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# Propulsion Systems for Unmanned Aerial Vehicles

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**Abstract**

Unmanned Aerial Vehicles (UAVs) have been surrounded by a number of issues since their inception. Undoubtedly, the use of these devices has reformed aviation, not only for military but also for civilian use. Every day, a number of areas emerge where their existence can contribute to their efficient operation, and the satisfactory technological development of the 21st century offers the opportunity to challenge these tools in a positive way, increasing their effectiveness. The performance required is strongly linked to the choice of propulsion technology, and research and development in this area is one of the most important directions. This article discusses the possible propulsion systems, their operating principles and their main characteristics. It is important to highlight the requirements of the specific applications, so that it is necessary to select the appropriate design on this basis. Potential challenges for the future should also be taken into account. There is an increasing focus on pure electric propulsion, not only on the ground but also in the air, and hence on the energy supply of systems and its industry. This article aims to provide a comprehensive view and comparison of UAV propulsion systems from several perspectives, with all their advantages and disadvantages.
**KEY WORDS:** *UAV, propulsion, battery, fuel cell, energy sources*

## 1. Introduction

The use of small unmanned aerial vehicles (UAVs), commonly known as “drones”, is growing in all sectors. UAVs can perform aerial operations that are difficult for piloted flight to cope with, and their use brings obvious economic savings and environmental benefits while reducing the risk to human life [1].

Currently, there are many types of UAVs and they are used in different domains, ranging from civil to military aviation. Therefore, a number of criteria have been proposed to classify UAVs into different groups [2]. Based on their design, UAVs can be categorized into rigid, rotary wing, hybrid and biological-based. Based on the propulsion mode, piston, gas turbine and electric motor solutions [4] are possible. Literature [8] provides a detailed discussion of possible designs including fuel, hybrid fuel-electric and pure electric. The propulsion technology of unmanned aerial vehicles is significantly related to the flight performance of UAVs, which has become one of the most important development directions in aviation. One of the most important challenges in UAV design and construction is to keep the system operational for as long as possible, which means increasing the UAV lifetime. Capacity limitation of the UAV energy storage system is a key technical challenge for UAV applications [8].

Of all UAV types, the category of mini (MAV) unmanned aerial vehicles is perhaps the most widely used in the use of electric motors and thus the various energy storage systems required to power them. Advances in electric motors, energy storage systems and power electronic converters are leading to the increasing electrification of aircraft propulsion [20]. The basic concept of the more electric aircraft (MEA) is to increase the electric propulsion of subsystems that were operated by a combination of mechanical, pneumatic or hydraulic systems on previous aircraft. The MEA therefore aims to completely replace the aircraft's non-electric power sources with electric ones.

Aircraft propulsion is gradually evolving from small all-electric urban aircraft to medium hybrid-electric aircraft, and within three decades to hybrid-electric regional aircraft. The study of hybrid electric propulsion systems requires a multidisciplinary, combined approach to cope with all the related fields, which is a challenging task [20].

The key point of any measurement on board an aircraft is what to do with the data. We can store it on board, or we can transmit it to a ground station, or we can do both at the same time for redundancy.

In the [18] article, we looked at one of our future scenarios. Our hypothetical measurements will result in small amounts of data at relatively long intervals, and we wanted to transmit them to a ground station in addition to storing them on board. To get a more complete picture, we examined key factors such as the link budget (which consists of transmitter power (TX), free space loss (FSPL - energy loss in free space as the signal travels from the transmitter to the receiver), antenna gain, receiver sensitivity (RX)).

The aim of this work is to present the energy supply system (battery, fuel cell, propulsion, etc.) relevant for the propulsion of UAVs, highlighting their main characteristics, advantages and challenges.

## 2. Energy Sources Used in the UAV

The UAV system consists of a number of different components. Depending on the mission requirements, some parts of the UAV may be interchangeable. However, it basically consists of two main systems: an airborne unit and a ground unit [18, 19], which include the following subsystems: air vehicle, payload, navigation, power supply, communications, launch and landing equipment, and control station [2, 8].

