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Oleksii Kolesnyk,
Artem Kolesnyk,
Denys Betin

FEATURES OF EXISTING DESIGN CONCEPTS OF MULTIROTOR-TYPE UNMANNED AERIAL VEHICLES AND PROSPECTS FOR THEIR DEVELOPMENT

The object of this study is the design of multirotor unmanned aerial vehicles (UAVs). One of the key challenges is the formulation of multirotor UAV design concepts for solving specific practical tasks.

Multirotor UAVs have recently experienced significant development both in terms of structural design and overall conceptual approaches. At the same time, the entire set of ideas, technical solutions, and justifications that determine the principles of design, structure, and the main characteristics of a future UAV has not been considered. Developers of multirotor UAVs have not established a comprehensive classification to support scientifically sound design decisions. This represents a challenge in UAV development, and the present study is dedicated to addressing it.

An analysis has been carried out of existing UAV design concepts, their on-board equipment, and fields of application, advantages and disadvantages, as well as potential opportunities for improvement. The study employed system and functional-structural analyses. All possible combinations of design variants were explored and compared with existing solutions.

An analysis of the characteristics of multirotor UAVs as a distinct class was carried out, and evidence supporting their designation as a separate type was presented. A study was conducted on the design features of five mini-class multirotor UAVs for performing various tasks, as well as four cargo multirotor UAVs from different countries of origin. Their advantages and disadvantages were identified. The characteristics of power components were described (all UAVs are fully electric, using brushless electric motors), as well as propulsion systems. Recommendations for the design of multirotor UAVs were developed.

The study provides insights into the design concept of multirotor UAVs, which can be used for the development of advanced models of such UAVs and the improvement of existing ones, and may serve as a topic for a promising direction of scientific research.

Keywords: *existing design concepts, unmanned aerial vehicles (UAVs), multirotor type, development prospects.*

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1. Introduction

Scientific communities have been studying the composition and properties of the atmosphere, as well as the challenges of movement through airspace, for several centuries, and the flight of aerial vehicles (AVs) for more than 120 years. On the basis of these communities, schools, universities, design bureaus, research centres, and scientific institutes were established.

Reference [1] shows that classical AVs are categorized by the principle of lift generation, purpose, structural features, and the presence of a crew. AVs that do not include a crew on board are commonly referred to as unmanned aerial vehicles (UAVs).

According to the U.S. Federal Aviation Administration (FAA) [2], manned aircraft are classified into the following classes based on their design and the principle of lift generation, and the following categories are defined:

– airplanes (classified by the number of engines and base location);
– rotary-wing aircraft, including:
1) helicopters;
2) autogyros (aircraft where one rotor generates only lift, and a separate engine provides propulsion);
3) tiltrotor aircraft;
– lighter-than-air aircraft or aerostats, which include:
1) airships;
2) balloons;
– gliders or sailplanes (which do not have propulsion systems);
– rockets;
– other types of aircraft.

Each corresponding category has further classifications that consider tactical and technical characteristics, structural features, and the areas of application.

As for UAVs, as noted in reference [3], there is currently no standardized approach to their classification for industrial purposes, which in turn complicates both scientific research and the work of experienced design bureaus and manufacturing organizations. The most common classifications of UAVs are based on weight, range, and flight altitude. As an example, we can refer to the NATO STANAG 4670 standard, which divides UAVs into three classes by weight, with each class further divided into categories (Table 1) [4].

Reference [3] shows that the mentioned classifier was developed for military structures, primarily for the organization of units operating UAVs and command spheres; however, this classifier is also incorporated into the regulatory frameworks of civil aviation in several countries. However, a major drawback of this classifier is that it does not take into account the specific design features and applications of UAVs in other fields of use. Thus, an agricultural multirotor UAV would fall into the same class and category as a fixed-wing reconnaissance UAV used for aerial photography of terrain.

Therefore, aircraft are primarily classified based on fundamental design features, which have no correlation with UAV classifications that is, mainly based on size, flight range, and weight. In accordance with this, UAVs are generally not differentiated by design and application, which significantly complicates the research, development, and use of UAVs that differ fundamentally in design and concept.

