drones

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Review

Unmanned Aircraft Systems (UASs): Current State, Emerging Technologies, and Future Trends

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Abstract: Unmanned aircraft, commonly referred to as drones, represent a valuable alternative for various operational tasks due to their versatility, flexibility, cost-effectiveness, and reusability. These features make them particularly advantageous in environments that are hazardous or inaccessible to humans. Recent developments have highlighted a significant increase in the use of unmanned aircraft within metropolitan areas. This growth has necessitated the implementation of new regulations and guidelines to ensure the safe integration of UAS into urban environments. Consequently, the concept of UAM has emerged. UAM refers to an innovative air transportation paradigm designed for both passengers and cargo within urban settings, leveraging the capabilities of drones. This review manuscript explores the latest advancements for UAS, focusing on updated regulations, definitions, enabling technologies, and airspace classifications relevant to UAM operations. Additionally, it provides a comprehensive overview of unmanned aircraft systems, including their classifications, key features, and primary applications.

Keywords: unmanned system; urban air mobility (UAM); UAS; UAV; drones; sensors; UTM; smart city; U-space

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1. Introduction

Advancements in technology have led to the development of various systems and vehicles that do not require the physical presence of human operators on board and are equipped with increasingly autonomous functionalities [1]. These systems are designed to overcome human limitations, address diverse application demands more efficiently, and enable novel tasks and applications.

UAS offer substantial advantages over manned vehicles, including enhanced mission safety, reduced operational costs, and notable improvements in payload capacity, ease of reuse, and advancements in battery endurance, propulsion systems, stabilization techniques, navigation, and onboard sensor technologies. These systems enable long-range operations beyond the detection capabilities of human observers and provide access to physically challenging or hazardous environments where human intervention is impractical or unsafe [2–4].

The acronym UAV refers specifically to the aerial vehicle itself. In contrast, the acronym UAS encompasses the entire system, which includes the aircraft, a GCS, and a communication subsystem (data link) for transmitting and receiving information (as illustrated in Figure 1).

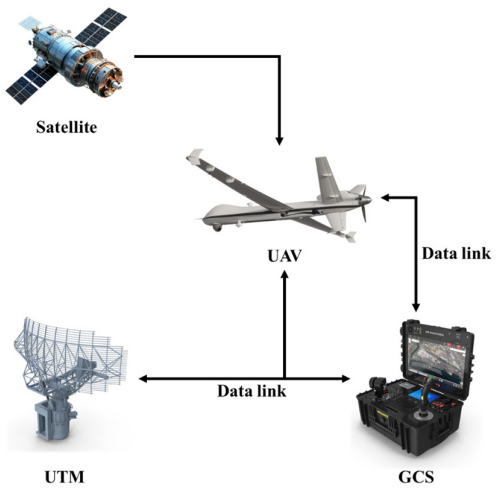


Figure 1. UAS components.

In recent years, the use of UAVs has been steadily increasing across a wide range of operational tasks in urban, suburban, and rural areas. Applications include precision farming, disaster management, surveillance, rapid delivery of emergency medical supplies to remote locations, SAR operations, coastguard and sea-lane monitoring, fire detection and response services, environmental conservation, pollution monitoring, and land surveying, among others.

To facilitate the safe integration of UAVs into urban environments, new rules and regulations have been introduced to ensure their accessibility and safe operation. This development has given rise to the concept of UAM as a novel air transportation paradigm enabling the use of drones for passenger and cargo transport within urban areas [5].

UAM, as defined by NASA, represents an emerging air transportation concept encompassing a range of vehicles, from small-package delivery drones to passenger-carrying air taxis, operating overpopulated areas, including small towns and large cities. UAM and AAM have the potential to revolutionize urban mobility by enabling individuals to traverse urban and peri-urban environments more efficiently [6] [7]. This could significantly reduce commute times, alleviate ground traffic congestion, and facilitate direct point-to-point flights across metropolitan areas. In recent years, multiple companies have made substantial progress in developing and testing key components of this concept. These efforts include the creation of VTOL-capable prototypes, exploration of operational concepts, and formulation of viable business models. While the realization of the UAM concept may benefit from the convergence of advancements in technology, urban infrastructure, and regulatory frameworks, several challenges could hinder its full implementation [8,9]. These challenges include societal acceptance, economic feasibility and affordability, regulatory compliance and certification processes, adverse weather conditions, competition with alternative transportation modes, infrastructure demands, air traffic management complexities, and a potential shortage of qualified pilots [10–12].

Drones for goods delivery are becoming a pivotal component of the rapidly evolving logistics industry. The transportation of goods is progressively transitioning from traditional methods, such as road transport, to innovative modalities. Cargo drones, in particular, are pioneering the operational use cases of AAM. This shift is largely facilitated by the issuance of permits by numerous national authorities, enabling logistics companies to deploy commercial cargo drones.

The primary advantage of cargo drones lies in their ability to significantly reduce delivery times. Furthermore, their use has the potential to alleviate traffic congestion in urban areas. To fully realize these benefits, it is crucial to establish designated areas within

cities to support cargo drone operations, including facilities for landing, take-off, and battery recharging. Figure 2 illustrates a conceptual urban scenario showcasing the integration of cargo drones into the urban logistics ecosystem [13].



Figure 2. Example of a vertiport for UAM cargo operations [5].

This manuscript presents an introduction to the updated regulations, definitions, technologies, and airspace classifications related to UAS operations. Additionally, it provides a comprehensive overview of the new UAS classifications, their primary characteristics, enabling technologies, and key applications, with a particular focus on current and future UAM applications. The paper is organized as follows: Section 2 discusses the regulations and requirements associated with UAS operations. Section 3 presents the current state of UAS development in terms of classifications, communications, and navigation systems. Section 4 highlights enabling current technologies, while main applications in Section 5 are described. Finally, Section 6 concludes the paper with final considerations and potential directions for future work.

2. Regulations

Unlike aircraft and helicopters, UAS predominantly operate at low altitudes (VLL < 500 feet), as depicted in Figure 3, where the density of obstacles and human activity is considerably greater. Many of these aircraft are autonomous or self-flying, necessitating stringent safety measures to ensure mission reliability.



Figure 3. Cargo drone delivery example.

Regulation (EU) 2019/947, effective since 31 December 2020, across all EU Member States, including Norway and Liechtenstein, applies to a wide range of civil drone operations and their associated risk levels. The regulation classifies civil drone operations into three distinct categories: the "open", the "specific", and the "certified" categories, as illustrated in Figure 4 [14].

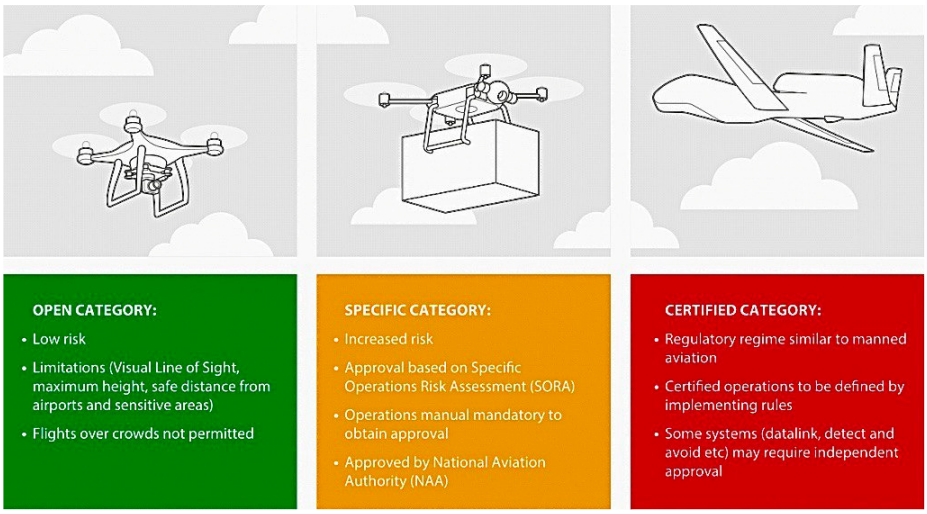


Figure 4. Categories of civil drone operations.

