Advancements in Solar-Powered UAV Design Leveraging Machine Learning: A Comprehensive Review

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Abstract: Unmanned Aerial Vehicles (UAVs), commonly known as drones, have seen significant innovations in recent years. Among these innovations, the integration of solar power and machine learning has opened up new horizons for enhancing UAV capabilities. This review article provides a comprehensive overview of the state-of-the-art in solar-powered UAV design and its synergy with machine learning techniques. We delve into the various aspects of solar-powered UAVs, from their design principles and energy harvesting technologies to their applications across different domains, all while emphasizing the pivotal role that machine learning plays in optimizing their performance and expanding their functionality. By examining recent advancements and challenges, this review aims to shed light on the future prospects of this transformative technology.

Keywords: Resource, NAV, Rotor-driven, controllers, SUAV, flight endurance.

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Introduction

Solar-powered UAVs represent a compelling convergence of clean energy and autonomous flight capabilities. This review explores the intersection of solar power and machine learning in the context of UAVs. We discuss the potential of this integration and its implications for various industries, including environmental monitoring, agriculture, surveillance, and more. The article introduces a new innovative method called power cognition, which focuses on intelligent energy harvesting and resource allocation to tackle the resource management issues faced by solar-powered unmanned aerial vehicles (SUAVs). The power cognition scheme relies on the reinforcement learning (RL) mechanism, allowing for a collective optimization of flight trajectory, energy harvesting, and information transmission through an intelligent self-learning process. The article evaluates the performance of the power cognitive SUAVs using simulation [1]. The findings indicate that the suggested approach, which incorporates a significant discount factor, delivers optimal throughput and energy efficiency. The SUAV determines the best course of action for the next state by considering the energy arrivals expected in the future. The article concludes by discussing the future work, which includes extending the work to distributed learning for multi-SUAV networks and considering the SUAV decision-making in continuous three-dimensional space [1]. The AtlantikSolar UAV is a significant achievement in the field of solar-powered aviation. It is the first solar-powered LALE UAV to demonstrate perpetual flight capability, and it has the potential to be used in a variety of applications [2].Recently the paper by Jurj et al, presents a significant contribution to the field of solar-powered Deep Learning (DL) systems. The authors have developed a system that can run real-time DL inference on solar energy, which could have a major impact on the development of IoT, environmental monitoring, and other applications [3].

Table 1. Features of AtlantikSolar UAV [2].

Feature	**Value**
Wingspan	5.6 meters
Mass	6.93 kilograms
Solar cells	60 high-efficiency solar cells
Battery	705-watt-hour battery
Continuous flight time	28 hours
Minimum state-of-charge	40%
Energetic margins	Several hours
Payload capacity	Small sensing payloads

Design Principles of Solar-Powered UAVs

This section delves into the fundamental design principles behind solar-powered UAVs. It covers aspects such as airframe design, energy-efficient components, and the incorporation of lightweight and high-efficiency photovoltaic cells. We also discuss the challenges of balancing weight and power generation. Before doing so it is important to classify the UAVs for different missions and applications.

Classification

UAVs are designed for different missions and applications, and their configurations vary accordingly. Various methods exist for categorizing UAVs, yet there is no one classification that is universally recognized.

One common way to classify UAVs is by size. Nano air vehicles (NAVs) are the smallest UAVs, weighing less than 0.2 kg. Micro air vehicles (MAVs) are slightly larger, weighing between 0.2 and 2 kg. Mini UAVs weigh between 2 and 20 kg, small UAVs weigh between 20 and 150 kg, and tactical UAVs weigh between 150 and 600 kg. UAVs that weigh more than 600 kg are typically referred to as medium altitude long endurance (MALE) or high-altitude long endurance (HALE) UAVs.

Another way to classify UAVs is by their flight endurance. The flight endurance of a UAV is the amount of time it can stay in the air without refuelling. UAVs with a long flight endurance are often used for surveillance and reconnaissance missions. UAVs with a short flight endurance are often used for more agile missions, such as search and rescue or delivery.