The number of rotors directly affects the design, weight, dimensions, payload capacity, and other parameters of a UAV, and is one of the primary initial criteria for the development of the multirotor model (Fig. 1). Accordingly, it is important to specify the types of designs based on rotor arrangement and quantity [4].

Multirotors are classified by rotor layout according to the following criteria [5]:

– "X" – shaped rotor configuration;
– "+" – shaped rotor configuration;
– "Y" – shaped rotor configuration;
– "V" – shaped rotor configuration.

Multirotors are classified by the number of propellers as follows:

– single-motor or single-rotor – have one large rotor and one small tail rotor (structurally similar to classic helicopters);
– dual-motor or dual-rotor – rarely encountered in practice;
– tricopters – have 3 rotors;
– quadcopters – have 4 rotors;
– hexacopters – have 6 rotors;
– octocopters – have 8 rotors;
– multirotors with more than 8 propellers – rarely encountered.

Table 1

UAV classification according to NATO STANAG 4670 standard [4]

Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Primary Supported Commander	Example Platform
Class III (> 600 kg)	Strike/Combat	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Reaper
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft MLS	Unlimited (BLOS)	JTF	Heron
Class II (150–600 kg)	Tactical	Tactical Formation	Up to 18,000 ft AGL	200 km (LOS)	Brigade	Hermes 450
Class I (< 150 kg)	Small (> 15 kg)	Tactical Unit	Up to 5,000 ft AGL	50 km (LOS)	Battalion, Regiment	Scan Eagle
	Mini (< 15 kg)	Tactical Subunit (manual or hand launch)	Up to 3,000 ft AGL	Up to 25 km (LOS)	Company, Platoon, Squad	Skylark
	Micro (< 66 J)	Tactical Subunit (manual or hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Platoon, Squad	Black Widow

