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Review

Unmanned Aerial Vehicles in Future Transportation Systems: An Overview

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Abstract: Unmanned aerial vehicles (UAVs) are transforming modern transportation systems, with applications in last-mile delivery, urban air mobility (UAM), traffic monitoring, infrastructure inspection, and integration with intelligent transportation systems (ITS). This paper provides an overview of UAV technologies, describing various UAV configurations, alongside advancements in autonomous flight optimization, sense-and-avoid technology, real-time data transmission, and cooperative navigation. The integration of machine learning (ML) also enhances UAV capabilities, particularly in autonomous flight, collision avoidance, and data analytics, enabling efficient trajectory planning and adaptive response in dynamic environments. Case studies in transportation, infrastructure maintenance, and logistics demonstrate the practical impact and interdisciplinary nature of UAV applications. The paper also addresses cybersecurity challenges, proposing engineering strategies for system resilience. Furthermore, future directions emphasize potential integrations with ITS, smart grids, smart cities enabled by IoT, and sustainable materials, offering a comprehensive view of the transformative role of UAVs in transportation systems and underscoring the technological, ML-driven, logistical and regulatory considerations necessary for their broader adoption.

Keywords: UAV traffic monitoring; last-mile delivery; machine learning in UAVs; UAV cybersecurity; intelligent transportation system (ITS); UAV infrastructure inspection

1. Introduction

The UAV market has experienced rapid global growth, with projected figures exceeding $91 billion in 2033 [1]. UAVs are gaining prominence due to their portability, versatility, low operational cost, and their ability to be rapidly deployed in areas where aerial coverage or communications are needed [2,3]. These attributes lead to the growth in the usage of UAVs in different sectors, and hence to the increased growth of UAV manufacturing companies. UAVs have the potential to address most pressing challenges facing modern transportation systems, including:

- Traffic congestion: All cities in the world are faced with increasingly serious road congestion problems, which lead to waste of time, pollution and economic losses.
- Safety concerns: Road accidents represent a severe public health problem, affecting millions yearly.
- Inefficient infrastructure management:Traditional methods of inspecting and maintaining facilities over time are costly and often pose a safety risk to employees.
- Limited accessibility: In areas recovered or affected by disasters, traditional transport can be difficult, aiding emergency interventions and preventing access to basic services.

UAVs possess distinctive capabilities such as vertical takeoff and landing (VTOL), autonomous navigation, and real-time data acquisition qualities that enable their integration into next-generation transportation systems. The consumer sector accounts for around 17% of UAV usage, and the commercial sector accounts for 13% [4]. UAVs have a long lifespan, often surpassing ten years, with low maintenance requirements [5]. Over the past two decades, technological advancements in batteries, sensor miniaturization, and autonomous control algorithms have significantly improved UAV functionality [6,7]. Modern UAVs now support extended range, higher payload capacity, and increased autonomy, laying the foundation for advanced applications across the transportation domain. These have laid the foundation for UAV research and incorporation of all the transportation usages.

UAVs have transformed delivery services by offering fast, efficient, and environmentally friendly alternatives to traditional ground-based logistics. They help overcome traffic congestion and reach remote areas, providing faster and more flexible last-mile deliveries [8,9]. This capability is particularly valuable in sectors like e-commerce, healthcare, and emergency services, where time-sensitive deliveries are critical. With advancements in payload capacity and autonomous navigation, UAVs are becoming essential to logistics networks, offering scalable solutions for both urban and rural environments [10]. In parallel, urban air mobility (UAM) envisions using the electrically powered vertical takeoff and landing (eVTOL) aircraft for point-to-point air transport within urban environments. UAM aims to reduce ground traffic congestion, shorten travel times, and improve urban mobility by integrating aerial transportation into city networks. UAVs play a key role in this emerging field, offering fast, sustainable transportation solutions for both passengers and cargo. Using autonomous flight technology, UAM has the potential to transform urban landscapes, creating a new dimension of mobility for efficient on-demand transportation services [11,12].

UAVs have also changed the way infrastructure inspections are conducted, offering a safer, faster, and more accurate method for assessing the condition of roads, bridges, tunnels, and other critical structures. High-resolution imaging and sensing allow early detection of structural issues such as cracks and corrosion even in hard-to-reach areas [13]. This reduces the cost and risk associated with traditional inspection methods, while improving the efficiency of maintenance operations. This enhances infrastructure safety and longevity by supporting timely interventions, helping authorities prioritize repair efforts. Additionally, UAVs are increasingly used for traffic monitoring and management, offering real-time aerial surveillance of road networks, traffic flow, and congestion patterns. Equipped with advanced sensors and cameras, they enable optimized signal control, safer road conditions, and reduced congestion. These capabilities are central to smart city initiatives, where UAVs integrate with intelligent transportation systems (ITS) to support dynamic traffic planning. When combined with ML approaches, UAVs enhance situational awareness and decision-making in urban mobility systems [14,15]. Table 1 illustrates some examples of ML applications for UAVs in transportation.

Table 1. Examples of machine learning applications for UAVs in transportation.

Application	Description
Delivery Route Optimization [16]	Optimize flight paths for UAV deliveries
Predictive Maintenance for UAVs [17]	Predict potential maintenance needs
Real-time Traffic Flow Prediction [18]	Predict traffic patterns and congestion

Furthermore, as UAVs are embedded morre in transportation networks, their connectivity also exposes them to cybersecurity risks. Cybersecurity has become a critical concern, as malicious actors can exploit vulnerabilities in UAV communication systems, navigation, and software. Attacks such as GPS spoofing, signal jamming, and data breaches can disrupt UAV operations, leading to compromised missions and security risks. ML and Blockchain technologies are being employed to enhance UAV security, providing real-time threat detection and secure data transmission. Ensuring robust cybersecurity measures is essential to safeguarding the future of UAV-enabled transportation systems [19–21].

Unlike prior reviews that often focus on a single UAV application or technology, this paper provides an integrated transportation-systems perspective by linking UAV platform characteristics, enabling technologies, transportation applications, cybersecurity considerations, and future research directions within a unified analytical framework. As illustrated in Figure 1, the framework is organized into four connected layers: UAV platform and operational characteristics, enabling technologies, transportation applications, and deployment challenges. This structure shows how UAV design capabilities such as endurance, payload, sensing, and communication support emerging technologies including ML, autonomous navigation, cooperative operation, and cybersecurity mechanisms. These technologies, in turn, enable transportation functions such as delivery services, UAM, traffic monitoring, infrastructure inspection, and secure UAV operations. The final layer captures deployment constraints, including regulation, public acceptance, energy efficiency, cyber resilience, and integration with ITS and smart-city infrastructure. By connecting these layers, the paper moves beyond a descriptive review and clarifies how technical capabilities translate into transportation-system functions and future research needs.

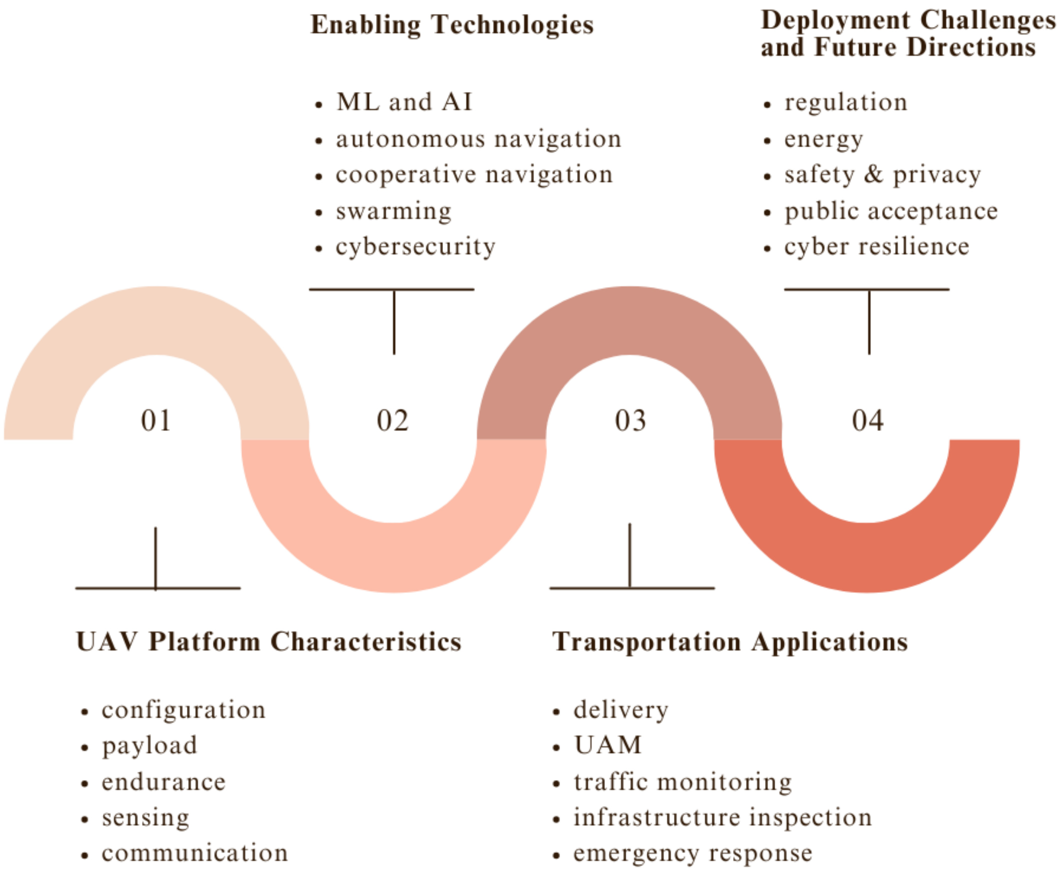

Figure 1. Conceptual framework illustrating the relationship among UAV platform characteristics, enabling technologies, transportation applications, and deployment challenges in UAV-based transportation systems.

This paper is divided into five sections. Section 1 provides an overview of the key points covered in this paper. Section 2 outlines the configurations, characteristics, and current applications of the UAVs. Section 3 covers different aspects of how UAVs are transforming transportation. Furthermore, Section 4 depicts the research directions and novel applications for UAV research for the future of the UAV-based transport system. Finally, Section 5 concludes the work.

2. Technical Background and Recent Developments

This section outlines the foundational aspects of UAV technology, focusing on its historical development, key design configurations, and core technical capabilities relevant to transportation systems. It also highlights emerging challenges such as cybersecurity and emphasizes the growing role of artificial intelligence (AI) and machine learning (ML) in enabling safe, scalable, and efficient UAV operations.

