

## Engines used in modern unmanned aerial vehicles

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*For several years, a rapid growth in interest in unmanned aerial vehicles (UAVs) in many applications has been observed. The UAVs are seen as both entertaining equipment for kids and sophisticated tools for agriculture, archaeology, and terrain scanning. There are also military applications for these flying objects across various missions. This allows multiple UAV configurations to be observed, thereby addressing specific requirements. The wide variety of UAV applications requires a wide range of propulsion systems. In the present paper, the authors sought to present and evaluate specific engine parameters used in modern UAVs. There are described electric motors, piston engines, and turbine engines that produce from about 18 W to 900 kW of power. That is a very wide power range, so the presented engines cannot be compared directly. However, after obtaining the power-to-weight ratio, it can be seen that, in most cases, it stays between 0.1 and 0.15 kW/kg. In some specific cases, this ratio has different values.*

### 1. Introduction

Unmanned aerial vehicles are often presented as a synonym of modernity, yet their history dates back about 100 years, to 3rd September 1924, when the first successful flight of a radio-controlled aircraft without a safety pilot was performed. In 1933, the UAF was first used as a target drone, and in 1944, both Germany and the USA first used UAVs in combat missions [7].

Recently, the unmanned aerial vehicle market has been growing rapidly. The forecast for 2022-2028 predicts an average annual increase in the value of unmanned aerial vehicle sales worldwide of 21.6% [52]. This is because unmanned aerial vehicles are increasingly used, both in civil and military applications [41, 42]. The variety of requirements placed on UAVs results in a range of structures differing in configuration and size. This entails different requirements placed on the propulsion units. In this paper, the units used to propel civil and military unmanned aerial vehicles will be analyzed from multiple perspectives.

Apart from the recreational use of unmanned aerial vehicles, in utility applications, such objects have numerous advantages over the use of manned aircraft, such as [44, 51]:

- Mass – no need to carry the pilot (or crew) and their equipment (seats, operational instruments and installations); this is a very important parameter in agricultural aviation or military applications
- Shape – no need to integrate the crew cabin, so the design could be focused on aerodynamic or useful properties
- Safety – the UAVs can enter areas, which could be dangerous for humans, like biological research, polar or volcanic research, disaster areas with high risk (flood, fire areas) of an accident or areas with radiation, military reconnaissance
- Efficiency – Some of the UAVs can perform autonomous or predefined missions, including the collection of specific data

- Higher maneuverability because the pilot's resistance to overloads during flight does not have to be taken into account, which is especially important in military applications.

There are applications where UAVs are the only possible solution. Such an area is training on air defense systems, where the target is to destroy the target [43].

An important factor in the use of military unmanned aerial vehicles is the lack of fear of losing the pilot, which, aside from the humanitarian factor, represents a loss of money spent on the pilot's training. According to U.S. Air Force data, for military pilots, costs can range from 1.1 million USD to about 11 million USD [49].

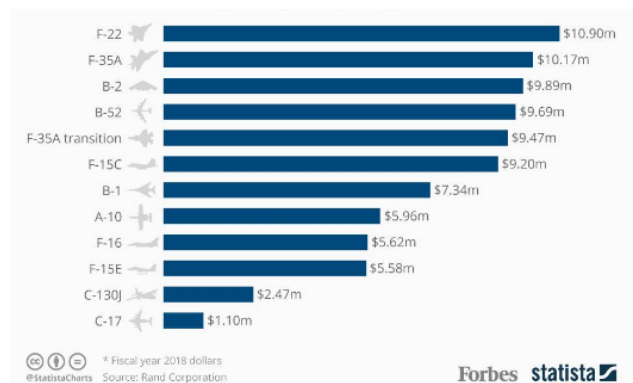


Fig. 1. The cost of training U.S. Air Force Pilots for different types of aircraft [49]

The aim of the paper is to present and evaluate specific parameters of engines used in modern UAVs. In the following chapters, the authors will describe the classification of UAVs and then the types of engines used to propel different types of UAVs. In that chapter, the data of engines used to propel the selected UAVs will also be presented. The next chapter will present an evaluation of parameters characterizing the analyzed engines and the flight parameters of the UAVs powered by them.

