AERONAUTICAL DRONES, PART 1: CURRENT STATUS AND TRENDS

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Abstract: *Unmanned aerial vehicles (UAVs), commonly referred to as drones, have become an essential component of modern aerospace systems due to their fast expansion across civil, commercial and military applications. Advances in lightweight materials, miniaturized electronics, navigation systems and manufacturing technologies have enabled the development of increasingly capable platforms ranging from small multirotor drones to high-altitude long-endurance aircrafts.*

This paper reviews the current status of the global drone sector by examining market evolution, industrial development and the principal regulatory frameworks governing UAV operations. A technical classification of drone configurations is presented, including fixed-wing, rotary-wing, hybrid VTOL and mission-oriented categories, highlighting their operational characteristics and engineering trade-offs.

Representative civil and military platforms are comparatively analyzed in terms of range, payload, endurance, cost and mission capability in order to illustrate current technological trends. Attention is also given to structural materials and manufacturing technologies employed in modern UAV design (composite materials, lightweight alloys, additive manufacturing and modular construction concepts).

The analysis shows that progress in materials engineering and airframe design, together with the diversification of operational requirements, is driving the development of increasingly efficient, specialized and adaptable unmanned aircraft. These trends confirm the importance of UAV technologies within the evolving aerospace industry.

Keywords: *Unmanned Aerial Vehicles (UAVs), Artificial Intelligence (AI), Autonomous Systems, Military Drone, Civil Drone*

1. INTRODUCTION

1.1 Background and scope.

Unmanned aerial vehicles (UAVs), commonly designated as drones, represent one of the most dynamic technological developments in modern aerospace engineering. Defined as aircraft operating without an onboard human pilot, UAVs may be remotely controlled, semi-autonomous or fully autonomous depending on mission architecture and onboard intelligence [1]. Initially developed for military reconnaissance and target practice during the twentieth century, drones have evolved into sophisticated systems capable of performing surveillance, logistics, mapping, precision strike, environmental monitoring and scientific missions.

The rapid expansion of the UAV sector during the last two decades has been driven by progress in lightweight composite materials, miniaturized electronics, high-efficiency electric propulsion, satellite navigation, advanced sensors, wireless communications and artificial intelligence (AI) [2].

These enabling technologies have reduced production costs while significantly increasing operational capabilities. Consequently, UAVs are no longer restricted to military organizations, but are widely used in civil sectors such as agriculture, construction, energy inspection, cinematography, public safety and emergency response.

From a strategic perspective, drones are now considered a core component of next-generation aerospace ecosystems. Military UAVs are increasingly employed for intelligence, surveillance and reconnaissance (ISR), electronic warfare, loitering munitions and collaborative combat operations [3]. Simultaneously, civil regulators and manufacturers are pursuing the safe integration of drones into controlled airspace for beyond-visual-line-of-sight (BVLOS) missions, parcel delivery and urban air mobility applications.

The scope of the present paper is to analyze the current status and future trends of aeronautical drones in both civil and military domains. Emphasis is placed on market development, classification of systems, structural materials, autonomy, AI integration, propulsion technologies and future operational concepts. The paper also compares existing and currently under development.

1.2 Definitions and classification of UAVs.

Although the terms UAV, UAS (Unmanned Aircraft System), RPAS (Remotely Piloted Aircraft System) and drone are often used interchangeably, technical distinctions exist. According to the International Civil Aviation Organization (ICAO), an RPAS includes not only the aircraft itself, but also the remote pilot station, communication links and associated operational infrastructure [4]. In broader industrial practice, the term UAS is increasingly used because it reflects the complete system architecture.

Drones can be classified using several criteria:

a) Aerodynamic configuration:

- Fixed-wing UAVs – efficient for long-endurance and long-range missions; used in mapping, surveillance and military ISR.
- Rotary-wing UAVs – multirotor or helicopter configurations capable of vertical takeoff and landing (VTOL), used in civil inspection and short-range tactical missions.
- Hybrid VTOL UAVs – combine vertical lift with efficient forward flight.

b) Size and mass:

- Nano and micro drones (<2 kg);
- Small drones (2–25 kg);
- Tactical UAVs (25–150 kg);
- Medium Altitude Long Endurance (MALE) systems;
- High Altitude Long Endurance (HALE) systems [5].

c) Operational control:

- Remotely piloted;
- Automated waypoint navigation;
- Semi-autonomous mission systems;
- Fully autonomous AI-enabled systems.

This classification demonstrates the exceptional diversity of the drone sector. Platforms may range from palm-sized indoor reconnaissance drones to strategic aircraft with wingspans exceeding those of regional manned airplanes.

1.3 Objectives and methodology.

The principal objective of this paper is to provide a scientific overview of the present condition of the drone industry and to identify major technological and operational trends shaping future developments.

The study investigates both civil and military UAV applications because the two sectors are increasingly interconnected through dual-use technologies such as sensors, propulsion systems, autonomy software and communication networks.

The specific research objectives are:

- to examine the current global status of the UAV market and industry;
- to classify major drone categories and compare operational capabilities;
- to assess the influence of science, propulsion and energy storage on performance;
- to analyze the role of AI in navigation, perception and autonomous decision;
- to identify future trends.

The methodology used in this paper is based on a structured review of scientific literature, aerospace industry reports, regulatory publications, defense assessments and manufacturer technical documentation. Data sources include ICAO, EASA, FAA, studies, journals and market analyses [4], [6], [7]. Comparative evaluations are conducted using measurable criteria such as endurance, payload, propulsion type, autonomy level and mission flexibility.

By combining engineering, operational and economic perspectives, this paper aims to provide a realistic and evidence-based assessment of the drone field. Such an approach is necessary because UAV technologies are advancing rapidly and are increasingly influencing both civilian infrastructure and modern military doctrine.

2. CURRENT STATUS OF THE GLOBAL DRONE INDUSTRY

2.1 Market size and economic indicators.

The global drone industry has transitioned from an emerging niche market into a major aerospace and technology sector with an important annual growth. This expansion is driven by falling component costs, increasing autonomy, broader commercial adoption and growing military demand. According to market analyses published in recent years, the global unmanned aerial vehicle market has been valued in the tens of billions of U.S. dollars, with projected compound annual growth rates commonly exceeding 10% over the present decade [8], [9].