2.1. Historical Evolution of UAV Technology

The concept of UAVs dates back to its debut in the 1900s. The first recorded UAVs were simply captured surveillance balloons used during World War I [22]. The 1930s marked a significant advancement with the introduction of radio control systems, laying the groundwork for more sophisticated UAV platforms. During this period, UAVs began to serve as training tools in military operations, particularly for target practice and simulation [23,24]. However, limitations of battery technology and control systems limited the general use of UAVs in the second half of the 20th century. The turn of the century marks the debut of innovation in UAV technology. The convergence of battery technologies, miniaturized sensors, global navigation satellite systems (GNSS), and powerful microprocessors enabled the development of smaller and more capable UAVs suitable for a range of applications [25]. This period also saw the emergence of commercial UAVs, initially targeted toward hobbyists, but quickly adopted for industrial, agricultural, and logistics purposes.

Over the past two decades, UAV development has accelerated rapidly. Driven by increasing investments in research and development, growing demand for flexible aviation solutions, and evolving regulatory frameworks, UAV technology has made significant strides across multiple domains. These advancements have laid the foundation for the widespread integration of UAVs into modern transportation, surveillance, environmental monitoring, and infrastructure systems.

2.2. Different UAV Configurations

The progress in communication, information processing, and sensing technologies has prompted researchers, academia, and aircraft businesses to aim toward the development of effective enabling technologies for UAVs [26,27]. The scientific community has established classifications for UAVs for military, civil, and commercial purposes, each tailored to a specific objective [28,29]. UAV platforms are typically classified based on their aerodynamic design and propulsion mechanisms. The three most widely adopted configurations are multi-rotor, fixed-wing, and hybrid UAVs, each offering distinct operational advantages and limitations.

2.2.1. Multi-rotors

Multi-rotors commonly referred to as quadcopters or multicopters, are the most common type of drone. They use multiple rotors (generally four or more) to generate lift and provide precise maneuverability. These UAVs excel in VTOL, hovering, and stable low-speed flight. These UAVs are well-suited for missions requiring precise control and stationary flight, including aerial photography, search and rescue, and domestic applications [6,30].

2.2.2. Fixed-wing UAVs

Fixed-wing UAVs resemble traditional aircraft, with a conventional wing-based design and wings that generate forward thruster lift. They are known for their energy efficiency and long-range capabilities, are ideal for applications such as agricultural surveying and pipeline inspection. However, their reliance on runways or catapult systems limits their suitability for confined environments, and they lack vertical takeoff or hovering capabilities unless specially modified [31,32].

2.2.3. Hybrid UAVs

Hybrid UAVs combine the vertical takeoff and hovering capabilities of multi-rotors with the long-range efficiency of fixed-wing designs. It can detach and land vertically like multi-rotors and realize longer flight times like fixed-wing UAVs. This versatility makes them ideal for applications requiring mobility and transportation, including infrastructure inspection, complex terrain mapping and preservation, environmental monitoring, and delivery in challenging environments [33,34]. Table 2 compares multi-rotor, fixed-wing, and hybrid UAVs, in terms of design, range, endurance, payload, and typical use cases.

Table 2. Comparison of Multi-rotor, Fixed-wing, and Hybrid UAVs.

Feature	Multi-rotor UAVs	Fixed-wing UAVs	Hybrid UAVs
Design	Vertical takeoff, multiple rotors	Single wing, horizontal flight	Combines rotors and wings
Flight Mechanism	VTOL, uses propellers	Horizontal, needs runway	VTOL with transition
Endurance	Short (20–40 min)	Long (1–3 h)	Moderate
Range	Short ($\leq$10 km)	Moderate	Long ($\geq$100 km)
Payload	Limited ($\leq$5 kg)	Moderate	Higher (5–50 kg)
Applications	Photography, inspections	Surveying, agriculture	Search and rescue, delivery

2.3. Key Characteristics of UAVs

UAVs are going through rapid technological advancement, gaining new capabilities across autonomy, sensing, navigation, communication, and energy efficiency. These developments have expanded their suitability for complex applications in transportation, surveillance, logistics, and emergency services [35]. This section outlines the core operational capabilities that enable UAVs to function effectively in dynamic and mission-critical environments.

2.3.1. Autonomous Flight Optimization

ML plays a significant role in improving the autonomy of UAVs. By learning from large volumes of sensor and environmental data, ML algorithms enable UAVs to perform complex tasks such as real-time trajectory planning, adaptive decision-making, and intelligent pathfinding in uncertain and dynamic environments [36]. It allows UAVs to navigate dynamic environments more effectively and safely. For example, the study of [37] demonstrated the application of a deep Q-learning algorithm for UAV trajectory planning. The results show that ML-based methods can effectively control UAVs in harsh environments, optimizing flight paths to improve effectiveness.

Reinforcement learning (RL), a subfield of ML, further improves autonomous decision-making by allowing UAVs to interact with their environment and learn optimal behaviors through trial and error. RL has shown promise in path planning, allowing UAVs to adapt to obstacles and reduce energy consumption [38]. The study of [39] demonstrates the application of RL for optimizing the path planning of UAVs. The results show that the RL algorithm can effectively help UAVs find the cable more quickly while reducing energy consumption.

2.3.2. Payload Capacity and Battery Life

The payload capacity of UAVs has evolved over time. Early UAVs were limited to lightweight sensors, but modern models can carry high-resolution cameras, LiDAR systems, multispectral sensors, and commercial delivery packages [40]. Payload capacity is a crucial factor in determining a UAV's suitability for specific applications [41], such as:

- High-resolution cameras for aerial photography and video recording.
- LiDAR scanners for 3D terrain mapping and infrastructure inspection.
- Multispectral sensors for agricultural surveillance and crop health assessment.
- Delivery packages for medical or commercial applications.

Moreover, battery life and port are always major limiting factors. Current electric UAVs typically offer a range of 10–15 km under optimal conditions [42]. Advances in battery technology, particularly the advent of lithium-ion (Li-ion) batteries, have significantly improved flight time. Compared to traditional nickel-metal hydride batteries, Li-ion batteries have a higher energy density, which allows the UAVs to rest in the air longer [43]. Alternatives like hydrogen fuel cells offer longer flight times, while solar energy is renewable but weather-dependent, making each suited for different UAV applications. Furthermore, research on alternative energy sources says that hydrogen fuel cells must extend flight time [44].

2.3.3. Sense-and-Avoid Technology

The use of Sense-and-Avoid (SAA) technology enables the safe operation of UAVs, especially in the areas surrounding the airspace being used. It is a technology that senses and avoids various environmental hurdles with the help of different sensors like radar, LiDAR and cameras. The flight controller processes this information in real-time and adjusts the flight path to avoid collisions [45].

2.3.4. Collision Avoidance

While SAA systems provide environmental awareness, advanced collision avoidance mechanisms use ML and computer vision to improve UAV perception. Deep learning algorithms can interpret data from onboard sensors to detect and classify obstacles in complex environments. Sensor fusion further enhances accuracy by combining data from multiple sources [46]. For example, [47] applied deep learning techniques for real-time obstacle detection, demonstrating significant improvements in autonomous navigation and environmental awareness. Table 3 presents quantum-inspired optimization and advanced sensor integration for UAVs.

Table 3. Emerging Quantum-Inspired and Sensor-Based Technologies for UAV Optimization.

Operational Domain	Technology	Purpose and Implementation
Route Optimization	Quantum Annealing	Uses quantum-inspired algorithms to compute optimal, energy-efficient flight paths in real-time for dynamic or constrained environments.
Data Management	Quantum Compression Techniques	Improves onboard storage by compressing high-resolution data streams using advanced quantum-based encoding approaches.
Navigation Adaptability	Geomagnetic Field Sensing	Allows UAVs to autonomously adjust flight paths by detecting anomalies in Earth's magnetic field and avoiding high-interference zones.
Micro-climate Awareness	Quantum Micro-weather Forecasting	Predicts localized atmospheric changes, enhancing route selection, timing, and overall flight safety under rapidly changing conditions.

2.3.5. Real-time Data Transmission

Real-time data transmission is crucial for a wide range of UAV applications. UAV can be equipped with communication modules that can transmit various types of data, such as sensor readings, video footage, and control signals to ground control systems. These communication modules typically employ various technologies, such as Wi-Fi, 4G/5G cellular networks, and dedicated RF communication systems to guarantee dependable and fast data transmission with minimal delay [48]. Due to its ability to greatly influence decision-making outcomes and operational effectiveness, accurate data is of utmost importance. Security and reliability are critical. Advanced protocols and cryptographic techniques ensure data integrity, confidentiality, and low-latency performance in mission-critical operations [49]. Figure 2 illustrates a flowchart of the real-time data transmission process.

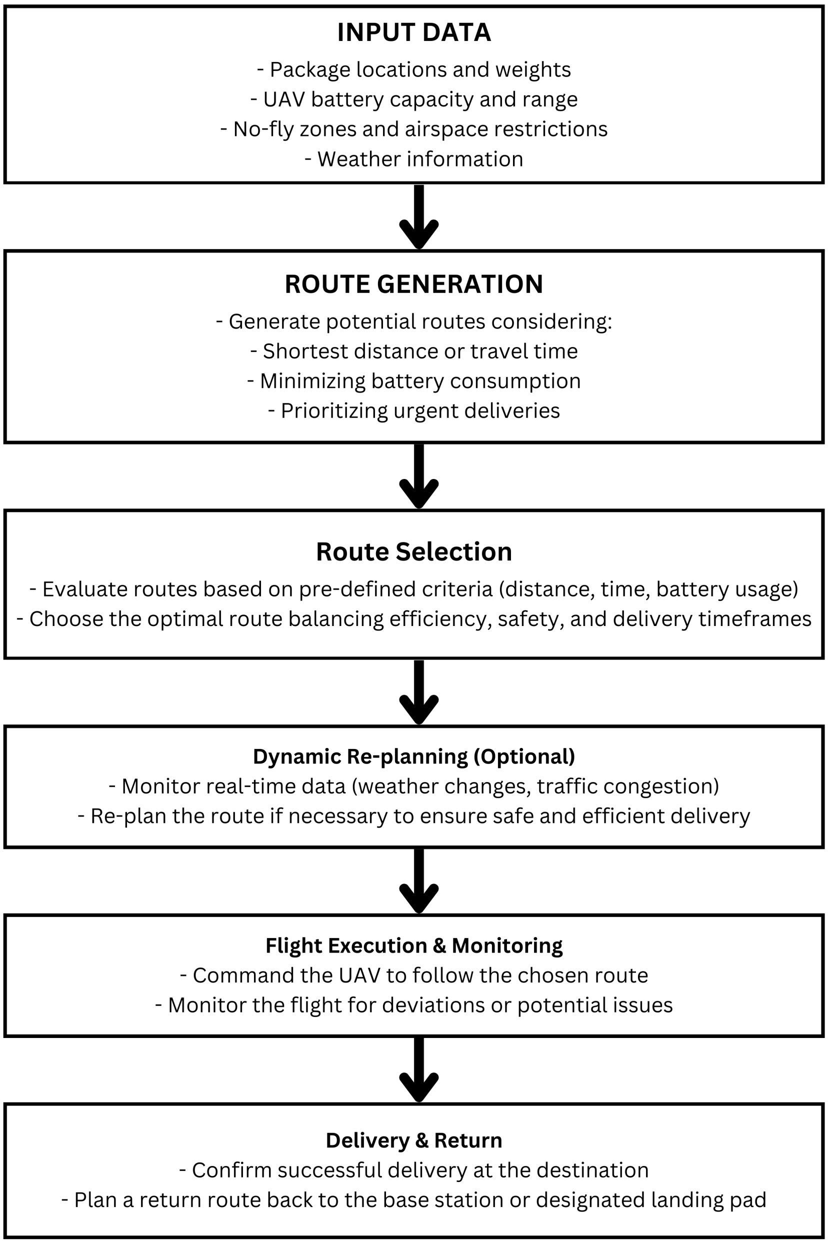

Figure 2. Real-time data transmission process.

