future transportation

Review

Advances of UAVs toward Future Transportation: The State-of-the-Art, Challenges, and Opportunities

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Abstract: The adoption of Unmanned Aerial Vehicles (UAVs) in numerous sectors is projected to grow exponentially in the future as technology advances and regulation evolves. One of the promising applications of UAVs is in transportation systems. As the current transportation system is moving towards Intelligent Transportation Systems (ITS), UAVs will play a significant role in the functioning of ITS. This paper presents a survey on the recent advances of UAVs and their roles in current and future transportation systems. Moreover, the emerging technologies of UAVs in the transportation section and the current research areas are summarized. From the discussion, the challenges and opportunities of integrating UAVs towards future ITS are highlighted. In addition, some of the potential research areas involving UAVs in future ITS are also identified. This study aims to lay a foundation for the development of future intelligent and resilient transportation systems.

Keywords: Unmanned Aerial Vehicles (UAV); drone; future transportation; intelligent transportation systems; ITS

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1. Introduction

The UAV is an aerial vehicle that does not have a human operator on board. Commonly referred to as a 'drone,' a UAV can fly autonomously or be piloted remotely. It is either operated remotely by a pilot on the ground or autonomously on a computer using pre-programmed flight plans or more sophisticated dynamic automation systems [1,2]. According to the degree of remote and/or automatic control, a UAV can be categorized as either expendable or recoverable [3]. Expendable UAVs are usually one-time use UAVs that are relatively more significant in a military context than for civil purposes. An example of expendable UAVs is kamikaze drones, which are designed to attack targets by crashing into them. On the other hand, recoverable UAVs refer to the UAVs that can be recovered and recycled after use. Civilian UAVs are usually considered to be recoverable drones [4]. Due to their unmanned capability, UAVs tend to offer a safer operating environment when compared to manned-aerial vehicles if appropriately regulated. A UAV can be an option for more dangerous missions and tasks without risking any operator's life. From the operational perspective, one major drawback is that UAVs have a relatively short flight, as compared to regular aircraft. Additionally, due to their size, which is often smaller than manned-aerial vehicles, UAVs are easily affected by the weather, and their maneuverability remains a challenge in bad weather conditions.

Starting with aerial recordings of world views, UAVs are already being implemented in various applications such as wildfire mapping, agricultural surveys, buildings and bridges inspections, powerlines surveys, pipelines monitoring, and many others. In the near future, the UAV industry will play a pivotal role in global technological advancement. At the time of writing, the emerging UAV-related market is valued at over 127 billion dollars, and this industry is predicted to create more than 100,000 new jobs [5]. Figure 1 highlights the global market size of UAVs in 2018 and the forecasted market size in 2024 for the different regions of the world [6].

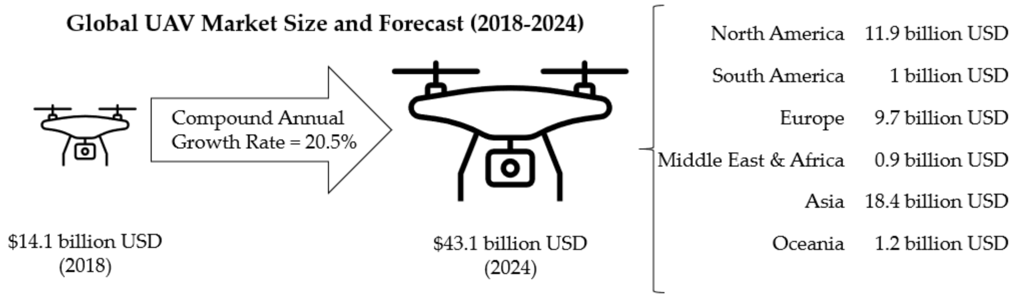

Figure 1. The global market size and forecasted global economies for UAVs in 2024 [6].

UAVs are often used for surveillance with their onboard camera. They can carry equipment other than cameras as well and can even deliver small loads. The military sector has extensively used UAVs for combat and humanitarian aid [7]. About 70% of UAVs available are used by the military sector, 17% by the consumer sector, followed by 13% used by the commercial sector. Although the military sector is the biggest market for UAVs right now, the commercial business sector has the fastest growth opportunity. Currently, the infrastructure sector seems to have the highest growth potential, followed by the agriculture and transportation sector [8]. Due to UAVs' enormous growth potential and market interest combined with the rapid advancement of technology and regulations, research on UAV-related applications and their capabilities is also rapidly increasing [9].

In recent years, the usage of UAVs in commercial industries has escalated, and UAVs are being deployed for various diverse tasks in different sectors. In the agriculture industry, farmers are using UAVs for crop data collection to help improve crop yields. UAVs are proving to be pivotal in environmental conservation efforts by providing detailed forest vegetation and water maps. They are also being used for indoor mapping and inspection by the mining industry, leading to improved worker safety. In the construction industry, UAVs are increasingly being used for mapping and surveying construction sites. This approach has claimed to result in saving both time and cost. Police, firefighters, and other rescue personnel have adopted the use of UAVs in recent years for surveillance, search and rescue, and public safety efforts. The high-resolution aerial photography and videography capabilities of UAVs have been extensively used by the film and entertainment industry.

The existing ground transportation infrastructure has become more congested each year with an increasing number of cars and reduced road capacity levels [10]. It was reported that in 2019, an average of drivers in the United States (US) lost about 99 h due to traffic congestion [11]. Many technologies and logistics industries have started to shift goods by employing UAVs to ease the unsolvable traffic congestion issues. UAVs are beginning to emerge and are slowly integrated into the current transportation infrastructures. UAVs can drastically change and become an integral part of the future transportation sector in the near future. The progress and advancement in UAV's capabilities have led to their usage in many different areas of the transportation sector.

The global UAV-assisted logistics and transportation market is proliferating, with projected market size of about 11 billion dollars by 2026, from about 5.3 billion dollars in 2019 [12]. UAVs have been employed for logistic delivery purposes in medical, e-commerce, and backyard delivery [13]. The rapid growth of UAV usage is primarily observed due to the emerging e-commerce market and growing customer expectations of faster delivery times. UAVs are also being integrated into other transportation sectors like urban planning and management, traffic monitoring, and disaster response or relief. With more and more vehicles being automated nowadays, in the future, UAVs will play a crucial part in developing a fully automated transportation system and assist in the form of the automated field support team, traffic police, road surveys, and rescue teams [14].