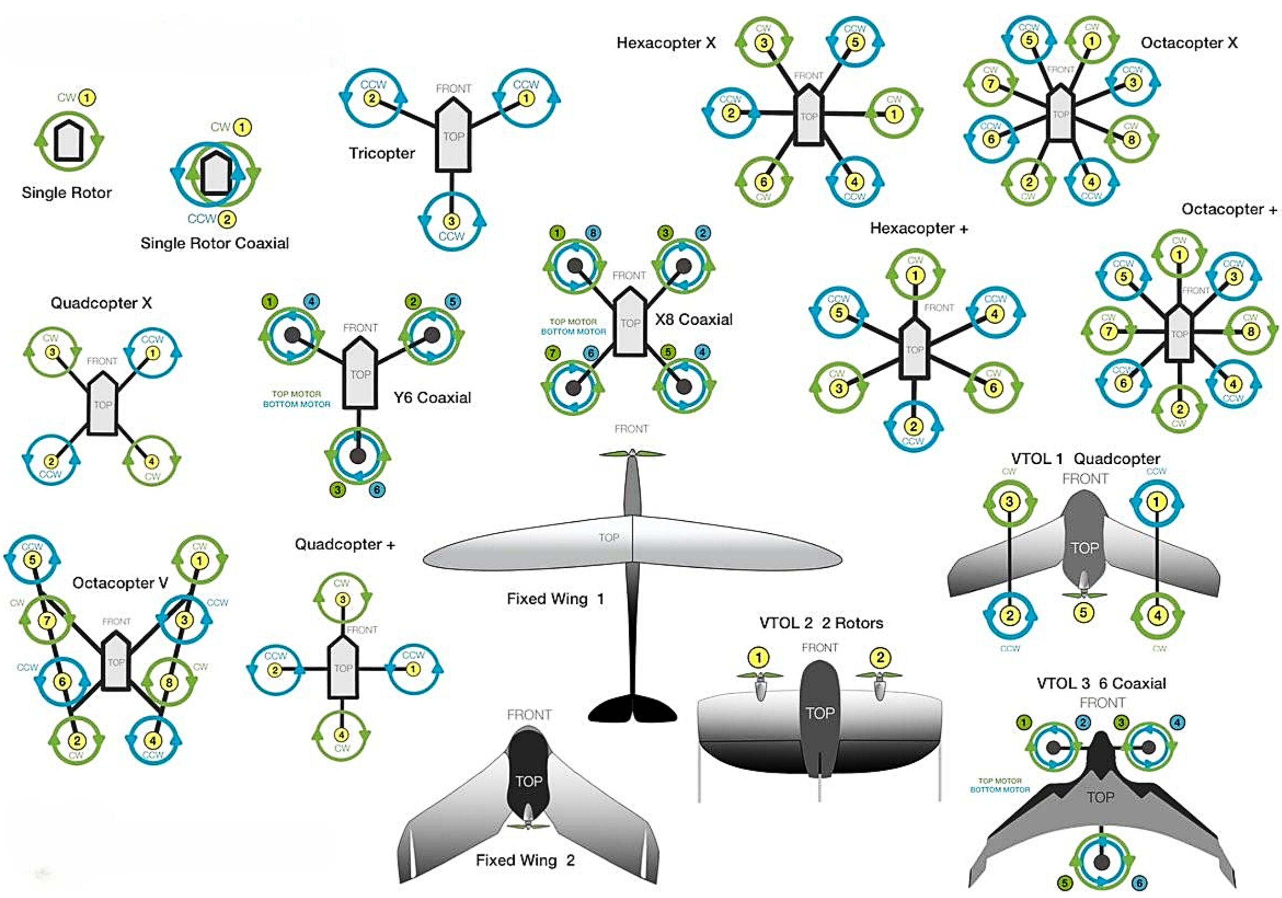

Fig. 1. UAV Rotor Layout Schemes [5]

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A separate feature is the coaxial rotor arrangement, where two propellers are mounted on the same axis and rotate in opposite directions. In such cases, UAVs are classified either by the number of rotors with a note about coaxial pairs or by the number of arms with an indication of coaxial rotors. For example, a UAV with 8 rotors arranged in coaxial pairs may be referred to as either a "quadcopter with coaxial motors" or an "octocopter with coaxial motors". This feature once again highlights the lack of a unified classification system for UAVs.

Hybrid UAV designs, known as VTOL (Vertical Take-Off and Landing), are also encountered. These are fixed-wing UAVs equipped with rotors for vertical take-off and landing, featuring various structural configurations.

Reference [6] establishes that the design of multirotor-type UAVs is determined by the method of lifting force generation, specifically, through the rotation of multiple motor-propeller groups.

Analysis in reference [7] of existing multirotor UAVs uses more than two rotors with fixed-pitch rotating blades to generate a lifting force. The rotor tilt angle is fixed and does not change, unlike in helicopters. During flight, multirotor UAVs remain in a horizontal position, can hover at any moment, move in all directions, and rotate around the vertical axis.

All multirotor-type UAVs are used to carry payloads, which can be divided into two categories:

– payload in the form of measuring equipment or sensors, such as optical cameras (digital or analogue), infrared sensors, laser sensors, or combinations thereof;

– payload in the form of optical sensors and cargo, transported from point A to point B.

For the analysis and demonstration of design concepts and applications, reference [8] examines a series of multirotor UAVs that are widely used in Ukraine.

The most common multirotor-type UAVs in Ukraine differ significantly in design and intended use [9]:

– multirotors with a maximum take-off weight of up to 5 kg, primary quadcopters with optical sensors, used for terrain imaging and real-time video transmission (particularly for reconnaissance in combat conditions);

– multirotors with a maximum take-off weight of up to 7 kg, equipped with optical sensors, designed for transporting cargo up to 2 kg, with or without the capability for repeated use. UAVs in this category typically have a uniform, simple design with minimal avionics and will not be considered in this article [10];

– multirotors with a maximum take-off weight of up to 100 kg, equipped with optical sensors, designed for cargo transport with or without the capability for repeated use.