2.3.6. Cooperative Navigation and Swarming

Next-generation UAV operations will increasingly depend on cooperative behavior, especially in multi-agent environments and swarming behavior to enhance operational efficiency. In cooperative navigation, UAVs would share real-time data on obstacles, weather conditions, and traffic patterns, enabling them to collaboratively adjust flight paths and avoid hazards. Swarming, where multiple UAVs function as a coordinated group, allows for complex tasks such as large-scale surveillance, mapping, or search operations. This approach not only improves safety by reducing the risk of collisions but also optimizes the overall effectiveness of UAV fleets in dynamic environments. These methods would significantly improve UAV capabilities in urban air mobility and other demanding applications. Autonomous flight enables UAVs to operate without human control, using sensors, flight controls, and advanced algorithms to reach set points, maintain altitude, and avoid obstacles, reducing the need for human intervention [24,50,51].

The technological capabilities discussed in this section have moved UAVs beyond experimental prototypes and into mainstream deployment across a wide range of civil, industrial, and public service sectors. In the following section, we explore the current applications of UAVs in the context of transportation systems, with a particular focus on last-mile delivery, urban air mobility, intelligent transportation systems, infrastructure monitoring, and cybersecurity. These examples illustrate how technical features translate into practical benefits, highlighting the impact of UAVs on modern transportation.

2.4. Current Applications of UAVs

UAVs have transitioned from experimental technologies to essential tools in modern engineering, transportation, and logistics. Their ability to operate autonomously, access remote locations, and collect real-time data has enabled wide-ranging applications across multiple sectors. This section reviews key current applications of UAVs, including last-mile delivery, UAM, ITS, infrastructure monitoring, and cybersecurity.

2.4.1. Last-Mile Delivery

One of the domains in which UAVs are actively used in the transportation setting is the last-mile delivery service. By bypassing ground-based infrastructure, UAVs significantly reduce delivery time, improve cost-efficiency, and offer faster access to critical supplies. Figure 3 depicts a conceptual illustration of urban UAV delivery system. Numerous companies are actively developing and testing UAV transportation systems. For example, Amazon Prime Air has UAVs for rapid and efficient delivery of packages [52]. It is noted that Amazon Prime Air offers 30-minute deliveries for orders up to 2.25 kg. The same goes for companies like UPS and DHL exploring the use of UAVs for medical supply deliveries and other time-sensitive applications [53,54]. A notable milestone includes a UAV successfully delivered a kidney for transplantation in 2019, highlighting its potential in medical deliveries [55].

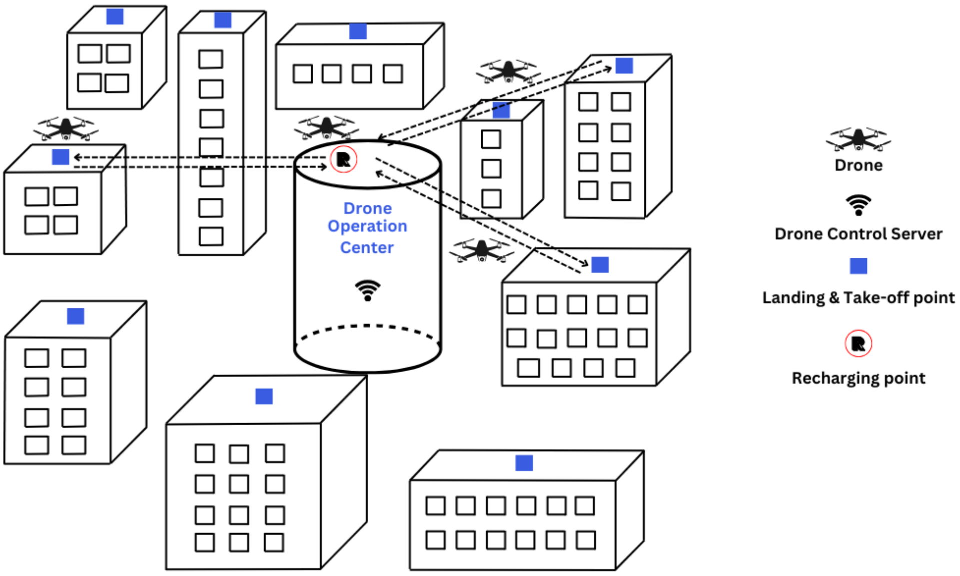

Figure 3. Conceptual diagram illustrating the integration of UAVs and eVTOL aircraft in an UAM network for point-to-point transportation. Adapted from [42].

2.4.2. Air Traffic Optimization

Building upon last-mile delivery, UAVs are also key enablers of Urban Air Mobility (UAM), which refers to the integration of electric vertical takeoff and landing (eVTOL) aircraft for urban passenger and cargo transportation. By offering faster, more efficient, and congestion-free travel options, UAM has the potential to revolutionize urban transportation, improving connectivity and reducing the strain on ground traffic systems. Figure 4 illustrates a conceptual diagram of the urban air transport network.

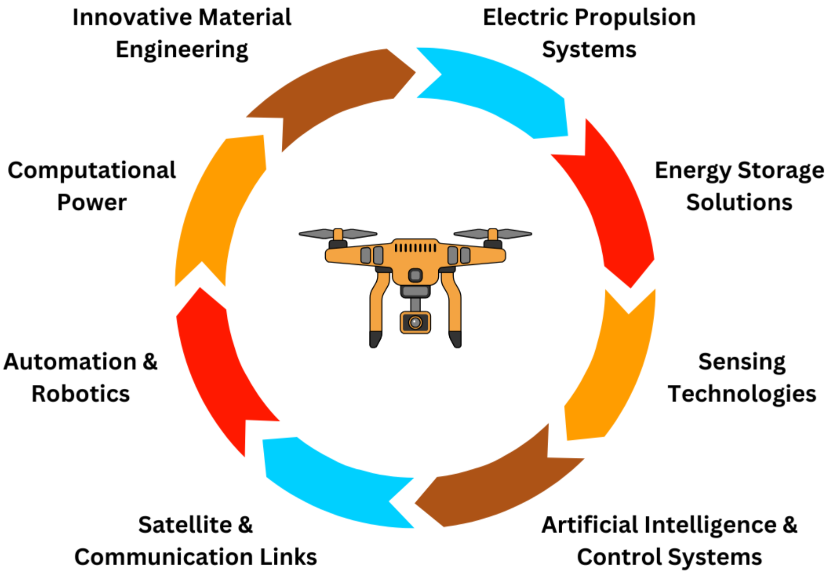

Figure 4. Conceptual diagram of the urban air transport network.

2.4.3. Intelligent Transportation System

UAVs are increasingly integrated into intelligent transportation systems (ITS), which use data, sensors, and connectivity to improve the efficiency and safety of transport networks. Since decision-making in ITS relies heavily on a substantial amount of data, UAV-enabled periodic data collection proves to be an efficient approach. UAVs can support ITS by adjusting their positions and offering real-time aerial data collection and traffic monitoring capabilities. Equipped with high-resolution cameras and sensors, UAVs can assess traffic flow, detect incidents, and evaluate road conditions from a bird's-eye view [56–58]. Figure 5 illustrates UAV-based traffic surveillance integration into ITS. Besides, UAVs can be used to create temporary communications networks in remote or disaster-stricken regions where traditional infrastructure is damaged or missing. They can also be used for law-enforcement purposes. By capturing video of traffic violations, UAVs can help law enforcement identify and punish crimes while potentially improving road safety and enforcement. They are also valuable in search and rescue operations. Outfitted with thermal cameras and high-zoom lenses, they can detect humans in low-visibility environments. Some UAVs include loudspeakers or payload bays for delivering medical supplies or establishing communication with survivors [59].

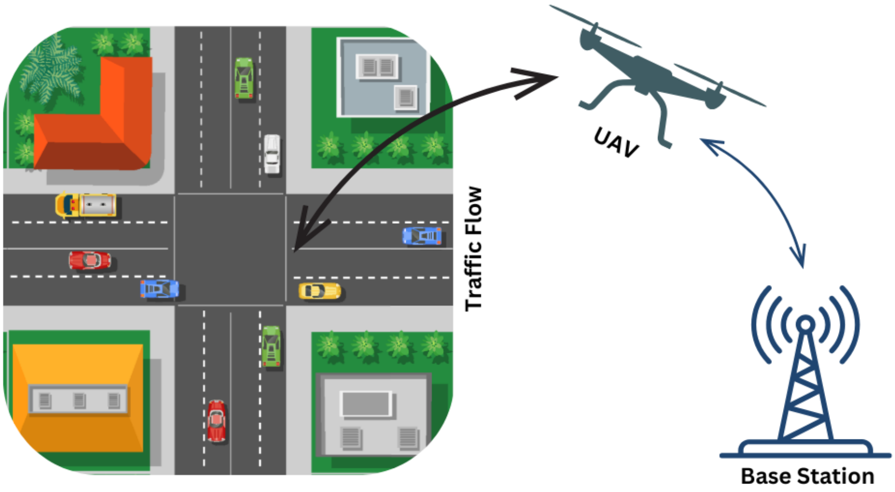

Figure 5. Illustration of a UAV-based traffic monitoring system.

2.4.4. UAVs for Infrastructure

Manual inspection of large-scale infrastructure like bridges, tunnels and roads is time-consuming, expensive, and even dangerous [60]. On the other hand, UAVs provide a safer and more effective alternative for infrastructure inspection. Figure 6 highlights two aspects: (a) a UAV being utilized for bridge inspection, and (b) a pure representation of road cracks monitoring. Using location-tagged image data, UAVs help maintenance teams prioritize repairs, deploy resources efficiently, and reduce repair times [61]. This targeted approach helps reduce repair times, improve road safety, and optimize resource allocation for road maintenance projects.