The type of propulsion system used by a UAV is also a common way to classify them. UAVs can be powered by propellers, jets, or rotors. Propeller-driven UAVs are the most common type and are typically used for short-range missions. Jet-powered UAVs are faster and have a longer range than propeller-driven UAVs, but they are also more expensive. Rotor-driven UAVs can take off and land vertically, making them well-suited for urban environments.

Table 2. The classification of UAVs

Classification	***Type***	***Weight (kg)***	***Endurance (h)***	***Range (km)***
Brooke–Holland [4]	Nano drones	<0.2	N/A	N/A
Brooke–Holland [4]	Micro drones	[0.2, 2]	N/A	N/A
Brooke–Holland [4]	Mini drones	[2,20]	N/A	N/A
Brooke–Holland [4]	Small drones	[20,150]	N/A	N/A
Brooke–Holland [4]	Tactical drones	[150, 600]	N/A	N/A
Brooke–Holland [4]	MALE/HALE/Strike drones	>600	N/A	N/A
Arjomandi et al [5]	High	>24	>1500	
Arjomandi et al [5]	Medium	5–24	100–400	
Arjomandi et al [5]	Low	<5	<100	
CASA [6]	µUAVs	<0.1	N/A	N/A
CASA [6]	Small UAVs	[0.1,150]	N/A	N/A
CASA [6]	Large	>150 for fixed wing	>100 for rotorcrafts	

Design of the Electrical System

Drones are flying robots that require propulsion systems to generate motion. The type of propulsion system used depends on the drone type and its flight mode. Fixed-wing drones, for instance, employ propulsion systems that bear resemblance to the ones utilized in conventional aircraft. This can save time and money in the design process. Other drones, such as rotary and tilt-wing drones, may require the development of new propulsion technologies. Two critical factors in any propulsion system are power density and energy density. The power converter is measured by power density, whereas energy density measures the energy of the power source and the efficiency of engine conversion [7].

The propulsion system should be small, lightweight, reliable, and fuel-efficient. The payload can make up to 60% of the drone's take-off weight, and its efficiency directly impacts the flying robot's overall performance. There are two main types of propulsion systems for drones: fuel-based and electrical. Fuel-powered engines encompass piston engines, gas turbine engines, and injection engines. Electric propulsion systems utilize brushed or brushless motors.

Among the fuel engines, gas turbine engines are the most promising because of their high power-to-weight ratio and reliability. However, they are also the most expensive. Piston engines are less expensive, but they have a lower power-to-weight ratio and endurance. For small drones, including micro-UAVs and MAVs, the most common propulsion system is the electric motor. Electric motors are reliable, controllable, and efficient. Brushless motors are more commonly used than brushed motors because they are smaller and lighter [9].

Flapping wing drones are equipped with electric motors that have minimal vibration, low fuel usage, and a high energy density. The motor connects with both the mechanical and electrical parts, with the voltage and current serving as inputs. The result is a rotational movement that can be controlled to achieve a wide range of angular velocities. This allows the drone to lift off and perform various functions. Flapping wing drones necessitate an actuation device in addition to the propulsion system, with the specific type varying based on the type of flapping. The actuation devices developed by Aero Environment company consist of strings and rollers for NAVs. To achieve the desired frequency, a motor equipped with a gear is utilized. The development of an efficient flapping wing drone relies heavily on the design of a suitable actuator. Various technologies have been implemented depending on the specific type of flapping wing drone, such as shape memory alloy-based wires, solenoids, electric motors, and piezoelectric components.

The propulsion system is an important part of any drone. The type of propulsion system used depends on the drone type and its flight mode. The propulsion system should be small, lightweight, reliable, and fuel-efficient.

Wooden Propeller 	**Advantages:** light weight, easy processing and low cost **Disadvantages:** Cumbersome production and low precision
Plastic 	**Advantages:** easy processing, low cost and high mold processing precision **Disadvantages:** low strength and prone to breakage
Carbon Fiber 	**Advantages:** Light weight, High tensile strength, and Friction resistance. **Disadvantages:** Brittleness and Poor wear resistance

Fig.1. Types of Popular Propellers commonly used.