The civil drone segment has become particularly dynamic due to applications in precision agriculture, topographic surveying, logistics, infrastructure inspection, mining, insurance assessment and emergency services. Commercial multirotor drones dominate unit sales because of their relatively low cost, ease of operation and modular payload capability. In contrast, fixed-wing and hybrid systems occupy smaller but higher-value segments requiring longer endurance and wider operational range [10].

Military expenditure remains one of the largest contributors to total market value. Defense procurement focuses on tactical reconnaissance systems, loitering munitions, maritime drones, MALE (Medium Altitude Long Endurance) aircraft and increasingly autonomous collaborative combat platforms. Recent conflicts have demonstrated the operational relevance of low-cost drones as well as larger strategic systems, accelerating procurement cycles in many countries [11].

From an industrial perspective, the drone economy also includes software development, sensor manufacturing, data analytics, maintenance services, operator training, cybersecurity and traffic management systems. Therefore, the total economic footprint of the drone sector extends well beyond aircraft manufacturing alone.

2.2 Main producing regions and industrial leaders.

Drone production is geographically concentrated in several major industrial regions: North America, Europe, East Asia and increasingly the Middle East.

Each region demonstrates different strengths based on regulatory environment, defense budgets, manufacturing capacity and technological specialization.

The United States remains one of the global leaders in military UAV development, with systems such as the MQ-9 Reaper, RQ-4 Global Hawk and numerous tactical platforms developed by companies including General Atomics, Northrop Grumman, AeroVironment and Anduril Industries [5]. The U.S. market is also relevant in software, autonomy, sensors and defense-oriented startup innovation.

China has become dominant in the consumer and prosumer civil drone market, especially through DJI, which established a leading global share in camera-equipped multirotor systems. Chinese industry also develops larger surveillance and strike UAVs for domestic use and export [13].

Europe maintains an important position in regulation, industrial quality standards and collaborative aerospace programs. Companies such as Airbus, Leonardo, Thales and Saab participate in tactical UAV production, counter-UAS technologies and future MALE drone initiatives such as Eurodrone [14].

Israel remains influential in tactical and surveillance UAVs, having pioneered many operational concepts since the late twentieth century. Israeli Aerospace Industries (IAI) and Elbit Systems continue to export advanced reconnaissance systems worldwide [15].

Türkiye has emerged as a major producer through Baykar and Turkish Aerospace Industries, especially with the global visibility of the Bayraktar TB2 and Akinci platforms. This demonstrates the increasing diversification of the global UAV base.

2.3 Regulatory environment and airspace integration.

One of the most significant limiting factors for civil drone expansion is not hardware capability, but regulatory integration into shared airspace. Traditional aviation regulations were designed for manned aircraft; therefore, UAV operations require new frameworks covering certification, pilot competence, operational risk, communication reliability, detect-and-avoid capability and cybersecurity.

The European Union Aviation Safety Agency (EASA) introduced a risk-based framework dividing operations into Open, Specific and Certified categories depending on mass, operational complexity and proximity to people [16]. This approach has become internationally influential because it allows proportional regulation according to operational risk.

In the United States, the Federal Aviation Administration (FAA) regulates civil drones primarily through Part 107 rules for small UAV operations. Additional waivers and certifications are required for beyond-visual-line-of-sight (BVLOS), night operations, flights over people and larger commercial missions [17].

Globally, current regulatory priorities include integration of drones into controlled airspace, remote identification and digital registration, UTM (Unmanned Traffic Management) systems, certification of autonomous systems, urban air mobility interfaces, protection of privacy and data security.

Progress in regulation is essential because many high-value commercial applications, especially logistics and long-range inspection, depend on routine BVLOS authorization.

2.4 Civil vs military market segmentation.

Although civil and military drones share many technologies, their market structures differ substantially.

The civil market is characterized by high unit volume, lower average platform cost and rapid replacement cycles. Major customers include agricultural operators, utility companies, engineering firms, media organizations, police agencies and logistics providers. Typical priorities are affordability, ease of use, camera quality, mapping precision, safety and regulatory compliance [10].

The military market is lower in unit volume but significantly higher in system value due to mission payloads, secure communications, survivability requirements, encryption, electronic warfare resistance and weapon integration. Military procurement often involves multi-year acquisition programs with substantial lifecycle support contracts [11].

An important modern trend is the growth of the dual-use segment, where civil technologies such as commercial imaging sensors, AI navigation, lithium batteries and low-cost manufacturing are adapted for defense purposes. At the same time, military innovations such as resilient datalinks and advanced autonomy increasingly transfer into civil markets.

This convergence suggests that future market leadership will depend not only on aircraft design, but also on software ecosystems, secure connectivity, manufacturing scalability and compliance with evolving international regulations.

3. TECHNICAL CLASSIFICATION OF AERONAUTICAL DRONES

3.1 Fixed-wing UAVs.

Fixed-wing unmanned aerial vehicles represent one of the most mature and aerodynamically efficient categories of drones. Their configuration is based on conventional aircraft principles, where lift is generated by a stationary wing and propulsion is provided by propellers, turboprops or jet engines. Compared with rotary-wing systems, fixed-wing UAVs generally offer superior endurance, higher cruise speed, longer operational range and improved payload efficiency [5].

These characteristics make fixed-wing drones suitable for long-duration missions such as border surveillance, environmental monitoring, cartographic mapping, maritime patrol and military intelligence, surveillance and reconnaissance (ISR).

Examples include small hand-launched reconnaissance UAVs, tactical battlefield systems and strategic MALE/HALE platforms such as the MQ-9 Reaper and RQ-4 Global Hawk [5].

The main operational limitation of fixed-wing UAVs is the requirement for launch and recovery infrastructure. Small systems may use catapults or net recovery, while larger aircraft require conventional runways. This limitation has stimulated the development of hybrid vertical takeoff systems combining fixed-wing cruise efficiency with VTOL capability.