The "open" category pertains to low-risk civil drone operations, where safety is ensured as long as the drone operator adheres to the prescribed requirements for the intended activity. This category is further divided into three subcategories: A1, A2, and A3. Given the low operational risks associated with the open category, no prior operational authorization is required before commencing a flight.

The following restrictions explicitly apply to operations within the open category:

– Overflight of groups of people;
– Carriage or disposal of hazardous materials or goods;
– Autonomous flight operations.

Table 1 outlines the requirements and limitations associated with each open subcategory (A1, A2, and A3).

Table 1. "Open" subcategories, limitations, and requirements.

Subcategory Limitation	UAS Requirements	Pilot Requirements
A1 Overflight of UAS is permitted by people outside the operation.	Private construction or pre-standard < 250 g and speed < 19 m/s.	Familiar with the manufacturer's user manual.
	Type C0 (<250 g).	Familiar with the manufacturer's user manual.
	Type C1 (<900 g and <80 Joule with e-ID and geo-awareness).	Familiar with the manufacturer's user manual. Online course Online theoretical exam
A2	Type C2 (<4 kg with low speed, e-ID, and geo-awareness).	Familiar with the manufacturer's user manual.

Flight is allowed near people outside the operation to maintain a safety distance of 5–30 m.		Certificate of competence of remote pilot, obtained through training, theoretical exam, practice, and practical exam.
A3 Operations in areas where people outside the operation are not endangered by maintaining a minimum 150 m distance from any populated area	Private construction or pre-standard < 25 kg.	Familiar with the manufacturer's user manual.
	Type C2 (<4 kg with low speed, e-ID, and geo-awareness).	Online course.
	Type C3 (<25 kg with low speed, e-ID, and geo-awareness). Type C4 < 25 kg. Type C5 STS-01 Type C6 STS-02	Online theoretical exam Pilot certificate (theoretical and practical examination).

Additionally, starting from 1 January 2024, all drones classified under categories C1, C2, and C3, as well as those operating in the specific category below 120 m, must be equipped with an active and up-to-date Remote Identification (Remote ID) system. Drones in categories C1, C2, and C3 are already designed with built-in Remote ID capabilities, which broadcast essential information such as the drone's position and the operator's registration number. According to EU Regulation 2019/947, from January 1, 2024, it is permissible to operate a drone without a class identification label in the open category under the following conditions:

- Subcategory A1: The drone has a MTOM of less than 250 g, including its payload.
- Subcategory A3: The drone has a MTOM of less than 25 kg, including fuel and payload.

The "specific" category encompasses higher-risk civil drone operations, where safety is managed through authorization obtained from the national competent authority prior to commencing the operation. To secure this authorization, the drone operator must perform a detailed risk assessment to identify and implement the necessary measures for ensuring safe operation. The risk assessment must adhere to the SORA methodology, which provides a structured approach to evaluate operational risks and establish the appropriate mitigation measures. SORA involves assessing the operational context, determining the level of risk to ground and airspace environments, and defining safeguards to ensure safety compliance [15,16].

In the "certified" category, operations involve a significantly higher level of safety risk, necessitating the certification of both the UAS and its operator, along with licensing for remote pilots. This ensures compliance with stringent safety standards. The key requirements for operations within this category are as follows:

1. UAS Certification: Drones must be certified according to the U-space concept of operations.
2. Flight Over People: Certification is mandatory when operating over people with a UAS that has a wingspan exceeding 3 m.
3. High-Risk Operations: Certification is required for flights over crowds, transport of dangerous goods posing a high risk in case of an accident, or passenger transport.

4. SORA Outcomes: If the risk assessment conducted under SORA indicates the necessity for UAS certification, operator certification, or the acquisition of a pilot's license, these must be obtained.

U-Space Services

The management of drone traffic will be facilitated by U-Space, a framework of services designed for airspaces with high-density traffic, particularly in urban areas. The U-Space regulation establishes and standardizes the essential requirements for the safe integration of manned and unmanned aircraft within this airspace. Its primary objectives are to prevent collisions and mitigate both air and ground risks. This regulatory framework ensures the safe operation of all types of unmanned aircraft across various environments. The U-Space regulation was officially adopted in April 2021 and serves as a cornerstone for harmonizing drone traffic management across Europe [17].

U-space has significant potential to facilitate flight planning, navigation, and monitoring in complex environments such as urban areas. It can be integrated with UAM, supporting passenger transport via drones and BVLOS operations. The focus is on the VLL airspace, defined as the airspace up to 500 feet (approximately 150 m), where manned aviation is generally absent under normal operating conditions, making it accessible for UAS operations.

The implementation of U-space services will occur gradually across four phases, from U1 to U4 (Figure 5), reflecting the progressive deployment of service blocks, enabling technologies, and increasing levels of drone automation. These phases also introduce more advanced forms of interaction between drones and other airspace users, ensuring a scalable and safe integration into the airspace system [18,19].

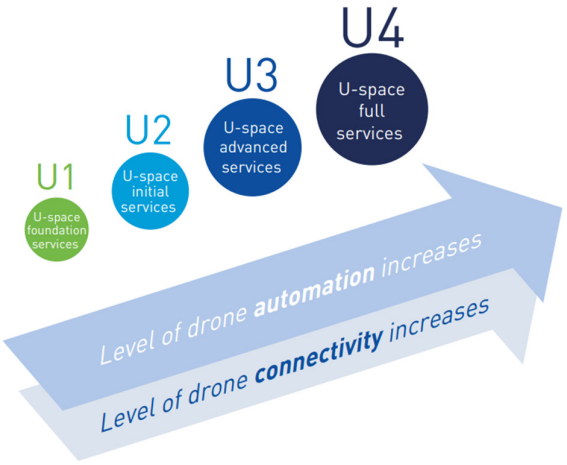


Figure 5. U-space service levels [18].

The services associated with each U-space phase can be summarized as follows [20]:

- U1—Foundation Services: This phase includes essential services such as e-registration, e-identification, and geofencing, establishing the groundwork for safe and controlled drone operations.
- U2—Initial Services: In this phase, services focus on operational management of drones, including flight planning, flight approval, real-time tracking, and integration with conventional ATC systems.
- U3—Advanced Services: U3 introduces support for more complex operations, particularly in dense and urban environments. It includes capabilities for conflict detection and automated DAA functionalities to enhance operational safety.

– U4—Full Services: This phase provides fully automated services, offering high levels of connectivity, digitalization, and automation for both drones and the U-space system, enabling seamless, large-scale drone operations across various scenarios.