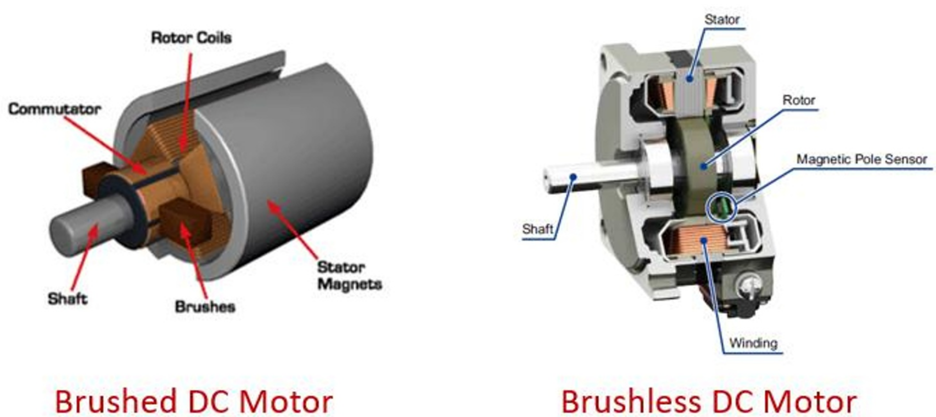

Fig.2. Types of DC motors used in Drones and UAVs

Controllers

The utilization of open-source flight controllers has proven to be a valuable strategy for addressing several challenges associated with the development and research of Unmanned Aerial Vehicles (UAVs). With a plethora of options available, there are currently more than 20 open-source flight controllers accessible online. These platforms typically leverage 32-bit Microcontroller Units (MCUs) that are built upon the ARM architecture, providing robust computing capabilities. Furthermore, all of these platforms are equipped with Inertial Measurement Units (IMUs) and offer support for essential communication interfaces such as UART, PWM, and I2C. However, it's worth noting that only a limited number of these platforms incorporate fault tolerance features to enhance reliability. Among these open-source flight controller platforms, the Pixhawk series stands out as one of the most widely recognized and favored choices within the UAV community [10]. Table 3 lists the various Open source controllers used in building UAV/drones.

Table 3. Open source Architectures for UAV/drone controllers

Platform	*MCU*		*Sensors*	*License*	*Interfaces*	*Dimensions*	*Weight*	*Fault*

						(mm)	***(g)***	***tolerance features***
[10]Pixhawk	STM32F427		b, m	BSD	c, s, a, pp, sb, ds	81.5 × 50 × 15.5	38	c, IMU
[11]Pixhawk 2	STM32F427		b, m	CC-BYSA-3.0	c, s, a, pp, sb, ds	38.5 × 38.5 × 23	39	trp
[12,13]PixRacer	STM32F427		b, m	CC-BY 4.0	c, pp, sb, ds	36 × 36*	10.9	c, trp, tri
[14]Pixhawk 3 Pro	STM32F427		b, m	CC BY 4.0	c, s, pp, sb, ds	71 × 49 × 23	45	i
[14]PX4 FMUv5 and v6	STM32F427		b, m	CC BY 4.0	c, s, a, pp, sb, ds	71 × 49 × 23	45	–
[15]Sparky2	STM32F405		b, m	CC BY-NC-SA 4.0	c, pp, sb, ds, da	36 × 36*	13.5	None
[16]Chimera	STM32F767		b, m, p	GPLv2	c, s, a, da, pp, sb, ds, x, au	89 × 60*	–	tsp
[17]CC3D	STM32F103		None	GPLv3	pp, ds, sb	36 × 36*	8	None
[17]Atom	STM32F103		None	GPLv3	pp, ds, sb	15 × 7*	4	None
[18]APM 2.8	ATmega2560		b	GPLv3	pp, a	70.5 × 45 × 13.5	31	None
[19]FlyMaple	STM32F103		b, m	GPLv3	None	50 × 50 × 12	15	None
[20]Erle-Brain 3	Raspberry Pi		b, m	CC BY-NC-SA	a	95 × 70 × 23.8	100	None
[20]PXFmini	Raspberry Pi		b, m	CC BY-NC-SA	a	31 × 73*	15	None