3.2 Rotary-wing UAVs

Rotary-wing drones generate lift through rotating blades and are divided mainly into single-rotor helicopters and multirotor systems such as quadcopters, hexacopters and octocopters. This category has become dominant in the civil market due to mechanical simplicity, vertical takeoff and landing capability, hovering performance and precise low-speed maneuverability [13].

Multirotor UAVs are widely used for aerial photography, infrastructure inspection, agriculture spraying, emergency response, police surveillance and parcel delivery trials. Their ability to operate in confined urban environments and without runway infrastructure gives them major operational advantages [10].

Military rotary-wing unmanned aerial vehicles are used for tactical reconnaissance, naval deck operations, logistics resupply and target designation. Some advanced systems are also designed for autonomous cargo transport or optionally piloted missions. However, rotary-wing UAVs are generally less energy efficient than fixed-wing aircraft because continuous power is required to maintain lift. Consequently, endurance is often limited by battery capacity in electric platforms or fuel consumption in larger systems [18].

3.3 Hybrid VTOL platforms.

Hybrid vertical takeoff and landing (VTOL) drones combine characteristics of fixed-wing and rotary-wing. They are designed to take off and land vertically while transitioning into forward fixed-wing flight for cruise. This concept has become increasingly important for missions requiring runway independence together with long range and endurance. Several engineering architectures exist, such as: tilt-rotor systems, tilt-wing aircraft, tail-sitter configurations and fixed-wing aircraft with separate lift rotors.

Hybrid VTOL UAVs are attractive for mapping, offshore logistics, pipeline inspection, military resupply and remote-area operations where runway access is unavailable [19]. They also play an important role in future urban air mobility and autonomous cargo concepts.

Despite their advantages, hybrid systems involve greater structural and control complexity than conventional configurations. Transition flight phases require sophisticated flight control algorithms, redundant sensors and careful aerodynamic design to ensure stability and reliability.

3.4 Nano, micro, tactical, MALE and HALE systems

Drone classification by size, altitude and mission scale is widely used in both industry and defense planning.

Nano and micro drones are very small systems, often weighing from a few grams to several kilograms. They are used for indoor reconnaissance, close-range inspection, search-and-rescue support and tactical urban surveillance. Their compact dimensions allow operation in confined spaces and low visual detectability [20].

Small and tactical drones are commonly used by military units, police forces and industrial operators. They typically provide ranges from several kilometers to more than 100 km depending on propulsion type and communication link. Tactical UAVs are frequently employed for battlefield reconnaissance, artillery spotting, infrastructure patrol and agricultural survey [5].

Medium Altitude Long Endurance (MALE) UAVs operate at medium altitudes for long mission durations, often exceeding 24 hours. These systems can carry radar, electro-optical sensors, communication relays and weapon payloads. The MQ-9 Reaper and Bayraktar Akinci are representative examples [5].

High Altitude Long Endurance (HALE) drones operate in the upper atmosphere for strategic surveillance, communications relay and persistent intelligence missions. Their endurance may extend beyond 30 hours, with very large wingspans and advanced propulsion systems. HALE UAVs are increasingly viewed as complements to satellites for regional persistent observation [21]. The diversity of these categories shows that modern drones are not a single technology class, but a broad family of aerospace systems optimized for different operational environments.

3.5 Comparative engineering considerations.

From an engineering perspective, no single drone configuration is universally optimal. Selection depends on mission priorities:

- endurance and range: fixed-wing or hybrid VTOL;
- hovering and close inspection: rotary-wing;
- confined-space reconnaissance: nano/micro drones;
- persistent strategic surveillance: MALE or HALE systems;
- rapid tactical deployment: portable small UAVs.

Future trends suggest increasing modularity, AI-assisted flight management, electric-hybrid propulsion and adaptive airframes capable of multi-role conversion. As materials and autonomy continue to improve, boundaries between current UAV classes may progressively diminish.

4. COMPARATIVE ANALYSIS OF DRONES

4.1 Civil commercial platforms currently available.

The civil commercial drone market is presently dominated by multirotor and hybrid VTOL platforms optimized for imaging, surveying, inspection, agriculture and industrial monitoring.

Due to low operating cost, portability and user-friendly control systems, multirotor drones have achieved the highest commercial adoption rates worldwide [13].

Among small professional systems, the DJI Mavic and Matrice series are widely used in aerial photography, mapping and infrastructure inspection. These aircraft integrate stabilized optical payloads, GNSS navigation, obstacle avoidance sensors and autonomous mission planning software. Their endurance typically ranges from 30 to 55 minutes depending on payload and weather conditions [13].

In the surveying and photogrammetry sector, fixed-wing platforms such as the WingtraOne and senseFly eBee provide superior area coverage compared with multirotors. These systems are optimized for topographic mapping, agricultural analysis and corridor inspection, where long flight lines and efficient cruise performance are required [22].

Agricultural UAVs form another major commercial category. Heavy multirotor spraying drones such as the DJI Agras series are designed for crop treatment, precision spraying and field monitoring. Their economic importance has grown rapidly due to labor shortages and increasing precision-farming requirements [23].

Current civil trends indicate developments toward increased autonomy and route automation, AI-based image interpretation, BVLOS operations, fleet management systems, improved battery endurance and integration into digital logistics networks.

4.2 Military systems in operational service.

Military drones now represent one of the most strategically significant aerospace categories. Operational systems vary from hand-launched reconnaissance UAVs to armed MALE and HALE aircraft capable of persistent surveillance and strike missions.

The Bayraktar TB2 gained international visibility due to operational use in multiple conflicts. It combines moderate cost, long endurance, electro-optical targeting capability and guided munition integration [24].

The MQ-9 Reaper, developed in the United States, remains one of the most recognized MALE combat UAVs. It is capable of ISR, strike and long-endurance missions, carrying advanced sensors and significant payload capacity [5].

The RQ-4 Global Hawk is a HALE surveillance platform designed for strategic intelligence collection over very long ranges and altitudes [21].

Loitering munitions such as the Israeli Harop and various tactical expendable drones have introduced a new category combining reconnaissance with one-way precision strike capability [26].

Current military trends include swarm-enabled tactical drones, electronic warfare resistant navigation, AI-supported target recognition, low-cost systems, manned-unmanned teaming, maritime unmanned aviation.