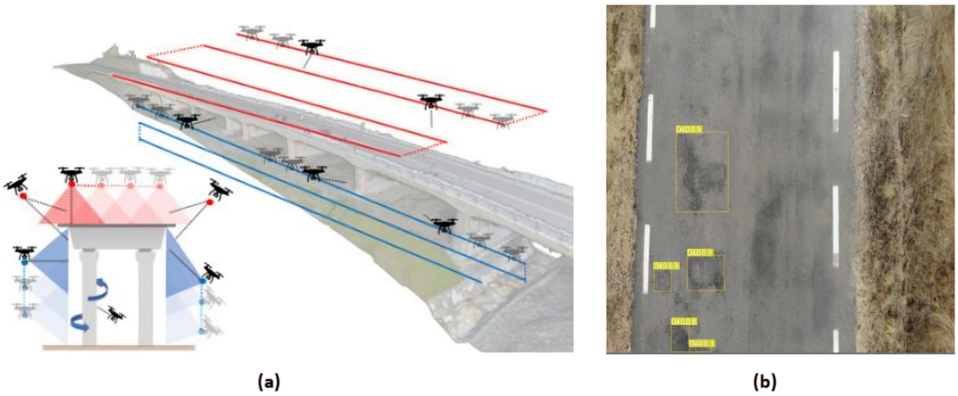

Figure 6. (**a**) UAV utilized for bridge inspection; (**b**) Pure representation of road cracks monitoring. Reproduced from [62,63].

2.4.5. Cybersecurity for UAVs

The rapid development of UAV technology in critical sectors raises serious concerns about cybersecurity. UAV networks are vulnerable to attacks such as GPS spoofing, data interception, jamming, and unauthorized control access. How to protect UAV network security has become an important issue that needs to be solved urgently. Whether in traffic management or civilian applications, strengthening UAV network protection is essential to prevent serious consequences from hacker attacks [64,65]. Conventional cybersecurity measures include encrypted data transmission, firewalls, cryptographic protection and frequent software updates. Figure 7 illustrates the UAV cyber attack architecture adapted from [66], emphasizing the need for multi-layered protection strategies.

In addition to these traditional security measures, emerging technologies like ML and Blockchain are proving to be powerful tools in securing UAV operations. ML algorithms can monitor UAV networks in real-time to detect anomalous behavior—such as spoofing or signal interference—and trigger automated responses. This helps UAVs respond to cyber threats dynamically, reducing the risk of system compromise. Meanwhile, blockchain technology further enhances security by creating an immutable and decentralized ledger for UAV data transactions, ensuring data integrity and protecting against tampering. By incorporating ML for threat detection and Blockchain for secure data transmission, UAV systems can become more resilient against cyberattacks, ensuring the reliability and safety of future UAV deployments in both commercial and civilian sectors [67,68].

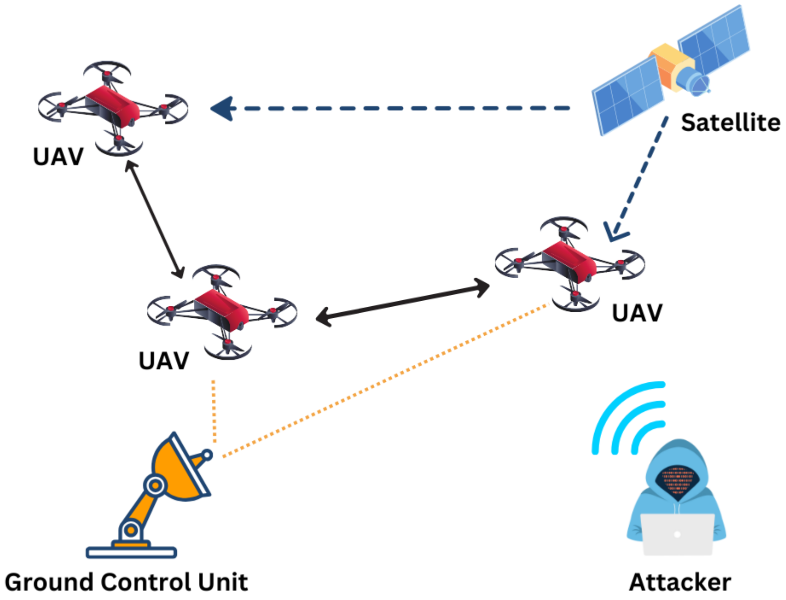

Figure 7. Conceptual UAV cyber attack architecture adapted from [66].

3. Impact of UAV Integration in Transportation Systems

While the previous section outlined the breadth of UAV applications across transportation systems, it is equally important to assess the broader impact these technologies are having on traditional operations, urban mobility models, infrastructure management, and cybersecurity readiness. The following section examines how UAVs are actively transforming key areas of transportation using real-world scenarios, highlighting advantages, discussing technical methodologies, and addressing challenges. Figure 8 illustrates the functional components of a UAV.

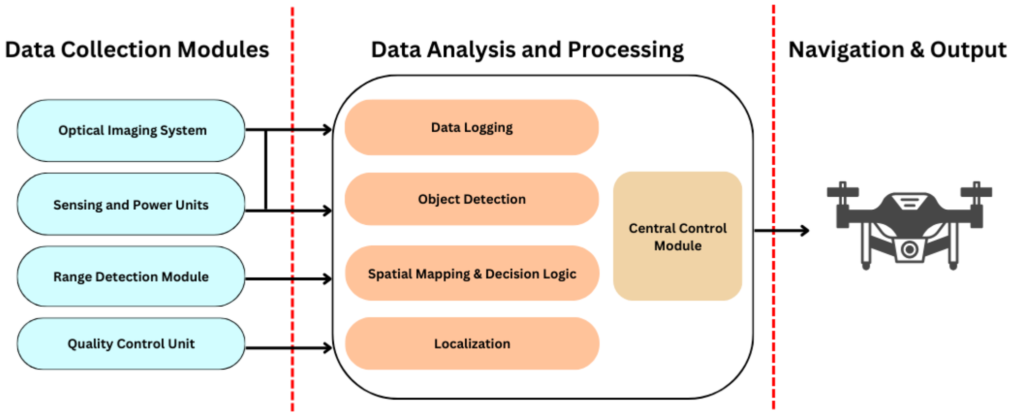

Figure 8. Functional components of a UAV.

3.1. Delivery Services

UAVs have significantly influenced the transportation services sector by offering efficient last-mile and remote transportation solutions, thereby enhancing overall effectiveness. The UAVs can fly above traffic-jammed roads and go directly to the customer's door, avoiding the circular chain delays in the customer city's downtown area, which are more expensive use of alternative transportation methods that are more rentable.

3.1.1. Operational Role and Capabilities

Many companies are interested in using UAVs for last-mile transportation in urban areas, which reduces the transportation time slack problem and decreases the congestion involved. The UAV can fly above traffic-jammed roads and go directly to the customer's door, avoiding the circular chain delays in the customer city's downtown area, which are more expensive use of alternative transportation methods that are more rentable. A case study in [69] showcases a scenario involving ten deliveries and four drones. The analysis in this study consists of a discussion of when the wind speed increases, making resilient provision for this purpose, detection of areas in which the UAVs do not have a single wing to land, and the finding of emergency strategies for return may arrive at the severity of the actual wind speed more than forecast. Figure 9 depicts a conceptual illustration of UAV-based delivery systems.

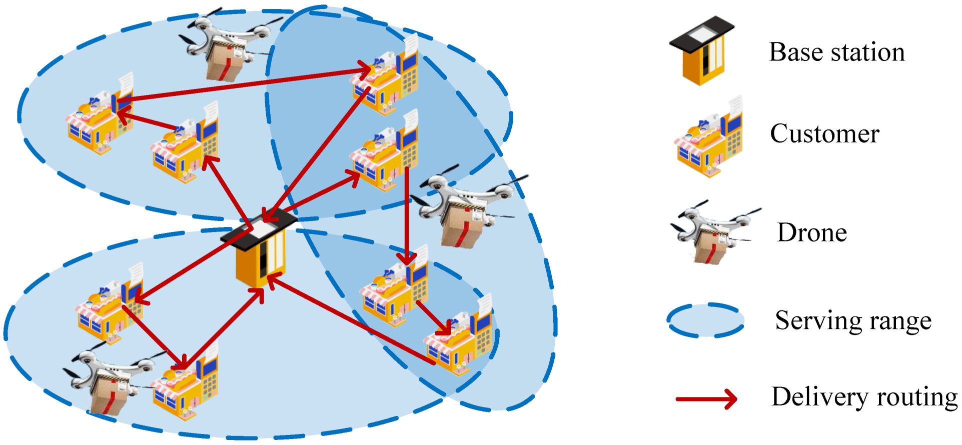

Figure 9. Conceptual illustration of UAV-based delivery systems. Reproduced from [70].

A promising application for UAVs is in last-mile delivery, which is the final stage of the delivery process at a distribution center or a warehouse just at the client's home. UAVs can avoid frequent and consistent routes, avoid bottlenecks, and transport packages directly to customers' homes or designated collection points. This can considerably reduce delivery times, especially in urban areas [71]. The analysis of 111 interdisciplinary publications since 2013 reveals that clear economic expectations drive discussions on delivery and passenger drones but also highlight significant societal and environmental concerns [72]. A comparative analysis in Table 4 highlights the unique benefits of UAVs relative to cars, trucks, and public transportation. UAVs have minimal impact on traffic, require less infrastructure, and offer electric-powered, low-emission operations. However, their range is limited by battery capacity, and they are best suited for short to medium-haul deliveries.

Table 4. Comparison of different transportation methods.

Factor	UAVs	Traditional Transportation (Cars, Trucks)	Public Transportation (Buses, Trains)
Delivery Range	Short to medium (depending on battery technology)	Long distances	Limited by network infrastructure
Operational Cost	Can be cost-effective for specific applications	High fuel and maintenance costs	Potentially lower operating costs per passenger
Environmental Impact	Electric UAVs offer lower emissions	Significant emissions from gasoline and diesel engines	Relatively lower emissions, especially electric modes
Traffic Congestion	Minimal impact on ground traffic	Contributes significantly to traffic congestion	Limited impact on existing traffic flow
Accessibility	Can reach remote locations	Limited access to remote areas	Offers wider accessibility within served areas
Infrastructure Requirements	Relatively minimal (landing pads for specific applications)	Extensive infrastructure network of roads and gas stations	Extensive infrastructure network of stations, tracks & maintenance facilities

3.1.2. Technological Framework and Methodologies

The effectiveness of UAV delivery systems is largely enabled by advances in onboard computing, sensor technology, and machine learning (ML). Companies like Amazon Prime Air and UPS employ ML to streamline delivery routes, enabling faster and more reliable service for essential shipments [73]. These cases show ML's impact on improving delivery speed and reliability without focusing on technical details.