Solar Energy Harvesting Technologies

Understanding the technologies behind solar energy harvesting is crucial for the development of solar-powered UAVs [21]. We explore different types of solar cells, energy storage solutions, and power management systems. The section also highlights innovations in flexible and lightweight solar panels. PV and CSP are two main technologies for solar energy conversion. PV is more efficient at converting sunlight to electricity, but it only converts a portion of the solar spectrum. CSP is less efficient at converting sunlight to electricity, but it can use the full solar spectrum. PV/T systems combine the advantages of PV and CSP by converting both electricity and heat from sunlight. There are two main types of PV/T systems: waste heat recovery systems and spectral splitting systems. Waste heat recovery systems recover the heat generated by PV cells to generate additional electricity. Spectral splitting systems use selective coatings to split sunlight into two parts: one part is converted to electricity by PV cells, and the other part is used to generate heat. Spectral splitting systems have the potential to achieve higher solar-to-electricity efficiency than waste heat recovery systems. However, they are more complex and expensive to develop. Some innovative PV/T systems have been proposed, but they are not yet mature. Overall, the paper provides a good overview of the state of the art in PV/T systems. It highlights the potential of spectral splitting systems to achieve high solar-to-electricity efficiency, but it also acknowledges the challenges that need to be addressed before these systems can be widely deployed. The authors point out that the full spectrum of sunlight contains a lot of energy that is not currently being utilized by PV or CSP systems. Spectral splitting systems could help to capture this energy and convert it into electricity or heat. The authors also discuss the potential for PV/T systems to be used in conjunction with other technologies, such as energy storage and smart grids. This could help to make solar energy a more reliable and affordable source of power.

Table 4. Metrics of Solar power extraction

References	***Wing type***	***Weight (kg)***	***Harvested power (W)***
SoLong [22]	Fixed	12.8	17.6
Multicopter [23]	Rotary	2.6	138.5
Robo Raven IIIv4 [24]	Flapping	0.394	27.8
Robo Raven IIIv5 [25]	Flapping	0.391	35.8
RoboBee X-Wing [26]	Flapping	2.59E-04	579.2
Hybrid PV, Syngas, SOFC [27]	Rotary	10	389

Machine Learning based Designs

Machine learning (ML) techniques can be used to design unmanned aerial vehicle (UAV)-based radio access networks (U-RANs) [28,29]. ML algorithms can be classified into supervised learning, unsupervised learning, and reinforcement learning. Supervised learning is used when the desired output is known. For example, supervised learning can be used to find the best UAV locations to cover a given area. Unsupervised learning is used when the desired output is not known. For example, unsupervised learning can be used to find patterns in data that indicate potential problems. Reinforcement learning is used when the output is a sequence of actions. For example, reinforcement learning can be used to find the best way for UAVs to fly to avoid each other. ML techniques can be used for a variety of tasks in U-RANs, such as radio resource allocation, design of collectors and relays, and UAV trajectory optimization. ML techniques can be used to improve the coverage of U-RANs. ML techniques can be used to reduce interference in U-RANs. ML techniques can be used to improve the reliability of U-RANs. The use of ML techniques in U-RANs faces some challenges, such as the need for large amounts of data, the need for accurate data, and the need for fast algorithms. Despite these challenges, ML techniques have the potential to significantly improve the performance of U-RANs. As the amount of data available for training ML algorithms increases, and as ML algorithms become more efficient, the use of ML in U-RANs is likely to become more widespread [28,29]. A novel UAV-RIS framework is proposed for optimizing the trajectory of the UAV and the passive beamforming at the RIS in RIS-enhanced UAV-enabled wireless networks. The proposed framework is based on a decaying learning rate deep Q-network (D-DQN) algorithm, which can converge under minor constraints. With the aid of the RIS, the energy dissipation of the UAV can be reduced by roughly 23.3% [29]. The RIS-NOMA case consumes 11.7% less energy than the RIS-OMA case. The proposed UAV-RIS framework jointly optimizes the trajectory of the UAV and the passive beamforming at the RIS. This is a challenging problem because the UAV and the MUs are both moving, and the RIS has discrete phase shifts. The D-DQN algorithm is able to solve this problem by learning from the environment and gradually finding the optimal policy. The proposed D-DQN algorithm uses a decaying learning rate. This means that the learning rate decreases over time, which helps to prevent the algorithm from overfitting the training data and converging to a local optimum. The decaying learning rate also helps to accelerate the training process. The simulation results show that the proposed UAV-RIS framework can significantly reduce the energy dissipation of the UAV. In the RIS-NOMA case, the energy dissipation is reduced by 11.7% compared to the RIS-OMA case [29]. This is because NOMA can improve the spectrum efficiency, which allows the UAV to transmit data to more users with less power. Overall, the proposed UAV-RIS framework is a promising approach for reducing the energy dissipation of UAVs in wireless networks. The framework is able to jointly optimize the trajectory of the UAV and the passive beamforming at the RIS, and it can be used to improve the spectrum efficiency of the network [29].

