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Overview of Propulsion Systems for Unmanned Aerial Vehicles

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Abstract: Unmanned Aerial Vehicle (UAV) propulsion technology is significantly related to the flight performance of UAVs, which has become one of the most important development directions of aviation. It should be noted that UAVs have three types of propulsion systems, namely the fuel, hybrid fuel-electric, and pure electric, respectively. This paper presents and discusses the classification, working principles, characteristics, and critical technologies of these three types of propulsion systems. It is helpful to establish the development framework of the UAV propulsion system and provide the essential information on electric propulsion UAVs. Additionally, future technologies and development, including the high-power density motors, converters, power supplies, are discussed for the electric propulsion UAVs. In the near future, the electric propulsion system would be widely used in UAVs. The high-power density system would become the development trend of electric UAVs. Thus, this review article provides comprehensive views and multiple comparisons of propulsion systems for UAVs.

Keywords: Unmanned Aerial Vehicle (UAV); electric aircraft; propulsion system; engines; power supply; electrified transportation; electric motor

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1. Introduction

In recent years, with the development of artificial intelligence technology and microprocessor technology, UAVs have received increasing attention as a type of aerial robot that can perform complex tasks [1]. With their ease of use, safety, low cost, and environmental friendliness, UAVs can perform various types of hazardous, long-range, and long-duration missions in military and civilian fields and thus occupy an increasing share of the aerial vehicle market [2,3]. Countries worldwide also attach great importance to the development of various UAV technologies to meet diverse mission requirements [4].

In general, UAVs can be classified into six categories: fixed-wing UAVs, multi-rotary-wing UAVs, unmanned helicopters, blimp, parachute-wing UAVs, and flapping-wing UAVs, according to their wing-type [5], as shown in Figure 1 [6–11]. Currently, fixed-wing UAVs and multi-rotary-wing UAVs are mainly used in military and civilian applications [12]. Table 1 shows the main characteristics of different wing-type UAVs, from which it can be seen that fixed-wing UAVs have long endurance, large payload, high stability, and adaptability, and thus are more widely used in the military field. Both the Global Hawk UAVs equipped by the U.S. Air Force and the Cai-Hong and Wing Loong series UAVs equipped by China belong to fixed-wing UAVs, which have excellent performance and can adapt to the complex battlefield posture in practice [13]. On the other hand, multi-rotary-wing UAVs are characterized by low cost, simple operation, lightness, portability, and flight stability and are more often used in civilian applications [14]. The Chinese company Da Jiang Innovations (Shenzhen, China) has launched the "Yu" Mavic series and "Xiao" Spark series of UAVs, which can meet the needs of flight photography in daily life. In addition, UAVs can be classified as mini, micro, and nano scales according to their size, and low-speed, subsonic, transonic, supersonic, and hypersonic types according to their flight speed [5].

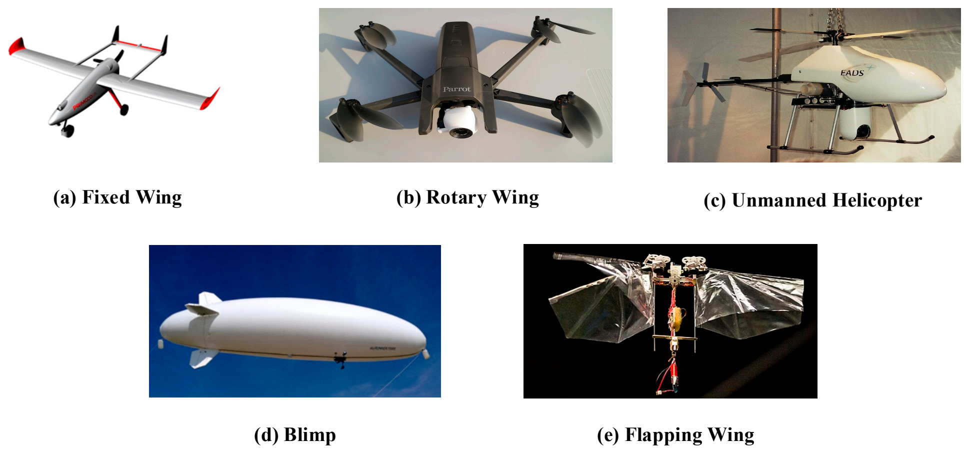

Figure 1. Classification of UAVs. Reprint with Academic Open Access [6–11]; 2021; Wikimedia.

Table 1. Characteristics of different wing-type UAVs.

Model	Type	Wing Length/m	Load Weight/kg	Speed	Endurance Time	Flight Height/m
RQ-4 [15]	Fixed Wing	35.4	10,400	650 km/h	32 h	20,000
Soar Dragon [16]	Fixed Wing	24.86	600	700 km/h	10 h	18,000–20,000
Inspire 2 [14]	Multi-Rotary Wing	N/A	0.8	94 km/h	23–27 min	2500–3000
S-100 [17]	Unmanned Helicopter	N/A	50	220 km/h	6 h	5500
CA-36R [18]	Blimp	N/A	150	72 km/h	5 h	1500
SY-2000 [19]	Umbrella Wing	2	3–5	60 km/h	3–4 h	4000
A160T [20]	Unmanned Helicopter	N/A	454	260 km/h	30–40 h	9144
ASN-211 [21]	Flapping Wing	600 mm	0.22	6–10 m/s	N/A	20–200
Robo Raven-V [22]	Flapping Wing	610 mm	0.71	6.7 m/s	10–15 min	N/A

The development of such a wide variety of UAVs is to meet multiple mission requirements. In reality, UAVs are generally used in military and civilian domains, where military uses generally include reconnaissance, combat, communications, and electronic jamming [23]. The U.S. Air Force's MQ-9 Reaper UAV can perform combat and reconnaissance missions [24]. China's ASN-301 anti-radiation UAV is capable of autonomously striking enemy radars. It can disrupt enemy detection and communication systems [25], and the UK's Taranis stealth UAV can perform surveillance and reconnaissance missions against the enemy and has the capability of long-range attacks [26]. While in the civilian sector, UAVs are more widely used in agriculture monitoring, urban cargo transportation, communication and relay, disaster monitoring, and firefighting with their low cost and safety features [27–29]. Multiple UAVs following specific path planning algorithms with each other can detect forests or farmlands in less time, thus playing a more significant role in agricultural planting and forest fire prevention [28]. In urban life, UAVs can achieve point-to-point freight transportation, as shown in Figure 2b. China's Jing-dong Company (Beijing, China) has used fixed-wing UAVs to achieve freight transportation between cities, while Jing-dong also uses quadrotor UAVs to transport goods over short distances within cities. As shown in Figure 2a, in some emergency moments, drones can build communication platforms in the air to provide data and communication services [30]. In the heavy rainfall flood disaster that occurred in Zhengzhou, China, in July 2021, China Aviation

Industry's Wing Loong-2H emergency disaster relief UAV carried a communication base station to restore communication in a 50 km^2 area for 5 h in the affected area without water and electricity as well as communication interruptions, supporting rescue operations [31]. Moreover, in the fire rescue of urban high-rise buildings where it is difficult for large rescue vehicles to extinguish fires, there are already firefighting drones to perform dangerous tasks instead of firefighters, effectively reducing the occurrence of casualties [32]. The eight-rotor projectile UAV "Tianlong I" designed by Northwestern Polytechnical University can fire extinguishing bombs into buildings during fires with high precision, low cost, and flexibility [33].

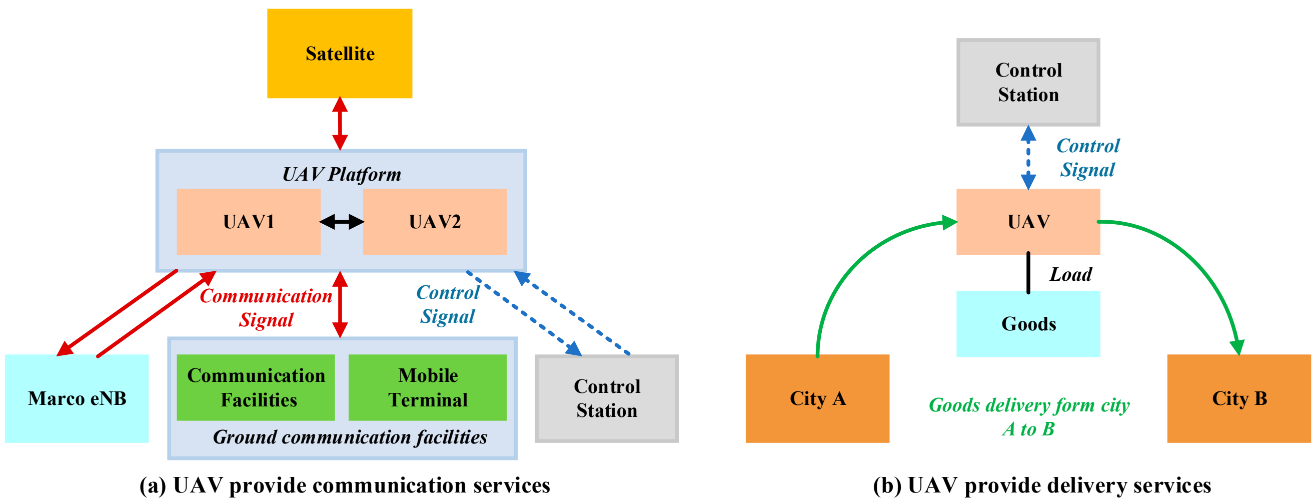

Figure 2. UAV providing services. (**a**) Communication services; (**b**) Delivery services.