## 2. Unmanned aerial vehicles classification

Due to the variety of available UAVs, there are many criteria for categorizing them. In the literature, you can find classifications based on parameters such as weight, flight range, flight duration, wing loading, maximum ceiling, and engine type [16]. Among the most popular classifications are those based on takeoff mass and range. According to the literature, 5 takeoff mass classes are listed (Table 1) [7]. Classification by UAV range comprises three classes that also depend on flight endurance (Table 2) [7].

Table 1. UAV classification according to takeoff mass [6, 7, 31, 45, 46]

Class	UAV mass [kg]	Example
Super heavy	Over 2000	RQ-4B Global Hawk
Heavy	200–2000	Bayraktar TB2
Medium	50–200	HESA Shahed 136
Light	5–50	Albatros
Micro	Less than 5	Hee Wing Ranger T1

Table 2. UAV classification according to UAV range and endurance [7, 13, 25]

Class	UAV range [km]	UAV endurance [hr]	Example
High	Over 1500	Over 24	MQ-9 Reaper
Medium	100–400	5–24	Camcopter S-100
Low	Less than 100	Less than 5	AeroVironment FQM-151 Pointer

The most popular and easily noticeable UAV classification is according to its configuration, following types of UAVs can be distinguished (Fig. 2) [1, 48, 55]:

- Fixed-wing
- Multirotor (Rotary-wing)
- VTOL (Hybrid).

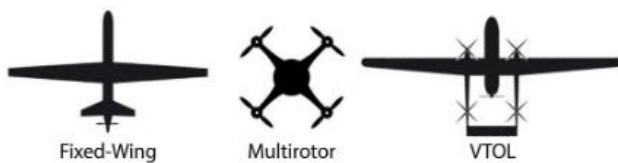


Fig. 2. Example of UAV classification [1]

In some classifications, different types are also listed, such as helicopters (which can be considered a type of rotary-wing configuration), blimps, and flapping-wing aircraft [55].

Due to the widespread use of UAVs, categories are sometimes created that incorporate multiple classification criteria. This is how the MALE (Medium-Altitude Long-Endurance) and HALE (High-Altitude Long-Endurance) classes were created. These classes refer mainly to drones in fixed-wing configuration, which are used both for military and civil purposes [36, 50]

Fixed-wing aircraft are designed to monitor large areas. This type of platform often resembles a typical aircraft (Fig. 3). It is particularly suitable for mapping terrain, monitoring high-voltage lines, or performing reconnaissance missions. This type of platform is characterized by higher cruising speeds and lower energy consumption than multi-rotors, which makes them well-suited for flights over longer dis-

tances. This type of UAV platform is less popular than multi-rotors due to the requirement of a more experienced pilot, more space for take-off and landing, and legal restrictions on flights beyond visual line of sight (BVLOS) [47].



Fig. 3. Example of UAV in fixed-wing configuration [54]

Multi-rotor platforms, in addition to standard flight, are characterized by their ability to hover and move at low speeds. The hovering feature, similar to helicopters, is particularly useful during monitoring point infrastructure and work requiring precision or time to collect the appropriate amount of data (Fig. 4). Another advantage of this type of platform is the possibility of vertical take-off and landing, which allows the mission to start and end on a small piece of flat terrain. This feature allows to work in difficult environments, such as urban or forested areas. These platforms are typically equipped with electric motors that drive propellers (main rotors), mounted symmetrically on the arms. The most common configurations of multi-rotor aircraft use 4 to 8 rotors [47].



Fig. 4. Example of UAV in multirotor configuration [34]

The solution that combines the advantages of both presented technical solutions is a hybrid VTOL platform (Fig. 5). It is most often built as a fixed-wing aircraft with a push or pull propeller and additional rotors, enabling vertical take-off and landing. Of course, this type of solution slightly disrupts aerodynamic properties during flight or reduces the payload, but these are small compromises compared to the wide range of flight properties. This type of construction is used in the unmanned transport of blood samples on the Warsaw-Sochaczew and Warsaw-Pułusk lines.