When designing a UAV, payload is one of the important factors to be considered. A larger payload will affect the power required to operate the UAV. However, the payload can basically be divided into two types: video cameras, thermal cameras, sensors, and payloads (e.g., weapons, missiles, and bombs for the military; spraying, seed sowing, weed detection, mapping for agriculture, or even firefighting materials for civilian purposes, and so on) [2].

The power system plays an important role in the UAV and can be considered the heart of the system, as it provides the power for the whole "operating system". The power system has a significant impact on the flight performance of the aircraft. The energy sources used to operate the UAV include mainly the heat engine, the fuel cell, the supercapacitor, the battery and external energy sources (solar, wind). They are classified into two categories: chemical systems and electrical solutions [2].

The heat engine is mainly used in large UAVs such as HALE and MALE. It converts thermal energy into mechanical energy, which is the source of the UAV's operation. However, due to the complicated control, high temperature characteristic, high noise, low fuel saving capability and the need for an auxiliary engine, the thermal engine is not suitable for use in small UAVs [2]. To overcome the above problems, environmentally friendly electric motors are being developed that use electric energy sources such as fuel cells, solar cells, batteries and supercapacitors due to their low emissions, low noise and low thermal radiation [10].

Batteries are a key component of electric propulsion systems as they provide the energy needed to power the motor and other electrical/electronic components (navigation, control, data acquisition) [11]. Batteries may be initially attractive due to their small size and low cost, but their power and energy density are much lower than other alternatives [9]. There are several different types of batteries used on board UAVs (Table), each with its own advantages and disadvantages [10], [12]. The types include: lead-acid, nickel-cadmium (NiCad), nickel-metal hydride (NiMH), alkaline, lithium-polymer (Li-Po), lithium-ion (Li-ion), zinc oxide (Zn-$O_2$), lithium-air and lithium-thionyl chloride (Li-$SOCl_2$) [12].

Table

Comparing the different characteristics of different battery types [10, 12]

| Types | Pb-acid | NiMH | Li-ion | Ni-Cad | alkaline | Li-Po | Zn-$O_2$ | Li$O_2$ | Li-$SOC_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Cell voltage (V) | 2.1 | 1.2 | 3.6–3.85 | 1.2 | 1.3–1.5 | 2.7–3 | 1.45–1.65 | 2.91 | 3.5 |
| Energy density (Wh/kg) | 30–40 | 60–120 | 100–265 | 40–60 | 85–190 | 100–265 | 442 | 11 140 | 500–700 |
| Power density (W/kg) | 180 | 250–1000 | 250–340 | 150 | 50 | 245–430 | 100 | 11 400 | 18 |
| Cycle life | <350 | 180–2000 | 400–1200 | 2000 | – | 500 | 100 | 700 | n/a |
| Charge/discharge efficiency (%) | 50–95 | 66–92 | 80–90 | 70–90 | 45–85 | 90 | 60–70 | 93 | 6–94 |
| Self-discharge rate (%) | 3–20 | 13.9–70.6 | 0.35–2.5 | 10 | <0.30 | 0.3 | 0.17 | 1–2 | 0.08 |
| Rating | 12 V 2 Ah | 12 V 2 Ah | 3.6 V 2 Ah | 12 V 1.8 Ah | 1.5 V 2.2 Ah | 3.7 V 2 Ah | 1.4 V 0.3 Ah | n/a | 3.6 V 2.2 Ah |

The most common batteries used in drones are Li-Po and Li-Ion. Li-Ion types can provide more power and performance per unit battery weight. They also have high energy efficiency, no memory effect and a relatively long life compared to other rechargeable batteries. Li-SOCl2 batteries have twice the energy density per kilogram compared to Li-Po and Li-Ion, and lithium-ion batteries can be up to seven times larger, but unfortunately they are not as widely available and are much more expensive than Li-Po and Li-ion [12].