Summarizing the above, it can be noted that the study revealed incompleteness or absence in open sources of the following essential information: the novelty of multirotor systems and the general lack of research on this topic; a unified classification and standardized approach to UAV classification; the distinction between multirotor UAVs and fixed-wing UAVs as separate design concepts; unified requirements for multirotor UAVs and methods for their calculation and design; and manufacturing technologies. The conducted study provides an understanding of the design concept of multirotor UAVs and can be used for the development of new multirotor UAVs as well as the improvement of existing ones. Taking into account the results of the analysis and data from our own research and development, it can be concluded that addressing the challenges of designing new multirotor UAVs for high-complexity practical tasks represents a promising direction for scientific research and experimental design work.

The aim of this study is to formulate recommendations for the design of multirotor UAVs, based on the results of the analysis of existing design concepts of multirotor-type unmanned aerial vehicles.

To achieve the stated aim, the following tasks need to be accomplished:

– to identify the most common types of multirotor UAV designs;

– to conduct an analysis of the structural advantages and disadvantages of a number of multirotor UAVs;

– to formulate recommendations for UAV design based on the conducted study.

2. Materials and Methods

The object of this study is the design of multirotor unmanned aerial vehicles (UAVs).

As it pertains to the initial stages of design and the analysis of existing concepts, it is reasonable at these stages to employ system and functional-structural analysis of available UAV design concepts, their onboard equipment, fields of application, advantages and disadvantages, as well as modernization opportunities aimed at their improvement.

The leading manufacturer of multirotor-type UAVs with sensors as payload is the Chinese DJI company, which currently offers a wide range of quadcopter UAVs (Fig. 2) [11].

In addition to Chinese-made UAVs in this class, there are Ukrainian and American counterparts. For example, the Shmavik UAV produced by Reactive Drones LLC and the Skydio X10 UAV produced by Skydio LLC (Fig. 3) [12].

a *b* *c*

Fig. 2. UAVs produced by the DJI company: *a* – DJI Mavic 4 Pro; *b* – DJI Avata; *c* – DJI Inspire [11]

a *b*

Fig. 3. UAVs similar to DJI: Ukrainian and American counterparts: *a* – Shmavik UAV produced by Reactive Drones LLC; *b* – Skydio X10 UAV produced by Skydio LLC [12]

For these UAVs, the authors have collected and presented design concepts, information on their applications, as well as their advantages and disadvantages.

DJI Mavic 4 Pro: number of rotors – 4 (quadcopter). Number of propeller blades – 2. Design features: internal fuselage placement of the battery, ability to fold UAV arms for transportation, semi-recessed payload mounting, and use of plastics for structural power elements. Maximum take-off weight – 2.2 kg. Operational information: widely used (this and previous models) in both civilian and military sectors. Advantages: advanced avionics, design allows folding of the UAV for transportation, capability to carry additional payloads up to 700 grams, compatibility with other UAVs of this DJI series, and internal fuselage battery placement. Disadvantages: low reliability and durability (including during crashes and hard landings), low maintainability, practical impossibility of upgrading components and structural elements, as well as avionics.

DJI Avata: number of rotors – 4 (quadcopter). Number of propeller blades – 3. Design features: internal fuselage placement of the battery, absence of arms as clearly defined structural elements, presence of ring structures around the moving parts of the propeller-motor group, semi-recessed payload mounting, and use of plastics for structural power elements. Maximum take-off weight – 0.38 kg. Operational information: narrowly used in the civilian sector (mostly for entertainment and competitions). Advantages: small size and weight, compactness, high movement speed and manoeuvrability, high durability and reliability, resistance to crashes and hard landings. Disadvantages: weak avionics, inability to upgrade, and inability to use additional payloads.

DJI Inspire 3: number of rotors – 4 (quadcopter). Number of propeller blades – 2. Design features: internal fuselage placement of the battery, "H"-shaped UAV design when viewed from above, vertically moving arms that change position during take-off and landing, external payload mounting, use of composite materials (carbon fibre-based) for some structural power elements. Maximum take-off weight – 4.31 kg. Operational information: no publicly available information on usage in Ukraine due to the novelty of the model for civilian sector use. Advantages: advanced avionics, high-quality optical sensor, good balance, focus position, and centre of mass of the UAV. Disadvantages: low reliability and durability (including during crashes and hard landings), low maintainability, low placement of payload, inability to carry additional payloads, practical impossibility of upgrading components and structural elements, as well as avionics.