Despite their various potential applications, there are some limitations and concerns regarding UAVs use. Some of the issues include intrusion of privacy, UAV collisions due to loss of control, hacking, and other security issues [15,16]. These issues need to be overcome before full-fledged active deployment in real-life transportation systems becomes a reality [16]. To employ UAVs successfully in future transportation systems, it is crucial to have comprehensive knowledge about the current and potential advancements of UAVs, their challenges, and opportunities of usage in the transportation sector. Thus, this paper provides concise analyses and reviews of some recent advances of UAVs and their roles in the current and future transportation systems.

The objectives of this paper are to (1) provide the state-of-art applications of UAVs in the future transportation sector, (2) analyze the advantages and disadvantages of using UAVs, and (3) identify some future research directions in order to achieve a robust UAV-enabled intelligent transportation system (ITS) in the future. Figure 2 represents the literature review flowchart and the structure of this paper. n denotes the number of research articles and transportation-related project reports reviewed and considered during the literature review process. Note that the numbers presented are the numbers after a rigorous screening.

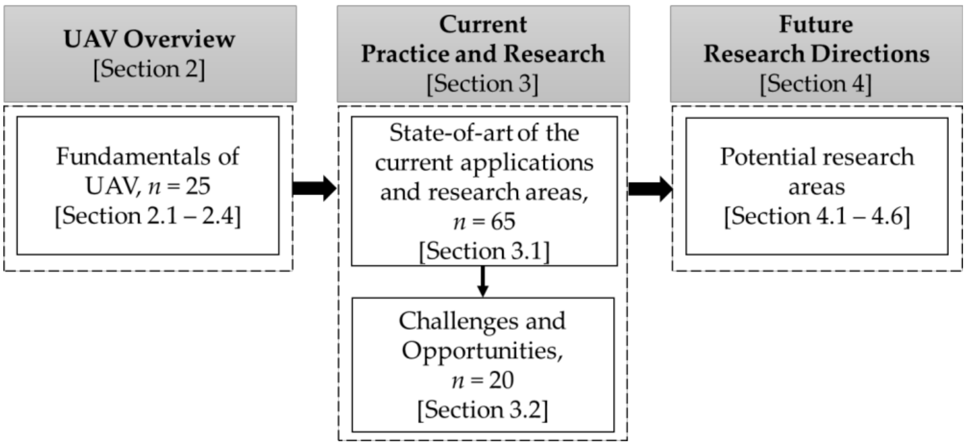

Figure 2. Literature review flowchart and paper structure (n = number of references cited).

The rest of the paper is organized as follows: Section 2 lays down the basics of UAVs and explains the fundamentals. Section 3 reviews the recent state of the art of application of UAVs in the transportation sector and identifies additional potential applications, challenges, and opportunities. Section 4 discusses the future research directions in the domain of UAV-enabled future transportation. Lastly, the concluding remarks are given in Section 4.

2. UAVs Overview

An overview of UAVs is provided in this section for a better understanding of the readers. This section explains the fundamentals of UAVs, including their general specifications, performance measures, network and communications, software architecture, and privacy and security concerns.

2.1. General Specifications

A UAV uses aerodynamic forces to provide vehicle lift. UAVs can be classified into two broad categories based on the vertical lift style: rotary-wing and fixed-wing [17,18]. Rotary-wing UAVs, also known as multi-rotors, are fundamentally rotorcraft with two or more rotors to generate lift. They can then be split up into subdivisions by the number of propellers that give the UAV vertical thrust. There are six specific subdivisions: bicopters, tricopters, quadcopters, pentacopters, hexacopters, and octocopters, refer to two, three, four, five, six, and eight-rotor, respectively. A facet of these types of UAVs is the vertical take-off and landing (VTOL) capabilities.

Fixed-wing UAVs are very energy efficient as they utilize their ability to glide to save on the fuel or energy source they are using. The most significant limitation with this UAV is the requirement of some catapult or runway for take-off and a runway for landing. They only can take off like an aircraft in the horizontal direction. Fixed-wing UAVs are generally more stable and larger, with more excellent flying capabilities, payload capacity, and endurance, but these UAVs are not as agile as multi-rotor because of their size. The hybrid UAVs take the functionality of both multi-rotor and fixed-wing. This specific type of UAV is still in the works. However, those working on it are attempting to combine the VTOL capabilities of the rotary-wing UAVs and the gliding capabilities of the fixed-wing UAVs.

When it comes to UAV structures, there is a general convention with the shape in all types. In multi-rotors, there are propellers attached to the center body via booms. Inside the propeller mechanisms, there are brushless motors and inside the body is the power source. The propellers are pointed upwards, so the UAV can remain at a constant altitude and use its VTOL capabilities. In fixed-wing, the body of the UAV typically has two wings, which often have propellers for horizontal thrust attached along the sides. As previously stated, this type is very similar to aircraft, and they use the same methods to take off cruising and landing. The major limitation to the fixed-wings is the take-off, and the rotary-wings are cruising because of battery consumption. The hybrids aim to circumvent both by taking the VTOL of the rotary wings and the cruising capabilities of the fixed-wing. Therefore, most hybrids have wings, but also propellers that provide vertical thrust [19].

2.2. Performance Measure

Specific types of UAVs have many uses throughout the public, private enterprises, and the military. In the public sector, UAVs are used more for recreational use. These UAVs are typically smaller and lightweight (<2 kg) rotary or fixed-wing UAVs. Private companies mostly use slightly larger (2 kg to 150 kg) rotary-wing and hybrid UAVs. The uses of these UAVs range from delivery of packaging to aerial photography to crop dusting to powerline inspection. The military uses mostly fixed-wing UAVs for tasks such as armed reconnaissance or surveillance. These UAVs are much larger in size and weight than the public or private sectors (>25 kg) [17].

When discussing a UAV's performance measure, it is integral to look at many things, such as maximum payload, the mass of the UAV, endurance, ceiling altitude, range of operation, and the flying mechanism. Table 1 summarizes performance measures of general rotary-wing, fixed-wing, and hybrid UAVs.

Table 1. Characteristics of different types of UAVs [17,20–23].

Flight Mechanism *	Rotary-Wing	Fixed-Wing	Hybrid
Mass (kg)	0.01 to 100	0.1 to 400,000	1.5 to 65
Payload (kg)	0 To 50	0 to 1000	0 to 10
Ceiling altitude (km)	4	0.1 to 30	n/a
Endurance (min)	6 to 180	60 to 3000	180 to 480
Range (km)	0.05 to 200	2 to 20 mil	n/a
Energy source	Battery	Fuel or Battery	Fuel or Battery

* These are estimated ranges from the references as they are specific for the specific UAV modes, but not flight group, or they did not cover all categories listed.