Phase U3 of the U-space service framework is pivotal for ensuring the safe and efficient development of UAM, as it introduces advanced functionalities such as conflict detection and automated detect-and-avoid capabilities. Furthermore, phase U4 will play a critical role in achieving full integration of UAM operations into civil air traffic management systems, enabling highly automated, large-scale drone operations.

The following Table 2 presents the U-space roadmap, outlining the progressive deployment of services across phases U1 to U4, along with their respective capabilities and enabling technologies [21].

Table 2. U-space roadmap [21].

Level	Name	Goal	Services
U1	U-space foundation services	2019	Electronic registration (e-registration), Electronic identification (e-identification), Geofencing
U2	U-space initial services	2022–2025	Flight planning, Flight approval, Tracking, Airspace dynamic information, Procedural interfaces with air traffic control
U3	U-space advanced services	2025–2030	Capacity management, Assistance for conflict detection
U4	U-space full services	2030–2050	Integrated interfaces with manned aviation

A critical pre-flight task for UAV operators is verifying whether the intended flight area is authorized. This involves checking geographical zones to ensure compliance with regulations and safety protocols. Understanding where UAV operations are permitted is essential to protect both airspace users and people on the ground. Unauthorized entry into restricted zones can pose serious safety risks, potentially leading to accidents and significant penalties. Therefore, thorough pre-flight planning is crucial to ensure safe and compliant operations. To ensure the safety of both aircraft and individuals on the ground, UAV geographical zones, or geo-zones, have been established across Europe by individual Member States. Geo-zones are defined as portions of airspace where UAS operations may be facilitated, restricted, or entirely prohibited. To enhance situational awareness and simplify identification, Member States can adopt a color-coded system for these zones. This system allows airspace users to quickly recognize the type of geo-zone and its associated restrictions, as illustrated in Figure 6 [22].



Figure 6. Geo-zones depiction [22].

The VLL airspace, designated for drone operations, is divided into three distinct volumes: X, Y, and Z (Figure 7). These volumes differ in two key aspects: the services provided and the access/entry requirements. The availability of specific services determines the types of operations permitted within each volume. Among these services, the provision of conflict resolution is the most critical distinction.

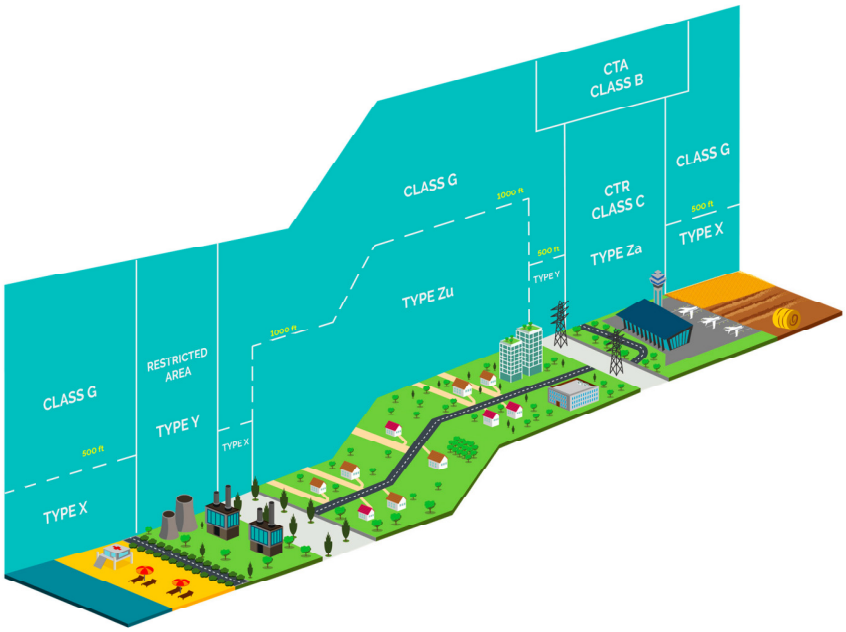


Figure 7. Airspace volume structures [23].

Conflict resolution, detailed further below, is a core function of U-space. Its primary objective is to mitigate the risk of collisions, either between drones or between drones and manned aircraft, to an acceptable safety threshold, thereby ensuring safe and efficient operations within the VLL airspace.

In X volumes, no conflict resolution services are provided, placing the full responsibility for ensuring safe operation on the remote pilot. The pilot is solely

accountable for maintaining separation from other airspace users and obstacles, without any external assistance. Operations in X volumes are conducted under VLOS conditions, requiring the pilot to maintain continuous visual contact with the drone throughout the flight. This direct oversight ensures the pilot can make timely decisions to uphold separation and safety during the operation (Figure 8).



Figure 8. X volume example [5].

In Y volumes, only strategic conflict resolution services are available. These services focus on pre-flight coordination of operation plans to mitigate potential collisions before the mission commences. The primary aim is to deconflict routes and schedules, ensuring safe and efficient operations. Technical requirements typically include a remote piloting station integrated with the U-space system and a UAS capable of transmitting its position reports (Figure 9). Y volumes support both VLOS and BVLOS flights, enabling a broader range of operational scenarios while maintaining safety through proactive planning.

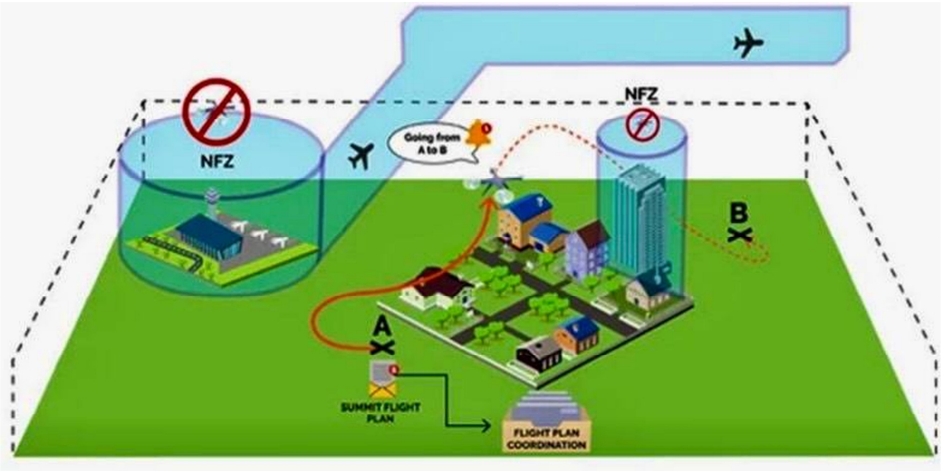


Figure 9. Scenario of a Y volume [5].

In Z volumes, both strategic and tactical conflict resolution services are offered (Figure 10). In addition to pre-flight coordination, real-time in-flight information is used to monitor the positions and movements of nearby aircraft. This allows for dynamic adjustments and guidance to avoid potential conflicts during the mission, enhancing operational safety [23]. Z volumes facilitate BVLOS and automatic drone flight and allow VLOS (Table 3).



Figure 10. Typic Z volume scenario [5].

Table 3. Services provided and flight conditions allowed in the Airspace Volumes.

Airspace Volume	Services	Flight Conditions
X	no services provided	VLOS
Y	strategic conflict resolution services	VLOS BLVOS
Z	strategic and tactical conflict resolution services	BVLOS Full Autonomy

3. UAV Overview

UAVs utilize aerodynamic forces to generate lift and can be classified into two primary categories based on their vertical lift mechanism: rotary-wing and fixed-wing UAVs.

