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Comparative Analysis of Unmanned Aerial Vehicles Used in Photogrammetric Surveys

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ABSTRACT: There are many manufacturers on the market offering various types of Unmanned Aerial Vehicles (UAV). The multitude of drones available on the market means that the choice of a UAV for a specific application appears to be a decision problem to be solved. The aim of this article is a comparative analysis of drones used in photogrammetric surveys. The criteria for evaluating the UAVs were: availability and product support, payload (min. 5 kg), price (PLN 100,000), as well as space available for measurement modules. These are the requirements that must be met for the implementation of the INNOBAT project, the aim of which is to develop an integrated system using autonomous unmanned aerial and surface vehicles, intended for bathymetric monitoring in the coastal zone. The comparative analysis of drones was based on 27 companies producing UAV. Based on the analysis, 6 drones that met the project requirements were selected. They were: Aurelia X6 Pro, Aurelia X8 Standard LE, DroneHexa AG, FOX-C8 XT, Hercules 10 and Zoe X4. Selected UAVs differ from each other, among others, in the number of rotors, flight duration and resistance to weather conditions. Individual characteristics of drones may have a different rank depending on their application, therefore the selection of UAVs should be made after prioritisation criteria of a given project.

1 INTRODUCTION

A UAV is an aircraft capable of performing a flight with no pilot on board. Therefore, the aircraft's flight must be performed autonomously, in pre-programmed mode, or using remote control. Another commonly used term for a UAV is a drone [1,2].

UAVs have revolutionised the aviation industry. This is mainly due to the fact that drones are characterised by much lower operating costs compared to manned aircraft. In addition, the continuous progress made in the field of innovation and technology has the result that UAVs are featured by high manoeuvrability and small dimensions, thanks to which they can be used to perform complex tasks [2,3]. Originally, drones were used for military applications such as land mapping, surveillance zone, performing reconnaissance and as long-range weapons. Currently, UAVs are widely used in civil applications, and continuous expansion of their capabilities leads to an increase in the number of sectors using drones. The main areas of UAV application include [4,5]:

- Agriculture: taking reliable measures aimed at saving money and time (e.g. precision farming), identifying damage quickly and accurately, as well as avoiding potential problems in the field [6–10];
- Archeology and architecture: surveys and 3D mapping of man-made structures and historical sites [11–15];
- Crisis management: UAVs are capable of quickly acquiring the information required for a rescue operation. Moreover, a flight using a drone can

also be performed above contaminated areas with no hazard to human health [16–20];
- Environment: thermal analyses [21], cadastral mapping [22], monitoring of land and water areas [23,24], as well as natural resources [25], road map compilation [26];
- Forestry: forest management, species identification, fire surveillance, vegetation monitoring and tree assessment [27–31];
- Traffic monitoring: parking occupancy detection, vehicle position monitoring and estimating the travel time [32–36].

The main components of UAVs include: a battery, engines, a flight controller, a frame, propellers, a receiver, sensors, a transmitter and velocity controllers. The propellers, along with the engine, are responsible for generating aerodynamic lift that allows the vehicle to move around in the air. Drone rotors are adjusted to engines in order to increase performance as much as possible. The UAV frame should be a simple and lightweight design that takes into account the aerodynamic impact on the improvement of flight characteristics. The material and design of a frame are important, as an improperly balanced or overly fragile frame can adversely affect the UAV's operation. The use of an excessively heavy frame will reduce the vehicle's payload, while an askew frame will bring about problems with flight stability. The materials used for the construction of drone frames mainly include carbon or thermoplastic fibres, including polyethylene, polystyrene and polyether ether ketone. The sensors, along with the flight controller, are used to enable the UAV to perform basic safety functions such as obstacle detection, maintaining the drone in a specified position and controlling it. As regards communication with the vehicle, a key role is also served by the ground station along with additional communication modules [3,37].

The multitude of UAVs available on the market means that the choice of a drones for a specific application appears to be a decision problem to be solved. The aim of this article is a comparative analysis of UAVs used in photogrammetric surveys. The selected drones had to meet the requirements for the INNOBAT project, which were: availability and product support, payload (min. 5 kg), as well as price (PLN 100,000).

This paper is structured as follows: Chapter 2 presents the classification and types of UAVs, communication during the drone flight and measurement modules for UAVs. Section 3 reviews drones produced by 27 companies. Moreover, in this chapter, 6 UAVs satisfying the INNOBAT project requirements were selected and a comparative analysis of their characteristics was made. The paper concludes with final (general and detailed) conclusions that summarise its content.

2 MATERIALS AND METHODS

2.1 *Classification and types of UAVs*

Due to the high diversity of the UAV sector, they are classified in many ways, and no single standard of drone classification can be identified. Therefore, they are divided based on different criteria, including weight, range, as well as methods and components that enable flight. The classification based on the weight is provided in Table 1 [38].

Table 1. Classification of UAVs based on the weight. Own study based on [38].