The payload is typically referred to as the maximum weight that a UAV can carry. The payload of a UAV could be a camera on a more miniature public-use UAV or a missile on a military-use UAV. The endurance refers to the maximum flight time of the UAV. The endurance of a UAV directly relates to the energy source, typically fuel or battery. Thus, it is also essential to consider a UAV based on its power needs and source. The ceiling altitude refers to the highest a UAV can fly. The distance from which a UAV can be controlled remotely is called its range [17].

2.3. UAV Networks and Communications

As it has been made clear previously, there are many types and uses for UAVs. This can be attributed to the components present and many vital systems, their communication and networking with other UAVs, navigation capabilities, and the software interactions in between these systems.

2.3.1. General Systems

Every UAV is different in that not every model has the same systems nor the capabilities of another. Many autonomous UAVs are equipped with a global positioning system (GPS) or global navigation satellite system (GNSS), but UAVs that are a little less advanced and require a remote pilot are not equipped with such systems [24]. GNSS is a generic term used to describe the various types of satellite navigation systems worldwide. GNSS applications for UAVs include positioning, navigation, and timing services. GPS is the most prevalent GNSS, and it is owned and operated by the United States. Figure 3 describes the various satellite systems of different countries that are typically included in GNSS.

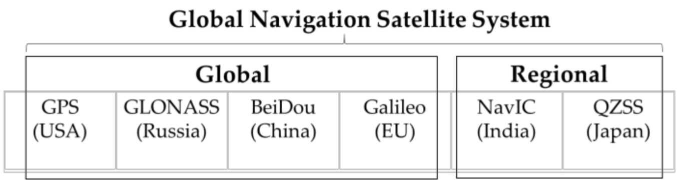

Figure 3. Satellite systems of various countries in GNSS [25].

UAVs equipped with GPS or GNSS typically can fly farther than those not equipped with either. Additionally, autonomous UAVs, or UAVs that do not require human intervention, is the UAV group kitted with the more independent systems. They are, in many cases, equipped with advanced navigation, collision avoidance, and environment detection systems, among others [26]. In the context of UAVs, the terms ‘autonomous’ and ‘automated’ are often used interchangeably, but these terms refer to different concepts. Automated systems are often limited in their tasks, and these systems function within a well-defined set of parameters. In contrast, an autonomous system is adaptive in nature and evolves following the environment around it. Autonomous UAV systems are built on the foundation of artificial intelligence and underlying machine learning capabilities, due to which they can adapt to dynamic environments [27].

2.3.2. Communications and Networks Systems

When discussing UAV networking and communications, a few definitions are needed. Three different types of aerial entities can be used as terrestrial networking: Low Altitude UAVs (LAUs), High Altitude UAVs (HAUs), and satellites. Through these entities, there is a sort of communication network. The LAUs and HAUs can communicate to each other, or other UAVs of that class, on an Air-to-Air (A2A) channel. HAUs communicate with the satellites on a Satellite-to-Air (S2A) channel. LAUs can communicate with ground objects on an Air-to-Ground (A2G) channel. This set of communication channels help develop the UAV assistance paradigm.

LAUs have many disadvantages as they are typically quadcopters, and so they have lower flight endurance, little geographical data, and lower payload capacity. Disregarding these disadvantages, LAUs are much cheaper and faster to deploy [21]. LAUs are commonly connected via a local area network (LAN) [28]. HAUs, as they are primarily found in fixed-wing, last longer in the air and are more energy-efficient to provide more extended coverage. The major drawback to this type of UAV is its cost and the possibility of interference in the networks. The satellites in this paradigm are often used to manage the HAUs' and LAUs' networks [21].

2.3.3. Navigation Systems

There are two general ways a UAV can move around. In automatic UAVs, a controller is used by the pilot and typically operated through the pilot's vision or a camera on the UAV. In autonomous UAVs, there are navigation systems. They have this for the apparent reason of no one piloting them. These navigation systems need to be extensively precise [26]. These UAVs are often fitted with a GPS or GNSS device to get the UAV's location. This would then translate to the navigation and autopilot software to find the UAV's bearing and distance left.

Because location, bearing, and distance are all variable during a flight mission, the GPS/GNSS systems send data frequently so the UAV autopilot can control the direction of flight [24]. Patrick et al. proposed a method of navigation that is extremely simple for the delivery of UAVs [24]. After the user inputs the target location, the UAV is to accept this data. Once accepted, the UAV uses the navigation systems to reach this location. After landing at the target, the UAV returns to its home (the take-off point), where it is to wait for another set of target data. Then, the UAV would repeat the process.

A significant navigation system goal is to reduce the probability of a crash and when pathfinding puts into account: stealth, feasibility, performance, and implementation. With stealth, many UAVs are used in dangerous environments; therefore, it is paramount to avoid detection. Feasibility refers to the physical capabilities regarding endurance and path length. Performance looks at minimum altitude and flight angles (turning, climbing, and diving). Implementation is likely the most important when stealth is not as important. Implementation refers to the actual efficiency of the route calculated [29].

2.3.4. Software Architecture

Previously, it was stated that LAUs were connected via LANs. A LAN is a network that connects processing systems, in this case, UAVs, in a localized area. In a LAN, a system can run multiple applications at once, meaning a UAV and a group of interconnected UAVs can do multiple tasks at once [28]. In a singular, autonomous UAV, the LAN helps the software programs communicate with each other and the flight hardware/external systems.

The general layout of the software systems includes the autopilot software, the navigation system, and the communication system [24]. This autopilot software can be broken into three levels: the execution level, the coordination level, and the organization level. These three levels all communicate with each other throughout the UAV's flight. The least intelligent but most precise level is the execution level. The execution level is responsible for sensing the UAV's surroundings as well as detecting failures. The middle level is the coordination level. The coordination level is responsible for mainly navigation, processing data, and trajectory planning. The least precise but most intelligent level is the organization level. This level is responsible for communication with other UAVs and the ground in A2G and A2A networks and decision-making [26].