Also referred to as multi-rotors, rotary-wing UAVs are rotorcraft equipped with two or more rotors that generate vertical thrust. These UAVs can be further categorized by the number of propellers, as shown in Table 4. A defining characteristic of rotary-wing UAVs is their VTOL capability, enabling operation in confined spaces without the need for runways (Figure 11c).

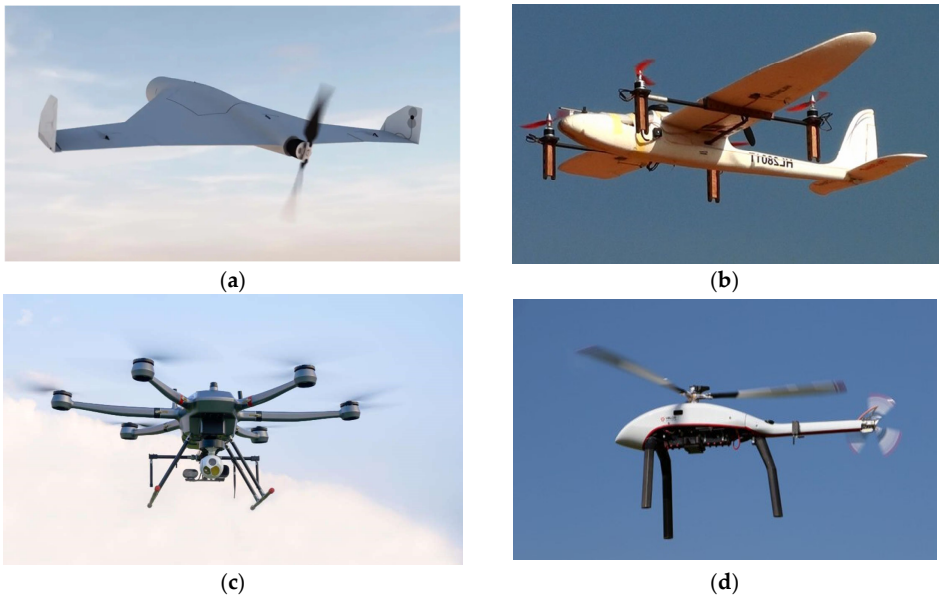
Table 4. UAV multirotor categories.

Types of Multirotor	Number of Propellers
Tri-copter	3
Quad-copter	4
Hexa-copter	6
Octo-copter	8

Fixed-wing UAVs are inherently energy-efficient, as they exploit gliding capabilities to conserve fuel or power during flight. However, their operation requires additional infrastructure, such as a runway or catapult, for horizontal take-off and landing. Fixed-wing UAVs are typically larger and more stable than rotary-wing UAVs, offering superior payload capacity, endurance, and flying range. Despite these advantages, they lack the agility of multi-rotor UAVs due to their size and fixed structural design (Figure 11a).

Hybrid UAVs combine the functionalities of both rotary-wing and fixed-wing systems, aiming to integrate the VTOL capability of rotary-wing UAVs with the energy-efficient gliding of fixed-wing UAVs. While still under development, hybrid UAVs represent a promising innovation, seeking to overcome the limitations of individual categories and enhance operational versatility (Figure 11b).

The rotary-wing UAVs are the most prevalent, especially quadcopters, gaining widespread adoption due to their vertical landing and take-off abilities, high maneuverability, agility, compact structure, cost-effectiveness, and ease of use. In Table 5 vantages and disadvantages have been depicted.



(**a**) (**b**) (**c**) (**d**)

Figure 11. (**a**) Fixed wing; (**b**) hybrid UAV; (**c**) multirotor; (**d**) single rotor.

Table 5. Caparison between UAV architecture.

UAV Types	Advantages	Disadvantages
Fixed wing	– Energy-efficient – Stability – Superior payload capacity – Endurance – Longer flight duration	– Lack agility – Additional infrastructure (runway for horizontal take-off and landing; catapults) – No hovering phase – More complex to pilot
Rotary-wing	– VTOL capability – Hovering phase – High maneuverability – Agility – Compact structure – Cost-effectiveness	– Limited autonomy – Reduced Speed – Limited payload capacity
Hybrid	– VTOL capability – Energy-efficient gliding – Hovering phase – Adaptability	– Structural limits (e.g., transition phase) – High Cost – Increased weight (additional mechanisms for VTOL)

3.1. Classifications

UAVs are classified based on various parameters, including weight, altitude, endurance, and degree of autonomy. The NATO UAS classification system categorizes UAVs into three main classes based primarily on weight (as illustrated in Table 6).

These classes are further subdivided according to operational parameters such as intended use, operating altitude, and mission radius.

Class I UAVs are typically lightweight systems subdivided into micro, mini, and small drones [24]:

- Microdrones are defined as Class I drones with a maximum energy state of less than 66 J.
- Mini drones fall under Class I with a weight below 15 kg.
- This classification helps in aligning UAV capabilities with specific operational requirements, including civilian, military, and commercial applications.

Table 6. UAV classification [25].

Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Example Platform
Class III (>600 kg)	Strike/ Combat	Strategic/National	Up to 65,000 ft	Unlimited (BVLOS)	Reaper
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BVLOS)	Global Hawk
	MALE	Operating/ Theatre	Up to 45,000 ft MSL	200 km (LOS)	Heron
Class II (150–600 kg)	Tactical	Tactical Formation	Up to 18,000 ft AGL	200 km (LOS)	Hermes 450
Class I (<150 kg)	Small (>15 kg)	Tactical Unit	Up to 5000 ft AGL	50 km (LOS)	Scan Eagle
	Mini (<15 kg)	Tactical Sub-unit (Manual of hand launch)	Up to 3000 ft AGL	Up to 25 km (LOS)	Skylark
	Micro (<66 J)	Tactical Sub-unit (Manual of hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Black Widow

Another classification exists for micro, mini, and small UAVs, based on key operational characteristics such as endurance, payload capacity, weight, altitude, and range. Table 7 summarizes these parameters, providing a detailed comparison of their capabilities. This classification is essential for selecting the appropriate UAV for specific missions, balancing operational requirements with performance constraints [24].

Table 7. Micro, mini, and small UAV classification.

Category	Weight (kg)	Normal Operating Altitude (m)	Maximum Range (km)	Endurance (h)	Payload (kg)
Micro	<2	<140	5	<1	<1
Mini	2–25	<1000	25	2–8	<10
Small	25–150	<1700	50	4–12	<50

3.2. Communication Methods

UAS communication relies on three primary methods: satellite, radio signals, and Internet-based connections. The communication framework for UASs involves several critical subcomponents, including communication protocols, network types, and the UAV model itself. Changes in the communication method may necessitate modifications to these components, thereby altering the system's architecture. Researchers have proposed various topologies and system designs, emphasizing that communication modules and protocols should be selected based on the specific mission requirements and the nature of operational tasks. This adaptability ensures optimal performance across diverse UAV applications [26].