The application scenarios in complex situations put higher requirements on the reliability of UAV systems. UAVs generally consist of a flight platform, propulsion system, onboard electrical system, mission load system, control system, and communication system. Moreover, the propulsion system is the core of UAV power and can determine the UAV can complete the corresponding tasks [34]. Propulsion systems usually consist of energy sources and power units, which include engines and motors [35]. According to energy sources, UAV propulsion systems can be broadly classified into three types, including fuel, hybrid fuel-electric, and pure electric. Among them, traditional fuel propulsion systems can be divided into several categories such as piston, gas turbine, and ramjet engines according to the difference of power units [5].

UAVs using traditional fuel propulsion systems have the advantages of high payload, long-endurance extensive range, and rapid resupply [36]. However, with the increasing environmental problems and depletion of fossil fuels, the energy problem of aircraft has become an ongoing challenge; thus, hybrid and purely electric UAVs are now the focus of attention. The hybrid propulsion system consists of an engine and an electric motor working together to generate the power required for aircraft flight, effectively saving about 30% of fuel consumption compared to the traditional fuel propulsion system [37].

While the pure electric UAV propulsion system uses only electric motors as the power source device and thus has the advantages of low carbon emissions, low pollution, low cost, and high energy utilization [38]. In addition, pure electric UAVs have a more comprehensive range of energy sources and can use new energy sources, such as lithium batteries, fuel cells, supercapacitors, solar energy. etc. [39]. Furthermore, using these clean energy sources, purely electric UAVs meet the current environmental needs of energy conservation and emission reduction and represent an important direction for UAV development. Electric propulsion UAVs often use high-energy-density permanent magnet motors as power output devices. Besides, a high-power motor system is decomposed into several low-power motor systems with the same total power, the power density and efficiency of the whole system remain unchanged. It is called the relative scale-independent property of motors. Thus, multiple relatively low-power motors driving small-diameter fans can be used instead of big fans to increase the culvert ratio of the propulsion system and achieve improved stability of the UAV and an optimized UAV energy management strategy [37]. This propulsion system is the distributed electric propulsion system.

Distributed electric propulsion is mainly applied to large and medium-sized passenger aircraft, which generates electricity through a gas turbine-driven generator. It subsequently transmits the electrical energy to an electric motor to drive a propeller or fan rotation to generate thrust through the onboard electrical system. National Aeronautics and Space Administration (NASA) N3-X and ESAero′s distributed electric propulsion aircraft ECO-150 belong to this category [40,41]. However, due to high energy density electric motors and battery technology constraints, distributed pure electric propulsion is mainly used in small and medium-sized general-purpose aircraft and UAVs. A distributed electric propulsion UAV prototype was designed and manufactured by Northwestern Polytechnical University, with a maximum power of 24 kW for the whole aircraft and about 5 kW for level flight [42]. Led by the current demand for carbon-neutral and carbon peaking, motors, power systems, motor control, and batteries have been further developed, driving the successful development of electric propulsion UAVs.

This paper analyzes the composition of UAV systems and provides an in-depth review of the technical research and academic development of fuel, fuel-electric hybrid, and pure electric UAV propulsion systems from the perspectives of their structure, working process, and classification, as shown in Figure 3. Then, this paper introduces the power unit of electric propulsion UAVs and finally analyzes the future vital technologies and development directions of electric propulsion UAV.

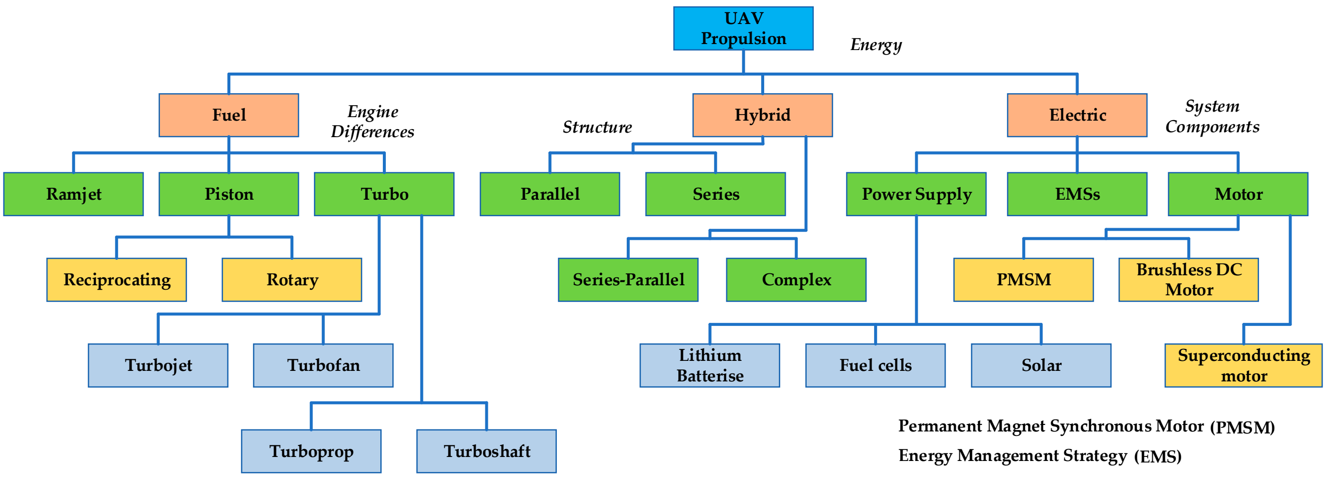

Figure 3. UAV propulsion classification based on energy types.

2. Propulsion System Configuration of UAVs

To complete the intended mission accurately, the UAV and its supporting systems need to cooperate in a stable and orderly manner. In general, as shown in Figure 4 [39,43], UAVs consist of a vehicle, ground control system, payload system, and data communication system. Some large UAVs often also need the support of a takeoff and recovery system, ground support system, and other parts [5].

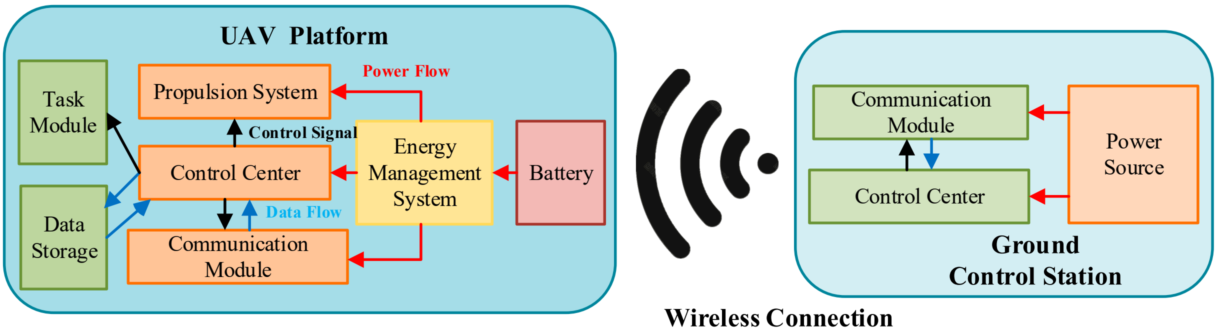

Figure 4. Unmanned aircraft system composition.

With the gradual maturation of artificial intelligence technology, artificial intelligence algorithms applied to UAV control systems have substantially enhanced the automation of target acquisition and mission execution by UAVs. UAV swarm technology is already applied in the military, combined with the corresponding control technology. UAV swarms rely on large numbers to enable saturation attacks on targets and substantially reduce mission costs [44].