In order to perform various tasks, different UAVs have varying speeds and ranges. Hence, they require different communication methods. The selection of the most compatible wireless communication methods and communication protocols greatly boosts the efficiency of UAVs [30]. The autopilot software platforms for UAVs, like ArduPilot and PX4, use certain communication protocols for UAV monitoring, control, and integration into the internet. These protocols comprise a set of messages exchanged between the UAV and ground stations. Micro Aerial Vehicle Link (MAVLink) is the most popular protocol for UAVs, which ensures bidirectional communication between the UAVs and the ground stations. MAVLink is a lightweight protocol that is apt for transmitting small amounts of data over wireless mediums [31].

2.3.5. Swarms

With the advancement of UAV systems, their usage is increasing. This also means the number of applications is increasing. When one looks at a singular UAV, the tasks that they can do are outstanding. A significant problem with a singular UAV is that they are generally slow and not very time efficient on their own. To increase efficiency, more UAVs can be implemented.

In general, a group or fleet of UAVs that work together to achieve a holistic goal is known as a swarm of UAVs. In addition to swarm, different terms are employed for multiple UAV systems based on the number of UAVs deployed. Ref. [32] provided three such classifications—teams, formations, and swarms. A ‘team’ is said to have less than ten UAVs working individually in a cooperative or competitive manner. ‘Formations’ have about tens or more of UAVs that usually interact cooperatively. ‘Swarms’ refer to a relatively larger UAV group consisting of dispensable units, in which the local interaction can be either competitive or cooperative. Ref. [33] proposed a similar classification, where multiple teams are termed a ‘squadron,’ and all squadrons collectively form a ‘group’ of UAVs.

Figure 4 depicts the pictorial representation of a UAV swarm controlled by an integrated control system. There are a variety of applications that multiple UAVs are helpful for. Video surveillance, photogrammetry, providing cellular networks, traffic monitoring, Simultaneous Localization and Mapping (SLAM), and search and rescue are just some of the applications of multiple UAVs [33].

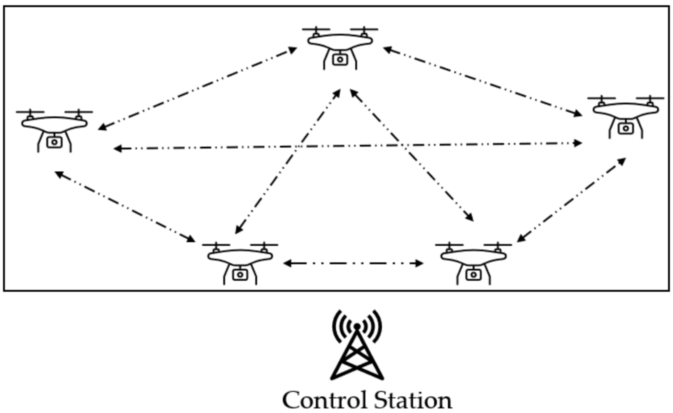

Figure 4. A representation of a UAV swarm.

2.4. UAV Security and Privacy

The use of UAVs in various sectors of the industry is rapidly growing as technology advances. However, privacy and security concerns, including proneness to hacking or theft, invasion of privacy, and collision liability, still need to be considered before the large-scale implementation of UAVs in ITS [34]. UAVs cover large areas and often fly in populated areas. This makes the system prone to hacking, and a UAV lacking security detrimental [33]. The weakness of UAV security was investigated in Ref. [35]. There are five ways a cyber-terrorist may hack and disrupt UAV usage, and most of them are highly likely to occur. The first method is signal jamming. In jamming, the culprit generates interference signals at a similar frequency band to disrupt the UAV’s reception [17,36]. Another way of hacking is eavesdropping. In this method, the hacker uses the cellular/Wi-Fi signal produced by the UAV to obtain the information being transmitted. Hijacking is yet another way a cyber-terrorist may misuse a UAV. In this case, the hijacker disrupts a UAV A2G channel and takes control of the UAV [17]. The following way a hacker may misuse the targeted UAV is by spoofing. In spoofing, the hacker acts like an entity with false information. Spoofs typically disrupt the UAV’s GPS signals [17,36]. The last way a cyber-terrorist could threaten a UAV is through Denial of Service (DoS). In a DoS attack, the hacker will send out many server requests, causing congestion in the network, and users will lose UAV service [17,37]. To prevent attacks such as eavesdropping or hijacking, higher levels of encryption would need to be put into place. In cases of jamming, one could implement a higher signal-to-noise ratio (SNR), but the power consumption in the UAV limits this method. For spoofing, one could implement a multi-antenna defense [17].

UAVs can intervene in residents' privacy if the flying path is close to the residences in urban areas, as most UAVs are equipped with cameras. Another issue is the noise of the UAVs, which might become a source of annoyance to the residents. UAV's photography capabilities can be misused. To combat this issue, a set of strict regulations and policies must be put in place by the government, such as the right for individuals to register their home address as a no-fly zone. When the issue involves national security, advanced detection technologies of unregistered drones can be implemented [38]. Moreover, other information such as the GPS location and time can be used to track anyone. Another way a user's privacy can be breached is through malicious software. In a few cases, this software can steal information from the user, such as the application data, if the UAV is operated from the user's cellular device.

Due to these safety risks and privacy concerns, the use of UAVs must be supervised and regulated by the government or the equivalent of the Federal Aviation Administration (FAA) for countries outside the US. The three main aspects of UAV regulations are controlled use of airspace by UAVs, operational limitations, and administrative procedures such as flight permits, pilot licenses, and data collection authorization [39].

3. State of the Art of Practice and Research

This section reviews the latest state-of-the-art application for UAV applications pertaining to the transportation sector. More than 100 papers were screened for this section, and about 85 papers are referenced in this section, with the most relevant information included. Google Scholar was used for finding references, and the keywords used for searching relevant papers mainly included "UAV transportation", "UAV applications", "UAV logistics", "UAV traffic management", "UAV surveillance", "UAV delivery", "UAV disaster management", "UAV remote sensing", "UAV urban planning", and "Intelligent Transportation System". The keywords were repeated by replacing the "UAV" term with "drone".

3.1. Current Practice and Research

While UAVs have their roots in military applications, they have become increasingly useful for scientific and commercial applications in recent years [40,41]. They have recently found wide applications globally, which include remote sensing, mapping, cartography, border patrol, inspection, search and rescue, fire detection, agricultural imaging, traffic monitoring, and package delivery, among many other applications. Figure 5 summarizes various usage of UAVs in both military and civil (private and public) sectors.