The advent of 5G networks has significantly addressed critical constraints in UAV communication, including data rate, latency, and coverage [27]. Recently, numerous studies have explored the potential of LTE-enabled UAVs. These investigations primarily aimed to assess UAV traffic requirements, develop channel modeling techniques tailored to air-to-ground propagation scenarios, and evaluate the feasibility of leveraging existing cellular networks to facilitate UAV communication. Additionally, researchers focused on LTE's capabilities and the necessary advancements to seamlessly integrate LTE technology into UAV systems, thereby enhancing their communication efficiency and operational reliability [28,29]. This advancement in communication technology not only addresses critical areas such as data transmission and latency but also significantly enhances the positioning accuracy and control of drones in various critical rescue and surveillance missions. To achieve these improvements, advanced flight control systems and multiple sensors are integrated alongside camera systems, strategically placed and operated. These components are controlled and communicated through different methods tailored to the drone's altitude and mission-specific requirements, ensuring optimal performance and reliability, as illustrated in Table 8.

Table 8. Communication methods for high- and low-altitude levels [26].

Altitude UAV	Communication Methods
High	Satellite Network Cellular Network
Low	Satellite Network Cellular Network Wi-Fi Radio Signals

These technologies are summarized in Table 9.

Table 9. Typical UAV communication channels.

Technique	Channel Width	Band	Bit Rate	Range
Wi-Fi	20 MHz	2.4 GHz to 5.2 GHz	6–54 Mbps	100 m
GPS	2 MHz	1176 to 1576 MHz	50 bps	-
UMTS	5 MHz	700 to 2600 MHz	2 Mbps	10 km
5G	2.16 GHz	57 to 64 GHz	Up to 4 Gbps	50 m
LTE	20 MHz	700 to 2690 MHz	Up to 300 Mbps	30 km
LTE-A	Up to 100 MHz	450 MHz to 4.99 GHz	Up to 1 Gbps	30 km

3.3. Navigation Systems

UAVs operate using two general navigation methods: automatic control and autonomous navigation. In automatic UAVs, navigation is controlled by a pilot through a remote controller, typically utilizing direct VLOS or visual feedback from an onboard camera (BVLOS). The pilot manually adjusts the UAV's movements during the mission. Autonomous UAVs, on the other hand, rely on sophisticated navigation systems to operate without direct human intervention. These systems are equipped with GPS/other or GNSS devices, which provide precise location data. The navigation and autopilot software process these data to determine the UAV's bearing, distance, and target location.

During flight, GNSS systems continuously transmit data, allowing the UAV autopilot to dynamically adjust its direction. After the user specifies a target location, the UAV interprets the input data and navigates toward the destination using its onboard navigation systems. Upon completing the mission and landing at the target location, the UAV autonomously returns to its home base (the take-off point), awaiting further instructions to repeat the process.

The primary goal of a UAV navigation system is to minimize the risk of collisions while achieving mission objectives efficiently. Path-finding algorithms must balance several factors:

- Stealth: In hazardous environments, avoiding detection is critical. UAVs are designed to minimize exposure to adversaries or threats.
- Feasibility: The UAV's physical capabilities, including endurance and permissible path length, are factored into the route planning process.
- Performance: Pathfinding considers operational constraints such as minimum altitudes, turning radii, climbing angles, and diving capabilities to ensure stable and effective flight.
- Implementation: When stealth is less critical, the focus shifts to optimizing the route's efficiency and execution.

UAVs are also equipped with supplementary navigation systems (ground or on-board) to ensure operational continuity in GNSS-denied environments [30–32]. These systems employ a range of sensors, which are categorized into functional groups:

- Attitude sensors: Measure orientation and stability [33–35].
- Localization sensors: Provide positional data independent of satellite signals [36].
- Altitude sensors: Determine flight height with high accuracy [37].
- Mapping sensors: Create real-time environmental maps for navigation [38].
- Obstacle detection sensors: Identify and avoid potential hazards [39].

By integrating these advanced navigation technologies, UAVs are capable of operating autonomously and effectively across diverse and challenging environments.

For civilian applications, inertial navigation systems employ small form factor strap-down MEMS-IMUs. A standard IMU consists of a triaxial rate gyroscope, a triaxial accelerometer, and a triaxial magnetometer [40]. The key IMU features are dynamic range, gyroscope in-run bias stability, accelerometer in-run bias stability, gyroscope angular random walk and accelerometer velocity random walk, and magnetometer to estimate the

heading. Inertial sensors have been widely applied to localization, attitude, and velocity estimation [41].

3.4. Main Characteristics

The primary characteristics of UAVs that determine their suitability for specific mission profiles are outlined below:

- Payload: The payload refers to the UAV's lifting capability to carry external loads, which can range from a few grams to several hundred kilograms, depending on the UAV category. A higher payload capacity often results in reduced flight time, increased battery consumption, and larger UAV dimensions. Payloads typically include sensors, cameras, and additional equipment such as onboard DAA systems, which enhance operational safety and mission versatility.
- Velocity: Velocity and flight duration are crucial parameters for UAV operations. Small UAVs typically achieve maximum speeds of less than 15 m/s, whereas larger UAVs can reach velocities up to 100 m/s.
- Time-of-Flight: The time-of-flight represents the maximum duration a UAV can remain airborne before its energy source is depleted. Large UAVs may sustain flight for several hours, whereas smaller UAVs are generally limited to 20–30 min of operation.
- Range: The range denotes the maximum operational distance over which the UAV can be remotely controlled. For small drones operating in VLOS, this distance is limited to a few meters, while larger UAVs designed for BVLOS operations can achieve ranges extending to hundreds of kilometers.
- Altitude: Altitude refers to the maximum height a UAV can achieve during flight.

UAVs are categorized based on their altitude capabilities, as shown in Table 10.

Table 10. UAV characteristics.

Category	Endurance (h)	Flight Altitude (m)	Range (km)	Mass (kg)
LADP	0.5–1	50–9000	>250	250–2500
LALE	>24	3000	>500	15–25
MALE	24–48	3000	>500	1000–1500
HALE	24–48	20,000	>2000	2500–5000

4. Technologies

During a mission, especially in UAM operations, UAS must be equipped with advanced sensing systems to ensure high levels of safety. These systems often include a variety of sensors employing different technologies, which detect phenomena through electromagnetic or acoustic means across various spectrum bands.

Multisensor detection, integrating several of these techniques, is critical for reliable UAV detection. Data fusion, the process of combining information from multiple sensors, enhances consistency and yields more informative and cohesive data than any individual input alone. This approach can improve detection performance by mitigating the limitations and challenges associated with each sensor type.

A key element of data fusion is data association, which links sensor observations to the same target. This process ensures that only measurements corresponding to the same UAV are merged. One method of achieving this is through spatial synchronization, which matches sensor observations based on similar position values. However, factors such as coordinate variations, bias estimation, and correction introduce potential errors that must be carefully managed in the data association process [42].

The use of one or more sensors to gather information from a monitored scenario enables the perception of potential threats, depending on the specific technology and signal processing techniques employed. The perception process can generally be divided into three key phases:

1. Detection: This phase involves identifying one or more objects within the monitored airspace. At this stage, the system does not yet distinguish whether the detected object is a drone. Two important performance metrics characterize this phase:
   - Detection Rate: The probability of correctly identifying a target.
   - False Alarm Rate: The probability of incorrectly identifying a non-target object.
2. Classification: After detection, it is necessary to confirm whether the object is indeed a drone. For instance, a detected target might be a bird with electromagnetic characteristics similar to a drone, such as its RCS or visual features like size and shape. This phase may be referred to as recognition or identification in the literature. The system extracts key attributes of the drone, including:
   - Type (size, propulsion method, number of rotors, model).
   - Remote pilot location (if applicable).
   - Payload presence and type (e.g., camera, package delivery).
3. Localization and Tracking: The target's position is estimated in terms of angle and distance. Techniques such as triangulation can enhance accuracy. Once the target is locked, it must be continuously tracked throughout its flight, and its trajectory may be predicted to anticipate future positions.