A UAV platform is a critical part of mission execution, and general UAV vehicles usually consist of energy, flight control systems, power propulsion systems, communication modules, and energy management systems [43]. As a purely electric aircraft, its structure as shown in Figure 5, the battery generally supplies energy, mainly used to maintain all UAV systems and loads, while the energy management system controls energy distribution. It is designed to maximize the endurance and range of the UAV [45]. In the electric propulsion system, high energy density and low loss converters are usually required to achieve the system′s energy management and motor control [46]. Furthermore, there are often unidirectional or bidirectional converters in the middle of the power supply and the DC bus to accomplish the battery charging and discharging control [47]. Some small UAVs often use brushless DC motors or permanent magnet synchronous motors as power source devices because of their high efficiency, high energy density, high reliability, high speed, and ease of control [48].

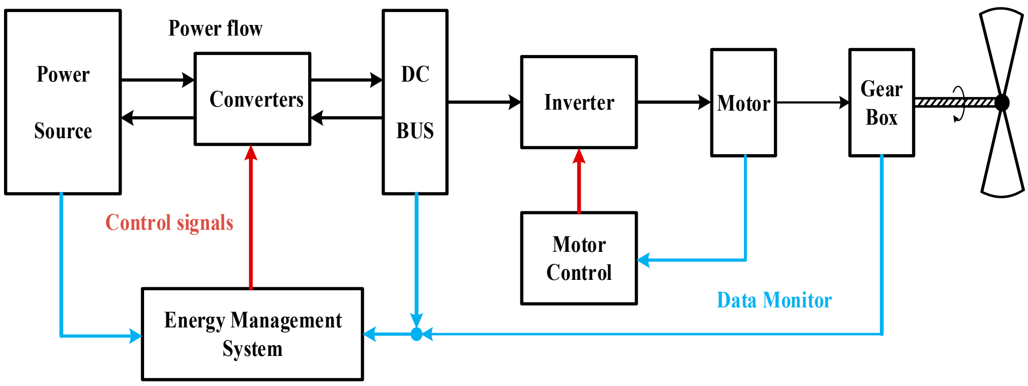

Figure 5. Composition of an electric propulsion system for UAVs.

3. Fuel Propulsion System for UAV

The fuel propulsion system of a UAV generally consists of a fuel supply system, engine, mechanical transmission, and propeller; its structure is shown in Figure 6. It is known from the system structure that the engine is undoubtedly the core of the fuel propulsion system, playing the role of energy conversion and UAV power supply [49]. Fuel engines can be mainly classified into two categories: piston and turbine [50]. Table 2 [50–54] shows the performance comparison of different engines. In addition, compared to civil airliners and crewed military aircraft, UAVs are much smaller in size. Therefore, although the engine fundamentals are the same as those of large aircraft, engines suitable for UAVs need to have many characteristics, including long endurance, small volume, high power-to-weight ratio, robustness, and ease of maintenance [51].

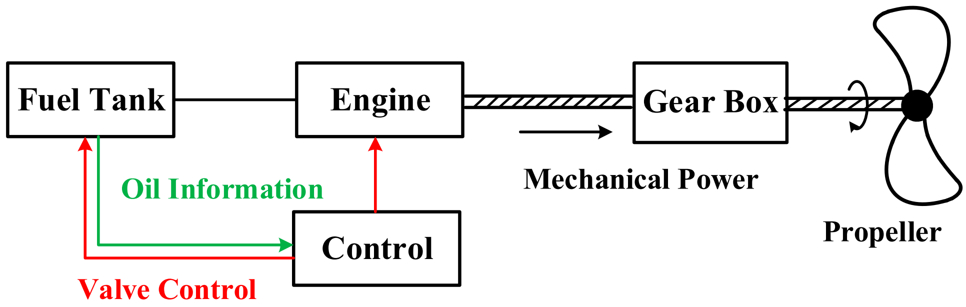

Figure 6. Composition of the fuel propulsion system for UAVs.

Table 2. Different Oil-Based Engine Characters.

Type	Engine Characters			UAV Characters			
	Output	Rotate Speed/rpm	Power to Weight Ratio/kW/kg	Speed/Km/h	Flight Height/m	Endurance Time/h	Flight Weight/kg
Piston Engine [50]	20–400 Hp	3000–7000	0.76–1.37	110–260	2500–9700	<40	<1150
Rotary Engine [50]	<120 Hp	6000–12,000	<4.1	N/A	2500–8000	N/A	<1000
Turbojet [51]	<170 kN	N/A	<10	700–1100	3000–14,000	<2.5	<2500
Turbofan [52]	<560 kN	N/A	<11	500–1100	3000–20,000	<42	<12,000
Turboprop [53]	<1000 Hp	1000	About 4	350–500	14,000–16,000	<32	<3200
Turboshaft [54]	<9000 Hp	N/A	3–7	180–300	4000–6100	<4	<1500

3.1. Piston Engine

A piston engine is an internal combustion engine that uses fuel as an energy source to convert chemical energy into thermal energy and then into mechanical energy. In UAV propulsion systems, a combination of a piston engine and a propeller is required to power the UAV flight. Based on the piston engines parameters, they obtain significant application advantages.

(1) Mature technology: Piston engines have been developed over a long period, and their technology has matured. So, the use of piston engines affects the weight of the load carried by the UAV.
(2) Simple structure: Compared to turbine engines, piston engines have a more straightforward structure. It is easier for daily maintenance of piston engines easier.
(3) Low cost: The piston engine is cheaper to manufacture and use and has good economy and reliability. It is suitable for the application of small and medium-sized UAV propulsion systems.

However, piston engines also have some limitations compared with turbo engines.

(1) Low power-to-weight ratio: Compared with turbine engines, the power-to-weight ratio of piston engines is low. So, the use of piston engines affects the weight of the load carried by the UAV.
(2) Speed limitation: Because the piston engine drives the propeller rotation to generate thrust, its maximum speed cannot exceed the speed of sound, so it cannot meet the needs of high-speed UAVs.

(3) Poor performance at high altitude: Since the piston engine needs to inhale a large amount of air during operation, the performance of the piston engine will be significantly affected in the environment of thin air at high altitudes.

One operating cycle of a piston engine includes four processes: intake, compression, power, and exhaust. Due to a lot of air needing to be inhaled during the combustion process, piston engines are often only suitable for low-speed and low or medium-altitude UAVs [55]. The thin air in the high-altitude environment will reduce the air intake of piston engines, which will affect their power performance. Thus, piston engines need to add a booster, an auxiliary system used in high-altitude environments to increase the oxygen content in the intake air, increase the output power of piston engines, and reduce their fuel consumption [56]. Piston engines can be classified into two main categories, reciprocating and rotary piston engines, based on piston movement [57].

3.1.1. Reciprocating Piston Engine

The reciprocating piston engine comprises a cylinder, piston, crankshaft, connecting rod, valve, reducer. Its principle is to use the internal energy generated by the combustion of fuel in the cylinder, under the action of the expanding gas, to convert the linear motion of the piston into the rotary motion of the crankshaft with the help of the crankshaft connecting the rod mechanism, which drives the external propeller rotation [58]. Its four-stroke working process is shown in Figure 7 [59].

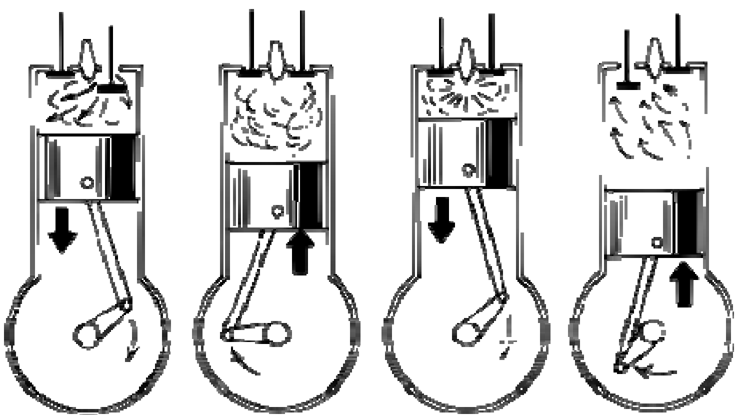

Figure 7. Four-stroke process of a reciprocating piston engine [59].

Usually, the operation of a reciprocating piston engine can be completed in two or four strokes, thus the existence of two-stroke and four-stroke piston engines. The two-stroke piston engine has the advantages of small size, lightweight, and simple structure, which is suitable for the use of small short-time and low-altitude UAVs. However, its cylinder number and cooling device restricts the power output. It is challenging to meet the needs of high-altitude and long-endurance UAVs. In contrast, the four-stroke piston engine has high power and high-efficiency characteristics, which can meet the needs of large UAVs [60].

