Technology of Propulsion System for Unmanned Combat Aerial Vehicle (UCAV) – A Review

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ABSTRACT - Unmanned Combat Aerial Vehicle (UCAV) is an unmanned aerial vehicle (UAV) that is used for intelligence, surveillance, target acquisition, and reconnaissance and carries aircraft ordnance such as missiles, ATGMs, and/or bombs in hardpoints for drone strikes. These drones are usually under real-time human control, with varying levels of autonomy. Unlike unmanned surveillance and reconnaissance aerial vehicles, UCAVs are used for both drone strikes and battlefield intelligence. Unmanned Combat Aerial Vehicle (UCAV) propulsion technology is significantly related to the flight performance of UCAVs, which has become one of the most important development directions of aviation. It should be noted that UCAVs 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 UCAV propulsion system and provide the essential information on electric propulsion UCAVs. Additionally, future technologies and development, including the high-power density motors, converters, power supplies, are discussed for the electric propulsion UCAVs. In the near future, the electric propulsion system would be widely used in UCAVs. The high-power density system would become the development trend of electric UCAVs. Thus, this review article provides comprehensive views and multiple comparisons of propulsion systems for UCAVs.

Keywords: UCAV, Propulsion System, Indonesian Air Defense System

INTRODUCTION

The State Capital is defined as the city where the seat of the center of government of a country is located or where the executive, legislative and judicial administrative elements are assembled. (KBBI)

The existence of a capital city in a country is usually a symbol of the identity of the nation that makes up the country. (Bartolini, 2005)

The President of the Republic of Indonesia, Joko Widodo, plans to move the capital city from Jakarta to Kalimantan. The relocation of the capital city is stated in the National Medium-Term Development Plan (RPJMN) for 2020-2024 and has been ratified by the State Capital Law (UU-IKN)

The relocation of Indonesia's new state capital (IKN) from Jakarta to Kalimantan aims to distribute development evenly and establish a bureaucratic system that covers all regions in Indonesia. (Andjarwati, 2019).

To achieve this goal, the new capital city must have ideal characteristics, at least better than the old capital city. One of these characteristics is having a safe environment, both safe from disasters and threats that endanger national security and defense. (Potter, 2017)

From a defense perspective, a capital city must consider the geographical position and defense infrastructure of the new capital so that it is not vulnerable to external attacks or natural disasters. The indicators that measure defense are the disaster-prone index, the global firepower index, and the global cybersecurity index as well as other threats that can endanger the security of the capital city (Defense, 2019).

The relocation of the capital city also creates a new geostrategic perspective. However, the strategic location of the State Capital (IKN) cannot be separated from the threat of defense and security disturbances carried out by state actors, non-state actors, and hybrids. For example, the location of the new capital city of Indonesia in Kalimantan is close to the land border to Malaysia along 2,062 km, and this is a door for defense threats and security disturbances. In addition, the location of IKN also coincides with the Indonesian Archipelagic Sea Lane (ALKI) II and the choke point or the narrow point of the world. Meanwhile, on the air side, IKN's location is close to the Flight Information Region (FIR) of neighboring countries, such as Singapore, Malaysia's Kinabalu, and Manila, the Philippines. Indonesia's new IKN is also within the cruising radius of ICBMs (intercontinental ballistic missiles) and hypersonic missiles of certain countries. And lastly, the position of the new IKN is surrounded by defense alliances, such as FPDA The Five Power Defense Arrangements (Australia, Malaysia, New Zealand, Singapore, UK) and the AUKUS alliance of Australia, America, and the UK. These threats are the center of attention. for the security and defense of the new National Capital (IKN) of Indonesia in creating state sovereignty.

The concept of the IKN defense and security system, especially for airspace, refers to the national defense and security system. Furthermore, the National Planning and Development Agency (Bappenas) or the Ministry of National Development Planning disclosed the design of the defense and security system for Indonesia's new State Capital (IKN). And the defense and security system at IKN is called smart defense which is a combination of hard defense and soft defense. This hard defense is technological deepening, meaning that the country's defense uses high-tech Main Weapon System Tools (Alutsista). Meanwhile, soft defense empowers the strengths of local wisdom or local wisdom. In terms of air defense for the new Indonesian National Capital (IKN), in accordance with the concept of a smart defense defense system, an air defense system is needed that can be used to conduct intelligence, surveillance, reconnaissance and even be able to carry out attacks in maintaining security in Indonesia's new IKN area.