These phases form the foundation of the DAA concept, which is critical for maintaining safety in complex airspace environments by enabling timely and informed decision-making.

4.1. Detect and Avoid Systems

DAA, also referred to as SAA, encompasses technologies designed to ensure the safe operation of both manned and unmanned aircraft. These systems detect potential collision risks, assess their severity, and execute the necessary maneuvers to avoid mid-air collisions. In manned aviation, DAA systems complement transponders and radars but are still heavily reliant on the human pilot's visual observation, as noted by the FAA. Both human operators and automated systems play crucial roles in collision avoidance [43] [44].

For UAS missions, however, the absence of a human pilot on board requires full reliance on DAA systems. These systems are pivotal for achieving autonomy, ensuring operational safety, and ultimately obtaining airworthiness certification. This is particularly critical for small UAS operating at low altitudes in minimally controlled or uncontrolled airspace, where quick and accurate responses to potential conflicts are essential. In DAA technologies for UAS, the selection of sensing devices is critical, as it directly impacts factors such as payload capacity, sensing accuracy, development costs, and maintenance complexity. The performance and efficiency of DAA systems depend not only on the sensors themselves but also on the underlying algorithms responsible for detection and tracking, which must minimize false alarms to ensure reliable hazard identification.

In general, a UAS equipped with cooperative sensors requires other aircraft or objects in the airspace to have compatible systems to complete detection and tracking [45]. Conversely, non-cooperative sensors do not rely on other aircraft possessing similar equipment, allowing for the detection of both airborne and ground-based objects. In addition to onboard or ground-based sensors, the algorithms used for detecting and tracking potential targets or hazards are crucial. These algorithms must ensure a low false alarm rate, thereby enhancing the accuracy and reliability of DAA technologies [5].

The core components of DAA Systems for UAS are as follows [46] (Figure 12):

- Sensing Hardware: Sensors such as radars, optical cameras, LiDAR, and acoustic sensors detect nearby aircraft and obstacles.
- Decision Mechanism: Algorithms evaluate the risk of collision and decide on the appropriate response based on the data provided by the sensors.
- Path Planner: Generates alternative flight paths to avoid detected threats while maintaining mission objectives and adhering to airspace regulations.
- Flight Controller: Executes the avoidance maneuvers by adjusting the UAS's trajectory in real time.

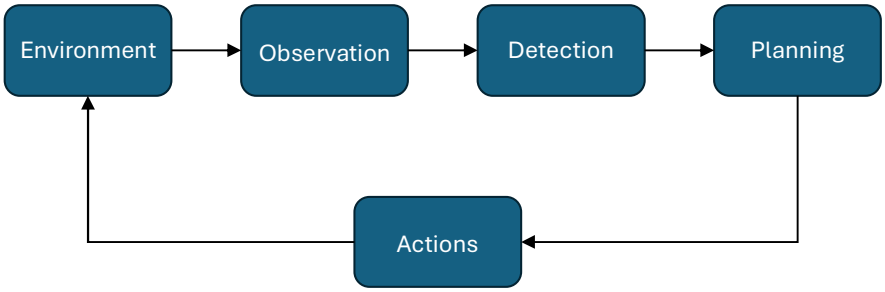


Figure 12. DAA block diagram.

DAA systems are critical to ensure that UAS achieve ELOS compared to manned aircraft, meeting regulatory standards for collision avoidance. These systems enable autonomous UAS to operate safely in shared airspace, making them indispensable for expanding UAS applications in areas such as UAM and BVLOS missions [47].

4.2. Sensor Characteristics and Performance in DAA Systems

The selection and performance of DAA sensors are crucial for ensuring the safe and efficient operation of UAS. These sensors function as transducers, converting physical phenomena into electrical signals that provide the telemetric data necessary for collision detection, tracking, and avoidance. The effectiveness of a DAA system depends on its ability to accurately measure key parameters, including the angle (azimuth and elevation), range, and relative velocity of potential obstacles or aircraft [48].

Different types of sensors are utilized in DAA systems, each excelling at specific measurements (Figure 13):

- Radar: Highly effective for detecting range and relative velocity, especially under adverse weather conditions and at long distances.
- Electro-Optical/Infrared Cameras: Useful for visual detection and classification but limited by lighting conditions and weather.
- LiDAR: Provides high-resolution three-dimensional mapping, offering precise range measurements and close-range detection capabilities.
- Acoustic Sensors: Capable of detecting the presence of drones or other aircraft based on sound but limited in range and susceptible to environmental noise.
- AI: High-performance capabilities; however, high computational costs and power are required.

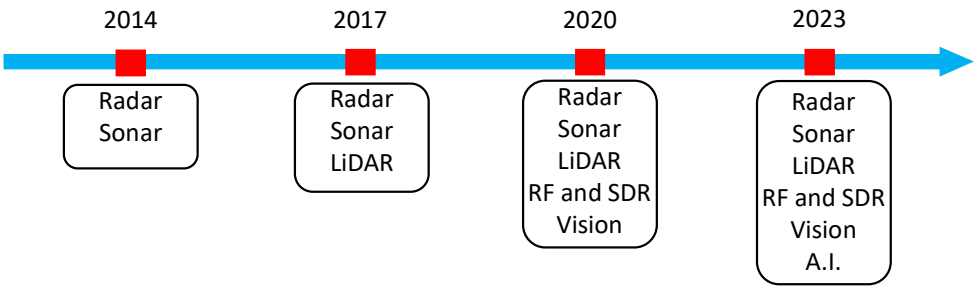


Figure 13. Evolution of UAS detection technologies.

Each sensing technology presents specific advantages and disadvantages, which are inherently tied to their structural design and operational characteristics.

In the context of UASs, DAA systems comprise methodologies designed to detect and prevent collisions with other aircraft or obstacles. This functionality can be implemented via onboard systems or through collaboration with ground-based stations. Typically, DAA sensor data include key parameters such as bearing angles (azimuth and elevation), range, and relative velocity. While individual sensor types are often optimized to measure specific parameters, the comprehensive determination of a target's relative trajectory is achieved by integrating data from multiple sensors or supplementary measurement sources.

Many researchers are concentrating on developing technical solutions to enhance the accuracy and reliability of UAS navigation and DAA systems. These efforts include the exploration of alternative technologies, which are rigorously evaluated against existing methods based on criteria such as accuracy, precision, coverage, computational complexity, cost, and compatibility.

Most of the solutions proposed in the literature leverage multi-sensor data fusion to enhance system performance. Commonly explored combinations include LiDAR and sonar [49], INS and LiDAR [50–57], radar and LiDAR [58–63], as well as camera and LiDAR [64–68]. This integration aims to capitalize on the complementary strengths of each sensor type, improving detection accuracy, reliability, and overall system robustness.

The evolution of AI has also made significant advancements in the development of DAA systems used to develop predictive models that can anticipate the behavior of drones and other aircraft in the airspace [69]. Technologies such as deep learning [70–72], machine learning, and neural networks [73–76] have emerged as transformative tools, representing a new evolutionary trend and a frontier in DAA systems. These models can be used to generate alerts and warnings for pilots, allowing them to take the necessary action to avoid collisions. Machine learning can also be used to develop algorithms for automated traffic management, such as route planning and collision avoidance [77].