4.3 Prototypes and programs under development.

The next generation of drones is focused less on basic flight capability and more on autonomy, survivability, networking and cooperative mission behavior.

The Eurodrone program aims to provide a European MALE platform with sovereign industrial capability and certified airspace integration [14].

The U.S. Collaborative Combat Aircraft (CCA) concept explores semi-autonomous loyal wingman drones designed to operate alongside crewed fighters [27].

Türkiye’s Kızılelma program demonstrates the trend toward high-speed unmanned combat aircraft with carrier and expeditionary capability [28].

Civil industry prototypes include cargo drones for regional freight transport, autonomous emergency medical delivery aircraft and urban air mobility vehicles with distributed electric propulsion.

Future development priorities include autonomous swarm coordination, Edge AI computing onboard the aircraft, hybrid-electric propulsion, reduced radar/acoustic signatures, resilient GNSS-denied navigation, full digital fleet management ecosystems.

4.4 Comparative assessment: range, payload, cost, endurance, autonomy.

A comparative engineering evaluation of representative drone systems shows direct relationships between cost, mission capability and platform size. Small commercial drones provide low-cost local capability, whereas MALE and HALE systems offer strategic endurance at exponentially greater acquisition cost.

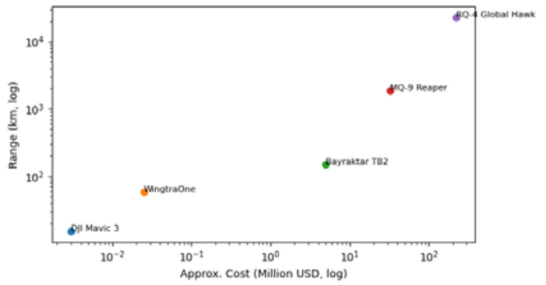
Key Observations:

- Range vs Cost: long-range systems require disproportionately higher investment due to propulsion, communication and certification complexity.
- Payload vs Cost: payload capacity generally increases with airframe size and power system sophistication.
- Size vs Payload: wingspan and structural volume correlate with payload potential.
- Range vs Endurance: endurance depends not only on fuel capacity but aerodynamic efficiency and mission profile.

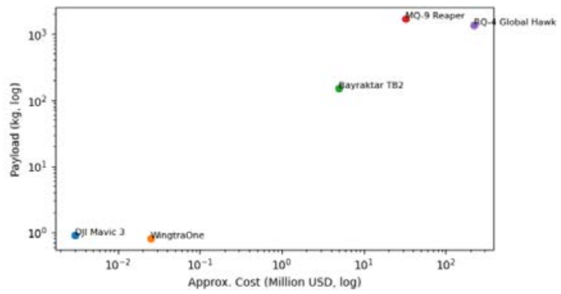
The FIG. 1 (a) to (d) below are containing representative approximate values from open-source manufacturer and defense publications and present a comparative assessment of Range, Payload, Cost, Endurance and Autonomy.

As observed in these graphs, small rotary-wing civil drones such as the DJI Mavic series optimize affordability and portability but remain constrained by battery endurance. Survey UAVs such as WingtraOne increase range efficiently through fixed-wing cruise.

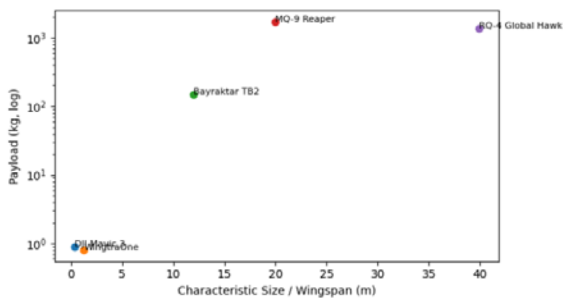
Tactical military systems such as Bayraktar TB2 provide a major jump in endurance and payload while remaining below the cost of strategic UAVs.



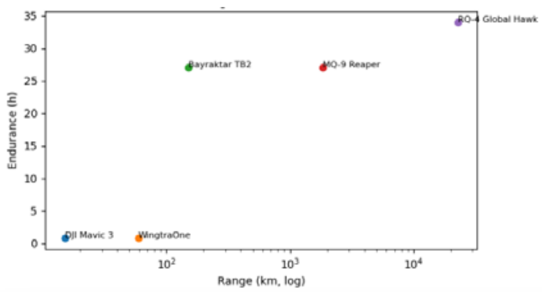
(a) Range versus Cost



(b) Payload versus Cost



(c) Size versus Payload



(d) Range versus Endurance

FIG. 1 Comparative Assessment: Range, Payload, Cost, Endurance, Autonomy

Strategic systems such as MQ-9 Reaper and RQ-4 Global Hawk demonstrate that mission persistence, sensor payload, secure datalinks and global deployment capability generate steep cost escalation. This indicates that future disruptive value may come from autonomous mid-cost systems capable of swarm cooperation rather than simply larger and more expensive aircraft.

5. MATERIALS, STRUCTURES AND MANUFACTURING TECHNOLOGIES

5.1 Composite materials and lightweight alloys.

Structural materials are among the most critical determinants of drone performance because mass directly influences endurance, payload fraction, maneuverability and operational cost. UAV airframes must simultaneously satisfy low weight, adequate stiffness, fatigue resistance, manufacturability, corrosion resistance and acceptable lifecycle cost. For this reason, modern aeronautical drones increasingly employ advanced composites, aluminum alloys, titanium components, engineering polymers and hybrid multi-material architectures [29].

Small commercial drones commonly use polymer-composite shells reinforced with localized metallic inserts. Tactical and medium-class UAVs frequently adopt carbon-fiber reinforced polymer (CFRP) skins and sandwich panels. Larger MALE and HALE platforms combine composite structures with metallic load-bearing joints, landing gear attachments, engine mounts and maintenance-critical interfaces [30].

The principal engineering advantages of composites include: high specific strength (strength-to-weight ratio), high specific stiffness, corrosion resistance, reduced part count through integrated molding, tailorable anisotropic properties and lower radar reflectivity in some military applications.

However, composites also present challenges including impact sensitivity, delamination risk, more complex repair procedures and higher raw material cost compared with conventional aluminum alloys [31].