Based on Minister of Defense Regulation Number 26 of 2016 concerning Unmanned Aircraft Systems for State Defense and Security Tasks

Table 1 PTTA System Classification and Mission

No	Klasifikasi	Berat (Kg)	Ketinggian Operasi (ft)	Radius Operasi (Km)	Waktu Operasi (Jam)	Satuan Pengguna	Misi Operasi Militer
1	Micro	<2	< 200	< 5 LOS	< 5	Perorangan - Peleton	
2	Mini	2 - 20	< 3 000	< 20 LOS	< 10	Batalion taktis	Pemotretan; Pengumpulan Data; Inspeksi; Alat Peluncur, Transportasi Kargo, Stasiun *Relay*, Mitigasi, Penangkalan, Pengamanan, Pengintaian, dan Pengawasan
3	Kecil	20 - 150	< 5 000	< 50 LOS	< 24	Brigade Taktis	
4	Sedang	150 -600	< 10 000	< 200 LOS	< 48	Formasi Taktis	
5	Besar	> 600					
	1. MALE	> 600	< 45 000	Tidak Terbatas BLOS	> 120	Teater Operasional	
	2. HALE	> 600	< 65 000	Tidak Terbatas BLOS	> 120	STRATEGIS / NASIONAL	
	3. STRIKE / COMBAT	> 600	< 65 000	Tidak Terbatas BLOS	> 120	STRATEGIS / NASIONAL	

The use of the Unmanned Aerial Vehicle (UAV) system can basically be an appropriate alternative to overcome existing problems, as well as a response to the influence of rapid technological advances, and in line with the implementation of Revolution in Military Affairs (RMA), which is aimed at achieving Network capabilities. Centric Operations or Network Centric Warfare. The UAV system is an unmanned aircraft flight system that is not manned by humans, which is controlled remotely, either manually or automatically, which consists of unmanned aircraft, payloads, human resources, control systems, data networks, and supporting elements. (Pasaribu, 2017)

Formulation of the problem

- How has UCAV Propulsion Technology developed in other countries in the world?

Research purposes

- To know the development of UCAV propulsion technology applied by other countries in the world

THEORY

Unmanned Aerial Vehicle

Unmanned Aerial Vehicles (UAVs) are remotely- piloted or self- piloted air vehicles that can carry payloads such as cameras, sensors, and communications equipment. All flight operations (including take- off and landing) are performed without an on- board human pilot. In some reports of Department of Defense (DOD), Unmanned Aerial System (UAS) is preferred. In media reports, the term "drone" is utilized. The UAV mission is to perform critical flight operations without risk to personnel and more cost effectively than comparable manned system. (Sadrey, 2020)

An unmanned aerial vehicle (UAV), commonly known as a drone, is an aircraft without any human pilot, crew, or passengers on board. UAVs are a component of an unmanned aircraft system (UAS), which includes adding a ground-based controller and a system of communications with the UAV. The flight of UAVs may operate under remote control by a human operator, as remotely-piloted aircraft (RPA), or with various degrees of autonomy, such as autopilot assistance, up to fully autonomous aircraft that have no provision for human intervention. (Wiki)

UAVs were originally developed through the twentieth century for military missions too "dull, dirty or dangerous" for humans, and by the twenty-first, they had become essential assets to most militaries. As control technologies improved and costs fell, their use expanded to many non-military applications. (Wiki)

Unmanned Aerial Vehicles (UAVs) are aircraft that can be operated autonomously and remotely from the ground without an onboard pilot. The idea to use a mechanism that can fly without a person on board has

always been in the researchers' mind. Ever since the inception of UAV technology, it has been considerably advanced, and major developments in safety, and reliability have been achieved. UAVs are increasingly used today, both commercially and by the military. The latter usage includes security and surveillance, search and rescue missions, detection of floating mines and coastal defences, and detection of naval artillery. While the commercial use ranges from agriculture to remote sensing, wildlife, photogrammetry, and sales delivery among others. The most important benefits of UAVs over manned aircraft are, they are proven to be cheap, have less operational cost and lessen the danger of a pilot’s life.