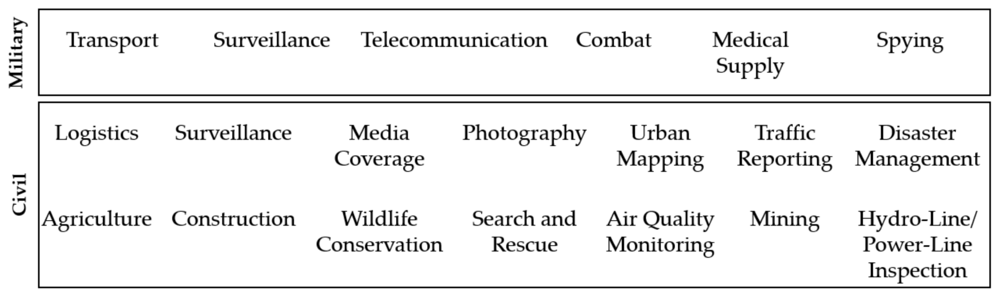

Figure 5. Usage of UAVs in various sectors [42,43].

The rapid pace of UAVs' technological advancements has led to the recognition of the widespread potential of UAVs for various applications in the transportation sector, ranging from delivery services to search and rescue during disasters. A summary of the recent UAV-related research no older than 2015 in the transportation sector is presented in Table 2. The following subsections will discuss UAVs' application focusing on the transportation sector in detail and highlight the numerous instances where the transportation industry uses the UAVs. Also, the recent research studies conducted on the use of UAVs in the transportation sector will be summarized.

Table 2. Recent UAV related research findings in the various areas of the transportation sector *.

References	Application	UAV Type/Model	Contribution/Findings
Yang et al. (2019) [44]	Surveillance	Parrot Bebop, DJI Matrix 100, DJI Phantom 2	Proposed panoramic UAV surveillance and recycling system for autonomous UAV recycling.
Jung et al. (2019) [45]	Surveillance	Multi-rotor type solar-powered UAV	Developed a photovoltaic power management system for continuous surveillance and estimated the UAV flight times using the state of charge estimation technique.
Kwak et al. (2021) [46]	Surveillance	-	Proposed a method for autonomous UAV surveillance and developed a framework based on flight records for precise control of UAVs in a complex environment.
Dwivedi et al. (2018) [47]	Surveillance, Urban Planning	Low-Altitude Long-Endurance fixed-wing UAV	Detailed design and fabrication of solar-powered UAVs for continuous surveillance operations were explained.
Erenoglu et al. (2018) [48]	Urban Planning	Mikrocopter Octocopter XL 8 multi-rotor UAV	Demonstrated a methodology to design a 3-D city model using the information provided by UAV imagery.
Latha et al. (2019) [49]	Urban Planning	Vehicle DJI Phantom 4 Pro	Presented a technical procedure for 3-D urban mapping using UAVs.
Tokarczyk et al. (2015) [50]	Urban Planning	Fixed-wing consumer micro-UAV	Demonstrated that urban drainage models with a high degree of spatial detail could be obtained via UAV imagery.
Esrafilian and Gesbert (2017) [51]	Urban Planning	-	Proposed a method for 3-D city map reconstruction using radio measurements made from UAVs flying at low altitudes and predicted the optimal UAV altitude.
Kedzierski et al. (2016) [52]	Urban Planning	Trimble UX-5	Presented an assessment of ortho-images based on UAV imagery to upgrade basic maps, which resulted in a reduction of the processing time by 40%.
Elloumi et al. (2018) [53]	Traffic Monitoring	-	Proposed road traffic monitoring system using multiple UAVs, with better performance than fixed UAV trajectory in terms of coverage rates and events detection rates.
Khan et al. (2017) [54]	Traffic Monitoring	-	Provided a framework for safe and efficient study of road traffic using UAVs by outlining all necessary hardware and software entities.
Khan et al. (2020) [55]	Traffic Monitoring	-	Proposed a smart traffic monitoring system using UAVs with 5G technology
Barmpounakis and Geroliminis (2020) [56]	Traffic Monitoring	Quadcopter DJI UAVs—Phantom 4 Advanced	Recorded traffic streams over a real-life urban setting using UAVs to investigate critical traffic phenomena.
Beg et al. (2021) [57]	Traffic Monitoring, Emergency Response	-	Proposed an intelligent autonomous UAV-enabled solution for the limitations of traffic policing and emergency response systems.
Themistocleous et al. (2014) [58]	Road Maintenance and Safety	-	Presented an approach for surveying road conditions by the integration of non-invasive remote sensing techniques with UAVs.
Knyaz and Chibunichev (2016) [59]	Road Maintenance and Safety	Geoscan 401	Presented photogrammetric techniques for road surface analysis using a UAV for obtaining road imagery.

Table 2. *Cont.*

References	Application	UAV Type/Model	Contribution/Findings
Brooks et al. (2016) [60]	Road Maintenance and Safety	Fixed-wing (Sensefly eBee), Bergen Hexacopter UAV	Conducted an experimental study in which the performance of a fixed-wing UAV was compared to that of a multi-rotor UAV for condition assessment of unpaved roads.
Congress et al. (2018) [61]	Road Maintenance and Safety	Aibotix Hexacopter UAV	Proposed and evaluated technology for infrastructure condition monitoring using UAVs. The data obtained could be used to identify distress features in infrastructure like permanent deformation and cracking patterns.
Iglesias et al. (2019) [62]	Road Maintenance and Safety	Quadcopter (Phantom 4 PRO UAV)	Presented a methodology to analyze the sight distance on highways for increasing highway safety, using UAV for data collection.
Guérin et al. (2016) [63]	Warehouse Inventory Management	Multi-rotor UAV	Presented an autonomous warehouse inventory management scheme with the cooperation of ground vehicles and UAVs.
Fernández-Caramés et al. (2019) [64]	Warehouse Inventory Management	Hexacopter UAV	Described the design and testing of UAVs using RFIDs for scanning warehouse inventory and using blockchain to receive inventory data.
Bae et al. (2016) [65]	Warehouse Inventory Management	DJI Phantom 2 Vision	Proposed a method to investigate inventory in an outdoor storage yard using RFIDs.
Javadi et al. (2020) [66]	UAV Delivery	-	Proposed a cooperative truck and UAV delivery system which combined UAVs with truck-based delivery operations with the end goal of minimizing the cumulative waiting times of customers.
Yakushiji et al. (2020) [67]	UAV Delivery, Disaster Management	M1000	UAVs could effectively provide emergency supplies (food, medicine, etc.) during disaster scenarios.
Aljehani et al. (2019) [68]	Disaster Management	-	Simulated mapping of disaster-struck areas by multiple UAVs, in which the flight plan design was based on UAV performance data and disaster area features.
Mayor et al. (2019) [69]	Disaster Management, Search and Rescue	-	Proposed a method to provide a reliable Wi-Fi communication service with a minimal number of UAVs.
Deruyck et al. (2018) [70]	Disaster Management	Multi-rotor UAV	Demonstrated that UAVs could effectively provide emergency cellular communication networks in disaster scenarios.