These AI-driven approaches enable enhanced detection, classification, and decision-making capabilities, contributing to safer and more efficient unmanned aircraft operations.

Table 11 summarizes the key benefits and limitations associated with various onboard sensing technologies, providing a comparative overview to support system design and application considerations.

Table 11. Advantages and disadvantages of sensing technologies.

Sensing Technique	Advantages	Disadvantages
Acoustic	Possibility to move close to the target and improve the identification task.	Need for proper ego-noise cancellation due to the propeller noise.
Optical	Possibility to change the perspective and to operate close to the target with a higher resolution and better identification capabilities	Limited computational power; need for efficient video stabilization.
RF	Better conditions of the air-to-air channel with respect to the ground-to-air one.	Limited on-board power.
LiDAR	Possibility to move close to the target and improve the detection phase	Limited on-board power.
RADAR	Due to the utilization of proximal sensing, the power demand of the active sensor is significantly reduced.	Limited on-board power.
A.I.	Good performance capabilities.	High computational cost and high power consumption.

4.3. Data Fusion Approaches

The continuous advancements in sensing devices for DAA systems have spurred parallel investigations into data processing techniques upon reception. Classical algorithms, which focus on motion and positioning estimation as well as measurement error reduction, are succinctly reviewed in this section. Given the influence of noise and bias errors, it is critical to deploy algorithms capable of enhancing data estimation accuracy while minimizing false alarms.

In radar-based systems, optimal estimation of both the position and velocity of ground-moving targets is typically conducted using pulse-Doppler radar technologies implemented in UASs [78,79]. The CRB is frequently employed to derive theoretically lower bound for error variance in the estimation of these variables [80]. For multi-target scenarios, especially in networks of multiple radars, MCMC methods combined with a sliding window approach are employed for effective tracking and target identity management [81–83].

In cases where electro-optical systems are utilized for small UASs, methodologies such as the Kalman filter [84–87], SQP [88,89], and LPV [90,91] approaches are applied to image tracking, error mitigation, and 3D target measurement error reduction.

For infrared systems, the improvement of estimation accuracy is achieved through the application of morphological filters to eliminate large-scale clutter and low-pass filters to suppress stationary background clutter [92]. Additionally, an interacting multi-model estimator is employed to enhance the estimation of sensor measurement noise variance and ensure track consistency, thus improving the overall efficiency of infrared systems.

5. Applications

The utilization of UASs is experiencing continuous growth, driven by their versatility, operational flexibility, cost-effectiveness, and reusability, even in hazardous or hostile environments unsuitable for humans. UASs find extensive applications across various domains, including military, scientific, and civil operations. This section provides

a concise overview of some of the most prominent applications of UAVs, highlighting their significance and impact in diverse operational tasks [93–95]. In this section the most significant applications of the UASs are described.

5.1. Risk Assessment and Disaster Management

In disaster scenarios, whether natural or human-induced, such as fires, tsunamis, or terrorist attacks, UAVs serve as invaluable support tools during operations that may be perilous or unfeasible for humans. Equipped with advanced onboard avionics systems and sensors, including radars, cameras, and LiDAR, UAVs assist rescue teams by identifying damage, initiating recovery operations promptly, and delivering essential resources such as first aid kits or aiding manned helicopters. Their capability to provide real-time coverage over extensive areas significantly enhances operational efficiency while ensuring the safety and security of personnel. Additionally, early warnings generated by UAVs play a crucial role in rescuing human lives and safeguarding wildlife in endangered areas [96]. The application of UASs in disaster management and fire protection is extensively documented in the literature. Research highlights their current roles and identifies future developmental directions for these platforms and autonomous technologies [97–100]. Notable advancements include swarm operations for coordinated tasks, early forest fire detection and monitoring, aerial fire extinguishing systems [101–104], the implementation of FANETs to enhance communication in remote or disaster-affected areas [105,106], and their use for cargo delivery and humanitarian aid during emergencies [107,108]. These developments underscore the expanding potential of UASs in addressing complex challenges in disaster scenarios.

5.2. Search and Rescue

UASs play a pivotal role in operations conducted in critical scenarios, particularly during SAR missions. They have proven to significantly accelerate SAR operations in disastrous situations such as missing person searches, avalanches, wildfires, and areas infiltrated with toxic gases. UAVs enable SAR teams to quickly identify areas requiring immediate assistance, facilitating timely intervention.

The primary objective of SAR missions is to locate targets as efficiently as possible and to execute subsequent actions, including information exchange and supply delivery, within tight time constraints. The advantages of using UAVs for SAR operations are numerous, including rapid deployment, low maintenance costs, high mobility, and the ability to operate in hazardous environments where human intervention is limited, unsafe, or necessitates swift decisions [109,110]. Moreover, UAVs are highly effective in identifying victims in challenging terrains or adverse atmospheric conditions. They can deliver essential medical supplies, such as first-aid kits, life-saving equipment, or food and water, to disaster-stricken or remote areas before the arrival of ambulances or rescue teams. Additionally, UASs can transport vital items, including clothing and survival supplies, to stranded individuals in inaccessible regions, thereby providing crucial support until ground rescue crews arrive. This capability underscores the significant value of UAVs in enhancing SAR operations and improving disaster response efforts [111].

5.3. Road Traffic Monitoring

UASs have emerged as innovative tools in the domain of RTM, offering a novel approach to gathering information about traffic conditions on road networks [112]. UAVs have the potential to enable complete automation in the transportation sector, encompassing rescue teams, road surveyors, traffic police, and field support teams. These versatile systems provide a cost-efficient alternative to conventional traffic monitoring devices such as microwave sensors, surveillance cameras, and loop detectors.

Drones can monitor extensive road segments effectively, making them ideal for real-time traffic monitoring and road accident management [113,114]. UASs are particularly useful for local law enforcement, offering a detailed visual perspective on road accidents or facilitating large-scale security operations. For instance, they can be employed in highway patrols to address criminal activities, such as car theft, and in operations involving suspect vehicle identification, armed robber pursuits, or apprehending violators of traffic laws [115].

In addition, UASs contribute to traffic management by detecting over-speeding vehicles, documenting accidents, and assisting in the mitigation of traffic congestion. Their ability to operate in dynamic and high-risk scenarios highlights their utility in improving the efficiency, safety, and effectiveness of traffic monitoring and enforcement processes.

5.4. Security and Surveillance Monitoring

UASs have become indispensable not only for civil applications but also as critical assets in military operations. Their versatility and effectiveness have led many countries to integrate UAVs into their strategic defense frameworks. These aerial robotic systems are extensively utilized for tasks such as enemy detection, anti-poaching efforts, border security, and maritime monitoring of vital sea lanes.

In military contexts, UAVs play a pivotal role in aerial surveillance and reconnaissance, enabling real-time monitoring of specific areas to identify and deter illegal activities [116,117]. Their capacity for persistent observation, coupled with advanced sensors and data transmission capabilities, allows for enhanced situational awareness and decision-making. UAVs are also employed in missions requiring precise and covert operations, making them invaluable for modern defense strategies and national security objectives.