3.1.2. Rotary Engine

The rotary piston engine is remarkable, and the difference between the conventional piston engine is that the rotor piston is a sudden arc triangle, the cylinder shape is an ellipse, as shown in Figure 8 [61]. When the rotary piston engine is working, the three vertices of the triangular piston are in contact with the cylinder so that the cylinder wall and the piston arc edge form three independent spaces. The volume of the spaces will follow the piston cycle change and show a regular change, and each space can complete four strokes of the work process. The rotary piston engine and reciprocating piston engine have the same principle of operation and four-stroke process, but the rotary piston engine does not require a crankshaft connecting rod and other transmission rotations. It does not need a complex intake and exhaust device, so it has a more straightforward structure than the reciprocating piston engine, and therefore also has the advantages of small size, low cost, high efficiency, and lightweight [62].

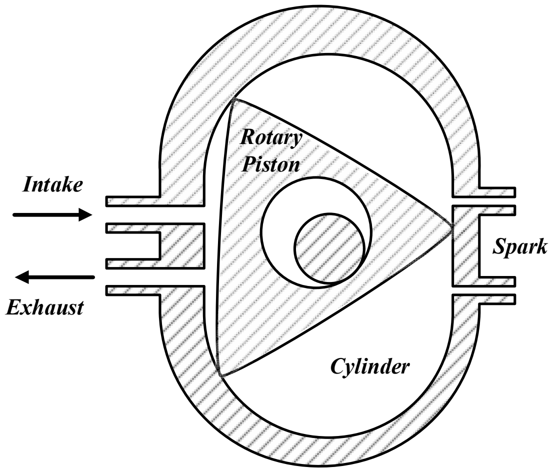

Figure 8. Rotary engine [61].

3.1.3. Key Technologies of Piston Engine

Nowadays, as the energy problem becomes the focal issue that human society has to face, people have more critical requirements for the performance of aviation piston engines. In order to adapt to the problems of reduced air density and oxygen content into the cylinder caused by the harsh environment such as high altitude and high altitude, piston engines need further research on multi-stage boosting technology to maintain the engine performance. In order to improve safety and economy, researchers have conducted relevant research on heavy oil engine technology for piston engines in recent years and have conducted several studies on heavy oil piston engine atomization, deflagration control, and combustion performance studied [36,63].

3.2. Turbo Engine

Due to the limitations of propellers, most piston engines are only suitable for low-speed, low-altitude UAVs, and with the development of the aviation industry, modern aircraft require high-performance aero engines, so in 1930 Frank Whittle designed the first turbojet engine. Due to its ability to meet the needs of high-speed, high-altitude navigation, the turbine engine has now become the mainstream power unit for UAV propulsion systems [64]. According to the differences in structure, gas turbine engines are generally divided into four categories: turbojet, turbofan, turboprop, and turboshaft, which emerged sequentially, but there is no strict distinction between advanced and backward, and they all perform well in their respective ranges of applicability [65]. The main parameters and applicable ranges of the four types of turbine engines are shown in Table 2, from which we can learn that turbojet and turbofan engines have very superior high-speed performance and high-altitude flight capability. They are therefore suitable for application in target aircraft, high-altitude reconnaissance drones, etc. At the same time, turboprop provides much less speed and cannot make the aircraft exceed the speed of sound because of the sound barrier. The turboshaft is a turbine engine that outputs shaft power mainly in helicopters and UAV helicopters.

3.2.1. Turbojet Engine

In general, the turbojet engine is mainly composed of intake, compressor, combustion chamber, turbine, and nozzle, and its structure is shown in Figure 9a. The turbojet's working principle is that the air is drawn into the engine through the intake ducts, where the compressor compresses the incoming air, resulting in a significant in-crease in air pressure. This high-pressure air is then mixed with fuel in the combustion chamber and burned on the ignition to produce high-temperature and high-pressure gas. This high-temperature, high-pressure gas drives the turbine, which drives the previous compressor and other components. Subsequently, the high-temperature and high-pressure gases are ejected at high speed through the nozzle to create power [66]. The turbojet engine has the advantages of negligible mass, sizeable power-to-weight ratio, and a wide range of applications, so it is widely used in UAV propulsion systems [67], such as the WP-11 small turbojet engine developed by the Beijing University of Aeronautics and Astronautics, which is used in China's Wuzhen-5 high-altitude un-crewed reconnaissance aircraft. However, because turbojet engines emit high-temperature and high-pressure gas, which still has much energy, turbojet engines have disadvantages such as low efficiency and high fuel consumption at low speeds [68].

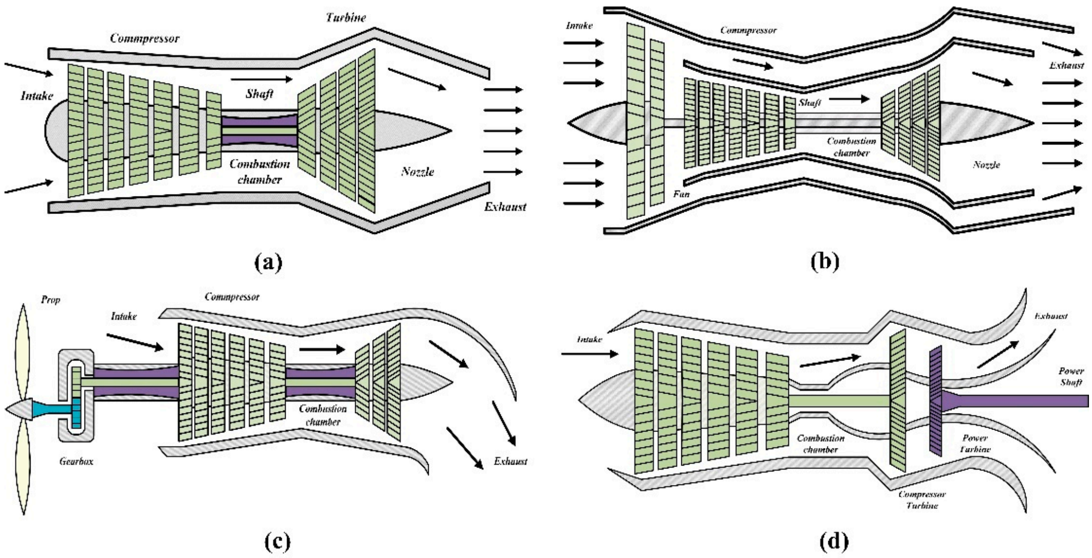

Figure 9. Structure of turbo engines. (**a**) Turbojet [66]; (**b**) Turbofan [69]; (**c**) Turboprop [70]; (**d**) Turboshaft [71].

3.2.2. Turbofan Engine

In response to the low-efficiency problem of turbojet engines, people have improved on the turbojet engine by adding a fan at the intake tract, and the other structures are similar to those of turbojet engines [69], its structure is shown in Figure 9b.

It should be noted that the high-temperature and high-pressure gas generated by the turbofan engine is mainly used to drive the rotation of the turbine, the rotation of the turbine will drive the fan and compressor in front of it, and the energy will be mainly consumed at the turbine. The source of thrust is mainly from the thrust of the fan compressed gas, which will make the energy of the ejected gas smaller than that of the turbojet, so the turbofan engine has higher efficiency and longer life, making them ideal for use in UAV propulsion systems [72]. However, the high-speed performance of turbofan engines is weaker than that of turbojet engines. In addition, the bypass ratio has an important influence on the high-speed performance of turbofan engines. Usually, the high-speed performance of a turbofan engine with a high bypass ratio is weaker than that of a turbofan engine with a small bypass ratio. The military fighter aircraft are often equipped with a small bypass ratio turbofan engine to meet the needs of a supersonic cruise. Therefore, supersonic UAVs mainly use turbojet engines, while high bypass ratio turbofan engines are more often used in civil airliners, and low and medium-speed UAVs, such as the U.S. X-47B naval UAV equipped with Pratt and Whitney F100-220U turbofan engines [73]; the RQ-4 "The Global Hawk" UAV is powered by Rollo's AE3007H turbofan engine [15].

Currently, the more common method used in aviation is on-condition maintenance. This is a method of inspecting engine components at a specified time to determine if they can work until the next service point based on engine wear or performance degradation. Temperature, on the other hand, is an essential factor that affects engine wear or performance. Due to the increase in thermal efficiency, the temperature of the gas ejected from a turbofan engine will be lower than that of a turbojet engine. This decrease in temperature will result in less fatigue of the internal engine components, which will extend the life cycle of the turbofan engine. In addition, the increase in component life will also save the maintenance cost of turbofan engines, thus improving the economy of turbofan engines, which is especially important for civil aviation.