Shmavic: number of rotors – 4 (quadcopter). Number of propeller blades – 2. Design features: external fuselage mounting of the battery, rigid fixed structure without moving elements or folding capability, external payload mounting, use of composite materials (carbon fibre-based) for the entire structural frame. Maximum take-off weight – 3.4 kg. Operational information: widely used in the military sector and only in Ukraine. Advantages: advanced avionics, ability to carry additional payloads up to 1 kg, equipment and interface compatibility with other products of the company "Reactive Drones", upgradeability of structural elements and avionics, high durability and reliability (including during crashes and hard landings). Disadvantages: fixed structure without folding capability, external placement of the battery and some electrical components, low performance during precipitation.

Skydio X10: number of rotors – 4 (quadcopter). Number of propeller blades – 3. Design features: internal fuselage mounting of the battery, ability to fold UAV arms for transportation, semi-recessed payload mounting, and use of plastics for structural power elements. Maximum take-off weight – 2.49 kg. Operational information: tested in Ukraine without further scaling, limited use in the manufacturing country. Advantages: advanced avionics, design allows disassembly of the UAV for transportation, internal fuselage placement of the battery, high-quality optical sensor. Disadvantages: poor durability and reliability (including during crashes and hard landings), low maintainability, practical impossibility of upgrading components and structural elements, as well as avionics, poor performance in harsh environmental conditions, and inability to carry additional payloads.

Multirotors with a maximum take-off weight of up to 100 kg equipped with optical sensors are designed for cargo transport and have been widely used in Ukraine since 2022. The payload weight averages up to 20 kg, and the use of such UAVs on the battlefield has become a unique feature in Ukraine. This class of UAVs is experiencing the fastest development, extensively incorporating new technologies (composite materials, neural networks, artificial intelligence, anti-jamming protection, etc.). UAVs of this class can be used both in the military sector – as bomber drones or logistics drones – and in the civilian sector, such as logistics, firefighting, agricultural drones, etc.

Among the representatives of this type of UAV in the military sector are the R-18 UAV, which became the first multirotor strike UAV, and the KAZHAN E620 UAV, which became the first serial UAV designed and manufactured in Ukraine, and was the first to receive the nickname "Baba Yaga". In particular, attention is given to the Malloy T150 military cargo UAV manufactured in the UK and the DJI FlyCart 30 civilian cargo UAV from China (Fig. 4, 5) [13, 14].

Below are presented the concepts of their designs, information on their applications, advantages, and disadvantages of these UAVs.

R-18: number of rotors – 8 (octocopter). Number of propeller blades – 2. Design features: large overall dimensions with relatively low maximum take-off weight, absence of landing gear for take-off and landing, exposed battery placement above the fuselage, presence of a mounting system for 4 cargo units, use of composite materials and plastics. Maximum take-off weight – 17 kg. Operational information: used in the military sector since 2019, gained widespread use during 2022–2023, and in 2025, the release of the next, larger model of this UAV was announced. However, none of the versions has yet seen widespread use. Advantages: The main advantage of the UAV was its actual uniqueness and innovation at the time (use of 8 rotors, which increases flight stability and reduces vibration). Disadvantages: absence of landing gear for take-off and landing, external above-fuselage placement of the battery, poor reliability, outdated avionics (including the use of analog systems), and operational complexity.


a


b

Fig. 4. The first multirotor strike and serial UAVs designed and manufactured in Ukraine: *a* – R-18 UAV; *b* – KAZHAN (BAT) E620 UAV [13]


a


b

Fig. 5. British and Chinese UAV counterparts of Ukrainian UAVs: *a* – DJI FlyCart 30 UAV [13]; *b* – Malloy T150 UAV [14]