(1) ML for Route Optimization:In urban environments, tall buildings, trees, and no-fly zones complicate route planning. ML-based dynamic routing enables UAVs to adapt flight paths in real-time, addressing unforeseen challenges such as sudden weather changes or unexpected obstacles. For instance, when adverse weather is detected, the UAV can promptly change its trajectory to evade the impacted area, ensuring safe and punctual delivery [74–76].

(2) ML for Predictive Maintenance: Preventive maintenance is critical for UAV reliability and safety. ML algorithms predict maintenance issues by analyzing operational data, battery status, motor performance, and flight logs. This predictive approach helps avoid unexpected downtime and ensures consistent service quality. Additionally, ML models can forecast wireless traffic congestion and deploy adaptive bitrate streaming to enhance UAV performance [77].

In addition to ML-driven decision-making, UAV operations rely on mathematical models to monitor and optimize key performance metrics. By calculating factors such as battery charge, payload capacity, and energy efficiency, these models help ensure safe, efficient, and sustainable delivery operations. Several mathematical models that support UAV operations:

(1) State of Charge (SoC): To predict the need for battery replacement or recharging, the State of Charge (SoC) can be calculated using the formula:

$$\mathrm{SoC} = \frac{Q_t}{Q_{\text{nom}}} \times 100\% \tag{1}$$

where Q_t is the current charge of the battery and Q_{nom} is the nominal charge capacity.

(2) Payload Capacity (P): The payload capacity of a UAV is a critical factor in determining its utility for tasks like package delivery. The available payload can be calculated using the following formula:

$$P = T - W \tag{2}$$

where P is the payload capacity, T is the total lift force generated by the UAV's rotors, and W is the weight of the UAV itself.

(3) Energy Efficiency (E): To maximize the energy efficiency of UAVs during their missions, the following formula is used to calculate the efficiency:

$$E = \frac{d}{P} \tag{3}$$

where d is the total distance traveled by the UAV, and P is the power consumed during the flight. This formula helps optimize flight routes, ensuring that energy consumption is minimized, thereby extending UAV operational time and reducing the need for frequent recharging.

Several recent studies have applied these principles in both experimental and simulated UAV delivery systems. Table 5 summarizes selected research, including their objectives, hardware/software setups, algorithms, and potential future applications.

Table 5. Highlights of some previous research related to Delivery Services.

Paper Focus	Key Findings	Hardware Used	Software Used	Algorithm Used	Future Possibilities
UAV for joint goods delivery [78]	Optimizes route planning and sensing tasks to reduce energy use and ensure timely delivery.	Not Specified	Not Specified	Bellman-Ford algorithm	Extension to multi-objective UAV delivery scenarios
Navigation system for autonomous drones [79]	Improves urban delivery accuracy through sensor fusion and precise landing.	DJI Matrice 100 GPS 9DoF IMU barometer	MATLAB / Simulink	Extended Kalman Filter Sensory fusion	Safer urban delivery operations.
Optimizing skyway networks for delivery [80]	Optimizes delivery time and energy use under urban skyway constraints.	DJI M200 V2 UAV	Real dataset from Sydney CBD 3D model	LOS heuristic composition	Weather-aware energy optimization.
Integrating tactical and operational plans for last-mile delivery [71]	Optimizes depot selection, fleet size, and delivery routes while considering energy use.	MATRICE 600 PRO UAV	Gurobi 9.1	MILP with load-indexed layered graphs	Multi-period planning and charging integration.

3.1.3. Challenges and Future Directions

Despite their rapid development, UAV-based delivery systems face several barriers that must be addressed before large-scale adoption is possible. Several challenges are discussed below:

- Payload Limitations: It remains one of the most significant technical constraints. Current UAV designs typically support only light to medium cargo, restricting deliveries to small packages, medical supplies, or specialized goods [6]. While this is sufficient for certain markets, it limits the broader applicability of UAVs for commercial logistics.
- Regulation: Many regions enforce strict rules on UAV altitude, flight distance, and operations in urban areas, making it difficult to deploy large UAV fleets without specialized approvals [81]. Low-altitude urban airspace in particular requires carefully designed traffic management systems to prevent congestion and accidents.
- Public Acceptance: Concerns over noise, safety, and potential privacy violations can generate resistance to UAV integration, particularly in densely populated areas [82]. Without community buy-in, even technically viable UAV programs may face public opposition.

Addressing these challenges requires a combination of technological innovation, regulatory evolution, and community engagement:

- Technological improvements: Advances in battery technology can enhance UAV charge capacity, allowing them to transport a wider range of cargo.
- Regulatory collaboration: Collaboration among businesses, regulators, and policymakers is essential to establish comprehensive regulations for safe and responsible UAV management.
- Public outreach programs: Implementing clear regulatory frameworks and launching community-driven pilot projects can address these concerns by ensuring safe operations and showcasing the benefits of UAVs in everyday life.

Several cities have launched community programs to educate the public on UAV benefits and safety, while collaborating with manufacturers to create quieter drones. These efforts, along with clear communication and regulations, have helped address concerns and increase acceptance of UAV technology in urban areas.

3.2. Urban Air Mobility (UAM)

Urban air mobility (UAM) leverages eVTOL aircraft for passenger transportation within urban areas. UAVs play a pivotal role in UAM, enhancing urban connectivity by offering efficient, congestion-free transportation solutions and transforming how people and goods move within cities.

3.2.1. Operational Role and Capabilities

All urban areas face chronic traffic congestion problems, leading to wasted time, increased fuel consumption, and air pollution. UAM offers a promising alternative, with eVTOL vehicles able to bypass ground routes and ensure point-to-point transportation within towns. This can significantly reduce congestion on land transport networks [83]. Beyond passenger transport, UAVs can support traffic departments by monitoring road networks from above and detecting potential violations in real-time [84]. Table 6 below highlights some previous research related to this topic, showcasing key findings, hardware and software used, algorithms applied, and future possibilities in the context of UAVs and flying car transportation systems.

Table 6. Selected representative studies related to urban air mobility.

Paper Focus	Key Findings	Hardware Used	Software Used	Algorithm Used	Future Possibilities
Flying car transportation systems (FCTS) [85]	Reviews FCTS design challenges, including takeoff/landing, pilot modes, and environmental impact.	Flying cars VTOL technology	Auto piloting software	Path and trajectory planning algorithms	Improved UAM and reduced urban congestion.
Trajectory evaluation for UAM using a simulation platform [86]	Uses simulation to evaluate UAM trajectory safety and efficiency for manned and unmanned eVTOLs.	Not Specified	Not Specified	Discrete Event Simulation (DES)	Improved UAM traffic management and safety protocols.
Energy and environmental performance analysis of passenger drones for UAM in Seoul [87]	Evaluates safe 3D routes, energy use, and emissions benefits for passenger UAVs.	E-hang184 passenger UAV	ArcGIS, LCP model	Least Cost Path (LCP) Algorithm, Entropy Weight Method	Improved UAM traffic management and safety protocols.

3.2.2. Technological Framework and Methodologies

This subsection introduces both the 5G network and AI-based air traffic control systems. The integration of 5G networks and AI-based air traffic control systems promises to revolutionize UAM operations. 5G network together with AI-based air traffic control systems are expected to revolutionize UAM systems [88]. The efficient and effective low latency communication that will be supported by 5G will enable UAM vehicles to communicate with other vehicles, with ground infrastructure, or with the real-time weather or traffic conditions so as to improve their operations. In addition, there will be AI-based air traffic control systems that will control the airspace in cities characterized by high traffic, thus providing UAM vehicles with algorithms to meet certain goals such as the avoidance of certain areas, avoidance of all obstacles and optimal time to travel. As well, smart infrastructure solutions concerning vertiports with self-sustaining recharging and servicing systems will yield additional advantages such as scalability and lower expenses for UAM services [11]. Such innovations partnered with other such solutions as solar charging stations will aid UAM systems to become easily adopted into the contemporary urban mobility systems. UAVs play a vital role in creating accurate maps, monitoring construction projects, and conducting surveys. They assist stakeholders by providing visual reports through photographs, videos, and three-dimensional mapping, which are useful for infrastructure inspections, tower evaluations, and monitoring power cables [72,89]. Again, advances in eVTOL technology are essential for the widespread adoption of UAM. Focus areas include increasing range, improving battery life, reducing noise emissions, and ensuring passenger safety through robust safety features [90].

In addition to technological advancements, understanding the physics of UAV flight is critical. For fixed-wing UAVs, the lift force L, which is necessary for maintaining flight, can be calculated using the formula:

$$L = \frac{1}{2}\rho v^2 A C_L \tag{4}$$

where ρ is the air density, v is the velocity of the UAV, A is the wing area, and C_L is the lift coefficient.

In path planning for UAVs, ML algorithms play a significant role in optimizing flight paths. These algorithms are designed to minimize travel time and reduce energy consumption. For example, the distance between two points in 3D space can be calculated using the following formula:

$$\text{Distance} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{5}$$

where (x_1, y_1, z_1) and (x_2, y_2, z_2) are the coordinates of the start and end points. This helps in generating the shortest and most efficient route for the UAV.

Another significant benefit of UAM is its potential to connect remote suburbs or underserved regions with key urban locations, such as business districts or transportation hubs. This enhanced connectivity can improve accessibility for residents and stimulate economic growth in these areas [91]. One of the challenges associated with drone-based transportation services is noise pollution. However, eVTOL vehicles used in UAM are specifically optimized for low noise productio*, making them a more sustainable solution compared to traditional helicopters. Their electric propulsion systems and innovative design features enable them to produce significantly lower noise levels, thereby mitigating the impact of noise pollution in urban environments and contributing to a greener transportation future [92].

3.2.3. Challenges and Future Directions

Despite the promise of UAM, significant challenges remain. As UAVs become more integrated into urban airspace, dynamic traffic management and predictive maintenance will be essential for ensuring safety and reliability. Several challenges include:

- Dynamic Traffic Management: UAM systems must navigate complex urban environments, which include dynamic traffic patterns, sun drift, and variable weather conditions.
- Preventive Maintenance: Predictive maintenance for urban air mobility vehicles is crucial for safety and reliability. Issues such as battery health, engine performance, and flight data must be monitored to ensure timely interventions.