3.2.3. Turboprop Engine

As shown in Figure 9c, turboprop and turbojet engines are similar in structure, with the same intake, compressor, combustion chamber, turbine, and nozzle. The difference is that the turboprop in the intake before assembling a larger diameter propeller. And the reducer is installed between the propeller the driveshaft. Turboprop engines work similarly to turbojet engines, but the high-temperature, high-pressure gas generated is partly used directly to generate thrust and drive the turbine rotation. The turbine drives the compressor rotation, and the driveshaft pushes the propeller rotation to generate power. As the turbine speed is much higher than the propeller speed, the propeller and the drive shaft often need to add a reduction device to make the turbine speed match the propeller speed. Therefore, turboprop engines have the advantages of sizeable power-to-weight ratio, low vibration, and compact structure compared with traditional piston engines and have higher efficiency than turbofan engines in low-speed application scenarios. So, they are widely used in low-speed UAVs, such as the Predator-B UAV of the United States, which uses Honeywell's TPE331-10T turboprop engine [70]. Turboprop engines are also fitted in some regional transport aircraft, such as the Chinese AG600 amphibious aircraft [74].

3.2.4. Turboshaft Engine

The structure of the turboshaft engine is similar to that of a turboprop engine, its structure as shown in Figure 9d. However, the turboshaft engine is usually closely connected to the gearbox and engine body, and the propeller needs to generate lift and bear the weight of the vehicle, while the turboprop engine is only responsible for generating lift and does not directly bear the weight of the vehicle. In terms of working principles, turboshaft and turboprop engines are the same. The main difference between them is that the high-temperature and high-pressure gas energy is almost all used to push the turboshaft turbine rotation and does not directly provide the thrust required for flight. So, the turboshaft engine output is mainly shaft power. Due to its characteristics of output shaft power, turboshaft engines are generally used in the propulsion system of helicopters, such as the RQ-8B unmanned helicopter of the United States, which uses the RR-250-C20W turboshaft engine of Rollo [71]. Table 3 shows the advantages and disadvantages of these four types of turbos.

Table 3. Advantages and disadvantages of the four types of turbos.

Turbo Types	Advantages	Disadvantages
Turbojet	• Wide application • High speed character • Suitable for high altitude	• High emission at low speed • High cost • Complex technology • Low efficiency
Turbofan	• High power-to-weight ratio • High power • High efficiency • Long endurance	• Not suitable for high speed (High bypass ratio) • High flight resistance
Turboprop/Turboshaft	• Compact structure • Low noise • Easy maintenance • High efficiency	• Not suitable for high speed • Narrow application

3.3. Ramjet Engine

In order to pursue a higher flight speed of drones, people have developed ramjet engines. Unlike the typical turbine engine, the ramjet engine does not have a compressor to compress air but uses the airflow of the aircraft at high speed to enter the air intake and then decelerate, as shown in Figure 10 [75]. It converts the kinetic energy of the air into internal energy and makes the air's pressure higher. The ramjet engine generally has intake, fuel injection, combustion chamber, and nozzle, etc. The structure of the ramjet engine is greatly simplified by the elimination of the compressor and turbine structure.

The thrust generated by the stamping engine is positively correlated with the intake airspeed, so the more significant the aircraft's flight speed, the greater the thrust generated by the ramjet engine. Due to this feature, the ramjet engine is not usable at rest and has poor low-speed performance, so it is often used in conjunction with other engines to form a combined propulsion system in applications, as an aircraft equipped with only a ramjet engine needs other aircraft to take it into the air and provide a certain speed for the ramjet engine to work correctly [52]. Due to their superior high-speed performance, ramjet engines are often assembled in hypersonic UAVs, such as the propulsion system of the U.S. X-51A hypersonic UAV with five times the speed of sound, which has a ramjet engine as its core [76].

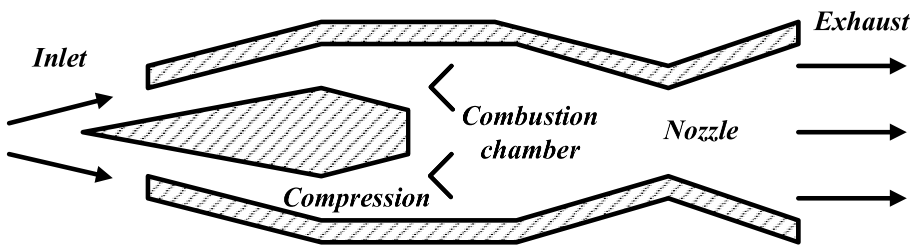

Figure 10. Ramjet Engine [75].

4. Fuel-Electric Hybrid Propulsion System for UAV

The development of fuel propulsion systems for UAVs is becoming increasingly mature. However, with the increasing depletion of petroleum resources and the increasingly severe climate problems, the traditional fuel propulsion system can no longer meet energy and environmental protection needs, while the pure electric propulsion system is still under development. The problem of battery energy density restricts its further application, resulting in the pure electric propulsion system not fully meeting the needs of air transportation, so people have proposed the fuel-electric hybrid propulsion system solution [77,78]. The fuel-electric hybrid propulsion system is an aviation propulsion system in which the fuel engine and generator act together to generate thrust [79–81].

In the fuel propulsion system, the loss mainly comes from the engine and the mechanical loss from the gear set and driveshaft friction. In the hybrid propulsion system, the motor itself has a certain amount of energy loss in addition to the actual mechanical losses and heat losses. At the same time, part of the electrical energy will be lost in the energy transfer between the motor and the battery. The increase of the motor and its related mechanical structure will inevitably bring additional energy consumption. In addition, the friction in the system, the motor, and the electrical energy transmission line generated by the heat loss is also not negligible [82,83]. Generally speaking, the hybrid structures can be broadly classified into parallel, series, series-parallel, and complex structures based on whether the engine provides thrust directly [84–87].

4.1. Parallel Hybrid Structure

The parallel hybrid propulsion system is the engine, and the electric motor/generator jointly drives the propeller's rotation through the mechanical drive transposition [88], and its structure is shown in Figure 11 [37]. The purpose of the existence of the electric motor/generator is to maintain the engine working under reasonable operating conditions. When the engine power is excessive, the excess power will be converted into electrical power through the generator and stored in the energy storage device. When the engine power is insufficient, the energy storage device will release electrical energy to drive the electric motor to compensate for the insufficient engine power. This mode can further improve the efficiency of the UAV propulsion system in order to reduce fuel consumption and further improve its flight time and range. Furthermore, it is essential to note that the engine type needs to be checked in a parallel-type hybrid structure. The energy management system can be controlled according to the specific engine and motor operating conditions to utilize energy fully. It is also required in series-parallel hybrid system structures [89].

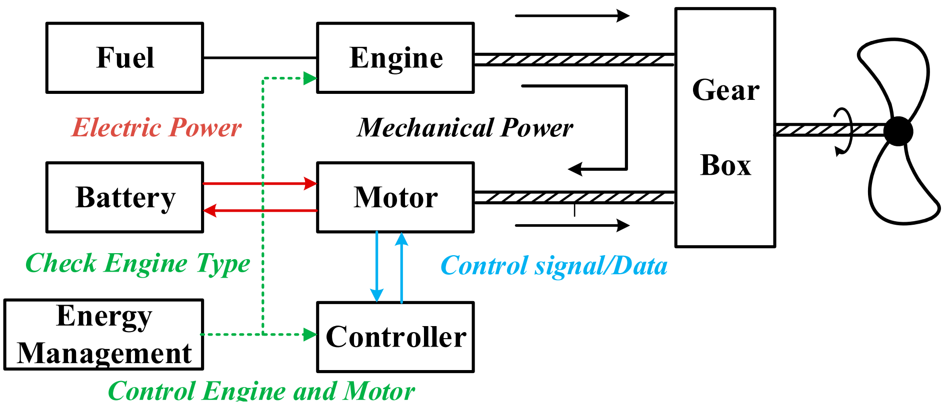

Figure 11. Parallel hybrid architecture.

4.2. Series Hybrid Structure

The most important feature of the series hybrid propulsion system is that the engine does not directly provide the power needed by the UAV but drives the generator to generate electrical energy, which in turn drives the electric motor to work and drives the fan rotation to generate power; its structure is shown in Figure 12 [37,88].

In the application, the electric motor can be used to drive the fan to generate thrust during the start-up and landing phases of the aircraft, which reduces the nitrogen oxides produced by the turbine engine near the ground, and the gas turbine can be used to drive the electric motor to generate electrical energy during the high-altitude cruise phase to increase the range of the aircraft. In this way, it is possible to improve energy use efficiency, reduce fuel consumption, and reduce NOx emissions, which is very important in environmental protection [88,90].

In addition, since gas turbines are mainly used to drive generators to generate electrical energy and aircraft power is derived from electric motors, the aircraft can adopt a distributed propulsion system, which provides more design options for the aerodynamic layout of UAVs. For example, NASA's N3-X uses a hybrid propulsion system fitted with two turboshaft engines, driving two generators, and a propulsion system powered by multiple electric motors [40]. It should also be noted that this motor connection structure, including the superconducting motor mentioned later, is not widely used in today's passenger aircraft due to the state of the technology. Therefore, it is still mainly used in UAV propulsion systems.