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KAZHAN (BAT) E620: number of rotors – 4 (quadcopter). Number of propeller blades – 3. Design features: 3-blade rotor, under-fuselage enclosed compartment for battery placement, modular payload mounting system, foldable arms for transportation, modular UAV design, center of mass positioned lower but directly under the focal point, use of composite materials, plastics, and aluminium alloys. Maximum take-off weight – 50 kg. Operational information – widely used since 2022 in the military sector of Ukraine (currently among the most common multirotor UAVs in its class). Some upgraded UAVs are used in humanitarian missions for cargo delivery and in firefighting operations. A specific modification has been actively used in the agricultural sector since 2019, with UAVs undergoing continuous upgrades and updates. The UAV is continuously being upgraded. Advantages: advanced avionics, modular design, well-positioned centre of gravity and focal point, foldable arms, separate battery container, modular pinpoint payload mounting system, 3-blade propeller design, relatively small dimensions, ease of use, iterative updates, high reliability and durability, good maintainability, good flight performance. Disadvantages: iterative development and improvement method (which involves frequent model upgrades), limited size of battery compartment, and overweight design.

Malloy T150: number of rotors – 4 (quadcopter with coaxial paired motors). Number of propeller blades – 2. Design features: coaxial paired motors, internal fuselage placement of the battery, single-point payload mounting, predominantly metal construction. Maximum take-off weight – not available in open sources (payload capacity up to 68 kg). Operational information: the UAV is designed for cargo transportation, primarily for military purposes (however, no publicly available examples of its use have been found). Advantages: high flight speed, high payload capacity, coaxial paired motors, use in water-based operations, high resistance to weather conditions (especially precipitation), good centre of gravity and focal point positioning, high reliability and durability. Disadvantages: large dimensions, high cost, inability to disassemble for transport, weak avionics, poor performance in hard landings, and low maintainability.

DJI FlyCart 30: number of rotors – 4 (quadcopter with coaxial paired motors). Number of propeller blades – 2. Design features: coaxial paired motors, internal fuselage placement of the battery, enclosed cargo container, foldable arms for transportation, and use of metals and plastics. Maximum take-off weight – 95 kg. Operational information: the UAV is used for civilian and humanitarian cargo delivery, mainly in mountainous and agricultural areas. There are cases of use in high-altitude regions (including deliveries to Everest). Officially, the UAV is not intended for military use, and no instances of its use in Ukraine have been found. Advantages: good peak performance of the battery, advanced avionics, coaxial paired motors, high resistance to weather conditions, separate enclosed cargo container, foldable arms. Disadvantages: poor reliability and durability, poor performance in hard landings, difficulty in upgrading and improving, limitations in battery interface and dimensions, and weak battery performance under peak loads.

It should additionally be noted that all of the above-described multirotor UAVs are fully electric, using brushless DC motors (BLDC), which provide high reliability and long service life, and are well-suited for use in autonomous systems [15].

These UAVs use lithium-polymer (Li-Po) batteries as power sources, which have proven effective due to their power-to-weight and capacity-to-weight ratios, making them ideal for autonomous applications [16].

3. Results and Discussion

The paper presents and examines a relatively small number of multirotor UAVs; however, they represent the most successful and widely used examples of this type of UAV. Among them are UAVs designed, manufactured, and operated in Ukraine (Shmavik, R-18, KAZHAN (BAT) E620). In fact, in the course of the theoretical research, the authors examined and analyzed about fifty UAVs of this type, which constitutes a sufficiently large sample to draw conclusions about the advantages and disadvantages of existing UAVs.

Having analysed the obtained information, it could be highlighted that the positive characteristics and design elements should be applied when designing these types of UAVs. These are presented as the following recommendations for designing multirotor-type UAVs:

1. Multirotor-type UAVs should be designed with electric propulsion, considering the widespread use of such systems, their proven effectiveness, simple construction, and minimal weight compared to hybrid and fuel-based systems.
2. Brushless DC motors should be used as the power units due to their high efficiency for systems of this type.
3. Lithium-polymer (Li-Po) batteries should be used as power sources.
4. A UAV should follow an "X"-shaped configuration, due to its popularity and favourable strength-to-size-to-weight ratio.
5. A 4–6-rotor configuration is preferable.
6. Optical sensors are recommended as an essential element of multirotor UAV avionics.
7. For attaching arms to the fuselage, hinged or other movable joints with locking mechanisms should be used to facilitate transportation.
8. Landing gear is recommended for take-off and landing manoeuvres.
9. The battery should be housed in a dedicated enclosed compartment, either inside the fuselage or externally.
10. The design should include a set of structural elements for payload mounting.
11. Modular construction and universal mounts or components should be used to simplify repairs and upgrades.
12. The design should account for future upgrades, allowing for the replacement or enhancement of components, especially avionics.
13. The UAV structure should use aluminium alloys, titanium, plastics, and carbon-based composite materials.
14. The design should incorporate increased strength reserves for landing gear elements, due to widespread use, average operator skill level, and frequent hard landings.

The scope, constraints, advantages, and disadvantages of this study are outlined as follows:

1. The takeoff weight of a multirotor UAV should not exceed 70 kg.
2. There exists a conditional independence, or a directive specification in the design requirements for a multirotor UAV, regarding the mass of equipment and payload.
3. Multirotor UAVs are employed for transporting payloads over short distances, typically with limited flight endurance.
4. Multirotor UAVs must possess high maneuverability and the capability for vertical take-off and landing.
5. Multirotor UAVs must be capable of carrying relatively large payloads.

These recommendations are important because they are the result of extensive analytical research related to existing UAVs from leading manufacturers, as well as UAVs developed in Ukraine. The conducted studies provide an understanding of the design concepts of multirotor UAVs, which can be used for the development of new models of such UAVs and the improvement of existing ones, and may also serve as a topic for promising scientific research directions.

4. Conclusions

1. At present, mass production of multirotor UAVs of various models is carried out mainly by selecting and combining different

components and units without a clear understanding of the final outcome. This approach makes it possible to create a functioning multirotor UAV without applying calculation methods and in-depth knowledge of UAV design and layout, which subsequently leads to a significant increase in financial and time costs. Studies were conducted on the design features of five mini-class multirotor UAVs for reconnaissance, photo and video recording, and additional tasks, as well as four cargo multirotor UAVs from different countries of manufacture (China, USA, United Kingdom, and Ukraine).

2. The advantages and disadvantages of all the considered multirotor UAVs were determined. The characteristics of power components and propulsion systems were described. The examined multirotor UAVs are fully electric, utilizing brushless DC motors (BLDC), which provide high reliability and long service life and are well-suited for use in autonomous systems. Additionally, electric drone systems use lithium-polymer (Li-Po) batteries as power sources, which have proven their effectiveness considering the power-to-weight and capacity-to-weight ratios, for application in autonomous systems.

3. The analysis of the characteristics of multirotor UAVs as a distinct class of UAVs was carried out, and evidence supporting their designation as a separate type was provided. In the course of the study, the lack of the following essential information in open sources was identified: the novelty of multirotor systems and the lack of research on this topic in general; the absence of a unified and standardized approach to UAV classification; the distinction between multirotor UAVs and fixed-wing UAVs as separate design concepts; unified requirements for multirotor UAVs and methods for their design and calculation; and production technologies. To address the methodological gap in practical development and design methods, the authors have developed recommendations for the design of multirotor UAVs.

Conflict of interest

The authors declare that they have no conflict of interest related to this study, including financial, personal, authorship-related, or other factors that could have influenced the research or its results as presented in this article.

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Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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Oleksii Kolesnyk, *CEO & Founder, LLC Reactive Drone, Dnipro, Ukraine, ORCID: https://orcid.org/0009-0008-9729-985X*

Artem Kolesnyk, *Chief Engineer, LLC Reactive Drone, Dnipro, Ukraine, ORCID: https://orcid.org/0009-0006-2464-8452*

✉***Denys Betin,*** *PhD, Assistant Professor, Department of Rocket Technology Design and Engineering, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: d.betin@khai.edu, ORCID: https://orcid.org/0000-0002-1895-5943*

✉*Corresponding author*