Table 1. Typical Structural Material Comparison for UAV Airframes

Material	**Density (kg/m^3)**	**Allowable Stress (MPa)***	**Relative Material Cost****	**Typical UAV Applications**
CFRP Laminate	1500–1650	300–900	Very High	Wings, fuselage shells, control surfaces
GFRP Laminate	1800–2000	150–450	Medium	Radomes, fairings, low-cost structures
Aluminum 2024-T3	2780	180–320	Medium	Frames, brackets, skins
Aluminum 7075-T6	2810	250–500	Medium-High	Highly loaded fittings, arms
Titanium Ti-6Al-4V	4430	600–950	Very High	Engine mounts, joints, landing gear parts
ABS / Nylon Polymers	1020–1150	30–80	Low	Covers, housings, printed parts

* Typical engineering allowable range depending on design method orientation, safety factor, manufacturing quality and environment.

** Relative raw material and processing cost.

Table 1 presents a typical structural material comparison for the UAV Airframes. As observed, the relatively low density and high resistance materials are used for the structural components, but cost is also an important factor.

Table 2 presents a material comparison for the specific strength (ratio between allowable tensile strength and density). Higher values for specific strength are more desirable.

Table 2. Specific Strength Indicator

Material	Tensile Strength (MPa)	Density (kg/m^3)	Strength / Density
CFRP (high-grade)	800	1600	0.5
Aluminum 7075-T6	570	2810	0.2
Titanium Ti-6Al-4V	900	4430	0.2
GFRP	350	1900	0.18

These values explain why CFRP remains attractive for endurance-critical UAV structures. For a given required stiffness or strength, a lighter airframe permits greater battery mass or fuel load, directly improving mission performance.

5.2 Additive manufacturing and rapid prototyping.

Additive manufacturing (AM), commonly known as 3D printing, has become influential in UAV development because it reduces prototype lead time, tooling cost and design iteration cycles. Components can be rapidly produced in polymers, reinforced thermoplastics and selected metallic powders for experimental or low-volume production [32], [12].

Typical UAV applications include sensor housings, aerodynamic fairings, cable routing components, cooling ducts, lightweight lattice brackets and custom payload adapters.

For startups and research laboratories, additive manufacturing enables rapid testing of alternative wing geometries, propeller guards, antenna mounts and modular payload bays. In military contexts, field-deployable printing may also support spare-part resilience.

Limitations remain in surface finish quality, repeatability, anisotropic strength, fatigue performance and certification for critical flight hardware. Nevertheless, AM is increasingly integrated into conventional aerospace production chains rather than replacing them entirely [33].

5.3 Modular design concepts.

Modern drone engineering increasingly favors modular architecture. Instead of designing a platform for one fixed mission, manufacturers create interchangeable subsystems such as payload bays, battery modules, landing gear, propulsion pods, sensor turrets, communication packages and mission computers [34].

The main advantages of modularity include reduced maintenance downtime; faster mission reconfiguration, simplified logistics, upgradeability over lifecycle, lower total ownership cost, easier export customization etc.

For example, the same tactical UAV may be configured for ISR, mapping, electronic surveillance or communication relay by exchanging payload modules rather than replacing the aircraft.

Modularity also supports future autonomy upgrades. As onboard AI processors and navigation sensors evolve rapidly, open-system architecture allows avionics replacement without redesigning the full airframe.

5.4 Survivability and maintainability.

For military drones, survivability includes resistance to detection, weather, battle damage, electronic warfare and navigation disruption. Structural design contributes through reduced radar signature shaping, internal cable routing, redundant flight controls and damage-tolerant materials [35].

Civil survivability focuses more on operational reliability and safety. This includes tolerance to vibration, moisture ingress, dust, repeated landing loads, battery thermal management and fault detection systems.

Maintainability is equally important because lifecycle cost often exceeds acquisition cost. Good maintainability design requires: quick-access avionics bays, replaceable arms or landing gear, standardized fasteners, built-in diagnostics, predictive maintenance using telemetry data and modular battery replacement systems.

As UAV fleets become larger, maintenance digitalization through health monitoring and AI-supported fault prediction is expected to become standard practice.

5.5 Future structural trends.

Future drone structures are likely to adopt:

- thermoplastic composites with faster manufacturing cycles;
- multifunctional materials with embedded sensing;
- morphing wings and adaptive surfaces;
- battery-integrated structural elements;
- self-healing polymers;
- recyclable lightweight composites.

These developments aim to reduce cost while improving endurance, durability and sustainability.

6. PROPULSION AND ENERGY SYSTEMS

6.1 Electric propulsion.

Electric propulsion has become the dominant solution for small and medium civil drones due to its mechanical simplicity, high controllability, low acoustic signature and reduced maintenance requirements. In most multirotor platforms, propulsion is provided by brushless direct-current (BLDC) motors powered by lithium-based battery packs and controlled through electronic speed controllers (ESCs). This configuration offers rapid thrust response, precise stabilization capability and efficient integration with autopilot systems [36].

Electric propulsion is particularly advantageous for rotary-wing UAVs because multiple independently controlled motors permit stable hovering, redundancy and agile maneuvering. For fixed-wing drones, electric systems are increasingly common in small reconnaissance and mapping aircraft where silent operation and low vibration improve payload sensor quality.

The principal benefits of electric propulsion include low mechanical complexity, high torque at low rotational speed, reduced vibration, lower maintenance cost, zero local emissions during operation and good compatibility with autonomous control systems.

However, electric drones remain constrained by battery energy density. While motor efficiency is high, available stored energy per unit mass is substantially lower than hydrocarbon fuels. This limits endurance, especially in heavy-lift or long-range applications [37].

Table 3. Typical Characteristics of UAV Electric Propulsion

Parameter	Small Multirotor	Survey Fixed-Wing	Heavy-Lift UAV
Motor Power (per unit)	100–500 W	500–3000 W	2–20 kW
Efficiency (%)	80–93	85–94	80–92
Typical Endurance	20–45 min	45–120 min	15–40 min
Noise Level	Low	Low	Medium

Table 3 summarizes the typical characteristics of electric propulsion systems across major UAV categories, showing the link between installed power, mission role and endurance. Small multirotor drones use lower-power motors for inspection and short-range tasks, but flight time is limited by the energy required for hovering.