UAV category	Weight m
C0	m < 250 g
C1	250 g ⩽ m < 900 g
C2	900 g ⩽ m < 4 kg
C3	4 kg ⩽ m < 25 kg
C4	m > 25 kg

Most drones used in commercial flights fall into category C1, C2 or C3. The UAVs belonging to groups C0–C3 have additional limitations of a flight altitude of up to 120 m. Table 1 provides the division introduced by Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems [38]. This division is applied in the European Union (EU) Member States. In other parts of the world, other divisions of drones based on the weight are also used.

Another frequently presented UAV classification is the division based on the altitude and range. The classification based on the flight range is provided in Table 2 [3].

Table 2. Classification of UAVs based on the altitude and range. Own study based on [3].

UAV category	Altitude	Range
Hand-held	< 600 m	< 2 km
Close	< 1500 m	< 10 km
NATO	< 3000 m	< 50 km
Tactical	< 5500 m	< 160 km
Medium Altitude Long Endurance (MALE)	< 9100 m	< 200 km
High Altitude Long Endurance (HALE)	> 9100 m	indefinite
Hypersonic	15200 m	> 200 km

Considering that the vast majority of commercially available UAVs fall into the hand-held or close category, this division is not practically applicable to the categorisation of consumer drones. Therefore, UAVs are commonly divided into categories based on the number of rotors and the presence of wings (Figure 1). Four basic drone categories can be distinguished: single rotor, multirotor, fixed-wing and fixed-wing hybrid Vertical Take-Off and Landing (VTOL). Due to their diverse characteristics, each of the above-mentioned UAV types is intended for different applications. The greatest advantages and disadvantages of the drone categories mentioned are provided in Table 3 [3].

Fixed-wing UAVs resemble traditional aircraft in design. They comprise a single rotor positioned centrally at the front of the fuselage and long wings to provide aerodynamic lift. Considering that, unlike the other solutions, the aerodynamic lift does not come from the rotors, these drones consume considerably less energy to fly. It is only used to maintain velocity and not to drift in the air, which makes these UAVs much more efficient. This also contributes to a very long flight range. In comparison to drones from the other categories, these are characterised by high flight altitudes and a great payload. Due to their inability to hover in the air, their applications are limited, e.g. they are not used for precision terrain mapping. The additional difficulties due to the requirement to use an appropriate runway for take-off and landing and the high prices contribute to less interest in this type of solution in the scientific and research sector [3].

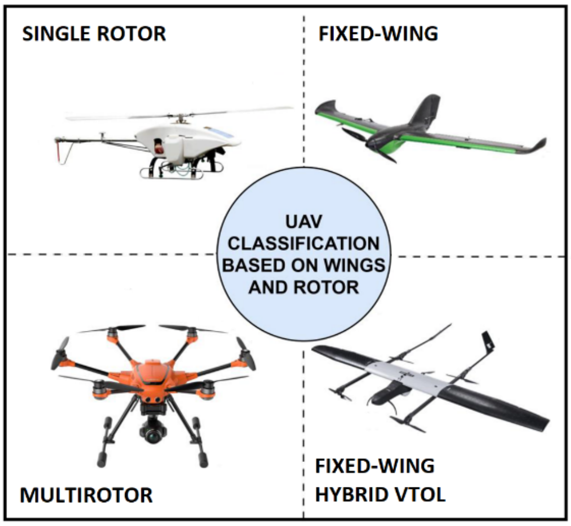

Figure 1. Classification of UAVs based on the rotors and wings. Own study based on [3].

The design of single rotor UAVs resembles that of helicopters. They are characterised by very high carrying capacities and a long flight range. The use of a horizontally positioned rotor allows them to hover in the air, which distinguishes them from fixed-wing drones. Actually, a single rotor UAV is equipped with two rotors, the main one centrally located in a horizontal position, responsible for maintaining the drone in the air, and the second, much smaller one, positioned on the tail, responsible for controlling the flight direction. A large rotor blade is more efficient than multiple rapidly rotating blades of a small size. This contributes to the ability to carry heavier loads and to operate longer on a single battery charge as compared to multirotor drones. Considering the precision of maintaining the set trajectory, single rotor designs are less accurate than solutions based on more rotors [3,37,39].

Multirotors can be additionally divided based on the number and arrangement of engines. The most popular ones include UAVs with four (quadrocopter), six (hexacopter) and eight (octocopter) rotors (Figure 2). In multirotor solutions, some propellers rotate ClockWise (CW), while the others rotate CounterClockWise (CCW) [37,40,41].