Fig. 5. Example of VTOL UAV platform [23]

In a fixed-wing configuration, most objects use only one engine to maintain the thrust to fly. Unmanned aircraft base their flight characteristics mainly on the strong lift generated by the wing. The engine, engine-gearbox-propeller assembly, or combination provides the necessary thrust to maintain flight conditions. Models with this solution take off in a conventional way, via a runway run, or with a launcher (pneumatic or mechanical), or manually (from "hand"). This group also includes unmanned helicopter models.

Fixed-wing aircraft can also use two engines. They use the same flight mechanics principle as the machines in the above-mentioned category with one engine. Two engines can be used, for example, to distribute thrust, allowing us to use cheaper engines that often generate less thrust as a single drive. The methods of getting into the air are also duplicated from the second paragraph of this subsection, but with some exceptions. Some concept models can take off vertically – these are the so-called "Tailsitters". They take off from a parking position, resting on their tail. Remote-controlled helicopters can also fall into this category.

Devices using three or more drive units are the largest group, including popular multi-rotor, fixed-wing, and tiltrotor aircraft. Remotely controlled multi-engine fixed-wing aircraft, however, are mainly found in hobby designs, e.g., models reproducing aircraft from the events of the last century.

Multicopter platforms typically use an even number of engines, such as four, six or eight (higher numbers are less common), but designs with three engines also exist.

### 3. Engines in unmanned aerial vehicles

Most commonly used propulsion systems are electric motors and combustion engines, which drive a propeller directly or via a gearbox. Additionally, in UAVs, turbine engines are used, which generate thrust via a propeller. The smallest group is the turbojet engines, which generate thrust directly by the exhaust gases leaving the engine.

Electric drives consist of an electric motor assembly directly connected to a propeller, with various parameters such as diameter, pitch, and number of blades, depending on the needs of the structure.

Electric motors themselves can be divided into three categories:

1. Due to the shaft arrangement:
  - with an internal shaft (so-called Inrunner): the housing is stationary, the shaft is inside, and it transmits the power

- with an external shaft (so-called Outrunner): the movable housing transmits the torque, the shaft is embedded in it.
2. Due to the power supply method:
    - single phase or DC power supply – only two wires required
    - three phase power supply – minimum three wires required.
  3. Electric motors may or may not contain brushes.

Internal shaft motors are also most often brush motors. This design is being replaced in many applications by brushless phase motors, but is still used in cheaper designs due to its low cost and simple operation and production. Such motors have different shapes and sizes. Such units are powered by direct current.

Brushless electric outrunner motors are the most popular type of this drive. They are characterized by high torque and high efficiency. They are powered by one or three phases. This motor, thanks to the shaft attached directly to the housing, which contains a certain (even) number of magnets, does not require the use of brushes, because the winding creating the magnetic field is located on the stator placed inside the housing.

The control system is usually implemented as a power amplifier based on switching transistors, the number of which depends on the number of stator windings. It performs basic functions such as changing the rotational speed, regulating acceleration, and analyzing rotor position information from feedback.

Table 1. Specifications of selected UAV equipped with electric motors [2–6, 11, 12, 19, 20, 29, 30, 38]

UAV name	UAV mass [kg]	Range [km]	Flight time [hh:mm]	Max ceiling [m]	Power of one engine [W]
DJI Mini 3 <sup>1</sup>	0.25	18	00:38	4000	22.3
Helion 10 <sup>1</sup>	0.95	10	00:30	7000	2143.8
BETA FPV Cetus X <sup>1</sup>	0.055	0.1	00:05	100	18.5
DJI Agras T25 <sup>1</sup>	32	2	04:00	120	1305
Altura Zenith ATX 8 <sup>1</sup>	9.65	1	00:40	1000	400
Albatros <sup>2</sup>	10	280	04:00	10000	260
Hee Wing Ranger T1 VTOL <sup>2</sup>	0.75	30	01:05	1000	206

1 – Multicopter, 2 – Fixed-wing

An example of UAVs powered by electric motors is shown in Fig. 6 and 7. The first object is a typical recreational UAV, and the second is more professional in a fixed-wing configuration. Electric-motor UAVs are the most popular, especially in civil applications (recreational and professional). In fixed-wing applications, a single engine is often sufficient (Fig. 7). In contrast, multicopter platforms require multiple engines (Fig. 6).