Another variant of lithium batteries is lithium-sulphur (Li-S) , which also offers a higher energy density of 2600 Wh/kg (theoretical) compared to Li-Ion (100-200 Wh/kg). Considering the ratio between actual and theoretical energy, the practical energy density of Li-S batteries is expected to reach 800 Wh/kg, and therefore Li-S batteries are considered as the next generation of battery technologies with a very significant application potential [15]. Most developed countries, including the United States, Japan, Russia, China and the European Union, strongly support the development of Li-S battery technology. Meanwhile, significant progress has been made in the research and development of commercial Li-S batteries worldwide, including companies such as Sion Power (USA), Polyplus (USA) and OxisEnergy (UK) [15].

Each of the criteria (see Table 1) affects different aspects of the drone: power density affects acceleration capabilities, energy density affects range, lifetime affects how often the battery needs to be replaced, and mass and volume affect the range of the system [12].

Another option for electrical energy sources is the fuel cell, which converts the chemical energy of a galvanic cell and fuel into electricity [2], [9]. Fuel cells do not emit harmful substances into the environment during their operation like conventional fuels (nitrogen oxides, sulphur dioxide or particulate matter) and could therefore be considered environmentally friendly. On the other hand, hydrogen fuels emit water vapour, which contributes to the greenhouse effect in the higher atmosphere where aircraft fly. In addition, the production of hydrogen for operation is currently overwhelmingly based on non-environmentally friendly technologies using fossil fuels (e.g. steam, catalytic reforming, electrolysis), which precludes $H_2$ from being classified as environmentally friendly [9, 14].

Fig. 1 shows that fuel cells have the highest specific energy, while the specific power is the lowest compared to other energy sources. Each of these energy sources has its own advantages and disadvantages, and many researchers have also sought to combine these energy sources with their advantages to create hybrid energy sources. For example, a hybrid energy source could be a combination of a battery and a fuel cell, taking advantage of the high power density, high efficiency, fast response and high energy density of the battery and the fuel. In this case, the battery is used as the energy source for peak power demands such as take-off and climb. In addition, the fuel cell can also be used in the cruise and descent phases [2].

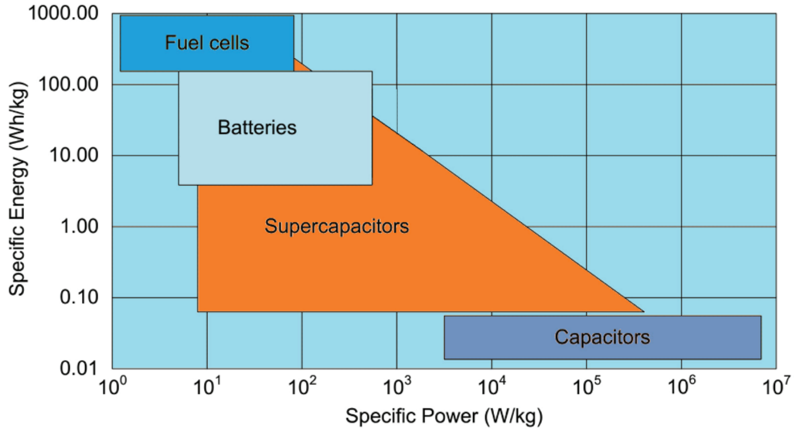


Fig. 1 Comparison of energy sources [2]

To compensate for these disadvantages of the battery, the use of supercapacitors can be considered, a much more powerful and faster energy storage system (faster charge/discharge rate) compared to the battery. The supercapacitor also has a reasonable cost, a wide operating temperature range, low maintenance cost and reduces DC bus voltage fluctuations. Compared to batteries, however, the specific energy capacity of supercapacitors is lower (only a few Wh/kg). Among supercapacitors, electric double-layer capacitors are the most common type, which are very durable and capable of fast charging and discharging and millions of cycles. The use of this type of supercapacitor also has environmental benefits, as they do not require expensive materials such as lithium and cobalt for their manufacture [2, 21].