ML techniques will play a crucial role in optimizing flight paths and predicting maintenance needs, but overcoming these obstacles will require continued innovation in both the technologies and regulations supporting UAM. Some of the future directions are discussed below:

- ML for Flight Path Optimization: Machine learning (ML) enables UAM vehicles to dynamically adjust their flight paths by analyzing real-time traffic data. This allows for optimal route selection, reduced travel times, and avoidance of congested airspace [93,94].
- ML for Predictive Maintenance: ML algorithms can analyze battery health, engine performance, and flight logs to predict potential maintenance issues. By providing proactive interventions, ML helps ensure the safety and reliability of UAM operations [1].

3.3. Traffic Monitoring and Management

UAVs offer innovative surveillance and traffic management solutions that can provide actionable data to optimize traffic flow and enhance safety. In a study by Hossain et al. [18], a UAV-based traffic management system is presented where users can select their destination, and UAVs capture real-time traffic images for analysis on a server. The system evaluates traffic conditions, adjusts routes, and assesses parameters such as delay and speed. If congestion exceeds certain thresholds, the system suggests alternative routes to users.

3.3.1. Operational Role and Capabilities

UAVs equipped with cameras can capture images of roads and vehicles. These images can be analyzed to calculate vehicle density, a key metric in traffic management. Vehicle density, D, is calculated as:

$$D = \frac{N}{L} \tag{6}$$

where N is the number of vehicles and L is the length of the road section.

High vehicle density typically indicates traffic congestion, allowing authorities to take corrective measures. Incorporating UAVs into ITS offers real-time monitoring and management solutions, improving traffic flow optimization and safety measures. UAVs, when integrated with ITS, enable data-driven decision-making processes that help authorities manage traffic more effectively.

3.3.2. Technological Framework and Methodologies

UAVs can significantly enhance traffic monitoring by providing real-time data on traffic patterns, accidents, and road conditions [95,96]. ML plays a pivotal role in analyzing large datasets collected by UAVs. ML algorithms identify traffic flow patterns, predict congestion points, and detect real-time incidents, enabling proactive traffic management strategies [97]. Moreover, UAVs help improve communication infrastructure by gathering and analyzing data to ensure uninterrupted vehicle operations [14,98]. This integration supports data-driven decision-making and allows for quick interventions in response to real-time traffic conditions. Table 7 below highlights some previous research related to this topic, showcasing the key findings, hardware and software used, algorithms applied, and future possibilities.

Building on these advancements, ML algorithms analyze large datasets gathered by UAVs. ML models can identify traffic flow patterns, predict congestion, and detect incidents in real-time, enabling proactive traffic management strategies that optimize traffic flow and improve transportation efficiency [97]. Some of them are:

(1) ML for Data Analysis and Pattern Recognition: Machine learning algorithms analyze large datasets collected by UAVs, identifying traffic flow patterns, predicting congestion points, and detecting real-time incidents. This enables ITS to implement proactive traffic management strategies, improving transportation efficiency.

(2) Dynamic Traffic Management: UAVs provide real-time traffic data that, when processed by machine learning models, allows for dynamic management strategies. These strategies adjust traffic signals, update guidance systems, and reroute traffic to mitigate congestion, reducing delays and improving road safety [99].
(3) ML for Predictive Traffic Flow Management: Machine learning models in ITS analyze historical traffic data, weather conditions, and upcoming events to predict future traffic congestion. These predictions allow authorities to proactively adjust traffic light timings or dispatch law enforcement to manage traffic flow and reduce disruptions.
(4) Accident Response: UAVs provide comprehensive real-time images of accident scenes, allowing first responders to assess the situation and allocate resources efficiently. This can help save lives and reduce secondary accidents.

Table 7. Highlights of some previous research related to Traffic Monitoring and Management.

Paper Focus	Key Findings	Hardware Used	Software Used	Algorithm Used	Future Possibilities
Traffic monitoring system for smart cities [18]	Uses UAV-captured traffic images and cloud processing to support traffic analysis.	UAVs with cameras	PTV Vissim 2020 sky software	Not specified	CNN-based traffic detection improvement.
Traffic analysis using UAV-based videos [100]	Applies DL to UAV videos for real-time vehicle detection and congestion analysis.	Mavic Pro Platinum Model	Not Specified	Mask Region Based Convolutional Neural Networks (RCNN)	Expanded UAV-based congestion monitoring.
Closed-loop control in traffic surveillance [101]	Uses UAV-WSN coordination for adaptive highway surveillance and speed-violation detection.	UAVs with speed sensors	Network Simulator-2	Probabilistic-based dynamic trajectory control model	Multi-UAV scalability and ITS integration.
Decentralized UTM using blockchain and mobile crowdsensing [102]	Proposes blockchain-based UTM for secure mission scheduling and airspace access control.	Not Specified	Ethereum Blockchain, Remix	Smart contract-based protocol, Poisson distribution model	Improved UAV compliance monitoring.

In autonomous UAV navigation for ITS, obstacle avoidance is a critical challenge that must be handled in real-time. One widely used method is the Potential Field Method, where the UAV is influenced by a combination of attractive forces toward its target and repulsive forces away from obstacles. The total force acting on the UAV is given by:

$$F = F_{\text{att}} + F_{\text{rep}} \tag{7}$$

where F_{att} is the attractive force pulling the UAV towards its goal, and F_{rep} is the repulsive force pushing the UAV away from nearby obstacles.

The attractive force can be calculated as:

$$F_{\text{att}} = -k_{\text{att}} \cdot (P - P_{\text{goal}}) \tag{8}$$

where P is the current position of the UAV and P_{goal} is the target position.

3.3.3. Challenges and Future Directions

UAVs offer immense potential for traffic monitoring and management, but several challenges need to be addressed for their widespread adoption. Some key challenges include:

- Privacy Concerns: UAV data collection raises privacy issues, necessitating clear rules and robust data security measures.
- Integration with Existing Systems: Integrating UAV data with ITS requires reliable communication and standardized data formats.
- Weather Limitations: Adverse weather conditions can affect UAV performance, particularly in heavy rain or strong winds.

To overcome these challenges, solutions include:

- Implement clear data privacy policies and secure data transmission protocols to address privacy concerns and gain public trust.
- Develop standardized communication protocols to ensure seamless integration of UAV data within ITS.
- Invest in weatherproof UAV technology and establish procedures for UAV operation under different weather conditions to ensure continuous data collection.

Future developments should focus on enhancing collision avoidance technologies for UAVs in dense air traffic environments, especially in urban settings where UAV deployment is expected to increase. Innovations in swarm intelligence and multi-UAV coordination will be essential for handling the growing number of UAVs in urban airspace.

3.4. Infrastructure Inspection and Maintenance

UAVs revolutionize infrastructure inspection and maintenance by providing a safe, effective, inexpensive solution for inspecting bridges, routes, power lines, and other critical infrastructure components. This approach reduces the need for manual inspections, minimizes downtime, and eliminates the need for lane closures, improving both safety and operational efficiency.

3.4.1. Operational Role and Capabilities

Traditional bridge inspection methods often require manual visual inspection or closing of lanes for detailed evaluations. UAVs can conduct comprehensive inspections from all angles without disturbing traffic, identifying cracks, corrosion, and other structural defects [103]. For road inspections, UAVs are equally effective in identifying potholes, cracks, and other road surface issues. By providing real-time data, UAVs enable preventive maintenance, enhancing road safety and prolonging the lifespan of infrastructure [104].

3.4.2. Technological Foundations and Methodologies

ML algorithms are essential for processing large datasets collected by UAVs during infrastructure inspections, such as high-resolution imagery and LiDAR point clouds. These algorithms automatically detect structural damage, including cracks, irregularities, and other defects, improving inspection accuracy and reducing the time required for manual evaluations. By leveraging ML, UAVs can provide more reliable, faster results, enhancing both safety and operational efficiency [60]. In addition, UAVs are a feasible and safe tool for inspecting power lines, especially in difficult-to-reach terrains. They capture high-resolution images and videos of power lines to detect issues such as insulation failure, corrosion, and vegetation interference. This data allows for scheduled maintenance, reducing the risks of power outages and system failures [105]. Additionally, integrating UAVs into Building Information Modeling (BIM) systems enables real-time monitoring, maintenance, and safety reporting. This integration enhances the efficiency of infrastructure inspections by providing up-to-date, detailed reports directly into BIM platforms, allowing engineers to make informed decisions faster and improve the overall safety and maintenance of structures [106]. Table 8 below highlights some previous research related to this topic, showcasing the key findings, hardware and software used, algorithms applied, and future possibilities.

Table 8. Highlights of some previous research related to Infrastructure Inspection and Maintenance.

Paper Focus	Key Findings	Hardware Used	Software Used	Algorithm Used	Future Possibilities
Intelligent powerline inspection [105]	Enables efficient powerline inspection using UAV LiDAR and point-cloud analysis.	UAV LiDAR system	PointNet for point cloud classification	DLPointNet, Dijkstra's algorithm	Multi-sensor real-time fault detection.
UAV-Based Remote Sensing [107]	Improves bridge inspection accuracy using UAV remote sensing while reducing traffic disruption.	DJI Phantom 4 Pro	Pix4D, Agisoft Metashape	Structure-from-Motion (SfM)	AI-assisted autonomous bridge inspection.
UAV-based inspection of bridge infrastructures [108]	Supports bridge damage assessment through UAV imagery, 3D modeling, and risk analysis.	DJI Spark, Parrot Anafi, DJI Mavic 2 Pro	Not specified	Photogrammetry, Finite Element modeling (FE)	AI-based damage classification and digital twins.
AI and edge platform for electricity infrastructure inspection [109]	Enables real-time power-infrastructure fault detection using AI, edge computing, and 5G.	Hex Cube Flight Controller (Pixhawk 2)	PX4, Keras, Open5G Core Toolkit	R-CNNs, Fast R-CNNs, Support vector machine (SVM)	Improved AI-based fault detection.

While inspection, to improve energy efficiency and manage power consumption in UAVs, it is important to consider the different flight phases. UAVs typically operate in either hover or cruise mode, with each phase requiring different amounts of energy. The total energy consumption during a mission can be calculated as:

$$E_{\text{total}} = P_{\text{hover}} \cdot t_{\text{hover}} + P_{\text{cruise}} \cdot t_{\text{cruise}} \tag{9}$$

where P_{hover} is the power consumption during hover, t_{hover} is the time spent in hover mode, P_{cruise} is the power consumption during cruising flight, and t_{cruise} is the time spent in cruise mode. This formula allows for an optimized calculation of energy usage across various mission profiles, aiding in the design of energy-efficient flight plans.

3.4.3. Challenges and Future Directions

As UAVs are increasingly integrated into infrastructure inspection and maintenance, several challenges remain, especially when transitioning from traditional methods. These challenges need to be addressed for UAVs to fully realize their potential in improving safety, efficiency, and cost-effectiveness.