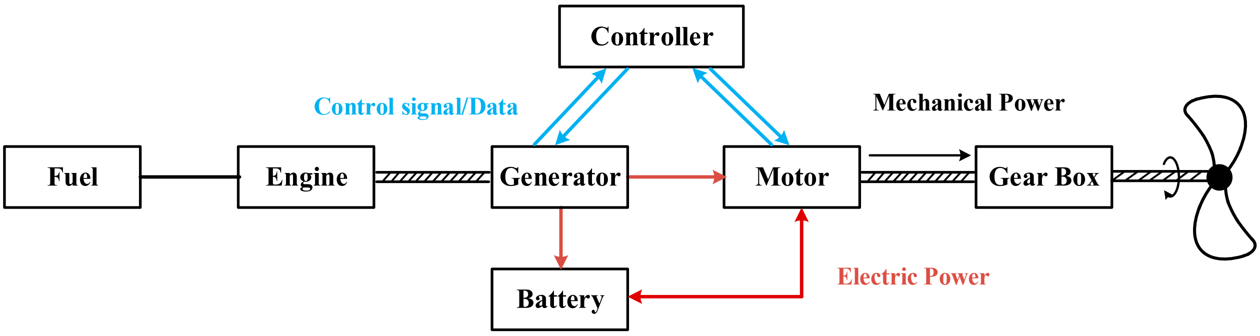

Figure 12. Series hybrid architecture.

4.3. Series-Parallel Hybrid Structure

As shown in Figure 13, the series-parallel hybrid structure is a fusion of series and parallel hybrid structures, where the power unit is also composed of an engine and an electric motor [84]. The mechanical energy generated by the engine is partly transferred to the propeller through the gearbox, while the generator generates the other part for the electric motor to rotate or is stored in the battery. During the flight, the electric motor and the engine together provide power for the propeller's rotation. When the UAV is operating at low speed, the hybrid power system works mainly in series form. When flying at high speeds, the system works in parallel. In addition, when the drone is in braking mode, the generator generates electrical energy and stores it in the battery. In this way, the UAV series-parallel hybrid power system can have the advantages of both series and parallel structures. Its ability to adjust the operating state flexibly allows the UAV to adapt to complex operating conditions and work with more sophisticated energy management strategies. Therefore, the series-parallel hybrid power system can improve fuel utilization efficiency, save fuel, and increase the range of the UAV [84,90,91].

To better control the generator and motor, based on the series-parallel hybrid structure, people design the complex hybrid structure, whose structure is shown in Figure 14 [84]. Based on the original structure, a power electronic converter is added to the complex hybrid structure so that the electric motor and generator can be controlled separately. In this way, more precise system control can be achieved, and fuel can be further saved [84].

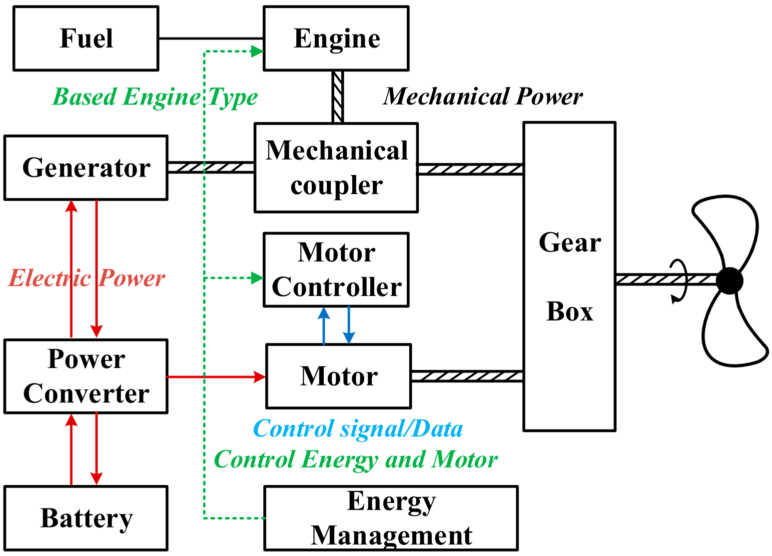

Figure 13. Series-Parallel Hybrid.

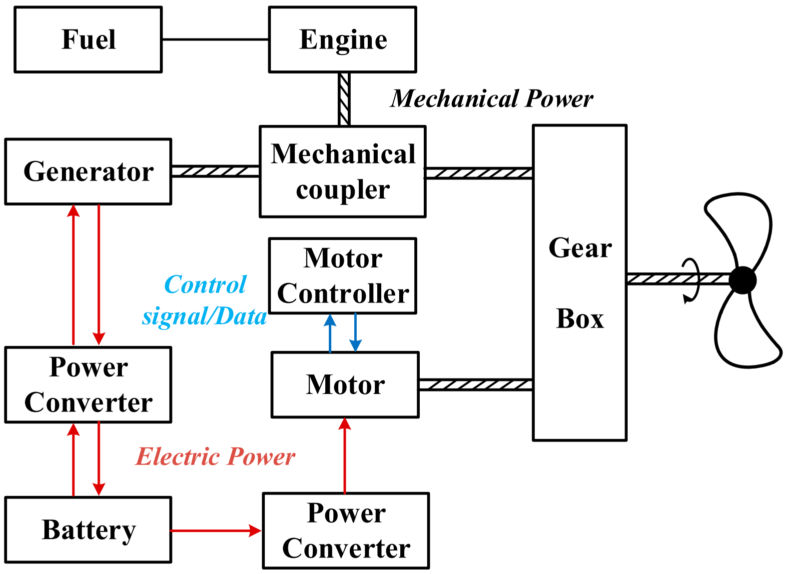

Figure 14. Complex hybrid.

In general, the series-parallel hybrid structure combines the advantages of the series and parallel structures, but it also has the disadvantages of a complex structure and complex control methods, which can cause an increase in the cost of the UAV and in the system complexity [84]. In addition, there are currently hybrid combinations of fuel cells, diesel engines, batteries, solar cells, which are not described in detail here in this paper. In short, Table 4 shows these four structures' features, advantages, and disadvantages.

Table 4. Comparison of four hybrid propulsion structures.

Structure Types	Features	Advantages	Disadvantages
Series	The propulsion system is powered by electric motors only.	• Simple structure • Easy to control and maintain • Low cost	• High emission • Low efficiency • Only has electric mode
Parallel	The propulsion system consists of an engine and an electric motor working together to generate power.	• High max power • Have fuel and electric mode • High reliability • Great performance at high speed	• High emission • Low efficiency • Short endurance
Series-Parallel	Integration of series and parallel structures, which can work in single or dual mode, respectively.	• High efficiency • High reliability • Long endurance	• Complex structure • Control hard • High cost
Complex	A converter has been added to the Series-Parallel to independently power the motor.	• High efficiency • Various operating conditions • Better performance	• Complex structure • More difficult Control • High cost

5. Electric Propulsion System for UAV

With the increasing shortage of petroleum resources, the energy supply of fuel and hybrid propulsion systems is facing increasingly severe challenges. Thus, attention has been directed to purely electric propulsion systems [92]. Compared with fossil fuels propulsion systems, electric propulsion system has great potential for more applications [93].

(1) Environmentally friendly: Electric propulsion UAVs use electrical energy as a power source, thus reducing fuel consumption and pollutant emissions. At the same time, this contributes to solving the increasingly tight energy problem and significantly reduces carbon emissions.
(2) Design versatility: Electric propulsion UAVs use electric motors to generate thrust and thus have a distributed layout. It allows for more aerodynamic layouts for better flight performance, which in turn can meet specific needs.
(3) Wide range of energy sources: Fuel cells, solar energy, and lithium batteries can all be used as energy sources for electric propulsion drones.
(4) Simple structure: The UAV electric propulsion system has a simple structure and is much easier to repair and maintain.

However, the electric propulsion system still has some disadvantages due to some technological limitations [94].

(1) Low energy density of energy storage devices: the current lithium battery energy density is insufficient, resulting in the weight of the battery carried being too large to meet the needs of the use of electric propulsion UAV.
(2) High cost: The key components of electric propulsion systems, such as lithium batteries, are costly. As the electric propulsion technology is not yet mature, the high development cost restricts its further application.
(3) Insufficient environmental adaptability: electric propulsion UAVs are challenging to make work satisfactorily in lousy weather. In the complex electromagnetic environment, the reliability of the electric propulsion system will be reduced to a certain extent.

The electric propulsion system of UAVs generally consists of a power source, an electric motor, and a corresponding control system [95]. The corresponding energy management system is often used for UAVs with higher range and flight time requirements to achieve higher energy utilization efficiency. The battery transmits electrical energy through the aircraft grid system to the motor in the electric propulsion system, which rotates the propeller or culvert fan to generate power [93].