However, the increasing use of UAVs creates a necessity to resolve several problems which consist of both constructional and operational problems. The propulsion system of any aircraft in many regards determines its performance. Thus, to overcome operational and constructional challenges, a reliable and certifiable propulsion system that meets the requirements of the UAV mission profiles is required. Moreover, the right choice of the light propulsion system and a power source that can endure long-range is inevitable today. This is to reduce the contribution of greenhouse gases by the propulsion systems using fossil fuels. This is one of the major tasks while designing any aircraft. So, in the design of UAV, it is pertinent to recognize the impact of the propulsion system operation on the environment. Depending on the tactical role, endurance, speed, range, payload, and size of a UAV are critical. Various types of propulsion systems are employed in UAVs; nonetheless, the piston and electric engines are the most widely used. -

Table 2 shows the UAV classifications from a few aspects including: (a) size (e.g., micro, mini, and small); (b) mass; and (c) mission (e.g., HALE, UCAV). In Table 1.1, the term “size” for fixed- wing UAVs, refers to the largest of the wing span and the fuselage length. However, for quadcopters, it refers to the outer distance between the tip of one propeller to the neighboring one. Moreover, the term weight refers to the maximum takeoff weight (MTOW) of the UAV. (Sadrey, 2022)

Table 2 Unmanned Aerial Vehicle (UAV) Classification

No	UAV Class	Weight (lb)	Size	Normal operating altitude	Range (km)	Endurance
1	Micro	<0.55	≤10 cm	<100 ft	0.1–0.5	≤1 hr
2	Mini	0.55–2	10–30 cm	<500 ft	0.5–1	≤1 hr
3	Very small	2–5	30–50 cm	<1000 ft	1–5	1–3 hr
4	Small	5–55	0.5–2 m	1000–5000 ft	10–100	0.5–2 hr
5	Medium	55–1000	5–10 m	10000–15000 ft	500–2000	3–10 hr
6	Large	10000–30000	20–50 m	20000–40000 ft	1000–5000	10–20 hr
7	Tactical/ combat	1000–20000	10–30 m	10000–30000 ft	500–2000	5–12 hr
8	MALE	1000–10000	15–40 m	15000–30000 ft	20000–40000	20–40 hr
9	HALE	>5000	20–50 m	50000–70000 ft	20000–40000	30–50 hr
10	Quadcopter	0.5–100	0.1–1 m	<500 ft	0.1–2	20 min–1 hr
11	Helicopter	0.001–200	13 mm–2 m	<500 ft	0.2–5	10 min–2 hr

It is a must for a UAV designer to be aware of classifications and applications of UAVs, which are based on various parameters such as cost, size, weight, mission, and the user. In addition, UAV missions range from: reconnaissance; combat; target acquisition; electronic warfare; surveillance; special purpose UAV; target and decoy; communication relay; logistics; research and development; civil and commercial UAVs; to Environmental application (e.g., University of Kansas North Pole UAV for measuring ice thickness. (Sadrey, 2022)

UAVs are considered as a great force multiplier within military use, as they offer many advantages. Commonly these advantages are attained at a lower risk and a lower cost than if a corresponding manned aircraft would do the same mission. Typical applications for the Navy include: (a) shadowing enemy fleets; (b) decoying missiles by the emission of artificial signatures; (c) electronic intelligence; (d) relaying radio signals; (e) protection of ports from offshore attack; (f) placement and monitoring of sonar buoys and possibly other forms of anti- submarine warfare; (g) optical surveillance and reconnaissance; and (h) Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR). (Sadrey,2022)

In US military, the classification is mainly based on a tier system. For instance, in US Air Force the Tier I is for low altitude, long endurance missions, while Tier II is for MALE missions (e.g., Predator). Moreover, Tier II+ is for HALE missions, and Tier III- denotes HALE low observable. MALE UAVs usually have a continental operating scenario, while HALE UAVs usually have an intercontinental operating scenario. For other military forces, the following is the classification: Marine Corp: Tier I: Mini UAV; (e.g., Wasp); Tier II: (e.g., Pioneer); and Tier III: Medium range, (e.g., Shadow). Army: Tier I: Small UAV, (e.g., Raven); Tier II: Short range, tactical UAV, (e.g., Shadow 200); and Tier III: Medium range, tactical UAV. (Sadrey, 2022)

In terms of wing, there are two groups of UAVs: (a) fixed- wing; and (b) rotary wing. A fixed- wing UAV often needs a runway or a launcher to take- off, while a rotary- wing UAV can take off and land vertically. Two popular groups of rotary- wing UAVs are: (a) unmanned helicopter; and (b) quadcopter. (Sadrey, 2022)