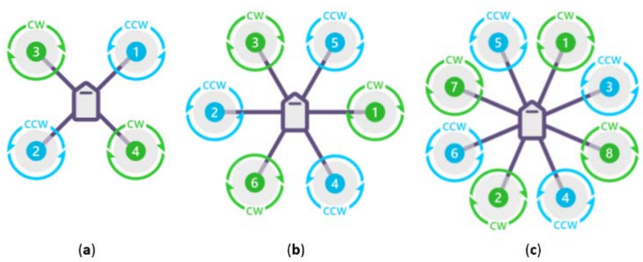

Figure 2. Division of multirotor UAVs: quadrocopter (a), hexacopter (b) and octocopter (c) [41].

Hexacopters and octocopters are available in a version with all the engines positioned in the same orientation and in a version in which the rotors operate in contra-rotating pairs (Figure 3). The application of such a solution allows stability to be increased, and the adverse effect of a failure of any of its drives to be reduced, as the drone does not lose its support point [37].

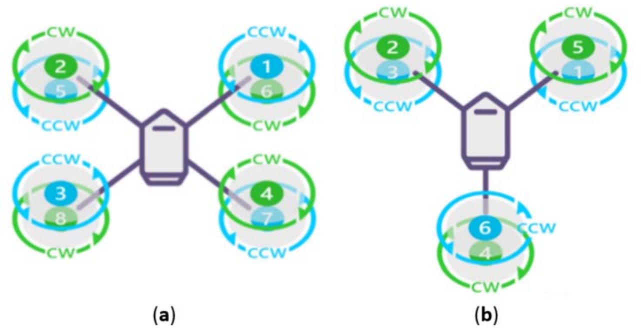

Figure 3. Division of multirotor UAVs with contra-rotating propellers: octocopter X (a) and hexacopter Y (b) [41].

Figure 3 presents the two most common design types based on the contra-rotating operation of two engines in UAVs, i.e. octocopter X and hexacopter Y. A greater number of rotors improves flight stability and contributes to failure-free performance, which is due to their redundancy. As the number of engines increases, so does the energy demand of the vehicle, which consequently results in a shorter flight duration. The greatest disadvantage of drone solutions based on multiple rotors is their short flight range and low velocity. These characteristics prevent the performance of measurements over a large area and over long distances. Of all the solutions discussed here, multirotor UAVs consume the most energy to stay in the air, which contributes to the shortest flight duration [37].

Multirotor drones have gained significant popularity in scientific and research applications. They owe this to their simple design that enables them to take-off and land vertically and to perform complex manoeuvres. Multirotors are the cheapest and simplest solution for getting measurement equipment up into the air. Accurate measurements taken in the air are aided by the high precision of flight and the hovering capability offered by multirotor UAVs. These characteristics make multirotors effective in areas where other types of drones have failed to perform well [42].

A fixed-wing hybrid VTOL is a combination of a fixed-wing UAV and multirotor vehicles. This combination of two drone categories enables vertical take-off and landing, as well as hovering. Consequently, the combination of the aforementioned categories results in pooled advantages of both aircraft and multirotors. However, this involves a very high degree of design complexity and the associated high degree of difficulty in its operation. A hybrid VTOL aircraft is a technology still under development. Given the complexity of the design, this solution is likely to prove to be very expensive. Nevertheless, considering the ongoing development of this technology, it may become a widely used in the future [3,37].

Table 3. A summary of the advantages and disadvantages of the most common UAV types. Own study based on [3,37,39,42].

UAV type	Advantages	Disadvantages
Single rotor drone	Multitasking High flight range High payload Possibility of hovering in the air	Difficult to use Little manoeuvrability High price
Multirotor drone	Multitasking Simple operation High manoeuvrability Possibility of hovering in the air Low price	Small flight range Short flight duration High energy demand
Fixed-wing drone	Long flight duration High flight range High payload High ground coverage Resistance to external conditions	Low versatility Little manoeuvrability Large take-off and landing space required No possibility of hovering in the air
Fixed-wing hybrid VTOL drone	Long flight duration High flight range High payload High ground coverage Resistance to external conditions	Complicated operation Technology still being developed Very high price

Because of the above-mentioned advantages, the most common UAVs in commercial use are multirotor drones. Due to the high costs and high degree of handling difficulty, the other solutions are less commonly used, while still finding their niche.

2.2 *Communication during the UAV flight*

Three basic methods of flight execution by UAVs, determined by the degree of their autonomy, can be distinguished. The simplest way to fly a drone is through manual control by the operator. This is the most common method involving communication via radio remote control. When controlling the UAV manually, the operator, based on the observations and information received from the sensors, manoeuvres the drone using a radio transmitter or other ground station [3,43,44].

Another method is semi-autonomous control, which allows more complex operations to be carried out. As regards the semi-autonomous system, some of the operations needed to perform a flight are transferred to the flight controller. The controller is most often responsible for carrying out basic flight safety operations, such as maintaining the correct altitude and detecting collisions using a variety of sensors available on the UAV. In such a case, the operator is responsible for carrying out the mission and controlling its parameters [43].