* Information contained in this table is summarized from references [44–70]. Any references older than the year 2015 are not included in this table.

3.1.1. Surveillance of Future Transportation Activities

UAVs have been known to possess surveillance features because of their relatively inexpensive feature, manageable size, and programmable features. With a similar purpose, UAVs also have an immense potential to contribute particularly to surveillance activities in the logistics industry. Apart from delivering packages, UAVs can be used for monitoring ongoing logistics activities and transport infrastructure. Additionally, UAVs can be used for security and surveillance in warehousing and port facilities due to their ease of access to areas that are difficult to reach for humans. Aerial surveillance can monitor vast regions with lesser efforts compared to those that are man-powered. For instance, Abu Dhabi Ports company announced using UAVs to improve protection and protect ships carrying high-value or sensitive material. To help secure products on the rail network, Polish freight carrier PKP Cargo tested surveillance UAVs and reported that the number of thefts on the network was reduced by 44% [71].

Yang et al. proposed panoramic UAV surveillance and recycling system for autonomous UAV recycling. The proposed approach was successfully tested in various challenging scenarios like poor weather conditions by employing multiple different UAVs [44]. Kwak et al. proposed a method for autonomous surveillance using UAVs considering various aspects of their operation [46]. They also developed a framework based on flight records for more precise controls of UAVs in complex environment surveillance.

With limited energy efficiency, it is challenging to keep the surveillance system running. That is why Sharma et al. proposed a low-power wide-area network (LoRaWAN)-based communication strategy to improve the UAV coverage and ensure energy-efficient surveillance with low power [72]. In an attempt towards continuous surveillance using solar-powered hybrid UAVs, Jung et al. [45] developed a photovoltaic power management system. They estimated the UAV flight times using the state of charge estimation technique. It was concluded that hybrid UAVs could obtain longer flight times during clear weather than traditional multi-rotor UAVs. A similar initiative was undertaken by Dwivedi et al. in which a detailed design and fabrication of solar-powered UAVs were laid out for continuous surveillance operation [47].

3.1.2. Future Logistics—Inventory Management

Transportation and logistics systems are highly interdependent. Good transportation infrastructures affect the success of global logistics activities. An efficient logistics system leads to a smooth day-to-day traffic environment and may promote other transportation development [73]. A primary area in the logistics sector where UAVs are emerging as the key element to improve the efficiency of the overall supply chain is inventory management.

Warehouse inventory management is an essential part of the supply chain and logistics system. Inventory management in industrial warehouses is often complicated, where multiple identical tall racks full of goods need to be navigated around for material procurement. This task is often time-consuming and can even lead to workers' injuries due to the height of the racks and the weight of the goods procured. These factors also result in a high cost of operations with low turnouts. Automating inventory management systems with the help of UAVs can save a lot of time, cut costs significantly, and prevent worker injuries. UAVs can be incorporated with unmanned ground vehicles (UGVs) for a fully automated inventory management system, as shown in Figure 6.

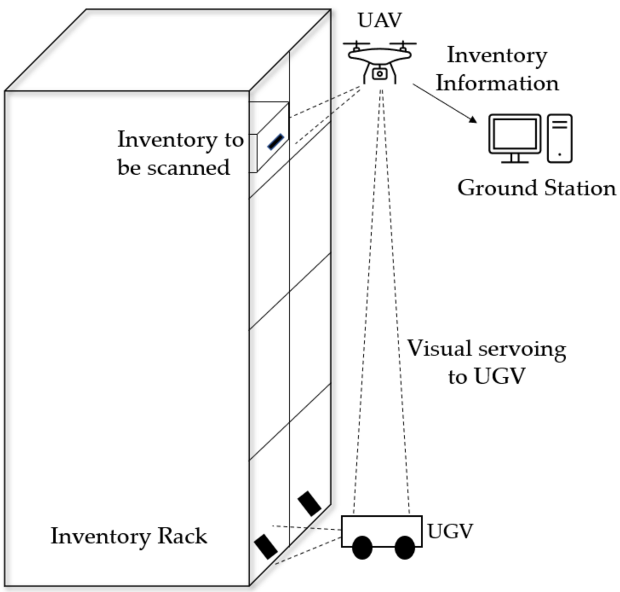

Figure 6. Autonomous warehouse inventory global architecture [63].

Guérin et al. presented an autonomous warehouse inventory management scheme in which a UGV and a UAV worked together controlled by a ground station [63]. In the proposed methodology, the UGV navigated the UAV to the inventory racks, and the UAV scanned the inventory marker for information collection. Fernández-Caramés et al. described the design and testing of UAVs using Radio-Frequency Identification (RFID) for scanning warehouse inventory [64]. The inventory data obtained by the UAV was proposed to be received using blockchain technology. Bae et al. investigated the inventory in an outdoor storage yard using UAV and RFIDs and implemented a prototype system to demonstrate the feasibility of the approach [65].

An example of a real-life case scenario where warehouse inventory management is done with the help of UAVs is a German company, Doks Innovation, which uses UAVs for automated warehouse management and inventory maintenance. The UAVs can find items in warehouses and outside areas and monitor barcodes and RFID tags, allowing them to be incorporated into warehouse administration systems, saving time and money, and minimizing errors.

An efficient warehouse inventory system leads to timely dispatch of goods and products to customers, which might help reduce traffic congestion due to delayed times and minimize traffic accidents. The next step in logistics from warehouse locations to customers is product delivery, which is another arena where UAVs are slowly establishing themselves as essential players in this field. The following sub-section will provide an overview of the current use of UAVs for delivery services in various industries.

3.1.3. Future Logistics—Delivery Services and Load Transportation

For efficiently delivering packages or parcels, UAV delivery is a highly promising application of UAVs. The potential of UAVs that can offer low-cost and faster delivery options will revolutionize how goods are delivered around the world. In disaster relief scenarios or for delivery of pharmaceutical supplies to remote locations, the use of UAVs can be valuable in cutting the cost and time involved in non-standard delivery networks [71]. However, the technology is still in its early stages of testing and is only available in a very specific region.