5.1. UAVs Electric Propulsion System Power Supply

For electric propulsion UAVs, the power source is a critical component that often needs to have a high energy density, low weight, and low noise, and needs to support the range and endurance of the UAV [39,96]. The primary power sources for UAVs are lithium batteries, fuel cells, solar photovoltaic, supercapacitors, etc. In addition, renewable power is also an essential source for current UAV electric propulsion systems, such as lithium batteries mixed with fuel cells and lithium batteries mixed with photovoltaics [39].

5.1.1. Lithium Batteries

Lithium batteries are a kind of battery that contains lithium elements (lithium metal, lithium-ion, lithium polymer, etc.) in the electrochemical system. Usually, lithium batteries can be roughly divided into two categories: lithium metal and lithium-ion batteries [97].

At the beginning of lithium-ion batteries, they were mainly composed of lithium storage materials with good reversibility, graphite, and organic electrolyte solutions, and nowadays, the anode systems of lithium-ion batteries mainly include Lithium Cobaltate (LCO), LiFePO4 (LFP), and ternary Nickel-Cobalt-Manganese (NCM) systems, etc. [98]. The working principle of lithium batteries is the transfer of charge between positive and negative electrodes with the help of the movement of lithium ions in the electrolyte solution. During charging and discharging, lithium ions are embedded and de-embedded between the positive and negative electrodes; during charging, lithium ions are de-embedded from the positive electrode and embedded in the negative electrode, while the opposite is true during discharging. The use of lithium batteries can make UAVs simpler and more flexible. However, due to energy density limitations, electric propulsion systems that rely solely on lithium batteries, which are often only applicable to small and micro-UAVs. It has a short endurance and does not meet the mission requirements of medium and large UAVs.

5.1.2. Fuel Cells

The energy storage device′s energy density and power density are directly related to the UAV′s range, flight time, and volume. It can be seen from Figure 15 that the fuel cell has a more extended use time for the same weight [99]. So, the fuel cell can be used in UAVs and increases the range of UAVs. Fuel cells can usually be divided into Alkaline Fuel Cells (AFC), Phosphate Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), and Proton Exchange Membrane Fuel Cells (PEMFC) [97]. The relevant characteristics and differences are shown in Table 5 [39,100–103], and the fuel cells currently used more in UAVs are proton exchange membrane fuel cells.

Moreover, the hydrogen fuel cell electric propulsion UAV system generally comprises a hydrogen storage device, fuel cell, electronic governor, motor, propeller, and other auxiliary power electronics [39].

In contrast, the hydrogen ions reach the cathode through the electrolyte and combine with oxygen atoms at the cathode to produce water, and the generation of heat accompanies the whole process. As we know from the working principle, the main product of hydrogen fuel cells is water, so it does not harm the environment. Moreover, the hydrogen fuel cell propulsion system also has a high energy density, which can meet the extended flight time of UAVs. For example, in 2016, ST Aerospace of Singapore developed the sky blade 360 fuel cell UAV with Horizon's Aeropak fuel cell system, with a UAV wingspan of 3 m and a total mass of 9 kg, and a flight time of 6 h [104].

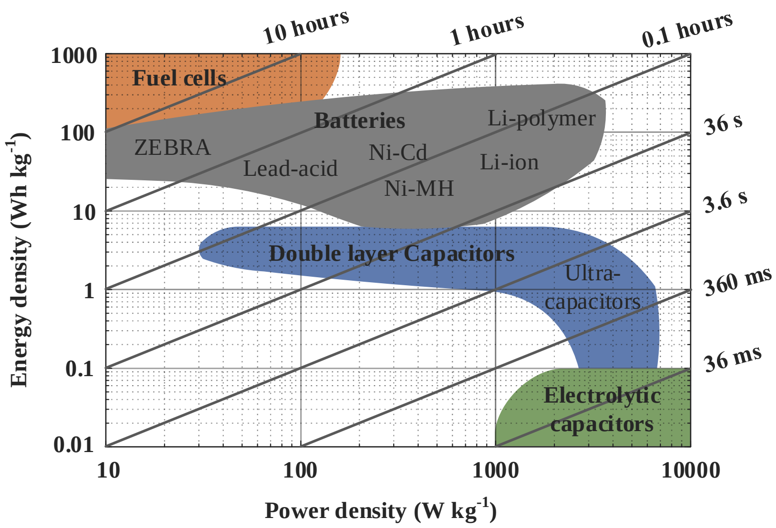

Figure 15. Energy density and power density of energy storage devices [99].

Table 5. Comparison between lithium batteries, fuel cells, and solar cells characteristics.

Type	Efficiency	Power	Work Temperature/°C	Power Density	Cycle life	Specific Capacity/mAh/g
LiPO4 [101]	90%	N/A	−20–60	549 Wh/kg	>2000 times	150
LCO [101]	95%	N/A	−20–55	200–250 Wh/kg	500–1000 times	145
NCM [101]	95%	N/A	0–45	588 Wh/kg	>1000 times	110–120
AFC [100]	60%	10–100 kW	50–200			
PAFC [39]	40%	1–100 kW	160–220			
MCFC [39]	45–50%	100–400 kW	620–660	>500 Wh/kg	5000–20,000 h	N/A
SOFC [39]	60%	300 kW–3 MW	800–1000			
PEMFC [39]	35–60%	1 kW–2 MW	60–80			
Solar Battery [102]	10.1–25%	10 W–50 MW	Best at 25 °C	80 W/kg *(Solar Impulse 2)* [103]	20 Year	N/A

However, hydrogen fuel cell propulsion systems also have some problems, such as the small power density, the fuel need to pass through the exchange membrane, and the time required for the electrochemical reaction, the soft voltage characteristics, the risk of hydrogen storage, the large volume and mass of other components of the system and the heat handling during the reaction [105–107]. These issues limit the fuel cell in the broad application of electric propulsion systems for UAVs.

Currently, a hybrid fuel cell and lithium battery propulsion system can solve the problems of slow fuel cell start-up and short lithium battery-driven flight time by using lithium battery power during the main stages of UAV takeoff and climb and fuel cell power during the cruise phase, which can achieve greater propulsion efficiency [108].

5.1.3. Solar Photovoltaic

Photovoltaic solar cells derive their energy from solar light input and use the photovoltaic effect to convert light energy into electricity, a green, non-polluting, and clean energy source. A solar UAV is an aerial vehicle that uses solar cells as an energy source and generally flies at 20,000 m. It is also known as a near-space solar UAV [109]. The propulsion system of solar UAVs generally consists of solar cell sets, lithium batteries, electric motors, propellers, controllers, etc. Due to the low conversion rate and low energy density of solar cells, the application often requires an increase in the coverage area of solar cells to guarantee access to sufficient energy. Thus, solar UAVs have a large wingspan chord ratio, and the solar cells are covered on the wings [108].

Solar UAV is a kind of high-altitude and long-endurance UAV, according to its working principle: during the daytime, solar cells generate energy, and the excess energy is stored in the high energy density lithium battery pack while ensuring the routine work of the UAV; at night, the energy stored in the lithium battery pack maintains the regular work of the UAV systems. It can be seen that, in theory, if the energy stored in the solar UAV during the day can be greater than its night flight needs, then the solar UAV can achieve permanent flight. However, there are problems such as too low energy density of solar cells, the insufficient energy density of energy storage battery pack, the difficulty of the energy management system in coping with a complex environment, and too many random disturbing factors, which restrict the ability of solar UAVs to fly across day and night [108]. Table 6 [104] compares the key performance indicators of various models of solar UAVs and fuel cell UAVs.

Nevertheless, solar-powered UAVs are currently characterized by high-altitude, long-endurance flight and can play a significant role in communication, navigation, monitoring, meteorology, and agriculture. Several studies on solar UAVs have been carried out in various countries, and several series of solar UAVs such as Solara 50, Apusduo, and Aquila have been developed in the United States. The Zephyr-S solar UAV developed in 2018 in the United Kingdom achieved 26 days of long-endurance flight, and the Cai-Hong series of solar UAVs have been developed in China [109].

Table 6. Comparison between fuel cells and solar UAVs characteristics.