The last of the discussed methods is fully autonomous control. Drones controlled by this method carry out the mission autonomously. The flight controller in the UAV is responsible for the execution of safety functions, the flight itself, and the planned mission. The operator prepares the mission scenario before its launch and is involved in monitoring the correctness of the flight without interfering with it [43].

The autonomous flight requires information on the current drone position, and access to the planned flight route. What is also important is the error checking in real time, and building a database that enables the safe return of the UAV following communication breakdown. The above-mentioned functionalities and the vehicle guidance capabilities based on telemetry commands, which enable autonomous flight, are provided by Ground Control Stations (GCS) [3,43,45].

The GCS is the central part of drones. Its functionalities include planning tasks for the vehicle during the flight and monitoring the actuator control for this purpose. It usually comprises the communication equipment, a disk for data storage, a display, a processor, telemetry and the section responsible for mission planning [43].

One of the essential components of a UAV is the flight control system. This is because the movements of a drone are solely determined by its control system. As the accuracy of the control system increases, so does the flight precision. Due to the large amount of data sent from the UAV, there is a need to use multiple stable and efficient data transmission channels. This enables safe and uninterrupted operation, as well as reading data from the drone in real time [40,44].

In addition to the ground station, effective communication requires a number of communication intermediary devices. Figure 4 presents the auxiliary devices and the relationships between them.

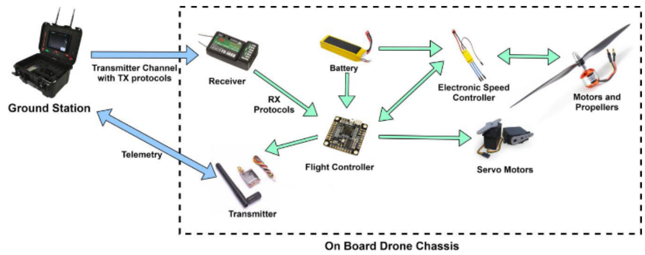

Figure 4. UAV components and operation. Own study based on [3].

Figure 4 shows a simplified model of communication going on between the ground station and the UAV. After sending the signal from the ground station, it is delivered to the radio receiver. The received signal is then converted into a Pulse-Position Modulation (PPM) or a Pulse-Width Modulation (PWM) signal. These signals are subsequently transmitted to the flight controller. Based on these, the controller performs specific actions by controlling the actuators, e.g. rotors or servomechanisms responsible for the movement of the ailerons. In addition to the modules responsible for the flight execution, there are also auxiliary modules that provide information on other crucial aspects, such as the battery charge status or radio signal strength. Wireless transmission protocols that specify the data packet structure and the rules needed for correct data exchange are implemented in the communication between the receiver and the transmitter. A popular practice followed by manufacturers is to use the same protocols in all the drones they sell [3,46].

GCSs should operate over a wide temperature and humidity range, as well as be resistant to other environmental conditions, such as precipitation. It is also advisable to display information on the UAV, including the altitude, flight velocity, heading and position [3].

In order to effectively autonomise the flight, the following are required [43]:

– Receiving and storing data on the current position of the vehicle;
– The opportunity to send commands to the vehicle in flight;
– Continuous monitoring of the system status and the ability to detect failures;
– The ability to return safely after a communication breakdown or another emergency.

Taking aerial measurements based on terrain photos and scanning requires planning the flight route and control points for georeferencing purposes. The flight routes are usually planned before the launch of the mission using dedicated software, taking into account both the flight parameters, such as the altitude, exact route to be followed by the vehicle and measurement equipment parameters. Depending on the specificity of surveys, the flight is performed in manual, assisted or autonomous mode. The presence of Global Navigation Satellite System (GNSS)/Inertial Navigation System (INS) is usually used for autonomous flight [4,45,46].

An important aspect when choosing a drone is the method for controlling its flight. Some of the most popular solutions include remote control, mobile applications and a GCS. The first of these solutions is characterised by a significantly lower cost. Considering the low level of automation, this solution is not applicable in missions where precise movement along a set trajectory is of importance. In such a situation, it is most optimal to use additional software operated from a mobile application or a dedicated ground station solution [3,46].

2.3 *Measurement modules for UAVs*

UAVs are currently regarded as a widely available platform for acquiring photogrammetric data. It has become very popular to combine digital cameras or laser scanners using Light Detection And Ranging (LiDAR) technology with GNSS/INS systems. This combination enables very precise georeferencing of the photos or scans taken, which consequently allows the areas surveyed to be accurately represented in the form of maps or models. Given the multitude of drones available on the market, it is easy to find a UAV in a very wide price range and then adjust it to one’s needs. This promotes the emergence of a large number of start-ups, as well as scientific and research projects based on drones [4,45,46].

2.3.1 *Exemplary measurement systems on UAVs*

Two types of technological solutions can be distinguished among the UAVs used for measurements and research. The first type is the measurement equipment forming an integral part of the drone, and the second type is the use of separate modules including the equipment.

