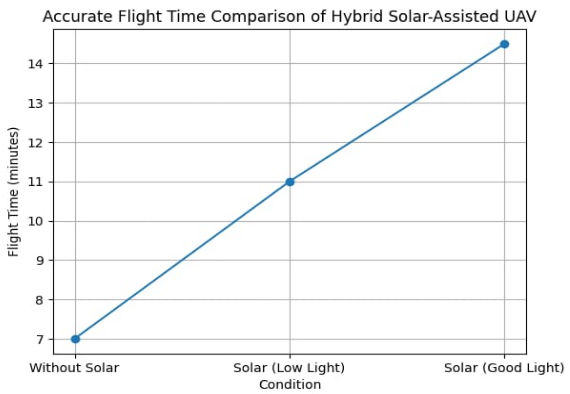

Figure 1: Flight time comparison of hybrid solar-assisted UAV under different operating conditions

DURING OPERATION

- Solar panels provide primary energy during daylight.
- The battery supplies power when solar input is low.
- The hybrid system increases endurance compared to conventional UAVs.

Thus, the integration of solar energy with battery storage enhances efficiency, reduces dependency on ground charging, and enables longer flight missions.

4. Component description

4.1 Solar panel

The solar power generation system is a crucial part of the hybrid UAV, responsible for converting solar energy into usable electrical power. It mainly consists of photovoltaic (PV) cells mounted on the wings or body of the UAV. These PV cells absorb sunlight and generate direct current (DC) electricity through the photovoltaic effect. During flight, the solar panel continuously generates power when exposed to sunlight. This energy is either directly supplied to the propulsion system or stored in the battery for later use. The integration of solar panels significantly enhances flight endurance and reduces reliance on ground-based charging.

4.2 Energy Storage and Battery Management System

The energy storage system in the UAV is typically a Lithium Polymer (Li-Po) battery, chosen for its high energy density, lightweight design, and ability to deliver high discharge currents. The battery stores excess energy generated by the solar panel and supplies power during low or no sunlight conditions. A Battery Management System (BMS) is used to monitor and control the charging and discharging process.

4.3 Flight Control System

The flight control system is the central unit responsible for stabilizing and navigating the UAV. It consists of a flight controller board integrated with sensors such as gyroscopes, accelerometers, magnetometers, and GPS modules. The flight controller processes real-time data from these sensors and compares it with user commands. Based on this information, it adjusts motor speeds to maintain balance and desired flight path. Advanced control algorithms such as PID (Proportional-Integral-Derivative) are used to ensure smooth and stable operation. This system enables various flight modes such as manual control, altitude hold, and autonomous navigation. It plays a critical role in maintaining UAV stability under varying environmental conditions like wind disturbances.

4.4 Efficient Power Distribution System in Hybrid UAV

An efficient power distribution system is a critical component in hybrid Unmanned Aerial Vehicles (UAVs), especially those integrating solar and battery energy sources. This paper presents a robust power distribution architecture designed to ensure stable, reliable, and efficient energy flow between solar panels, battery storage, and onboard subsystems. The proposed system minimizes power loss, improves energy utilization, and enhances overall flight endurance. Advanced techniques such as voltage regulation, load balancing, and intelligent energy switching are implemented to optimize performance under varying environmental conditions.

4.5 Battery Management System (BMS) in UAV

Battery Management System (BMS) in a UAV is an electronic system that monitors, controls, and protects the battery to ensure safe and efficient operation. It manages key parameters such as voltage, current, temperature, and state of charge, helping to improve battery performance and extend its lifespan. The BMS is an integrated electronic system that regulates battery operation by performing functions such as cell balancing, overcharge protection, thermal monitoring, and state estimation to maintain optimal performance and safety in UAV applications.

4.6 Types of Existing UAV Systems

Fixed-Wing UAVs

Fixed-wing UAVs operate like conventional airplanes and use wings to generate lift. They are highly energy-efficient and suitable for long-endurance missions. However, they require runways or launching systems and cannot hover.

Rotary-Wing UAVs (Multirotors):

Rotary-wing UAVs include quadcopters, hexacopters, and octocopters. They can take off and land vertically (VTOL) and hover in place, making them ideal for inspection and photography. However, they consume more power and have shorter flight duration.