Fixed-wing survey UAVs achieve longer endurance through better aerodynamic efficiency, while heavy-lift drones need much higher power to carry payloads, often reducing flight duration. Overall, the table confirms the high efficiency and controllability of electric propulsion, while showing that energy storage remains the main limitation.

6.2 Hybrid systems.

Hybrid propulsion combines an internal combustion engine (ICE), microturbine or generator set with electric propulsion architecture. Such systems are increasingly attractive because they unite the high energy density of liquid fuels with the controllability of electric motors [30].

In many hybrid UAVs, a combustion engine drives a generator that powers motors and charges onboard batteries. Batteries may supply peak power during takeoff or transient maneuvers, while the fuel-powered generator sustains cruise operation.

Advantages that could be noted: extended endurance compared with battery-only drones, better payload capability, lower fuel consumption than pure ICE systems in some profiles, redundant energy pathways and improved suitability for BVLOS operations.

Hybrid systems are particularly relevant for cargo drones, long-range inspection UAVs, military logistics aircraft and maritime surveillance platforms [38].

The disadvantages include increased system mass, thermal management complexity, acoustic signature, vibration and maintenance burden.

Table 4. Comparison of Energy Sources

Energy Source	Masic Energy Density (Wh/kg approx.)	System Complexity	Typical UAV Use
Li-ion Battery	180–280	Low	Small civil drones
Li-Po Battery	150–260	Low	Racing / multirotor UAVs
Gasoline Fuel	11,000+ (fuel only)	Medium	Long-endurance ICE UAVs
Hybrid Fuel-Electric	Variable	High	Cargo / endurance UAVs
Hydrogen Fuel Cell	700–1500 system-level equivalent*	High	Advanced endurance UAVs

* Depends on storage architecture and balance-of-plant mass.

Table 4 compares the principal energy sources used in UAV propulsion systems in terms of energy density, complexity and typical applications. Batteries remain the preferred solution for small drones because of their simplicity and low maintenance, while gasoline fuels offer much higher energy content and are suitable for long-endurance missions. Hybrid systems combine both advantages but involve greater mechanical complexity. Hydrogen fuel cells represent a promising future option, providing extended endurance with low emissions, although storage, cost and infrastructure challenges still limit widespread implementation.

6.3 Hydrogen fuel cells.

Hydrogen fuel cell propulsion has gained attention as a promising alternative for endurance-critical UAV missions. Fuel cells convert hydrogen and oxygen electrochemically into electricity, producing water as the primary by-product. Compared with batteries, fuel-cell systems can offer significantly higher endurance for equivalent mass in selected mission classes [39].

Hydrogen-powered drones are used for: long-duration mapping, border surveillance, scientific atmospheric monitoring, maritime patrol and communication relay missions.

Key advantages include low noise, reduced vibration and reduced emissions. But widespread adoption is limited by hydrogen storage challenges, infrastructure requirements, certification complexity and cost of proton exchange membrane systems [40]. Compressed gas tanks, cryogenic storage and chemical carriers are all under active development. For many UAV categories, the engineering challenge lies not in fuel-cell stack performance alone, but in achieving a practical total system mass and robust field logistics.

6.4 Solar-powered long-endurance UAVs.

Solar-powered UAVs represent one of the most advanced endurance concepts in unmanned aviation. These aircraft typically use large, lightweight high-aspect-ratio wings covered with photovoltaic cells that recharge onboard batteries during daylight and sustain night operation through stored energy [41].

Such platforms are often positioned between conventional aircraft and satellites, functioning as High Altitude Pseudo-Satellites (HAPS). Potential applications include: persistent regional communications, earth observation, environmental monitoring, border surveillance or disaster connectivity restoration. Notable demonstrators include Airbus Zephyr and other ultra-light stratospheric platforms. Their endurance can extend from weeks to months under favorable environmental conditions.

The main limitations are: low payload capacity, dependence on solar flux and weather, complex lightweight structures, high sensitivity to atmospheric turbulence during climb/descent, expensive development cycles.

6.5 Propulsion selection vs mission requirements.

Propulsion architecture must be matched to operational need rather than chosen solely by technological novelty.

Table 5. Recommended Propulsion by Mission Type

Mission Type	**Preferred Propulsion**
Urban Inspection / Photography	Battery Electric
Agricultural Spraying	Battery Electric / Hybrid
Long Corridor Inspection	Hybrid / Fuel Cell
Tactical Reconnaissance	Electric / Small ICE
Cargo Delivery (Regional)	Hybrid
Strategic Persistent Surveillance	Fuel / Turbine / Solar HAPS

Table 5 presents the recommended propulsion solutions according to mission requirements, showing that no single system is optimal for all UAV applications. Battery-electric propulsion is suitable for short-range urban and inspection missions due to its low noise and simplicity, while hybrid and fuel-cell systems are better adapted to long-range.

The future direction of UAV propulsion is likely to involve multi-source energy systems integrating batteries, hydrogen, solar input, regenerative control strategies and AI-based power management.

6.6 Future trends in UAV energy systems.

Major research trends include:

- solid-state batteries with higher safety and energy density;
- distributed electric propulsion and swappable battery ecosystems;
- AI-optimized energy management;
- hydrogen storage miniaturization;
- sustainable aviation fuels for hybrid UAVs;
- ultra-efficient propellers and variable-pitch electric drives.

These innovations will directly influence future range, autonomy, payload capacity and economic viability of next-generation drones.

7. AUTONOMY, AI AND INTELLIGENT CONTROL

Autonomy and artificial intelligence (AI) are among the most transformative technologies in modern drone systems. While early UAVs relied almost entirely on manual remote piloting, contemporary platforms increasingly perform navigation, stabilization, obstacle avoidance, mission execution, sensor interpretation and cooperative decision-making with minimal human intervention. This transition significantly improves operational efficiency, mission endurance, scalability of fleets and resilience in complex environments [42].

Autonomous capability is especially important in beyond-visual-line-of-sight (BVLOS) operations, swarm missions, contested military environments and repetitive industrial inspection tasks. AI methods now support perception, path planning, predictive maintenance, image recognition and adaptive control.