As regards UAVs with integrated equipment, popular solutions include drones equipped with GNSS/INS systems along with a camera or LiDAR. The NEXUS 800 manufactured by HYPACK can be mentioned here as an example. This UAV is equipped with both a digital camera and LiDAR working with GNSS/INS module. The essence of its operation is combining photogrammetric camera data and LiDAR data, as well as processing the data using specialised hydrographic software [47].

A second solution gaining in popularity is the use of separate modules including the measurement equipment. It enables the complete separation of a drone from the measurement equipment. The modules described here can work with any UAV that satisfies certain criteria, such as the max payload and appropriate load space dimensions. This solution is more versatile, as it enables the use of a single drone that can perform a variety of tasks depending on the module being currently installed. It contributes to a significant reduction in costs. The modular nature of the described solution allows the entire measurement system to be established based on commercially available UAVs.

An example of the application of such a solution is the INNOBAT optoelectronic module, which comprises a camera mounted on a gimbal, a communication module, a GNSS/INS system, a LiDAR and a power supply. The aforementioned components weigh approx. 5 kg, which represents the min. payload of the drone working with the system. The main application of the INNOBAT module is to determine the shallow waterbody depth and topography in the coastal zone. The data acquired and processed using an optoelectronic module installed on the UAV will be completed with the data sourced from a GNSS receiver and a MultiBeam EchoSounder (MBES) mounted on an Unmanned Surface Vehicle (USV). The min. isobath recorded via the echo sounder positioned on the vessel will be supplemented with aerial photos taken using the optoelectronic module. The data acquired using unmanned measurement platforms will enable the development of Digital Terrain Models (DTM) of the coastal zone. The analysis presented in Chapter 3.1 will concern the selection of a drone for the INNOBAT optoelectronic module discussed above [48–50].

2.3.2 *Requirements for UAVs by measurement modules*

In order to select a UAV that can serve as a carrier of measurement modules, a number of criteria and factors that translate directly into the ability to perform the mission correctly must be taken into consideration.

The most important parameters to consider when choosing a drone include the physical requirements related to the space available for the load and the max weight enabling the UAV to fly safely. The weights of measurement modules are determined by the components included in their equipment, and usually range from 2 to 5 kg. For this reason, the vast majority of drones available on the market will not be able to carry out flights with advanced professional measurement equipment [51].

The weight criterion is closely linked to the max flight duration on a single battery. This parameter is important in the context of how long the mission lasts and whether or not a flight on a single battery enables the entire mission, or a significant part, to be completed. Figure 5 presents the relationship between the flight duration and the weight of the load being transported for the selected commercially available UAVs.

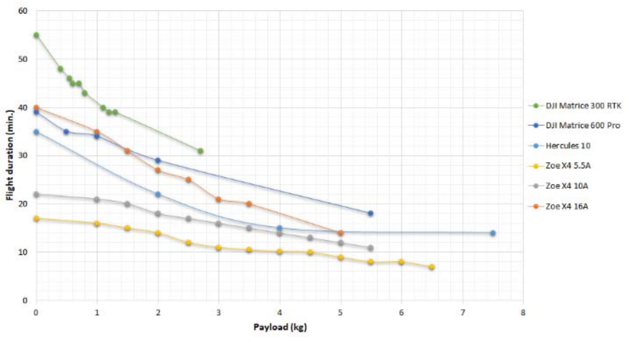

Figure 5. The relationship between the flight duration and the load weight for selected UAVs [52–54].

Figure 5 shows a decrease in the flight duration with a gradual increase in the load weight. The flight duration of the UAVs presented in Figure 5 is shortened under the max load by approx. 50% as compared to the flight carried out with no load. The flight duration, along with the power output of the receivers and transmitters installed in both the drone and the ground station, translate into the flight range. This parameter is of particular importance if the operator is required to stay in a specific location, while the drone needs to complete distant profiles.

Due to the limited payload of the UAV, both storage mediums and other devices should be as lightweight as possible. Considering the large volume of remote sensing data, a high data transmission rate and the use of anti-interference systems are required to ensure their integrity. To this end, Remote Sensing Instruments (RSI) must implement communication via numerous efficient and stable data transmission lines, which allows data transfer in real time. Consideration should also be given to additional data carriers, which enable data pre-processing and storage [40].

The other technical aspect that should be paid attention to when choosing drones for flights with measurement modules is the precision of the flight carried out, achieved using built-in compass and GNSS system. What is also important is the resistance to vibrations that can be induced by rotating measurement equipment such as LiDAR. The final aspect is the resistance to weather factors such as very low or too high temperatures, strong wind and rain [51].

3 RESULTS

3.1 *An overview of UAVs available on the market*

There are numerous companies on the market that manufacture UAVs. However, the drones considered in this overview, with a payload that enables a flight with professional measurement equipment, represent a niche. A large proportion of UAV manufacturing companies are oriented towards selling systems, which are an integrated part of drones.