Piston engines in the described designs are most often four-stroke units, with an even number of pistons (usually four). The cylinder arrangement is most often a boxer, though there are units with a linear or "V" arrangement. The ignition method in UAV engines is dominated by spark ignition (SI) with a carburetor, but compression ignition (CI) has been implemented, e.g., in the MQ-1C Gray Eagle,

Table 2. Specifications of selected UAVs equipped with piston combustion engines [9, 13–16, 22, 24, 25, 31, 33, 35, 37, 39, 53]

UAV name	Engine name	UAV mass [kg]	Range [km]	Flight time [hh:mm]	Max ceiling [m]	Power of one engine [kW]
Bayraktar TB2 <sup>1</sup>	Rotax 914	700	300	27:00	5486	75
Elbit Hermes 900 <sup>1</sup>	Rotax 916	1270	1000	36:00	9100	160
HESA Shahed 136 <sup>1</sup>	Mado MD-550	200	2500	--:--	4000	37.3
MQ 1 Predator <sup>1</sup>	Rotax 914	1020	1250	24:00	7600	86
MQ 1C <sup>1</sup>	Thielert Centurion 1.7	1633	400	27:00	7600	123
IAI Heron <sup>1</sup>	Rotax 914	1150	1000	45:00	10500	160
Mohajer 6 <sup>1</sup>	Rotax 914	670	200	12:00	5500	84.6
Wing Loong I <sup>1</sup>	Rotax 914	1100	4000	20:00	5000	75
Kronstadt Skorpion <sup>1</sup>	Itlan APD-115T	1150	1440	24:00	7500	86
Forpost <sup>1</sup>	APD-85	454	350	16:00	5797	58.85
Falco Xplorer <sup>1</sup>	Rotax 914	1300	300	24:00	9144	86
Camcopter S-100 <sup>2</sup>	AE-50R	200	100	06:00	5900	40.4

1 – Fixed-wing, 2 – Helicopter

which uses the Thielert Centurion 1.7 HFE (Heavy Fuel Engine). It can be seen that many unmanned aerial vehicles use engines used in small aviation, such as the Rotax 914, which is used not only in UAVs but also in many small manned aircraft.



Fig. 6. DJI Mini 3 [19]



Fig. 7. UAV Albatros [6]

Combustion engines used in UAVs are divided into piston engines and turbine engines: turboshaft, turboprop, or turbojet. Each of them is connected to the propeller via an appropriate gearbox, except for turbojet engines, which generate thrust directly (they do not drive propellers). It should be emphasized at this stage that the use of a combustion engine by civilian unmanned aerial vehicles is legally prohibited (except for model and specialist models) - such designs are not classified in the open category. Therefore, we can expect these engines to be used in specialist and military designs.

Piston engines are mostly used in fixed-wing UAVs, but this type of powerplant also propels other UAV configurations, such as helicopters (Fig. 8 and Fig. 9). This type of propulsion system is used more in military than in civil applications.



Fig. 8. UAV Bayraktar TB 2 [10]



Fig. 9. Unmanned helicopter Camcopter S-100 [17]

Turbine engines in UAV systems are of three types: turboshaft, turboprop, and turbojet. Two of the three types predominate in implementation. Turboshaft and turboprop engines allow for a significant increase in power while slightly increasing weight. They also enable flights at much higher altitudes, resulting in increased flight time and range.

Jet engines are used in the heaviest unmanned aerial vehicles and are mainly used in structures intended for mili-

tary purposes. Currently, only two such machines are used – the RQ-4B Global Hawk and the Guizhou WZ 7 Soaring Dragon (it should be mentioned that other producers work on that type of UAVs). Both designs are specialized machines, though their tasks differ slightly. The Global Hawk is a machine with an almost global range, which acts as a machine for collecting radio-electronic and radar information about the battlefield (e.g. SIGINT – Signal Intelligence). The mission specification of the WZ 7 is not fully known, though it is assumed to be a heavy-strike drone.