Another alternative could be lithium-air batteries, which can significantly extend the range of electric (aircraft) vehicles because they have a very high energy density (specific energy), almost comparable to kerosene [12]. One kg of kerosene contains about 43 MJ of energy (11.94 kWh) [22]. They can store 5-10 times as much energy as Li-ion batteries for the same mass, or twice as much energy for the same volume. For comparison, their estimated energy density is around 2000-3500 Wh/kg (practical energy density is expected to reach 1700 Wh/kg) [13, 15-17], which is much higher than any other known battery. A small-scale lithium-air battery with a density of 600 mAh/g has already been designed, compared to the density of the same size Li-ion battery 100-150 mAh/g [12]. With all these advantages, there are some disadvantages, the rechargeable version of this battery is challenging because the number of recharge/discharge cycles is very limited, the recharge rate is very slow, and they are extremely dangerous when water vapour is present in the oxygen, as the lithium reacts with it violently [12].

In summary, the maximum specific energy of today's modern batteries is about 400 Wh/kg. So the specific energy of kerosene is about 30 times higher than the specific energy of available batteries. An acceptable level would be about 750 Wh/kg, which will not be available before 2035 [22].

## 3. Hybrid Propulsion

The development of fuel propulsion systems for UAVs is maturing. Depleting oil reserves or worsening climatic conditions resulting from high emissions of pollutants show that well-established, traditional methods are becoming obsolete and do not meet the requirements of the new era [8]. Similar obstacles are posed by the foreign policies of individual countries. No state has a fully independent economy, natural resources are scattered all over the world, and production is influenced by the economic policies of other countries [3].

Hybrid-electric aircraft are being investigated as a possible solution for the future of aviation, and could even be the ultimate solution to challenges such as flight economy, increased fuel efficiency, quieter aircraft and pollutant-free air according to the European Union's Flightpath 2050. The future development of aviation is shaped by the Flightpath 2050 Vision, NASA's N+ strategy, and the requirements to meet environmental targets set by the FAA and ICAO. The most ambitious targets are those set by the European Union Flightpath 2050 Vision, which aims to reduce perceived noise emissions by 65%, carbon dioxide emissions per passenger-kilometre by 75% and nitrogen oxides (NOx) emissions by 90% compared to the state of the art (SOA ) in 2000 [5].

The ideas are quite forward-looking. Aircraft designs based on electric propulsion are promising to make aircraft operation desirable for an environmentally sustainable world. Consistent research investment has been and is being made to unlock its potential, with a view to meeting environmental targets [5].

Even the replacement by a purely electric energy system is still hampered by the fact that such technologies are still under development and the main problems are still the low energy density of the battery and the efficient storage of resources [8].

In the fuel-drive system, the loss is mainly due to the drive train and the mechanical loss is due to the friction between the transmission and the drive shaft. In a hybrid drive system, in addition to the actual mechanical losses and heat losses, there is also some energy loss from the engine itself. At the same time, some electrical energy is lost in the energy transfer between the motor and the battery. The growth of the motor and its associated mechanical structure inevitably leads to additional energy consumption. In addition, the friction in the system, in the motor and in the wiring during the transfer of electrical energy due to heat loss cannot be neglected [5, 8].

As both drive modes are necessary to provide the required parameters, earlier developments have taken the direction of combining the two to create a hybrid drive system. In other words, the fuel-electric hybrid propulsion system used in UAVs is an aircraft propulsion system in which the fuel engine and the generator together provide thrust [8]. In general, hybrid structures can be broadly divided into parallel, series, series-parallel and complex structures depending on whether the engine provides thrust directly.

## 4. Electric Propulsion Structure

Literature [8] describes the drives in detail, but there may also be an architecture that uses pure electrical energy to provide thrust. By itself, this type of propulsion is not capable of providing the power that would be sufficient to achieve major goals and perform a task.