The following overview of drones focuses on analysing UAVs with a min. payload of 5 kg and a price of no more than PLN 100,000. An additional criterion taken into account was its availability, product support and space available for measurement modules. The overview focuses on commercially available UAVs, excluding custom-made ones.

All the conditions were laid down based on the requirements of the INNOBAT project, described in more detail in Chapter 2.3. A market analysis of 27 companies manufacturing drones was conducted. The companies are as follows: AceCore Technologies, Aerial Technology, Anavia, Aurelia Aerospace, Autel Robotics, Birdpilot, Delair, DJI, DRONE VOLT, Dronetools, Height Technologies, HSE-UAV, Indudro, Inspired flight, Italdron, Kespry, Microdrones, OnyxStar, Parrot, Pilgrim technology, Prodrone, Skydio, Steadicopter, Threod Systems, Vulcan UAV, Yuneec and Ziyan UAS.

3.2 *UAVs satisfying the INNOBAT project requirements*

Based on an analysis of the UAV offers, 6 drone models that satisfy the requirements (availability, payload, price and space) were selected: Aurelia X6 Pro and Aurelia X8 Standard LE manufactured by Aurelia Aerospace, DroneHexa AG manufactured by Dronetools, FOX-C8 XT manufactured by OnyxStar, Hercules 10 manufactured by DRONE VOLT, as well as Zoe X4 manufactured by AceCore Technologies.

The above-mentioned UAV models, along with their manufacturers and prices in the seller's currency and the approximate prices after conversion to PLN, are presented in Table 4 (at the PKO BP bank exchange rate of 04 February 2022 of USD 1 = PLN 4.1424, EUR 1 = PLN 4.7468).

Table 4. An overview of UAVs satisfying the INNOBAT project requirements. Own study based on [53–57].

UAV type	Company	Original price	Price in PLN
Aurelia X6 Pro	Aurelia Aerospace	USD 10,000	PLN 41,400
Aurelia X8 Standard LE	Aurelia Aerospace	USD 7300	PLN 30,300
DroneHexa AG	Dronetools	EUR 13,000	PLN 61,700
FOX-C8 XT	OnyxStar	EUR 16,800	PLN 79,700
Hercules 10	DRONE VOLT	EUR 20,000	PLN 95,000
Zoe X4	AceCore Technologies	EUR 13,900	PLN 66,000

All the drones satisfy the cost criterion of PLN 100,000, set out at the beginning of Chapter 3.1. UAVs considered are described below, and their selected characteristics are compared in Chapter 3.3.

Aurelia X6 Pro drone manufactured by Aurelia Aerospace is a hexacopter (Figure 6). The use of six rotors enables an efficient flight in case of a failure of one of them. The body is a single piece made from carbon fibre, which contributes to a significant reduction in the UAV's weight. The span of the arms, also made from carbon fibre, is 125 cm. The drone arms can be folded to facilitate transport [57].

Figure 6. Aurelia X6 Pro UAV manufactured by Aurelia Aerospace [57].

Aurelia X6 Pro UAV enables a flight with a load of 5 kg. The flight duration of an unloaded drone is 55 min., while with a load of 5 kg, it is 27 min. The UAV uses the Pixhawk Control Zero flight controller, which only weighs 5 g. Moreover, the manufacturer enables its replacement with more efficient Pixhawk Cube Blue model. The drone incorporates an accurate Global Positioning System (GPS) receiver that is able to work with the ground station to use Real Time Kinematic (RTK) corrections and ensure flight accuracy at a level of 2 cm. The max UAV velocity is 56 km/h. The max allowable wind speed during the flight is 32 km/h. The drone is additionally equipped with LiDAR sensors for the obstacle detection [57].

Aurelia X8 Standard LE drone manufactured by Aurelia Aerospace is an octocopter (Figure 7). The use of eight rotors enables an efficient flight in case of a failure of one of them. The UAV frame is made from carbon fibre, and its arm span is 137 cm. The drone arms can be folded to facilitate transport [57].

Figure 7. Aurelia X8 Standard LE UAV manufactured by Aurelia Aerospace [57].

Aurelia X8 Standard LE UAV enables a flight with a load of 8 kg. The flight duration of an unloaded drone is 30 min., while with a load of 5 kg, it is 15 min. The UAV uses the Pixhawk 2.1 flight controller, with the manufacturer enabling its replacement with more efficient Pixhawk Cube Blue model. The max drone velocity is 56 km/h. The max allowable wind speed during the flight is 32 km/h. The UAV is additionally equipped with LiDAR sensors for the obstacle detection. The drone has no ability to carry out missions in the rain. However, the manufacturer states that in the event of rain during the flight, it can be landed safely [57].

Dronehexa AG drone manufactured by Dronetools is a hexacopter (Figure 8). The UAV is characterised by very large dimensions, and its arm span is 210 cm. The drone arms can be folded to facilitate transport [55].