Applications of Solar-Powered UAVs

Solar-powered Unmanned Aerial Vehicles (UAVs) represent a cutting-edge technology with a broad spectrum of applications across various domains. Their ability to harness energy from the sun not only extends their flight endurance but also makes them environmentally sustainable. In this expanded discussion, we will explore specific use cases where solar-powered UAVs are making a significant impact.

- *Agriculture and Precision Farming:*

One of the most promising applications of solar-powered UAVs lies in agriculture and precision farming. These UAVs can be equipped with a variety of sensors, such as multispectral and thermal cameras, to monitor crop health and environmental conditions. By capturing high-resolution images and data, they enable farmers to make informed decisions regarding irrigation, fertilization, and pest control. Solar-powered UAVs can fly for extended periods, covering large agricultural areas, and relay real-time information to farmers. This not only enhances crop yields but also reduces resource consumption and environmental impact [30].

- *Environmental Research and Monitoring:*

Solar-powered UAVs are invaluable tools for environmental research and monitoring. They can be deployed to study various ecosystems, including forests, wetlands, and oceans. Equipped with specialized sensors, they collect data on temperature, humidity, air quality, and even wildlife behavior. Researchers use this data to track environmental changes, study biodiversity, and assess the impact of climate change. Solar-powered UAVs are particularly advantageous in remote or hard-to-reach areas, where traditional data collection methods may be impractical [31].

- *Disaster Management and Relief:*

During natural disasters such as hurricanes, wildfires, or earthquakes, rapid and accurate data collection is crucial for effective disaster management and relief efforts. Solar-powered UAVs can quickly survey affected areas, assess damage, and identify hazards such as blocked roads or collapsed buildings. They can also transmit live video feeds and images to emergency responders, aiding in real-time decision-making. Furthermore, these UAVs can be equipped with communication relays to restore connectivity in areas with damaged infrastructure, facilitating coordination and communication during crises [32].

- *Telecommunications and Connectivity:*

In remote or underserved regions with limited infrastructure, solar-powered UAVs serve as mobile communication hubs. They can carry communication equipment such as satellite transceivers or high-frequency radios to establish temporary networks. This capability is particularly valuable in disaster-stricken areas, remote research expeditions, or during events where temporary connectivity is needed. Solar-powered UAVs can extend the reach of communication networks, providing essential services in remote or isolated communities [33].

- *Wildlife Conservation and Anti-Poaching:*

Solar-powered UAVs are instrumental in wildlife conservation efforts, particularly in the fight against poaching. Equipped with thermal imaging cameras and GPS tracking systems, these UAVs can monitor and protect endangered species. They patrol vast wildlife reserves, detecting illegal activities and providing crucial data to park rangers. By serving as a deterrent to poachers, solar-powered UAVs contribute to the preservation of biodiversity [34].