UAV delivery has a number of advantages over the conventional means of delivery. UAV delivery is much faster due to the fact that the UAVs are often unaffected by road infrastructure and traffic conditions. If permitted, UAVs travel via an optimal aerial path from origin to destination. It is also cost-effective in terms of delivery time and being environmentally friendly. UAV delivery produces significantly lesser carbon footprints as compared to the standard road-based delivery methods, like package delivery with trucks [74]. In the United States, Amazon Prime Air is a futuristic delivery service that aims to offer packages to customers in under half an hour via UAVs. Following the lead of Amazon Prime developing a fleet of UAVs for small parcel deliveries, several businesses like DHL, Google, Mercedes-Benz, and UPS also continue to improve delivery technology while trying to comply with different regulations to use UAVs in the urban logistics sector [13]. Domino's Pizza has also begun testing UAVs to deliver the order to the customers.

Along with the delivery services, many other researchers have also been working on efficient load transportation strategies employing UAVs. The performance of the UAV flight time is directly associated with the load they are carrying. In future transportation systems, the load may include passengers loads in addition to a large number of packages. This will be another new paradigm of UAV usage.

With the emerging investigation, several dimensions and limitations of UAV load transportation have been unfolded. One of the critical issues of UAV load transportation is the trajectory tracking problem. To solve this problem, Rafo and Almeida proposed a nonlinear control strategy for transporting a suspended load [75]. Another challenge is navigating UAVs by avoiding obstacles along the way to ensure successful delivery. Pizetta et al. investigated the importance of the inclusion of obstacle avoidance techniques in navigation UAVs in the forestry environment [76]. Along with many other applications, the use of multiple UAVs in load transportation is also explored. Hedge and Ghose discussed the application of multi-agent load transportation agriculture spraying [77].

3.1.4. Remote Sensing of Future Transportation Infrastructures

UAVs have already been implemented for remote sensing applications, which refers to identifying and monitoring an area's physical features by measuring the reflected and emitted radiation from a distance. This process requires data acquisition with the aid of specialized cameras and sensors. UAVs can provide a safe and cost-efficient way of data acquisition. They can also operate at low altitudes, resulting in ultra-high-resolution spatial data. Remote sensing is a generic and broad term. Its various applications, primarily in the transportation sector, encompass vehicle navigation, monitoring rural roads' conditions, measuring vehicle emissions, urban planning, and other traffic management [78].

Information regarding road pavements' health and damage level could be obtained non-invasively using remote sensing techniques. Themistocleous et al. presented an approach for surveying road conditions by integrating remote sensed aerial and satellite visual and thermal image data from UAVs, spectroscopy, and ground-penetrating radar [57]. Knyaz and Chibunichev presented photogrammetric methods to analyze road surface analysis using a UAV to obtain road imagery [59]. This imagery was then used for three-dimensional (3-D) reconstruction of the road surface.

In the experimental study by Brooks et al., the performance of a fixed-wing UAV was compared to that of a multi-rotor UAV for condition assessment of unpaved roads. It was concluded that multi-rotor UAVs could provide better resolution than fixed-wing UAVs, and fixed-wing UAVs should be preferred when data collection takes a long time [60]. Iglesias et al. presented a methodology to analyze the sight distance on highways for increasing highway safety. A small UAV was employed to collect the data in this experimental study, and subsequently, a 3-D road environment model was built [62]. This model was concluded to be adequate for sight distance assessment on highways, thus increasing highway safety and possibly preventing road accidents. Congress et al. proposed and evaluated technology for infrastructure condition monitoring, using UAVs coupled with a high-quality camera and a global navigation satellite system [61]. The data obtained can be used to identify distress features in transportation physical infrastructure like permanent deformation and cracking patterns.

3.1.5. Urban Planning of Future Transportation Infrastructures

Due to the flexibility in data acquisition and sensor integration, in the domain of urban planning, UAVs can collect the spatial extent and setting of urban areas, the spatial distribution of the varied land use and land cover types, census related data, and land change detection over a period of time [79]. The Department of Transportation (DoT) can employ these data to study and plan the expansion of the current transportation infrastructures or networks.

Erenoglu et al. demonstrated a methodology to design a 3-D city model using the information provided by UAV imagery [48]. Their research concluded that urban planners could effectively use UAV data for 3-D city modeling in terms of boundary mapping, change monitoring, and topographical surveying applications. A similar study by Latha et al. presented a technical procedure for 3-D urban mapping using UAVs, considering site area, built-up area, building dimensions, building setbacks, and building height as the primary measurement parameters [49].

A research study by Tokarczyk et al. demonstrated that urban drainage models with a high degree of spatial detail could also be obtained via UAV imagery [50]. Esrafilian and Gesbert proposed a 3-D city map reconstruction method using radio measurements made from UAVs flying at low altitudes [51]. The optimal altitude for UAVs was predicted analytically based on the reconstruction quality of the map. Kedzierski et al. presented an assessment of ortho-images based on UAV imagery to upgrade basic maps [52]. The experimental study concluded that the accuracy of UAV-derived ortho-images was sufficient, and the update of basic maps using these ortho-images reduced the processing time by 40%.

3.1.6. Future Intelligent Transportation Systems (ITS)

With the world population forecasted to be doubled by 2050, there is an increased interest in innovative smart city development. For designing smart cities, there is a need to fully integrate the information and communication technology solutions and their trends. UAVs can be integrated tighter with the vision of creating smart cities. An intelligent transportation system is one of the key elements for developing a smart city. With the continuous advancements in ITS, efforts have been made for the worldwide deployment of smart vehicles. As the number of autonomous and connected vehicles increases, many new elements and services will be enabled.

Some of the possible ITS applications of UAVs and the potential challenges for UAV-enabled ITS in smart city development are identified by Menouar et al. [14]. These include flying accident report units, flying roadside units, and flying police eyes. One of the most investigated areas is the development of a UAV-enabled traffic monitoring system. To date, UAVs have been used to collect traffic information in image or video formats, but still, the full-fledged usage of UAVs in real life for road traffic management is in the early stages of development [20,54,80].

Kanistras et al. performed a survey on the variety of UAV-based traffic monitoring systems that were proposed by several researchers [81]. Khan et al. systematically reviewed the research studies conducted in traffic monitoring and analysis by UAVs until the year 2016. They provided a detailed step-by-step framework in this domain [54]. Barmpounakis et al. presented a review of existing literature until the year 2016 about UAV applications in the transportation sector, including traffic monitoring and management [82].