Hybrid UAVs:

Hybrid UAVs combine the advantages of fixed-wing and rotary-wing systems. They can take off vertically and transition into efficient forward flight. These UAVs offer improved endurance and flexibility but are more complex in design.Modern solar UAVs often use hybrid energy systems that combine solar power with battery backup to ensure continuous operation. Lightweight and flexible solar panels are preferred to reduce additional weight and maintain aerodynamic performance. Proper power management systems are also used to control energy.

Hybrid Energy System in UAV’s

Hybrid energy systems in Unmanned Aerial Vehicles (UAVs) combine multiple power sources, typically solar energy and battery Power, to improve overall performance and flight endurance. In this system, solar panels generate electrical energy during Flight, while batteries store energy and provide backup when solar energy is insufficient.A hybrid energy system improves UAV endurance by efficiently managing and utilizing available energy sources, reducing dependence on a single power supply.

Wing Design and Aerodynamics

Wing design and aerodynamic characteristics of the UAV play a crucial role in The determining its flight efficiency, stability, and Endurance. In a hybrid solar-assisted UAV, the wings are not only responsible for generating lift but also serve as a platform for Mounting solar panels. Therefore, the design must balance aerodynamic performance with maximum surface area for solar Energy collection.The wings are designed with a high aspect ratio, meaning they are long and narrow. This type of wing reduces induced drag and Improves lift efficiency, making it ideal for long-endurance flights. A larger wingspan allows the UAV to glide more efficiently And consume less power during flight.Aerodynamically, the lift generated by the wing must be sufficient to counteract the weight of the UAV. The lift depends on Several factors including air density, velocity of the UAV, wing surface area, and the lift coefficient of the airfoil.

Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is an essential technique used in solar photovoltaic (PV) systems to maximize the power Output from solar panels under varying environmental conditions. In a hybrid solar-assisted UAV, MPPT plays a crucial role in Improving energy efficiency and extending flight endurance by ensuring that the solar panels operate at their optimal power Point.The power generated by a solar panel depends on solar irradiance and temperature, and it varies continuously throughout the day. For a given set of conditions, there exists a unique operating point known as the Maximum Power Point (MPP), at which the product of voltage and current is maximum. Operating the solar panel at this point ensures maximum energy extraction.

Power Distribution System

The power distribution system is a critical component of the hybrid solar-assisted UAV, responsible for delivering electrical power from the energy sources to all onboard subsystems in a stable and efficient manner. It ensures that each component receives the required voltage and current for proper operation. In this system, power is primarily sourced from the battery and supported by the solar panels through the charge controller.

Flight Testing

The flight testing of the hybrid solar-assisted UAV was conducted to evaluate its performance in real-time operating conditions. The primary objective of the testing was to analyze stability, control response, flight duration, and the contribution of the solar Power system. The UAV was tested in an open environment under moderate weather conditions to ensure safe and controlled Operation. Before takeoff, all components including the flight controller, sensors, battery, and solar panels were properly Calibrated and checked for functionality.

Future Scopes

1. Use of high-efficiency solar cells to increase power generation.

2. Implementation of advanced MPPT algorithms for maximum energy extraction.

3. Integration of lightweight flexible solar panels to reduce weight.

4. Development of high energy density batteries for longer flight time.

5. Improvement in power management systems for better energy utilization.

5. Results and Discussion

The hybrid solar-assisted UAV was successfully designed and tested to evaluate its performance in terms of flight stability, Energy efficiency, and endurance. The integration of solar power with the conventional battery system demonstrated a Noticeable improvement in overall flight duration. During testing, the UAV achieved stable flight under normal environmental Conditions. The flight controller effectively maintained balance and orientation using sensor feedback and control algorithms. The propulsion system provided sufficient thrust for lift-off and maneuvering, confirming the suitability of the selected motors And propellers. The solar panels contributed to supplementary power generation during operation. Under adequate sunlight Conditions, the panels were able to provide partial energy support to the system. The battery system performed reliably, Supplying consistent power during low-light or no-sunlight conditions. The power management system efficiently regulated Voltage and ensured safe charging and discharging cycles. No major issues such as overheating or voltage instability were Observed during testing. The circuit design and hardware integration proved to be effective, with smooth power distribution and Minimal energy loss. The use of protection components helped in maintaining system safety and preventing electrical faults.

6. Conclusion

The hybrid solar-assisted UAV system successfully improves flight endurance by integrating solar energy with battery power. The results demonstrate enhanced efficiency, reduced battery dependency, and stable flight performance. Although solar output varies with environmental conditions, the system proves to be a reliable and sustainable solution for extending UAV.

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