Unmanned Combat Aerial Vehicle

Unmanned Combat Aerial Vehicle (UCAV) is an unmanned aerial vehicle (UAV) that is used for intelligence, surveillance, target acquisition, and reconnaissance and carries aircraft ordnance such as missiles, ATGMs, and/or bombs in hardpoints for drone strikes. (Wiki)

These drones are usually under real-time human control, with varying levels of autonomy. Unlike unmanned surveillance and reconnaissance aerial vehicles, UCAVs are used for both drone strikes and battlefield intelligence. -

Aircraft of this type have no onboard human pilot. As the operator runs the vehicle from a remote terminal, equipment necessary for a human pilot is not needed, resulting in a lower weight and a smaller size than a manned aircraft. Many countries have operational domestic UCAVs, and many more have imported armed drones or are in the process of developing them. (Wiki)

Propulsion System

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. -

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. (1)

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. (2) Propulsion systems usually consist of energy sources and power units, which include engines and motors (3). 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. (4)

UAVs using traditional fuel propulsion systems have the advantages of high payload, long-endurance extensive range, and rapid resupply (5). 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. (6)

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 (7). 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. (8). 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 (6). 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 (9,10). 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 (11). 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 1. Then, this paper introduces the power unit of electric propulsion UAVs and finally analyses the future vital technologies and development directions of electric propulsion UAV. -

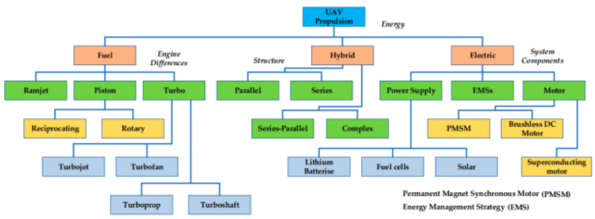

Figure 1. UAV propulsion classification based on energy types.

METHODS

This study uses a literature review method to collect, identify and evaluate the Technology of Propulsion System for Unmanned Combat Aerial Vehicle (UCAV). The data sources used in this study came from previous journals from Sciencedirect, Researchgate, Elsevier, etc.

RESULTS

Propulsion System

To complete the intended mission accurately, the UAV and its supporting systems need to cooperate in a stable and orderly manner. UAVs consist of a vehicle, ground control system, payload system, and data communication system. Some large UAVs often also need the support of a take-off and recovery system, ground support system, and other parts (12).

1. Fuel Propulsion System

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 2. 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 (13). Fuel engines can be mainly classified into two categories: piston and turbine (14). Table 3 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 (15).

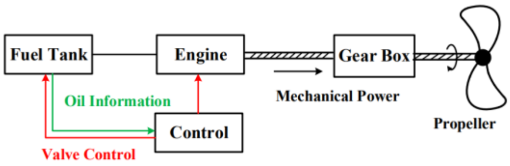

Figure 2. Composition of the fuel propulsion system for UAVs.

Table 3 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	20–400 Hp	3000–7000	0.76–1.37	110–260	2500–9700	<40	<1150
Rotary Engine	<120 Hp	6000–12,000	<4.1	N/A	2500–8000	N/A	<1000
Turbojet	<170 kN	N/A	<10	700–1100	3000–14,000	<2.5	<2500
Turbofan	<560 kN	N/A	<11	500–1100	3000–20,000	<42	<12,000
Turboprop	<1000 Hp	1000	About 4	350–500	14,000–16,000	<32	<3200
Turboshaft	<9000 Hp	N/A	3–7	180–300	4000–6100	<4	<1500

a. 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 straight- forward 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 (16). 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 (17). Piston engines can be classified into two main categories, reciprocating and rotary piston engines, based on piston movement (18).

b. 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 (19). 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 (20). The main parameters and applicable ranges of the four types of turbine engines are shown in Table 1.3, 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.

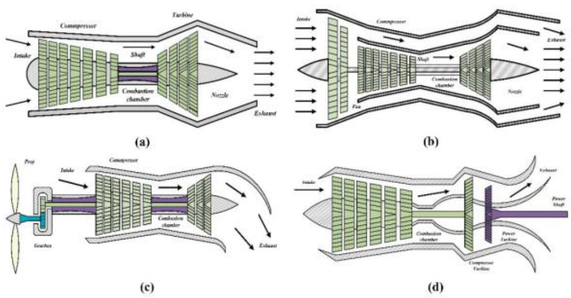

Figure 3. Structure of turbo engines. (a) Turbojet ; (b) Turbofan ; (c) Turboprop ; (d) Turboshaft

c. 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 4 (21). 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 (22). 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 (23).