Although experiments and research are being carried out with a view to giving drones a prominent role in the near future, not only in civil but also in industrial and military applications, the low energy density of energy storage devices does not yet allow the necessary steps to be taken, resulting in an unfavourable ratio between weight and performance. Although revolutionary processes have emerged in the automotive industry and the length of the journey on a single charge has increased significantly, such an increase in flight time and the integration of a similar system remains to be seen, the use of hybrid propulsion may well be a significant initial success and it has been shown that electric propulsion (Fig. 2) is a satisfactory solution for low flight speeds and altitudes [6, 8].

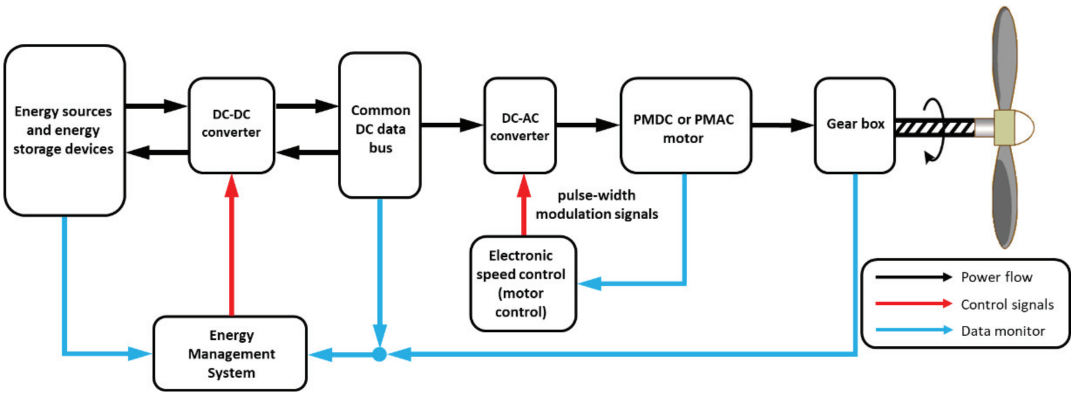


Fig. 2 Electric UAV propulsion system (based on Bertold Békési [8, 18])

In addition, the response of the system to different environmental influences must be taken into account [7]. Due to the nature of the system, electromagnetic phenomena can reduce the reliability and control efficiency. Although the design and the process allow design versatility due to the distributed system, thus increasing the favourable aerodynamic properties, it is not possible to build a structure that can withstand most forces in general [8].

As for the design and maintenance costs, they are very high in this case. The presence of a battery alone is not enough; redundant batteries must be installed, and the number of batteries increases proportionally as power and operating time increase. In the case of hybrid systems, the presence of an electrical system is essential, despite the costs, maintenance is easier and the wide range of energy sources can allow the drive to be tailored to the needs of the future.

## 5. The Flight Scenario of an UAV

The energy system has a significant impact on the aircraft's flight performance. If we know the trajectory of the UAV, we can calculate the energy used to fly it. Fig. 3 shows a UAV flight scenario. During the flight from the starting point to the end point, the UAV consumes a lot of energy in areas C1 and C2, and stores the energy by converting wind energy into electrical energy in area R1. In order to achieve the objective of maximising the efficiency coefficient (efficiency) of the UAV, an efficient coefficient for converting wind energy into electrical energy must be found. Since the UAV is influenced by environmental factors and the varying speed of the engines, the UAV energy consumption model is in fact a non-linear model. The energy consumption model becomes complex because of the many parameters that have to be taken into account. However, our goal is to find the maximum efficiency, so we consider the energy consumption model as linear [2].