Challenges:

- The risks associated with manual inspections in hazardous locations such as high-voltage power lines or structurally unsound bridges pose safety concerns.
- The time and cost constraints of traditional inspection methods that require lane closures and manual evaluations.

Solutions:

- Improved Safety and Increased Efficiency: UAVs improve safety by minimizing the need for workers to access dangerous areas during inspections. In addition, UAV-based inspections are faster and more efficient than manual inspections, reducing both downtime and costs [5,110]

Several exciting developments are expected to enhance their role in infrastructure inspection. Advanced Automation and AI will enable greater autonomy in inspections, with ML and AI systems improving real-time damage detection, predictive maintenance, and decision-making. These AI-driven systems will analyze data on-the-fly, making inspections more efficient and accurate. Another critical area for future growth is the development of Enhanced Regulatory Frameworks. The lack of standardized regulations currently hinders the widespread adoption of UAVs in infrastructure inspections. Governments and industry stakeholders must collaborate to create clear guidelines for safe UAV operations, including airspace management, data privacy, and UAV certification, particularly in complex and high-risk environments. The integration of Digital Twins will also play a pivotal role. By incorporating UAV systems with digital twin technologies, real-time 3D mapping of infrastructure will be possible, allowing for more detailed, proactive maintenance and ultimately extending the lifespan of critical infrastructure.

3.5. Vulnerability and Cyber Attacks

The dynamic structure, high mobility, and diverse operational methods of UAVs present extra physical risks to both individuals and infrastructure in urban areas [111–113]. UAVs are vulnerable to cyber attacks that can compromise their control systems and create security risks. Strict cybersecurity measures are essential to protect UAVs from unauthorized access and ensure aviation safety [114]. Anomaly detection algorithms can analyze flight data and identify patterns performing normal operations that may indicate a cyber breach. Furthermore, predictive maintenance techniques using machine learning can help identify potential vulnerabilities in these systems and prevent exploiters' attacks [115,116]. Besides, in Refs. [117,118], it is said that Blockchain technology can improve the privacy and security of UAVs, guaranteeing the protection of data shared with ground-based networks.

3.5.1. Operational Role and Capabilities

UAVs are critical components of smart cities and modern infrastructures, playing pivotal roles in traffic monitoring, surveillance, and environmental monitoring. However, their high mobility and dependency on wireless communication make them attractive targets for cyber attacks. A common scenario involves a fleet of UAVs which is deployed for real-time traffic monitoring in a smart city. These UAVs are connected to a centralized control system for continuous data transmission. An attacker launches a GPS spoofing attack to misguide the UAVs or disrupt communication channels. In such a case, ML algorithms could be employed to detect abnormal behavior patterns in UAV flight paths, while blockchain technology could ensure the integrity and security of the transmitted data, making it tamper-proof and verifiable by all network participants [76,119].

3.5.2. Technological Framework and Methodologies

Cybersecurity measures for UAVs heavily rely on machine learning ML and blockchain technology. ML algorithms are instrumental in detecting anomalies in flight paths and data transmissions, identifying potential attacks in real-time. By analyzing historical flight data, ML models can distinguish normal behavior from suspicious patterns, enabling quick responses to potential threats. On the other hand, blockchain technology ensures secure, decentralized communication between UAVs and ground stations. Every data exchange is encrypted and recorded on an immutable ledger, making it virtually impossible for attackers to manipulate or tamper with the data [120]. Table 9 below highlights some previous research related to this topic, focusing on data security and opportunistic utilization of UAVs in wireless networks.

UAVs face significant vulnerabilities due to their reliance on wireless communication, navigation systems like GPS, and software interfaces. These vulnerabilities expose UAVs to various cyberattacks that can compromise their control systems, communication, and data security. Understanding the potential risks is crucial for developing robust security measures to ensure the safe and efficient operation of UAVs in critical applications. Below are some of the primary risks and vulnerabilities faced by UAVs:

- Communication Interception: UAVs transmit data over wireless networks, making them vulnerable to interception and spoofing. Without secure communication protocols, attackers can hijack UAVs or manipulate data.
- Software Exploitation: Vulnerabilities in UAV software can be exploited by injecting malicious code, causing system failure or unauthorized data access.
- GPS Spoofing: Since UAVs rely heavily on GPS for navigation, GPS spoofing attacks can manipulate the UAV's location data, redirecting it to unintended areas.
- Denial of Service (DoS) Attacks: Overwhelming the UAV control system or communication channels with excessive traffic can lead to mission failure.

Table 9. Highlights of some previous research related to Vulnerability and Cyber Attacks.

Paper Focus	**Key Findings**	**Hardware Used**	**Software Used**	**Algorithm Used**	**Future Possibilities**
Data security for UAV multimedia transmission [121]	Uses AES encryption for secure real-time UAV multimedia transmission with low overhead.	DJI MATRICE 100, Raspberry Pi 3 and 4	Pycrypto-dome	Advanced Encryption Standard (AES)	Secure UAV data streaming.
Opportunistic UAV utilization in wireless networks [31]	Shows UAVs can support relay, collection, caching, computing, and data dissemination.	UAVs, ground sensors, base stations	Not Specified	Not Specified	UAV integration in IoT and wireless networks.
UAV vulnerabilities and threats [122]	Classifies UAV vulnerabilities and highlights battery-depletion attack risks.	Not specified	Not specified	Vulnerability taxonomy, Battery management strategies	Real-time protection against energy-depletion attacks.
Cyber attack detection [123]	Detects and isolates false-data, random-data, and denial-of-service attacks in quadrotors.	Quadrotor UAV	MATLAB	Modified Sliding Innovation Sequences (MSIS), Extended Kalman Filter (EKF)	MSIS extension to other UAV platforms.

UAVs operate in dynamic and complex environments, requiring robust technologies to secure their communication, navigation, and operations. Two key technologies that help secure UAVs from cyber threats are ML for anomaly detection and Blockchain for secure data transmission.

- Machine Learning for Anomaly Detection: Machine Learning algorithms can enhance UAV security by detecting irregularities in data transmission and flight paths. ML models, trained on normal UAV behavior, can identify potential attacks like jamming, spoofing, or unauthorized access in real-time and trigger appropriate defensive responses [124]. Additionally, to evaluate the performance of ML algorithms in detecting these anomalies, the Risk Mitigation Efficiency (RME) can be calculated using the following formula:

$$RME = \frac{T_{deleted}}{T_{total}} \times 100 \tag{10}$$

  where $T_{deleted}$ is the number of detected anomalies and T_{total} is the total number of anomalies encountered. This formula helps evaluate the effectiveness of ML in detecting cyber threats in real-time.
- Blockchain for Secure Data Transmission: Blockchain technology can be used to create a decentralized, immutable ledger for UAV communication and data exchange. Every data transaction is recorded and verified by multiple nodes, making it nearly impossible for attackers to tamper with the data or hijack the UAV's control system [120]. Table 10, showcases several access control features for UAV Operational Security.

Table 10. Access Control Features for UAV Operational Security.

Feature	**Description**
Neuro-signature Authentication	Allows only authorized operators with verified brainwave patterns to control UAVs for enhanced access security.
Real-time Pulse and Gait Analysis	Continuously verifies operator identity through unique physiological signatures, reducing the risk of hijacking.
Voice-activated Emergency Mode	Activates secure emergency protocols based on the verified vocal signature of the operator.

3.5.3. Challenges and Future Directions

As UAV technology continues to evolve, it faces several challenges that must be addressed to ensure secure, reliable, and efficient operations. These challenges involve both technical vulnerabilities and operational limitations, which impact UAV security, performance, and overall adoption. Below are the key challenges followed by potential solutions and future directions for overcoming them:

- Data Breaches: UAVs are susceptible to data breaches due to insufficient encryption and secure transmission methods.
- Unauthorized Access: Weak access control mechanisms can lead to unauthorized control of UAVs.
- GPS Vulnerabilities: GPS signals are prone to jamming and spoofing attacks.

To address these challenges and enhance UAV security and efficiency, several technological advancements and research directions can be explored:

- ML for Threat Detection: Various object detection models have different levels of accuracy, speed, and robustness [125]. ML-based systems continuously monitor UAV activity to detect anomalies, such as unusual flight patterns or data tampering, and flag potential security breaches.
- Blockchain for Tamper-Proof Data: Implementing Blockchain to ensure that every UAV transaction and

communication is securely recorded and verified across the network, eliminating the risk of data tampering and ensuring transparency.

- GPS Signal Verification: Anti-spoofing algorithms powered by ML can authenticate GPS signals to prevent unauthorized manipulation of UAV navigation.

Future UAV systems will need to implement stronger encryption methods for data transmission. This will protect sensitive information from breaches and mitigate the risk of data interception or manipulation. As UAV technology continues to grow, it is essential to establish robust regulatory frameworks that standardize security measures, such as mandatory encryption, secure communications, and access controls. Governments and regulatory bodies should collaborate with industry stakeholders to define and enforce these security standards. Additionally, anti-spoofing technologies will improve GPS reliability, while predictive maintenance driven by AI will proactively address vulnerabilities before they lead to failures. Furthermore, establishing standardized regulatory frameworks for security will play a crucial role in fostering trust and widespread adoption, ensuring that UAVs operate securely in complex environments.

4. Implementation-Based Evidence of UAV Performance Improvements

Although this paper primarily provides an overview of UAV technologies in future transportation systems, implementation-based studies are important for demonstrating the practical value of emerging methods such as ML-based perception, cooperative navigation, and autonomous decision-making. As a representative example, our recent conference work on ultra-lightweight multi-object tracking for UAVs in diverse weather environments demonstrates how lightweight ML models can improve UAV perception under operational constraints [126]. The study evaluated three advanced MOT frameworks: FairMOT with YOLOv5 and HRNet18 backbones, and ByteTrack with a YOLOX-S backbone under adverse weather conditions using the UAVDT dataset.

As shown in Table 11, FairMOT with YOLOv5 provides the most practical trade-off for UAV deployment. HRNet18 offers a marginal object-count improvement of only 0.30 percentage points over YOLOv5, but requires nearly three times longer runtime. ByteTrack with YOLOX-S achieves higher precision in the detailed evaluation, but its lower object count accuracy and longer runtime make it less suitable for resource-constrained UAV traffic surveillance. Therefore, the implementation evidence supports the use of lightweight ML-based tracking models for improving UAV perception and operational efficiency in transportation applications.

Table 11. Implementation-based evidence of UAV performance improvement using lightweight MOT models.