Figure 8. Dronehexa AG UAV manufactured by Dronetools [55].

The max payload for Dronehexa AG UAV is approx. 10 kg (or 16 kg if flights are carried out close to sea level). The flight duration with a 10 kg load is 18 min., while with a 16 kg load, it is 10 min. The system is water- and dust-resistant, capable of flying in winds reaching speeds of up to 29 km/h. The dedicated loads include tanks with liquids and a spraying system. Such solutions mainly prove their worth in agriculture and during disinfection through the decontamination of public spaces. The drone enables carrying out flights with a precision of approx. 30 cm thanks to the possibility of using RTK corrections [55].

FOX-C8 XT drone manufactured by OnyxStar is an octocopter designed to provide quality, efficiency and versatility (Figure 9). The UAV frame is made from carbon fibre, and its arm span is 96 cm [56].

Figure 9. FOX-C8 XT UAV manufactured by OnyxStar [56].

FOX-C8 XT UAV enables a flight with a load of 5 kg. The flight duration of an unloaded drone is 44 min., while with a load of 5 kg, it is 20 min. The design is characterised by its high resistance to external conditions. The UAV is resistant to operation in light rain and has the ability to carry out flights in winds reaching speeds of up to 50 km/h. It is equipped with state-of-the-art electronics responsible for flight, which ensure high efficiency, precision and reliability. The drone is capable of determining position in the classic manner or using RTK corrections to ensure accuracy at a level of single centimetres [56].

Hercules 10 UAV manufactured by DRONE VOLT is an octocopter X with contra-rotating propellers (Figure 10). The design features drive redundancy thanks to the use of eight engines on four arms. The drone has a durable carbon fibre frame and mounting made from anodised aluminium. The arm span is 90 cm. In order to facilitate handling and transport, both the arms and the chassis are removable [53].

Figure 10. Hercules 10 UAV manufactured by DRONE VOLT [53].

The manufacturer allows the simple incorporation of different camera types into the design, as well as a spraying system that enables pumping liquid from the ground. The flight duration of an unloaded UAV is 35 min., while with a load of 5 kg, it is approx. 14 min. The drone was designed with a high level of payload stability in mind. The max payload that can be carried by Hercules 10 is 7.5 kg. The UAV is characterised by a high flight velocity of up to 90 km/h, and is capable of operating in moderate rain and wind, reaching speeds of up to 50 km/h. Data transmission between the control equipment and the drone is encrypted. The flight controller used in this UAV is a DV CORE, based on the popular Pixhawk solutions. A dedicated manufacturer's application is used for controlling the flight, and the drone is capable of operating with RTK corrections [53].

Zoe X4 UAV manufactured by AceCore Technologies is a quadrocopter intended for commercial use (Figure 11). The base of the drone is a lightweight frame constructed from Carbon-Fiber-Reinforced Polymers (CRFP), and its arm span is 69 cm [54].

Figure 11. Zoe X4 UAV manufactured by AceCore Technologies [54].

Zoe X4 UAV is available in three variants differing in the battery pack used, selected depending on the flight duration and the payload preferences. The max flight duration (in the variant with 2x 16A batteries) is 40 min., while the flight duration with a load of 5 kg (in the variant with 2x 10A batteries) is 14 min. The max payload that the drone can carry (in the variant with 2x 5.5A batteries) is 6 kg. The design allows the load to be located either below or above the frame. In order to reduce vibrations affecting the load, additional stabilisation was used to enable operation with vibration-sensitive equipment. The UAV is able to carry out a mission in light rain, and the control function can be fulfilled by one or two operators. The Cube Orange flight controller, interacting with the most popular applications, including Mission Planner, is responsible for the flight control. The manufacturer also offers accessories to be selected depending on the requirements of the missions being carried out [54].

3.3 *A summary of characteristics and comparison of selected UAVs*

The selected characteristics of UAVs described in Chapter 3.2 are compared in tabular form and presented in Table 5. The features compared include the flight duration with no load and with a 5 kg load, max payload and the effective communication range.

Table 5. A summary of selected characteristics of the UAVs under consideration. Own study based on [53–57].

UAV type	Flight duration with no load	Flight duration with a 5 kg load	Max payload	Effective communication range
Aurelia X6 Pro	55 min.	27 min.	5 kg	15 km
Aurelia X8 Standard LE	30 min.	15 min.	8 kg	20 km
Dronehexa AG	70 min.	28 min.	16 kg	No data
FOX-C8 XT	44 min.	20 min.	5 kg	4 km
Hercules 10	35 min.	14 min.	7.5 kg	2 km
Zoe X4	40 min.	14 min.	6 kg	10 km

The first analysed characteristics are flight durations with no load and with a load of 5 kg. The load weight being compared arises from the adopted drone selection criteria presented at the beginning of Chapter 3.1. The flight duration indicated by manufacturers is measured under optimum flight conditions. As regards Zoe X4, the surveys were taken at an ambient temperature of 20°C, in the presence of a light wind (approx. 15 km/h), and the entire measurement was carried out when flying at the altitude of 5 m above the ground. Under different conditions, the flight durations can prove to be shorter than those declared by the manufacturer. Since not all companies carry out precise tests to determine the flight duration under specified load, some of the flight durations with a 5 kg load presented were provided by the manufacturers as a rough guide (Dronehexa AG and FOX-C8 XT). Of all the UAVs concerned, the longest flight duration with no load and with a load was achieved by Dronehexa AG manufactured by Dronetools. The shortest flight durations were noted for Hercules 10 manufactured by DRONE VOLT and Zoe X4 manufactured by AceCore Technologies.