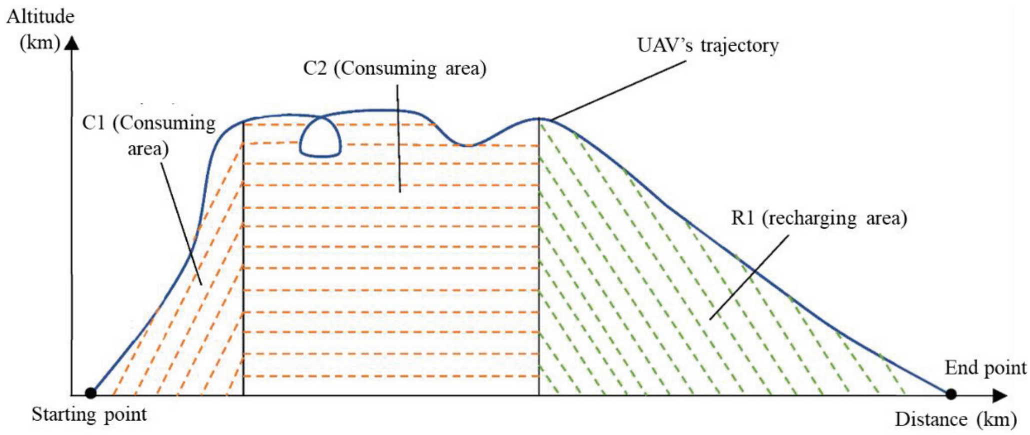


Fig. 3 Flight scenario of a UAV (based on Bertold Békési [2])

The UAV's energy consumption is mainly concentrated on the propulsion system. The current flowing through the engine is very high, so the quadrocopter usually has a short operating time. The propulsion power consumption can be calculated as follows:

$$E_{pr} = \int_{t_o}^{t_f} \sum_{i=1}^{4} \left( J\dot{\omega}_i\left(t\right) + K_T\omega_i^2\left(t\right) + D_v\omega_i\left(t\right) \right) \omega_i\left(t\right) dt \, , \tag{1}$$

where $\omega_i$ – is the angular velocity of motor $i$; $J$ – is the inertia of the motor; $D_v$ – is the viscous damping coefficient and $K_T$ – is the drag coefficient.

The energy converted from wind energy can be calculated according to the following formula:

$$E_c = \int_{t_2}^{t_1} \eta_0 P_w\left(t\right) dt \, , \tag{2}$$

where $\eta_0$ – efficiency coefficient for the conversion of wind energy into electricity; $P_w$ – wind energy.

The UAV's performance between power conversion and power consumption can be calculated as follows:

$$\eta = \frac{E_c}{E_{pr}} \, . \tag{3}$$

From Eqs. (1) and (2), it can be seen that the power consumption of the UAV depends to a large extent on the angular velocity of the engines. It is very important to control the current of the electric motors or the electric drive (propulsion) of the system. The efficiency of these electric drives is affected by the level of current. Meanwhile, the energy conversion through the $\eta_0$ and the propeller cross section is influenced by wind energy [2].

## 6. Conclusions

Electric propulsion of aircraft will have an impact on air traffic at airports. The Nordic countries are moving towards sustainable air transport and have set a target of 100% electric short-haul and domestic air transport by 2045. This timeframe is needed because electric aircraft require charging standards, new infrastructure and new business models to be defined. With the uptake of electric aircraft, a 50% reduction in aircraft maintenance costs is expected, as well as savings in fuel costs [20].

Batteries are currently the most popular way to power UAVs. The main challenges in using batteries in UAVs are (1) insufficient specific energy and power density (to achieve autonomous electric propulsion range); (2) insufficient battery lifetime (charge-discharge cycles); and (3) insufficient safety, thermal instability, long charging time [10], [22].

The advantages of a UAV using a fuel cell as a power source include no direct pollution, no noise, high energy density and almost instant recharging. The disadvantages are that the size is significantly larger than conventional battery-powered drones, the operating costs depend on the availability of hydrogen gas, and the size of the hydrogen gas tank limits the drone's design. Furthermore, the hydrogen tank must be taken into account when balancing the drone, bearing in mind that its weight decreases as the tank is emptied [12].

The aim of the study was to briefly summarise the energy supply systems important for the propulsion of UAVs, such as batteries, fuel cells, etc., highlighting their main characteristics, advantages and challenges. In conclusion, the incremental improvement of current technologies will not be sufficient to achieve the objectives set, a so-called "disruptive" change is needed. Further studies and technological development are needed to mitigate the problems. Hybrid-electric propulsion, new technologies, configurations and solutions seem to be the most likely solution to achieve the objectives.

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