Table 3. Specifications of selected UAVs equipped with turbine engines [8, 13, 26, 27, 32, 40, 45]

UAV name	Engine name	UAV mass [kg]	Range [km]	Flight time [hh:mm]	Max ceiling [m]	Power of one engine [kW*]
MQ-8 <sup>1</sup>	RR 250	1430	203.7	08:00	6100	313
IAI Eitan <sup>2</sup>	PT6-67A	5400	7400	30:00	14000	900
Bayraktar AKINCI <sup>2</sup>	–	6000	7500	24:00	13750	560
MQ-9 Reaper <sup>2</sup>	TPE331-10	2223	1900	27:00	15420	671
RQ-4B <sup>2</sup>	F137-RR-100	14628	22800	34:00	18000	34 kN
UZGA AL-TIUS <sup>2</sup>	WK-800S	7500	3600	48:00	12000	589
Guizhou WZ 7 <sup>2</sup>	Guizhou WP-13	7500	7000	10:00	18000	43.1 kN

1 – Helicopter, 2 – Fixed-wing  
\* – beyond another unit in the cell

The turbine engines are used mostly in military drones, like RQ-4B Global Hawk (Fig. 10). In most civil applications sufficient power is delivered by electric motors or piston engines.



Fig. 10. RQ-4B Global Hawk in flight [28]

#### 4. Comparison of UAV engines

Small UAVs powered by electric motors have different applications, which implies different efficiencies across the criteria shown in the above graphs. The Helion 10 UAV is a system designed to fly in FPV (First Person View) mode, allowing real-time observation of the drone's flight from the camera's perspective. Such systems are characterized not necessarily by a large range but by a very high engine pow-

er-to-weight ratio, which ensures high maneuverability and speed of the remotely controlled multi-rotor.

It should be noted that for legal reasons, civilian UAVs do not use combustion engines, except for strictly model-oriented designs (the author of the article noted the dominance of single-cylinder two-stroke piston engines in this area of use) or special-purpose designs (however, these designs/systems require certification, e.g., from the domestic Civil Aviation Authority). The list included in this article includes all designs, therefore, as military, special-purpose, and/or experimental. Such a decision is also driven by the desire to achieve, for example, greater UAV performance, such as flight endurance. Of course, today the army also uses UAVs powered by electric motors (e.g. the Polish Warmate system from the WB Electronics Group), but it is not limited only to them, as is the case with civilian customers.

The range of UAVs produced for different applications is very broad. The mass of those objects ranges from about 100 g to 8000 kg. Also, drones are produced for different uses, which is why engine power ranges from about 18 W to 900 kW (Fig. 11). As shown in the figure, electric drones are very close to zero at the left edge of the graph. Also, the piston-engine drones differ by only a very narrow range, which is why there are additional graphs for electric UAVs (Fig. 12) and piston-engine UAVs (Fig. 13). Of course, the most powerful are the turbine-engine UAVs. Of course, the turbine drones are the heaviest too – up to 7500 kg for the analyzed objects. However, the turbine engine-propelled drones, in case of their application, operate at higher speeds and altitudes than other UAVs.

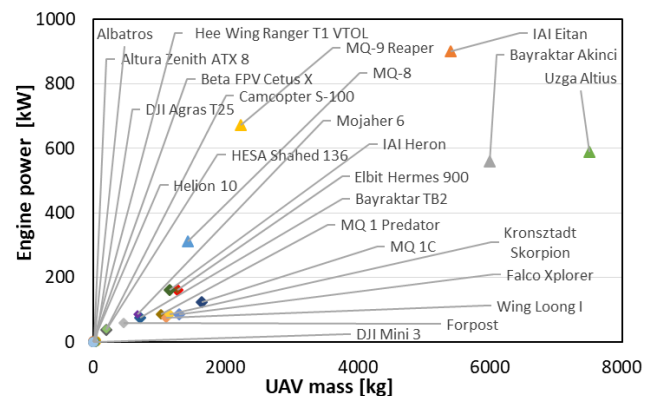


Fig. 11. Engine power as a function of UAV mass in all categories of analyzed UAVs