Other characteristics being compared include the max payload and the effective communication range. Of all the drones under consideration, Aurelia X6 Pro and FOX-C8 XT have the lowest payload. Dronehexa AG is characterised by the highest payload of 10 kg, with its manufacturer also declaring that for flights carried out close to the sea level, the UAV is capable of flying with as much as 16 kg of load. The effective communication range reduces the range of the drone itself. Dronetools, the manufacturer of the Dronehexa AG does not provide this parameter. As regards the other UAVs, the longest transmission range is noted for the drones manufactured by Aurelia Aerospace (Aurelia X6 Pro and Aurelia X8 Standard LE), and reaches 15/20 km when in interaction with the ground station.

Another aspect under analysis is the environmental conditions under which selected UAVs are capable of carrying out a flight. Table 6 compares the max wind speeds and the ambient temperature ranges at which a flight can be carried out. It also shows whether a particular drone is capable of operating under precipitation conditions.

Table 6. An overview of environmental conditions for the UAVs under consideration. Own study based on [53–57].

UAV type	Max wind speed that allows flight	Ambient temperature range	Ability to work in the rain
Aurelia X6 Pro	32 km/h	-15°C to 40°C	Yes, in light rain
Aurelia X8 Standard LE	32 km/h	-15°C to 40°C	No possibility
Dronehexa AG	28.8 km/h	0°C to 50°C	Yes, in accordance with the IP65
FOX-C8 XT	50 km/h	-15°C to 40°C	Yes, in light rain
Hercules 10	50 km/h	-20°C to 45°C	Yes, in light rain
Zoe X4	50 km/h	-15°C to 50°C	Yes, in accordance with the IP43

Table 6 addresses the max wind speeds and the ambient temperature ranges that enable flight. FOX-C8 XT, Hercules 10 and Zoe X4 are capable of carrying out a flight in strong winds up to 50 km/h, corresponding to 6° on the Beaufort scale, while Dronehexa AG is capable of flying in winds up to 28.8 km/h, which corresponds to 4° on the Beaufort scale. Of all the above-mentioned UAVs, only Dronehexa AG is not capable of flying in sub-zero temperatures.

The last of the aspects being compared is the ability to carry out flights in the rain. The weather resistance of the Dronehexa AG and Zoe X4 is compliant with the International Protection Rating (IP). Zoe RFT, which satisfies the IP43, provides protection against water spraying at any angle up to 60° from the vertical on any side. Dronehexa AG is compliant with the IP65, which denotes protection against a water stream (12.5 L/min.) being poured from any side. The other drones, excluding Aurelia X8 Standard LE, is capable of carrying out a flight in light rain. Aurelia X8 Standard LE is the only UAV not capable of operating in the rain. The manufacturer states that in the event of rain during a mission, the vehicle can be landed safely.

4 CONCLUSIONS

This article provides an overview of the UAV types along with the range of their applications, and analyses the drones available on the market. Many UAV division criteria can be distinguished, including design, flight range and weight. A drone is selected based on the application for which it is intended. The greatest differences between the UAV categories are their ability to hover in the air and to perform certain manoeuvres. The most popular drones are multirotors due to their wide range of applications and low prices. The arm arrangement and the number of rotors affect the stability and reliability of the design, but from the perspective of the mission being carried out, they are not the key features. It is the communication methods that are of significance. In order to carry out flights involving measurement equipment, it is important to be able to plan a mission precisely before launch, which is ensured by the use of the GCS. In addition to mission planning, it enables flight control and is involved in communication.

Carrying out missions using specialised measurement modules requires significant criteria to be considered when selecting a UAV. A drone must provide aerodynamic lift to maintain the equipment, ensure appropriately high flight precision and provide a sufficiently large space for the measurement module. There are many manufacturers on the market that offer a variety of UAVs. For overview purposes, the study adopted the criterion of a min. drone payload of 5 kg. Another aspect considered in the analysis in question was having a price under PLN 100,000. The comparative analysis considered 6 UAVs that meet the assumptions made. Selected drones differ from each other, among others, in the number of rotors, flight duration and resistance to weather conditions. Individual characteristics of UAVs may have a different rank depending on their application, therefore the selection of drones should be made after prioritisation criteria of a given project.

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