5.5. Remote Sensing

Amateur drone technology has gained widespread popularity for recreational activities, particularly in capturing high-resolution images and videos of scenic landscapes such as islands, mountaintops, and coastlines. Beyond leisure, UASs equipped with advanced remote sensing capabilities are increasingly being utilized in various environmental and scientific applications.

These include water and air quality monitoring [118], drought assessment, oil and gas exploration, yield estimation in agriculture, hydrological modeling, biodiversity conservation [119,120], and geological disaster surveys [121]. Additionally, UASs are instrumental in terrain analysis [122], forest mapping [123], and crop monitoring, enabling efficient and precise data collection over large areas.

The technology is also extensively employed for creating detailed maps and 3D environmental models, which have become valuable tools in fields such as archaeology and cartography. By providing an aerial perspective and integrating advanced sensors, UASs offer unparalleled support in studying, conserving, and managing natural resources and cultural heritage.

The use of UASs has transformed site inspection and construction monitoring, making these processes more efficient, faster, and easier. UAV technology offers substantial support for infrastructure and construction-related inspections through advanced capabilities such as 3D reconstruction and the generation of detailed reports containing imagery and video.

Drones are particularly valuable in applications such as GSM tower inspections, gas pipeline monitoring, power line assessments, and the oversight of construction projects [124,125]. Their ability to capture high-resolution aerial data and provide real-time visuals ensures precise and comprehensive analysis, reducing risks to human inspectors and

enhancing overall project management. The integration of UAVs in these domains continues to drive improvements in operational safety, efficiency, and accuracy.

5.6. Precision Agriculture

UASs are revolutionizing precision agriculture by enabling the efficient collection of critical data through ground sensors. These systems are applied in various agricultural practices, including water quality assessment, soil property analysis, moisture measurement, pesticide application, disease detection, irrigation scheduling, weed detection, and crop monitoring and management [126].

The integration of UASs in precision agriculture has introduced a time-saving and cost-efficient approach, significantly enhancing profitability, productivity, and crop yields. UASs have the potential to transform the agricultural industry by facilitating smart aerial mapping and monitoring. Equipped with advanced sensors and specialized cameras, UASs can assess crop health by measuring parameters such as leaf thickness, foreign contaminants, chlorophyll content, and temperature [127,128].

In the future, advancements in image processing techniques will further enhance UAS capabilities, allowing for the precise identification of plant diseases and the evaluation of other critical traits through high-resolution imagery. These developments promise to make agriculture more sustainable and data-driven, ensuring optimal resource utilization and improved yield outcomes.

5.7. UAVs in Delivery and Load Transportation Applications

With the evolution of UAM, UAS delivery operations represent a highly promising application. UASs possess the potential to provide low-cost, rapid delivery solutions, revolutionizing global logistics [129]. In critical scenarios such as disaster relief or the delivery of pharmaceutical supplies to remote or inaccessible areas, UASs offer significant advantages by reducing both costs and delivery times, especially when standard delivery networks are not feasible [130]. However, this technology is still in the nascent stages of development and is currently limited to pilot programs in select regions [131].

UAS-based delivery systems provide several advantages over conventional delivery methods:

- Speed: UASs operate independently of road infrastructure and traffic conditions, allowing for direct, optimized aerial routes from origin to destination.
- Cost-effectiveness: Reduced delivery time and energy efficiency contribute to lower operational costs.
- Environmental Sustainability: UAS delivery systems produce significantly lower carbon emissions compared to traditional road-based methods, such as delivery trucks.

Beyond parcel delivery, research is also focusing on efficient load transportation strategies using UAVs. The performance of UASs, particularly their flight endurance, is strongly influenced by the payload weight they carry. Future transportation systems may include UAVs designed to transport passenger loads alongside large volumes of cargo, marking a paradigm shift in UAV applications.

Additionally, the use of multiple UAVs in coordinated load transportation has emerged as an area of interest. Swarm-based approaches, where multiple UAVs collaboratively carry heavier payloads, are being explored to enhance load capacity and operational efficiency. These advancements underline the versatility and transformative potential of UAVs in modern logistics and transportation systems.

5.8. UAV Swarms

UAV swarms can be categorized based on their autonomy level as semi-autonomous or fully autonomous systems [132]. This classification can also be further divided into single-layered and multi-layered swarms. In single-layered swarms, each UAS functions as a leader drone, operating independently while contributing to the overall swarm objective. In contrast, multi-layered UAV swarms are hierarchically structured, with each layer consisting of dedicated groups of drones that report to leader drones specific to their layer.

In all swarm configurations, each UAV is equipped with real-time data collection and processing capabilities, while centralized data aggregation and processing are performed in the cloud or at a base station. UAV swarms employing intelligent monitoring mechanisms can efficiently and reliably cover designated areas through the parallel operations of multiple drones [133]. Numerous research studies have explored the operational dynamics and applications of UAV swarms, emphasizing their potential in diverse fields [133].

6. Conclusions and Future Work

UAVs are potentially one of the fundamental elements of future technological applications. This paper provides a comprehensive overview of recent advancements in UAV research and their expanding roles within contemporary and future transportation systems. A detailed examination of the fundamentals of UASs is presented, covering their specifications, updated regulations as of January 2024, classifications, current technologies, communication networks, navigation systems, and principal applications.

The state-of-the-art in both existing and potential UAV applications is explored, emphasizing their deployment in areas such as surveillance, logistics, urban planning, transportation management, and disaster response. From this discussion, several critical challenges associated with UAV integration are identified.

With the increasing integration of UAVs into transportation systems, research has shifted towards envisioning their role in the future of cargo and passenger transportation. Key emerging challenges include the integration of ATM and UTM systems, enabling seamless coordination between manned and unmanned vehicles operating in shared airspace.

This paper highlights both the advancements and limitations of UAV technology and offers insights into future research directions. It underscores the potential of UAVs to facilitate the development of a robust and resilient air transport system, supporting the vision of innovative and efficient transportation networks in the years ahead.

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Acronym List

The following abbreviations are used in this manuscript.

UAS	Unmanned Aircraft System
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
GCS	Ground Control Station
SAR	Search and Rescue
AAM	Advanced Air Mobility
VTOL	Vertical Take-Off and Landing
VLL	Very Low Level
MTOM	Maximum Take-Off Mass
SORA	Specific Operations Risk Assessment
BVLOS	Beyond Visual Line of Sight
ATC	Air Traffic Control
DAA	Detect And Avoid
VLOS	Visual Line of Sight
HALE	High Altitude Long Endurance
MALE	Medium Altitude Long Endurance
LTE	Long Term Evolution
GPS	Global Positioning System
UMTS	Universal Mobile Telecommunications System
GNSS	Global Navigation Satellite System
MEMS	Micro Electro-Mechanical Systems
IMU	Inertial Measurement Unit
LADP	Low Altitude Deep Penetration
LALE	Low Altitude Long Endurance
RCS	Radar Cross Section
SAA	Sense And Avoid
FAA	Federal Aviation Administration
LiDAR	Light Detection and Ranging
ELOS	Equivalent Levels of Safety
AI	Artificial Intelligence
RF	Radio Frequency
CRB	Cramer–Rao Bound
MCMC	Markov Chain Monte Carlo
SQP	Sequential Quadratic Programming
LPV	Linear Parameter-Varying
FANET	Flying Ad hoc Networks
RTM	Road Traffic Monitoring
ATM	Air Traffic Management
UTM	Unmanned Traffic Management

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