Model	Backbone	Parameters	Object Count Accuracy	IDF1	MOTA	Runtime
FairMOT	YOLOv5	7.2M	61.53%	54.3%	30.2%	∼8 h
FairMOT	HRNet18	21.3M	61.83%	53.2%	28.7%	∼22 h
ByteTrack	YOLOX-S	8.97M	42.46%	48.0%	27.2%	∼48 h

5. Research Directions

The future of UAV technology in transportation is set to usher in a new era of autonomy, connectivity, and sustainability. With rapid advancements in machine learning, AI, renewable energy, and material sciences, UAVs will continue to expand their roles in numerous sectors. This section delves into novel applications and future possibilities that will redefine how UAVs contribute to various industries.

5.1. Autonomous Coordination and Swarming

In the future, we can expect UAVs to operate in highly autonomous, self-coordinated swarms. These swarms will communicate seamlessly with each other, working in harmony to complete complex tasks without human intervention. Applications could range from large-scale environmental monitoring to coordinated search-and-rescue missions in disaster-hit areas. Each UAV in the swarm would take on specialized roles, optimizing task completion through AI-driven real-time decision-making [127–129]. This coordinated approach could drastically reduce the time taken for search operations, agricultural monitoring, and even forest fire containment.

Future studies should include more sophisticated metrics when exploring larger regions with mobile UAVs, as current traffic metrics remain limited in scope [121]. Additionally, there is a significant gap in creating faster and more robust object detection systems that work efficiently in constrained environments, where computational power and energy are limited [125]. Furthermore, efficient strategies are required to mitigate strong interference in cellular-connected UAV communications, particularly during high-altitude operations [98].

5.2. Smart Grids and Renewable Energy Integration

Future UAVs will play a key role in the development and maintenance of smart grids. Equipped with specialized sensors and repair tools, UAVs will monitor power lines, perform predictive maintenance, and even handle repairs autonomously. These UAVs could minimize blackouts by detecting faults early, offering real-time data analytics to improve the efficiency of energy distribution networks [6,130]. The integration of UAVs in smart grids will ensure more resilient energy infrastructures, particularly as global demand for renewable energy grows.

At present, UAV batteries make up around one-third of their mass and contribute roughly 60% of the overall expenses for operation. Increasing the duration of battery usage by 1% can result in a 2% boost in profitability [83]. The future will also see UAVs becoming self-sustaining, with built-in solar panels or other renewable energy technologies enabling extended missions. For example, UAVs equipped with flexible solar arrays could recharge during flight, allowing for continuous operations in areas with limited access to charging stations. Such systems would be particularly beneficial for applications in remote regions, where consistent UAV operation is critical [131].

5.3. UAVs for Climate Change Monitoring

The anticipated advantages of utilizing UAVs for transportation encompass economic gains (49.3%), benefits for urban populations (20.2%), and environmental benefits (11.3%), with a specific emphasis on reducing traffic, decreasing travel time, and providing environmental respite [82]. In future environmental applications, UAVs will be pivotal in monitoring climate change. They will gather real-time data on atmospheric conditions, sea-level changes, glacier melt rates, and forest density. Equipped with advanced multispectral and thermal imaging sensors, UAVs will offer unprecedented insights into environmental health. This will support global climate models and enable more precise predictions for natural disasters, thus enhancing global preparedness for climate change impacts [5,132].

Future research must also focus on conducting comprehensive assessments of the environmental, social, and economic impacts of UAVs and other high-performance transportation technologies, such as Hyperloop, to ensure their sustainable integration into existing transport networks [6]. Real-time traffic monitoring solutions for developing regions are necessary, with UAV deployment and data processing algorithms optimized to handle traffic monitoring in countries with different infrastructure and environmental conditions [57].

5.4. Blockchain and Secure Logistics

Future UAV delivery systems could be enhanced by blockchain technology, which would ensure secure and transparent supply chain management. Blockchain-enabled UAVs could autonomously verify delivery locations, ensure cargo integrity, and document the entire delivery process on an immutable ledger. This approach would be invaluable for high-value cargo, such as medical supplies or sensitive data shipments, ensuring accountability at every stage of the delivery [133,134].

Beyond their role in delivering medical supplies, UAVs are poised to revolutionize humanitarian aid and disaster relief. Equipped with modular payload systems, future UAVs will be able to deploy shelters, food, and water supplies to disaster-stricken areas. Autonomous UAV systems can map disaster zones in real-time, determining optimal delivery paths and dropping life-saving supplies exactly where they are needed, without the need for human intervention [135]. Their ability to navigate difficult terrain, such as mountainous regions or flood zones, makes them invaluable during large-scale crises.

For efficient integration of blockchain in UAV systems, enhanced predictive analytics and command recognition systems must be developed, as there has been little research into predictive analytics technologies and natural language command recognition systems in autonomous decision control systems (ADCS) for eVTOL aircraft [136]. UAV routing and in-situ sensing tasks lack integrated solutions, requiring the development of algorithms capable of handling time-sensitive and energy-constrained operations [78].

5.5. Smart Cities and IoT Integration

As cities evolve into smart cities, UAVs will serve as an essential part of the IoT ecosystem. By acting as mobile sensors, UAVs will monitor air quality, detect pollution levels, and contribute to real-time urban management systems. They will relay critical data about city infrastructure, including traffic conditions, energy consumption, and public safety, directly to municipal authorities. By integrating with existing IoT frameworks, UAVs will help optimize city operations, improving efficiency while reducing environmental impact [27,137].

Urban air mobility (UAM) systems struggle to handle data variability and integrate diverse data sources, which could be improved through advanced AI-based solutions [105]. More advanced AI-based solutions are necessary to improve UAV mobility support, especially in 3D spaces and high-speed environments [91]. Advanced UAV-based traffic monitoring systems capable of efficiently processing and integrating real-time data are needed for accurate traffic management in smart cities [18]. Effective algorithms are needed for UAV navigation systems that can dynamically adjust to evolving operational requirements and environmental conditions [81].

Efficient spectrum management, airspace regulation, and coordination between UAVs and terrestrial networks present challenges for the integration of UAVs into existing wireless networks [31]. Improved autonomous dock operations require robust control strategies to manage environmental disturbances and complex maneuvering scenarios [45].

5.6. Future Materials for UAV Construction and Self-Sustaining Technologies

With advancements in material science, future UAVs will be lighter, more durable, and capable of withstanding extreme environmental conditions. The development of advanced composites, including graphene-based materials, will significantly reduce UAV weight while increasing structural integrity. These materials will enable UAVs to fly longer distances with heavier payloads, pushing the boundaries of their current operational capacities [40]. Moreover, self-healing materials could be incorporated into UAV designs, allowing for minor damage to be repaired autonomously, increasing the longevity of UAVs in harsh conditions [138].

Autonomous dock operations require more robust control strategies to manage environmental disturbances and complex maneuvering scenarios [45]. Self-healing materials and lightweight composites will be integral to future UAVs, reducing maintenance requirements and enhancing structural durability. Further research is needed to develop adaptive computing offloading techniques to support UAV operations in smart cities, especially under variable computational loads and network conditions [34]. Below, Figure 10 illustrates the envisioned UAV ecosystem for future transportation and logistics.

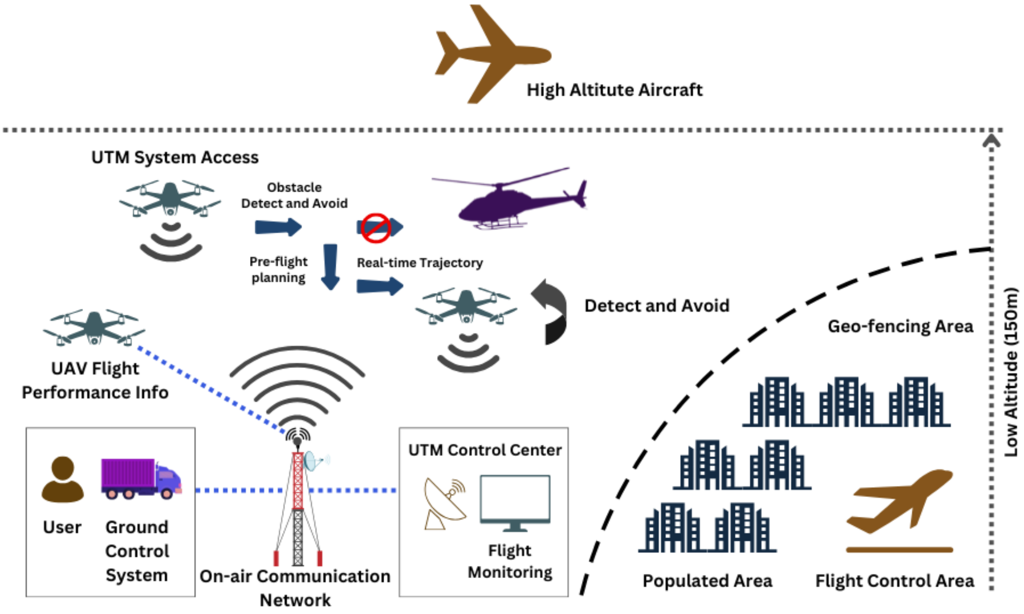

Figure 10. Envisioned UAV ecosystem in future transportation and logistics. Adapted from [4].

6. Conclusions

This paper discusses the potential and future impacts of UAVs on transportation systems, with emphasis on delivery services, urban air mobility, traffic management, infrastructure inspection, and search-and-rescue operations. ML has become central to UAV decision-making and management, particularly in route planning, maintenance scheduling, and other safety-critical operations. As UAV and eVTOL technologies continue to advance, they are expected to transform urban mobility by reducing congestion in crowded cities and improving connectivity to suburban and underserved areas.

However, several challenges remain: batteries, legislation, and acceptance. Mitigating these challenges by improving battery technologies, establishing sound policies for UAV operations, and implementing pilot community-led trials will be instrumental in specifying how best to incorporate the UAVs in the current transportation systems safely. Moreover, the future presents promising opportunities due to artificial intelligence-based vehicles, proactively controlled logistics with the help of blockchain and smart infrastructure.

With advancements in the use of UAVs, the broader integration of UAVs into society will require coordinated efforts from industry professionals, regulators, policymakers, and urban planners in order to effectively tackle these challenges and ensure the full potential of UAVs in revolutionizing transportation be met. By focusing on such fields, UAVs can provide even better foundations for development in transport systems and other sectors that are more sustainable, have improved efficiency, and are safer.

Author Contributions

M.F.F.R.: conceived the study, conducted the literature review, performed the analysis, and drafted the manuscript; I.A.: contributed to the preparation of graphs, figures, and illustrations and editing the manuscript; N.Z.: assisted with validation and verification of the findings; E.A.-R.: provided overall review, critical feedback, and final approval of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editor-in-Chief, N.Z. had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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