In the presented UAVs which use an electric motor, there are only civil drones. Despite it the motor power and UAV mass vary respectively from about 2 W to 2.1 kW and from 100 g to 32 kg (Fig. 12). These values range, because also in that class of UAVs, there can be several applications listed, like: recreational use with camera (DJI Mini), very fast flying (Helion 10) and agricultural application, where payload is also important (DJI Agras).

The power and weight parameters of UAVs with piston engines vary between 40 kW to 160 kW and 200 kg to 1600 kg (Fig. 13).

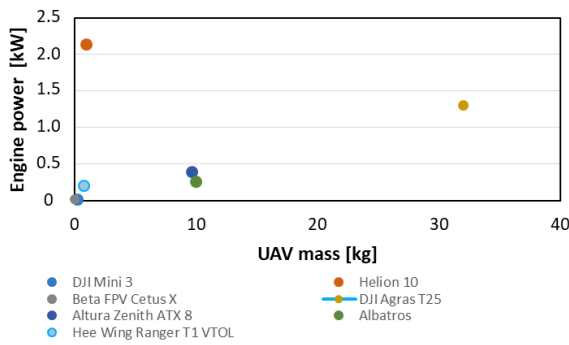


Fig. 12. Electric motor power as a function of UAV mass in electric motor-propelled UAVs

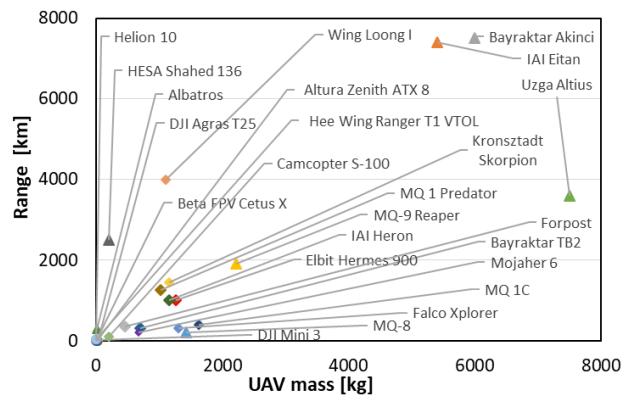


Fig. 15. Range for analyzed UAVs

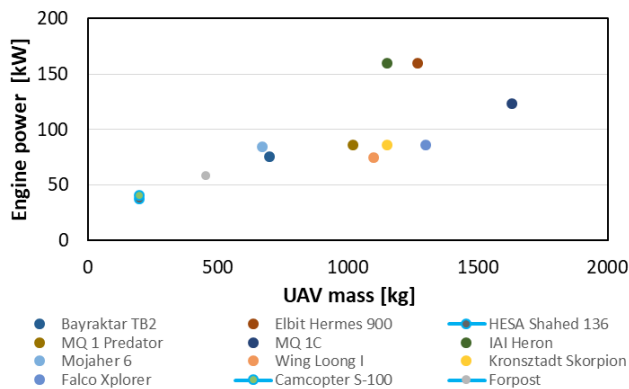


Fig. 13. Piston engine power in function of UAV mass in piston engine-powered UAVs

An interesting comparison is the power-to-mass ratio in kW of engine power per 1 kg of UAV mass (Fig. 14). Most drones have values around 0.1 kW/kg. That value is especially relevant for a fixed-wing configuration. There are higher values of that parameter in some multirotor or helicopter configurations, like Camcopter (0.2 kW/kg) or BETA FPV Cetus X (0.34 kW/kg). Higher values are observed for special-purpose objects, such as the MQ-9 Reaper (0.3 kW/kg).