- *Infrastructure Inspection and Maintenance:*

Solar-powered UAVs are increasingly employed for inspecting critical infrastructure, including power lines, pipelines, bridges, and buildings. They can access difficult-to-reach or hazardous locations, reducing the need for manual inspections. Equipped with high-resolution cameras and sensors, these UAVs can identify structural defects, leaks, or other issues, allowing for timely maintenance and repairs. This not only enhances safety but also reduces operational costs [35].

- *Scientific Research and Exploration:*

Solar-powered UAVs are valuable tools for scientific research and exploration in remote or extreme environments. They have been used in missions to study the Arctic and Antarctic regions, providing valuable data on climate change and glaciology. Additionally, they can be deployed in the exploration of volcanoes, caves, and other challenging terrains, collecting data and samples without risking human lives [36].

- *Search and Rescue Operations:*

In search and rescue operations, time is often of the essence. Solar-powered UAVs equipped with thermal imaging cameras and advanced sensors can quickly locate missing persons in vast or inaccessible areas. They can cover large search areas efficiently and transmit real-time data to rescue teams on the ground, expediting the rescue process and potentially saving lives [37].

Challenges and Future Directions

Despite their promise, solar-powered UAVs face challenges, including limited endurance, unpredictable weather conditions, and regulatory hurdles. We explore these challenges and propose potential solutions. Additionally, we speculate on the future directions of this technology, including advancements in energy storage, improved machine learning algorithms, and broader integration into the Internet of Things (IoT) [38].

Artificial intelligence (AI) has been used to solve many problems in UAV systems, such as path planning, obstacle avoidance, and resource allocation. Some of the most promising future research directions in AI-enabled UAV communications include:

- UAV-mounted RIS: RISs are intelligent surfaces that can reflect radio waves in a controlled manner. By mounting an RIS on a UAV, it is possible to improve the wireless coverage and accuracy of the UAV.
- Multi UAV path planning: Path planning is the process of finding a safe and efficient path for a UAV to travel from one point to another. In the case of multi UAV path planning, the goal is to find a path for multiple UAVs such that they do not collide with each other and they can all reach their destinations in a timely manner.
- UAV for V2X: V2X refers to vehicle-to-everything communication. This is a type of communication that allows vehicles to communicate with each other, with infrastructure, and with pedestrians. UAVs can be used to improve V2X communication by providing a high-altitude platform for communication.

- Meta learning aided UAVs: Meta learning is a type of machine learning that allows algorithms to learn to learn. This means that meta learning algorithms can be used to train UAVs to perform new tasks without being explicitly programmed for those tasks.
- UAV aided Wireless Power Transfer: Wireless power transmission (WPT) involves the wireless transfer of energy from one device to another. UAVs can be used to provide WPT to mobile devices.
- MEC aided UAVs: MEC refers to mobile edge computing. This is a type of computing that brings computing resources closer to the end users. MEC can be used to improve the performance of UAV-based networks by offloading computation from the UAVs to edge servers.
- Security/Privacy: Security and privacy are important concerns for UAV-based networks. UAVs can be used to collect sensitive data, such as images and videos. It is important to ensure that this data is secure and that it cannot be accessed by unauthorized parties.
- Energy consumption: UAVs are powered by batteries. The energy consumption of UAVs is a major concern because it limits the range and endurance of UAVs. It is important to develop techniques to reduce the energy consumption of UAVs.
- UAV aided network caching: Caching is the process of storing data in a local memory. UAVs can be used to cache data in areas with poor or unreliable network connectivity. This can improve the performance of applications that require access to data, such as video streaming and gaming.

3.Conclusion

In conclusion, solar-powered UAVs represent a remarkable fusion of renewable energy and autonomous flight. When coupled with machine learning, their potential for applications across various sectors is vast. This review highlights the critical components of solar-powered UAV design, the significance of machine learning algorithms, and the challenges and opportunities that lie ahead. As technology continues to evolve, solar-powered UAVs will undoubtedly play an increasingly vital role in shaping our future.

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