7.1 Levels of UAV autonomy.

Drone autonomy may be classified into progressive levels depending on the degree of human involvement.

Table 6 illustrates the progressive levels of UAV autonomy, ranging from fully manual remote control to complete mission autonomy. Lower levels still depend heavily on continuous pilot input, while intermediate levels introduce automated navigation and adaptive assistance. Higher autonomy levels enable coordinated fleet behavior and minimal human intervention, where operators mainly supervise mission objectives rather than direct flight control.

Table 6. Typical Levels of UAV Autonomy

Level	Description	Human Role
0	Manual remote control	Continuous piloting
1	Stabilized flight / assisted modes	Pilot supervises
2	Automated waypoint navigation	Mission setup
3	Adaptive autonomy	Human supervises decisions
4	Cooperative semi-autonomous fleet	Human commands intent
5	Full mission autonomy	Human-on-the-loop

Most commercial drones currently operate between Levels 1 and 3, whereas advanced defense programs increasingly target Levels 4 and 5 [43].

7.2 Flight control and guidance laws.

At the foundation of autonomy lies flight control. UAVs continuously regulate attitude, altitude, velocity and position using onboard sensors and control loops.

The proportional-integral-derivative (PID) control remains common in small UAV autopilots due to simplicity and robustness. More advanced systems employ Model Predictive Control (MPC), adaptive control, nonlinear control, reinforcement learning control, fault-tolerant control systems [44].

Table 7. Common UAV Control Methods

Method	Advantages	Limitations
PID	Simple, proven, low computation	Limited in nonlinear dynamics
LQR	Optimal linear control	Requires model accuracy
MPC	Constraint handling	High computation load
Adaptive Control	Handles uncertainty	More complex tuning
Reinforcement Learning	Learns complex behavior	Certification challenges

Table 7 compares the main control methods used in UAV systems, highlighting the trade-off between simplicity, performance and computational demand. PID controllers remain widely used because they are reliable and easy to implement, while LQR and MPC methods provide improved optimization and constraint handling for more advanced missions. Adaptive and reinforcement learning approaches offer greater capability in uncertain or complex environments, although they require higher processing power and more challenging validation procedures.

7.3 Computer vision and perception.

Computer vision has become one of the most valuable AI domains for drones. Cameras, infrared sensors, LiDAR and radar can be processed onboard to identify objects, terrain, obstacles and mission targets.

Applications include precision landing, power-line inspection, crop stress detection, vehicle/person detection, search and rescue and autonomous navigation in GNSS-denied environments.

Typical convolutional neural network (CNN) systems detect targets in real time using edge processors [45].

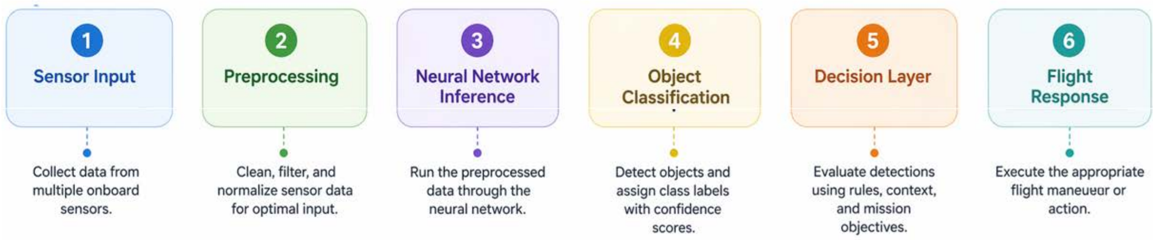


FIG. 2 Typical AI Perception Chain (AI generated based on the chain flowchart)

Figure 2 illustrates the typical AI perception chain used in autonomous UAV systems, where raw sensor data is progressively transformed into actionable flight decisions. Information acquired from cameras, LiDAR, radar or other sensors is first preprocessed, then analyzed through neural-network inference for object detection or classification.

The resulting outputs are evaluated by the decision layer, which generates navigation or control responses, enabling the drone to react intelligently to its environment in real time.

Table 8. Sensors Used for UAV Perception

Sensor	Strengths	Limitations
RGB Camera	Low cost, rich imagery	Sensitive to lighting
Thermal Camera	Night / heat detection	Lower resolution
LiDAR	Accurate 3D mapping	Expensive, heavier
Radar	Works in fog/rain	Lower image detail
IMU/GNSS	Navigation reference	GNSS vulnerable to jamming

Table 8 summarizes the principal sensors used for UAV perception and autonomous navigation, showing that each technology offers specific advantages and limitations. Cameras provide rich visual information at low cost, thermal sensors are effective in low-visibility and search missions, LiDAR enables accurate three-dimensional mapping and radar performs reliably in adverse weather. In practice, modern drones increasingly combine several sensors through data fusion in order to improve robustness, accuracy and situational awareness.

7.4 Autonomous navigation and path planning.

Navigation systems combine inertial sensors, GNSS, magnetometers, barometers, terrain maps and AI estimators. A common challenge is route optimization subject to fuel, weather, risk and obstacle constraints.

Modern algorithms include:
- A* search,
- rapidly Exploring Random Trees (RRT),
- genetic algorithms,
- swarm intelligence,
- deep reinforcement learning [46].

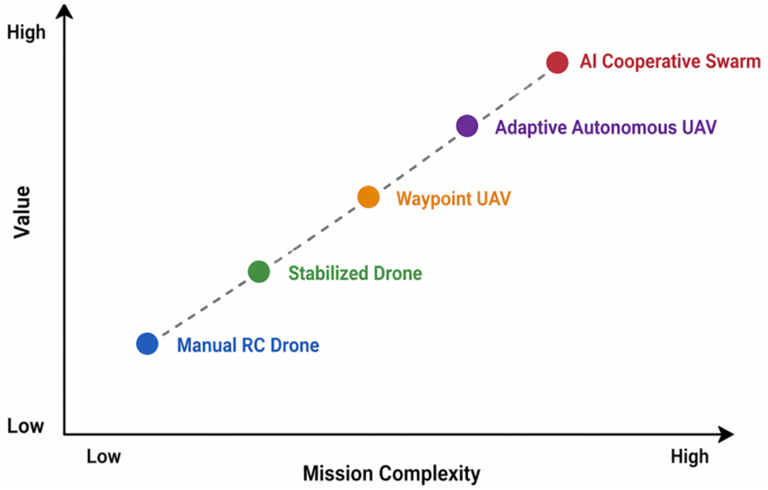


FIG. 3 Autonomy Benefit vs Mission Complexity

Figure 3 shows the relationship between mission complexity and the value of different levels of UAV autonomy. On the horizontal axis, mission complexity increases from low to high, while the vertical axis represents the corresponding autonomy benefit or operational value. With lower complexity, manual RC drones and stabilized drones provide sufficient capability, where human control or basic stabilization is adequate.