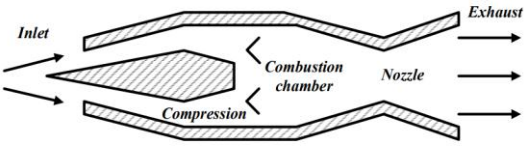

Figure 4. Ramjet Engine

Table 4. Different Oil-Based Engine Characters.

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

2. Hybrid Propulsion System

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. The fuel-electric hybrid propulsion system is an aviation propulsion system in which the fuel engine and generator act together to generate thrust.

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. 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.

a. Parelel System

The parallel hybrid propulsion system is the engine, and the electric motor/generator jointly drives the propeller's rotation through the mechanical drive transposition, and its structure is shown in Figure 5. 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 im- prove 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.

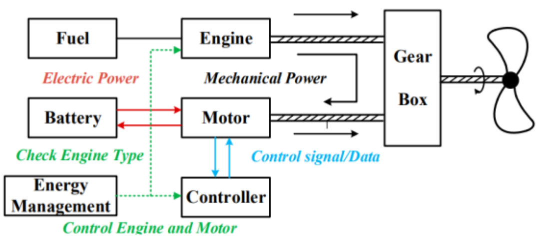

Figure 5. Parallel hybrid architecture.

b. Series System

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 6.

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.

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. 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.

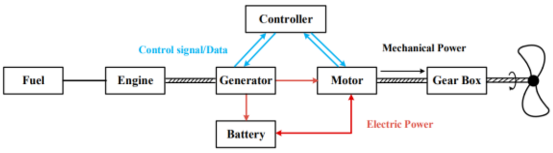

Figure 6. Series hybrid architecture.

c. Series-Paralel System

As shown in Figure 7, 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. 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.

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 8. 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.

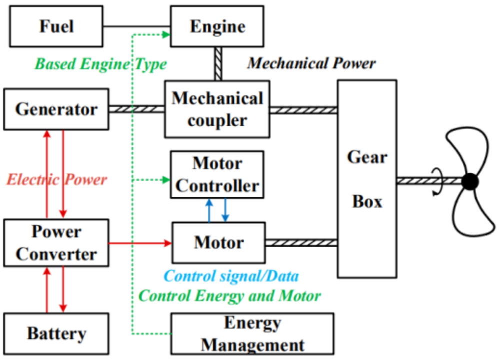

Figure 7. Series-Parallel hybrid architecture.

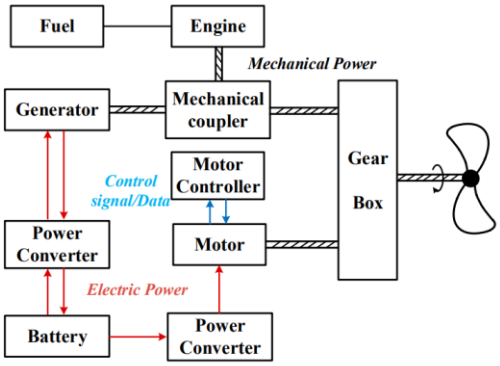

Figure 8. Complex hybrid.

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. 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 5. 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

3. Electric Propulsion System

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 (24). Compared with fossil fuels propulsion systems, electric propulsion system has great potential for more applications (25).

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 (26).

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 (27). 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 (25).

Table 5. Comparison of propulsion system.

System	System	Operations		Design	Weight	Pollution	
Classification		Fuel Efficiency	Durability			Noise	Environmental
Conventional Propulsion System	2-Stroke reciprocating engines	Low	Low	Simple	Light	High	High
	4-Stroke reciprocating engines	High	High	Complex	Heavy	Low	Low
	Wankel engine	Low	Very High	Very Simple	Light	High	High
	Gas Turbine Engine (GTE)	Average	Very High	Complex	Heavy	High	High
Unconventional Propulsion system	Hydrogen Fuel-Cell Based Hybrid Power Systems (Electric Propulsion)	Average	Medium	Complex	Average	Low	None
	Solar Powered	Nil	High	Simple	Heavy	None	None

Requirement

The most important features of a UAV engine are as follows:

1) Lightness of design. In order to decrease the construction mass manufacturers use:
   - lower pistons, shorter shafts – thus lowering the engine height and facilitating its arrangement;
   - aluminium and magnesium alloys, occasionally composites – light and strong materials;
   - multi-cylinders for proper engine balancing;
   - relatively high downsizing – obtained from operating on high revolutions, which in turn entails using high quality fuels (high octane rating, or possibly cetane rating), high quality engine oils with good grease parameters in a wide range of temperatures;
   - light start-up systems – often based on inertia devices (flywheel in the starter system, occasionally pneumatic start-up);
   - lack of a flywheel in an engine (the function taken over by a propeller).
2) Due to the manoeuvres that a UAV performs in three dimensions, its engine must be prepared for such manoeuvres through:
   - properly designed greasing system with an uninterrupted operation of the oil pump and constant lubrication of the key engine elements;
   - properly constructed power supply system which ensures, on the one hand, constant fuel supply to the engine; on the other hand, it must protect the tanks against excessive fuel movement, provide appropriate air venting and secure it from fuel spill during a flight;

- properly designed cooling system which provides either tightness and uniform-temperature liquid cooling, or a required flow of air which cools the ribs of the cylinder block and the head.

3) Adaptation to operation at various altitudes – manufacturers usually fit various, sometimes sophisticated methods of recharging so as to reduce the rate of the loss of power during climbing. Usually these included:
   - compressors (most commonly centrifugal);
   - turbochargers;
   - complex systems (first step turbocharger, second step centrifugal charger), sometimes additionally the load passes through an intercooler.
4) Reliable and steady operation. In order to minimise the risk of engine stopping during a flight, the following are used:
   - two ignition plugs per cylinder;
   - two independent ignition systems;
   - light and efficient cooling systems of the engine oil;
   - air filters with heating systems, which protect the engines from icing;
   - advanced control-measurement systems which enable monitoring the parametres of engine operation and the fuel level during a flight.
5) High propulsive efficiency. In a piston engine, thrust is produced by a propeller, which must operate at an optimal range of revolutions. In order to combine it with a high engine rotations, constructors frequently use a governor, which slows down the revolutions of the propeller. The propeller is larger in diameter, which increases its thrust.

Challenges and Future Trends

Since stealth is a critical requisite for UAVs, lessening engine noise is necessary. Similarly, increasing the engine's fuel economy is important, since the fuel weight is the main part of the total aircraft mass. The stringent global demand for cleaner energy as a result of the fall in fuel prices, global warming, and the need to reduce pollutants/emissions from aircraft have resulted in research on unconventional propulsion systems like hybrid electric systems and solar powered systems. Hybrid engines provide the best from both worlds (gasoline and electric) as they offer superior

efficiency, better power, and fuel economy. However, the major drawback of hybrid engines is the increase in weight due to the need to carry batteries as well as fuel. Also the complex systems of the solar-powered aircraft demand effective energy management throughout flight making the cost of operations relatively high when compared to the IC engines. Looking into the future, ICE will continue to be a major source of a propulsion system for most vehicles, as shown in Figure 8.

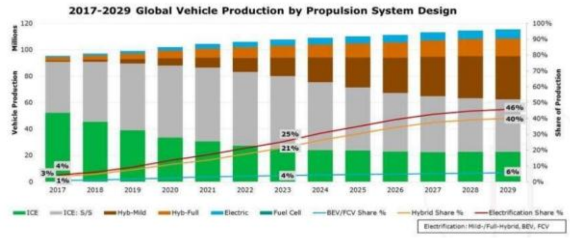

Figure 8. Projected global vehicle production by propulsion system design

DISCUSSION (CONCLUSION)

In conclusion, the above analysis indicates that a future propulsion system for an UAV should be designed on the basis of a rotary piston combustion engine or a flat engine (boxer type). It should be digitally controlled, so that the operator receives information about the engine's working parameters, in real time. The intake system should be equipped with air purification devices. The engine should be characterised by the lowest possible noise level and minimal infra-red signature. In the near future, there is every likelihood of emerging UAVs, whose mass will exceed 50 kg, and that will be driven by electrical engines, powered by fuel cells.

The predicted and desired ways of propulsion systems development in UAVs also include reducing the fuel consumption, a possibility of generating more power for

on-board instruments. In order to lower the risk of detection of the aerial vehicle, it is recommended to better integrate the propulsion system with the airframe and to decrease infra-red radiation, emitted by the engine. In the process of designing the propulsion system, it is necessary to include specific conditions of exploiting UAVs, tasked with relatively long missions and few engine start-ups and shut-downs

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, comprehen- sive 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 aero- dynamic 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 dissipa- tion 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.

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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