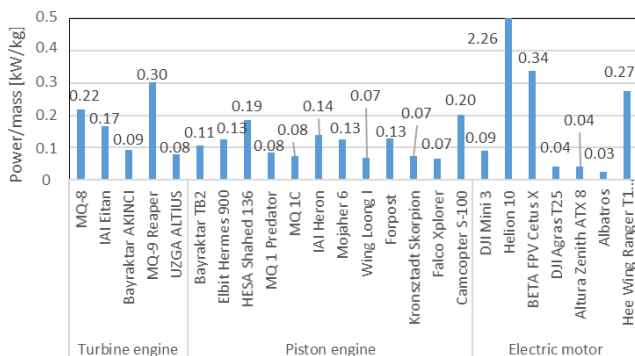


Fig. 14. Power-to-mass ratio for analyzed UAVs

Similar observations could be formulated in the case of the presented UAVs range (Fig. 15). Most of these objects can fly up to a few hundred kilometers. Some fixed-wing aircraft can fly around 1000 km, and some specialized applications can reach up to 7500 km (Bayraktar AKINCI and IAI Eitan).

It should be noted that at this point, UAVs with jet engines have been omitted due to the difference in the method of generating thrust. The graphs include unmanned systems powered by internal combustion turbine engines of the turboshaft or turboprop type.

The use of an internal combustion turbine engine is associated with higher costs of purchasing and maintaining the drive unit than the previously mentioned types of engines. However, it should be noted that these are also the most powerful engines of the types described in this article, allowing one to reach nearly any place in the world and to reach the highest altitudes.

### Summary

Work on UAVs began shortly after the first flight of an aircraft – the first launch of an unmanned aircraft took place in 1922. That was a RAE 1921 Target for training purposes. After the mentioned date, the development of military drones accelerated, culminating in the first combat mission in 1944 [7]. However, last years make the UAVs more popular in civil applications, which can be used for transport of goods, archaeology, agriculture, or even a drone can be a play for kids. Very often in some applications, the UAVs have to carry some specific equipment, like cameras, lidar or ground penetrating radar. Agricultural drones have to carry the spraying equipment, along with fertilizers or plant protection agents. Even more sophisticated requirements are sometimes set for military drones, because the agricultural drone, even if it has to carry some load, does not have to fly to another continent; it can just turn around to charge or change the battery, whereas the military drone often has to fly longer distances and/or stay in the air for a long time.

Above listed requirements resulted in a very wide range of UAVs on the market. If we assume the drone's mass as a criterion, we can find a drone weighing about 100 g, while on the other end of the scale, a drone weighing about 8000 kg. The different masses of objects that should be propelled result in the power of a single engine, which varies from about 18 W for Beta FPV Cetus X to 900 kW in IAI Eitan.

Only the engine's power isn't everything. The characteristics of every drone can vary depending on the type of engine used, which can also affect the power-to-weight ratio. For recreational use, only electric motors are used. This type of propulsion is also used in military drones,

where the electric motor provides silent operation. Another type is the piston engine, which is used in heavier UAVs. Also, this type of engine is used when a longer range is needed, because liquid fuels have a higher energy density than electric batteries. The largest UAVs with the highest ceiling use turbine engines.

Interesting results are observed regarding the power-to-mass ratio. In that case, most of the analyzed UAVs represent values at around 0.1 kW/kg. It can be observed that this value is specific to the aircraft (fixed-wing configuration). The multirotor and helicopter configurations are more likely to exhibit higher power-to-weight ratios. Also, some specialized application drones exhibit higher values of the mentioned ratio, such as the MQ-9 Reaper (0.3 kW/kg).

The presented material shows the variety of UAVs and their engines. According to the analysis in this paper, drones used for civil applications are propelled by smaller, less powerful engines. The reasons are the operational parameters, which, compared to military drones, are: mostly lower mass (less than 50 kg), lower flight speed, and lower ceiling. It should also be noted that turbojet engines are not considered in this paper. Turbojet engines are characterized by thrust rather than power, so it will be problematic to compare all the powerplants together. Nevertheless, it can be very valuable to include that type of engine in the comparison in the future, thereby making the study more complex. This type of drive will become increasingly popular as new UAVs are developed (e.g., Bayraktar Kizilelma).

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