As complexity increases, waypoint-based UAVs offer improved efficiency through pre-defined navigation, reducing operator workload. In more demanding environments, adaptive autonomous UAVs provide higher value by dynamically responding to changing conditions and partially independent decision-making. At the highest level of mission complexity, AI cooperative swarm systems deliver the greatest benefit by enabling coordinated multi-agent behavior, scalability and resilience, demonstrating that increased autonomy becomes more advantageous as operational complexity grows.

7.5 Swarm intelligence.

Swarming refers to coordinated behavior among multiple drones sharing tasks, sensing, communication and adaptive decisions. Instead of relying on one expensive platform, a swarm distributes risk and function across many smaller systems.

Applications are possible in a multitude of fields like: area surveillance, search patterns, communication relays, saturation attack missions, environmental mapping, cooperative logistics.

The shift toward Swarm Intelligence (SI) in aerial robotics is driven by the principle of graceful degradation. Unlike a single large UAV, which possesses a concentrated vulnerability profile, a swarm maintains operational integrity even when individual units are neutralized. This makes swarms particularly effective in "contested environments" where the probability of attrition is high.

However, as can be observed from Table 9, the advantages of swarms come at the cost of computational and communication overhead. To function effectively, swarms demand high-bandwidth coordination and sophisticated collision-avoidance algorithms.

Conversely, the single large UAV remains the gold standard for missions requiring heavy lifting or long-distance transport, where the physics of scale favor a larger, more aerodynamically efficient airframe over a collection of smaller ones.

Swarm control remains a major research area due to communication latency, deconfliction and ethical concerns [25].

Table 9. Swarm vs Single Large UAV

Parameter	Swarm Fleet	Single Large UAV
Redundancy	High	Low
Cost per Unit	Low	High
Persistence	High	Medium
Coordination Need	High	Low
Vulnerability	Distributed	Concentrated

7.6 Human-machine teaming.

The most realistic near-term future is not total human replacement, but human-machine teaming. In this concept, operators provide mission intent, rules of engagement, priorities and supervision, while drones execute lower-level tasks autonomously.

Examples could include: one operator supervising many drones, fighter aircraft controlling loyal wingman UAVs, emergency responders directing autonomous search drones, logistics managers assigning routes to delivery fleets.

7.7 Reliability, ethics and certification.

Despite rapid progress, AI integration raises critical engineering and societal questions as: explainability of decisions, false target recognition, cybersecurity vulnerability, adversarial sensor deception, civil privacy concerns or responsibility in lethal military decisions.

For certified civil aviation, regulators require deterministic safety evidence. This remains difficult for self-learning adaptive systems [16].

Table 10. Main Risks of AI UAV Systems

Risk	Impact
Dataset bias	Wrong decisions
GNSS spoofing	Navigation failure
Cyberattack	Loss of control
Sensor occlusion	Collision risk
Over-trust by operators	Human error

Table 10 summarizes the principal risks associated with the integration of artificial intelligence in UAV systems and their operational consequences. Errors in training data or dataset bias may lead to incorrect recognition and unsafe autonomous decisions, especially in complex environments. External threats such as GNSS spoofing and cyberattacks can compromise navigation accuracy or even result in complete loss of control. Physical limitations, including sensor occlusion caused by weather, obstacles or poor visibility, increase the probability of collision or mission failure. In addition, excessive operator confidence in autonomous functions may reduce human supervision, creating new forms of human-machine error.

7.8 Future trends.

The next decade is expected to bring: edge AI processors with low power demand, fully autonomous inspection fleets, resilient GNSS-free navigation, real-time language command interfaces, large-scale drone traffic management, loyal wingman combat systems, self-healing distributed swarm networks.

Autonomy will likely become the primary differentiator between drone manufacturers, even more than airframe hardware.

12. CONCLUSIONS AND REMARKS

The rapid expansion of unmanned aerial vehicles has established drones as one of the most dynamic sectors of modern aerospace engineering. Continuous advances in airframe design, lightweight materials, manufacturing technologies and system integration have enabled the development of platforms capable of addressing an increasingly diverse range of civil and military applications. At the same time, the global UAV market continues to evolve through sustained industrial investment, expanding regulatory frameworks and broader operational adoption [8], [9], [16].

The analysis presented in this paper demonstrates that the diversity of existing UAV configurations reflects the wide variety of mission requirements rather than the existence of a universally optimal design. Fixed-wing, rotary-wing and hybrid VTOL platforms each offer distinct engineering advantages depending on operational priorities such as endurance, payload capacity, maneuverability and deployment flexibility [5], [19]. The comparative assessment of representative commercial and military systems further illustrates the close relationship between aircraft configuration, mission capability and overall system complexity, while highlighting the growing diversification of both civil and defense UAV markets [10], [11].

The review also emphasizes the increasing role of advanced structural materials and modern manufacturing technologies in improving UAV performance. Composite materials, lightweight alloys, additive manufacturing and modular design concepts contribute to lower structural mass, improved maintainability and greater design flexibility while supporting shorter development cycles and more efficient production processes [29]–[34].

Overall, current developments indicate that future progress in unmanned aviation will continue to rely on the combination of innovative structural solutions, efficient manufacturing methods and mission-oriented platform design. As UAV applications continue to expand across industrial, scientific and defense sectors, further advances in materials engineering, modular architectures and production technologies are expected to strengthen the capabilities and versatility of next-generation UAV [30], [32], [34].

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