Type	Battery Type	Wing Length/m	Battery Power/W	Flight Time/h	Speed/m/s
Sunrise I [104]	Solar Battery	9.76	450	3–4	6–9
Sunrise II [104]	Solar Battery	9.76	600	N/A	10.67
Solong [104]	Solar Battery	4.75	225	>48	12–22
Sky-Sailor [104]	Solar Battery	3.2	90	27	8.3
AtlantikSolar [104]	Solar Battery	5.65	275	81.5	8.6
Spider Lion [104]	PEMFC	2.2	115	3–4	N/A
XFC [104]	PEMFC	3	300	6	N/A
Ion Tiger [104]	PEMFC	5.2	550	48	N/A
Stalker XE [104]	SOFC	3.6	300	8	N/A
FAUCON H2 [104]	PEMFC	3	310	310	10

5.2. Electric Propulsion System Power Units

The electric motor is the core electromechanical energy conversion component in the electric propulsion system. Its role is to convert electrical energy into mechanical energy to drive the propeller or turbofan rotation to generate the power required for the UAV flight. Due to size and weight constraints, UAV electric propulsion systems often require high power density motors, and the parameters that affect the motor power density are mainly magnetic load, electrical load, frequency, linear rotor speed, and current density [110]. By improving these parameters, the power density of the motor can be increased, and the motor's output power can also be increased, which in turn can meet the demand of the UAV power unit [111]. The main motors commonly used on UAVs are permanent magnet synchronous motors, superconducting motors, and permanent magnet brushless DC motors [108,112].

5.2.1. Permanent Magnet Synchronous Motor

With the development of rare-earth permanent magnet materials, the maximum magnetic energy product and maximum operating temperature of permanent magnet materials have been increased, and thus the power density of permanent magnet synchronous motors has been further improved [113]. Permanent magnet synchronous motors are widely used in UAV propulsion systems for high power density, efficiency, and low technical risk [114]. Since the increase of motor speed can increase the motor power density, PM synchronous motors often work at high speed and usually need to be used with gearboxes when applied to UAVs, but this also brings the problem of size and weight of components such as gearboxes and the loss of motor power [115].

In addition, increasing the number of pole pairs and frequency of permanent magnet synchronous motors and improving the air gap magnetic density can also increase the motor power density [37]. However, permanent magnet synchronous motors also have heat dissipation and permanent magnet demagnetization problems, making it difficult for permanent magnet synchronous motors to output high power for a long time, and the reliability will be affected accordingly. In the future, the UAV-equipped permanent magnet synchronous motors will be further developed toward high power, and effective cooling and heat dissipation methods will be further designed to meet the requirements of future UAV electric propulsion systems. The University of Illinois proposed a high-speed external rotor permanent magnet motor based on a slotless structure with the structure shown in Figure 16, capable of outputting 1 MW of power at high-speed operation, and its power density also reaches 14 kW/kg [116].

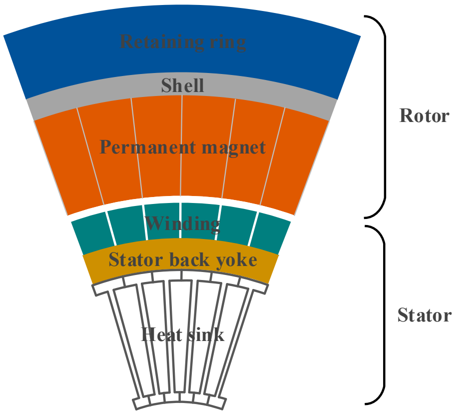

Figure 16. Structure of high-speed permanent magnet motor [116].

5.2.2. Permanent Magnet Brushless DC Motor

A permanent magnet brushless DC motor (PMBLDC) is a special magnet synchronous motor with a trapezoidal or square wave counter-electromotive force waveform [117]; its structure is shown in Figure 17. Usually, a PMBLDC motor consists of a motor body, inverter, sensor, etc. Since a PMBLDC motor has an inverter inside, it is powered by DC power in the application. The significant difference between brushless DC motors and traditional brushed DC motors is that they use electronic switching circuits instead of brushes and commutators, making them spark-free during commutation [118]. In addition, the brushless DC motor retains the wide range and smooth speed regulation performance of DC motors with good controllability. Moreover, permanent magnet brushless DC motors are widely used in UAV electric propulsion systems because of their excellent reliability, low noise, small size, long life, and easy maintenance [112].

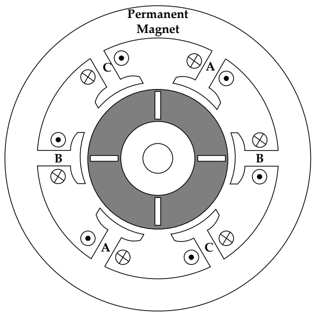

Figure 17. Structure of brushless DC motor [117].

5.2.3. Superconducting Motors

A superconducting motor is a promising power device for the electric propulsion system of UAVs. The superconducting motor is used to increase the air gap magnetic density and armature line load of the motor by using the high current density and low loss characteristics of superconducting materials to increase the power density of the motor in order to reduce the volume and weight of the motor and improve its efficiency [37]. Compared with conventional motors, the conductors of superconducting motors do not have heat losses when energized, which can reduce the cooling system′s power and thus the size of the cooling system. The mainstream rotor-excited superconducting type motors can be used in aircraft because of their high-power density, small size, lightweight, high efficiency, small number of ferromagnetic materials, and low armature reactance. The high-temperature superconducting motor proposed by Florida State University in the United States can reach a speed of 3000 rpm, a superconducting coil operating temperature of 25 K, an output power of 1.5 MW, and a power density of 6.6 kW/kg [119], and even so, it is still some distance from being applied to large aircraft.

Superconducting motor technology is still at the stage of theoretical exploration and preliminary application; even for high-temperature superconducting motors, the critical temperature of the superconducting material is still low, and the practicality is significantly affected. Meanwhile, superconducting motors have significant AC losses under high-speed rotation. In the future, superconducting motors need to reduce the AC loss of superconducting armatures, increase the critical temperature of superconducting materials, and reduce the cost of cooling to achieve applications in electric propulsion systems UAVs [120].

6. Conclusions and Prospect

This paper mainly introduces the key technologies of UAV propulsion, including fuel power, fuel-electric hybrid power, and electric power. Moreover, it addresses three energy sources of electric propulsion systems, namely lithium batteries, fuel cells, and solar cells. Furthermore, the work introduces the characteristics, advantages, and disadvantages of PMSMs, superconducting motors, and BLDC motors applied for electric propulsion systems. The essential summation and key contributions are listed below.

(1) With the increasingly severe problems of energy and the environment, the problems of fuel propulsion pollution systems should be solved in effective ways. Fuel propulsion systems will develop toward higher efficiency, such as heavy oil technology to fully utilize most fossil fuels.
(2) The hybrid fuel-electric propulsion system can significantly improve the UAV flight efficiency and save fuel consumption. Over time, it can provide sufficient power for UAVs, and it can reduce energy consumption, which is suitable for a wide range of medium and large UAV applications.
(3) The electric propulsion system will become one of the mainstreams for future UAV propulsion systems thanks to its advantages of environmental protection, comprehensive energy source, and diverse aerodynamic layout.
(4) The UAV electric propulsion system needs to select suitable energy storage devices with the high-power density and high energy density. The fuel cell has a broad development prospect at present.
(5) The distributed electric propulsion system will make the UAV have a more aerodynamic layout, and the development of a high-power density permanent magnet synchronous motor will make it have a higher power-weight ratio.
(6) The use of superconducting motors will effectively solve the power and heat dissipation problem of UAV motors, thus reducing the weight and volume.

However, UAV electric propulsion systems are still constrained in batteries, motors, and energy management, and electric propulsion is still problematic for application to high-altitude, long-endurance large UAVs. Therefore, in the future, the UAV electric propulsion system needs to focus on developing the following technologies [37].

(1) Safe, reliable, and high-density energy storage technology. At present, the energy density of lithium batteries is still not enough, and fuel cells have a large volume and weight due to the hydrogen storage device and control device. The storage of hydrogen has a particular danger, which leads to the low load-to-weight ratio of electric propulsion UAVs. This could become the biggest problem that restricts the application of electric propulsion systems.
(2) High power density motor technology. UAV electric propulsion systems in the future need to reduce the volume weight to improve the load capacity. And a high-power density motor has a smaller volume weight and can produce a higher propulsion power. When the power density of the electric propulsion system has 3~8 kW/kg, it has the additional practical value.
(3) High efficiency and high-power density converter. The high-power density converters play a vital role in electric propulsion systems, and the control of motors often requires large-capacity power converters, such as rectifiers and inverters. The electric propulsion system will adopt the larger power converters, which will bring much more losses. Additionally, the high-efficiency power converters can save energy consumption and increase the range and endurance of the UAV.
(4) Efficient heat management technology. The electric propulsion system will use many electronic components, which will inevitably bring a lot of heat. Excessive heat accumulation in the UAV that cannot be dissipated will affect the device service life. For instance, the healthy cooling can improve the current density of the motor winding, reduce the conduction loss of the switching tube, and extend the service life of the motor insulation layer. Therefore, UAV electric propulsion systems require the thermal management techniques that are small, efficient, and suitable for distributed systems.

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