Up to the year 2018, most of the existing UAV-based traffic monitoring systems only used one UAV with a fixed trajectory to extract vehicle information. Khan et al. proposed a smart traffic monitoring system that can use UAV with 5G technology [55]. Elloumi et al. proposed a road traffic monitoring system using multiple cooperative UAVs [53]. It was concluded that the performance of the proposed multiple UAV system was better than that of the fixed UAV trajectory traffic monitoring system in terms of coverage rates and event detection rates. In another recent research study, Barmpounakis and Geroliminis conducted an experimental research study to monitor urban congestion with a swarm of UAVs [56]. In the study, traffic streams were recorded in a congested urban setting using a UAV swarm to investigate critical traffic phenomena.

Another major area of the current application is how to retrofit the existing transportation infrastructure to accommodate UAVs for future ITS. Ghazzai et al. investigated the UAV docking station placement problem for ITS [83]. In their following research, a generic management framework of UAVs for ITS was developed [84]. Figure 7 depicts an example case scenario for UAV-enabled ITS, adapted from Ref. [14].

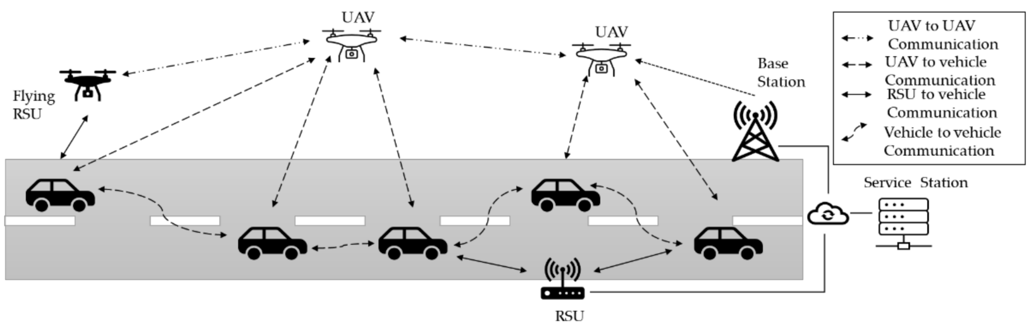

Figure 7. An example case scenario for UAV-enabled ITS [14].

UAVs are introduced in ITS as a tool for traffic monitoring that requires coordination between UAVs and vehicles. UAVs could also be utilized as Roadside Units (RSUs) to support communications by ensuring reliable internet access, emergency response, and other safety notifications [85]. Compared to fixed RSUs, UAVs have an additional degree of freedom due to their three-dimensional mobility. Fixed ground-based RSUs only detect incidents in areas within their specific range, and they are subject to placement restriction constraints. In comparison, due to the flying abilities of UAVs, challenges such as area coverage size and road network restrictions can be overcome. Hence, UAVs' wireless channel qualities and communication ranges can be superior to that of the fixed RSUs [84].

Both vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2X) communications could be ensured by using UAVs. The communication network between UAVs and vehicles needs to be kept functioning all the time to ensure the operation of ITS. This requires UAV communications to be energy-efficient so that the UAV could fly for a long enough time. Ahmed et al. designed a UAV trajectory path for establishing energy-efficient UAV communication [86].

Enhancing the communication networks could improve the data routing through UAVs. For this purpose, researchers have worked on considering UAVs as mobile aerial RSUs ad-hoc vehicular networks (VANET) in recent years. Oubbati et al. proposed a routing technique for VANET named UVAR (UAV-Assisted VANET Routing Protocol) to improve the reliability of data delivery [87]. The data routing process becomes challenging due to rapid topology changes, high vehicle mobility, and connectivity issues [88]. To overcome the routing issues, Fatemidokht et al. proposed a routing protocol that includes two ways of routing [89]. Data collection using UAVs is also challenging due to the limited resources of UAVs. As direct data collection from all storage devices is not possible, this could result in unfair data collection. Li et al. proposed a UAV speed control-based fairness data collection (USCFDC) scheme to address this issue [90].

3.1.7. Future Transportation for Emergency Response and Management

With the continuous growth of population and number of vehicles, violation of traffic rules and unexpected incidents also increases. Moreover, the transportation system is significantly affected during disasters. The current transportation system would not be responsive enough in a shorter period to handle any emergency circumstances. Incorporating UAVs in the transportation system might reduce the emergency response time. With the real-time emergency response system, the extent of traffic congestion can be reduced. Autonomous UAVs can play a significant role in the regulation of real-time emergency response. Some work has been done to design a UAV-based real-time emergency response system. Zhao et al. established a unified framework for a UAV-assisted emergency network [91]. It included both trajectory scheduling and communication network design. The emergency response system can be made more responsive with autonomous UAVs. Beg et al. proposed an intelligent autonomous UAV-enabled solution for the limitations of traffic policing and emergency response systems [57]. Apart from these, UAVs could also be employed in medical emergencies [92].

Moreover, UAVs have been successfully employed during disasters and post-disaster scenarios for various applications ranging from monitoring hazards such as floods, fires, and landslides, to disaster response, relief, and recovery [93,94]. Due to their surveillance and sensing capabilities, UAVs enhance the effectiveness of responders. They can also provide the view of disaster-struck areas at low altitudes, which cannot possibly be accomplished by manned aircraft. UAVs are invaluable in search and rescue operations, as they can scan through vast and remote areas with much more ease than humans can [95]. UAVs have been used to deliver supplies and recover hazardous materials. UAVs can be deployed to provide communication capabilities in the cases of destroyed communication channels or damaged transportation infrastructures [93].

In a recent research work by Garnica-Peña and Alcántara-Ayala, a review of the current applications of UAVs in the field of hazards and risks associated with landslides was conducted [96]. An experimental study by Yakushiji et al. examined UAV-assisted transportation in Japan and highlighted the potential uses of UAVs for medical and food supply in disaster-struck regions where transportation efforts by road means are infeasible [67]. Deruyck et al. proposed a deployment tool for UAV-aided emergency communication networks for disaster scenarios. [70]. Huang et al. developed a UAV-based highway landslide warning and emergency response system [97]. Mayor et al. proposed a method that focused on dispatching a minimal number of UAVs to provide reliable communication service in disaster scenarios [69]. Aljehani et al. simulated mapping of disaster-struck areas by multiple UAVs [68]. Figure 8 represents a scenario of a post-disaster mapping mission undertaken by fixed-wing and multi-rotor UAVs with users and ground control stations in the loop [68].

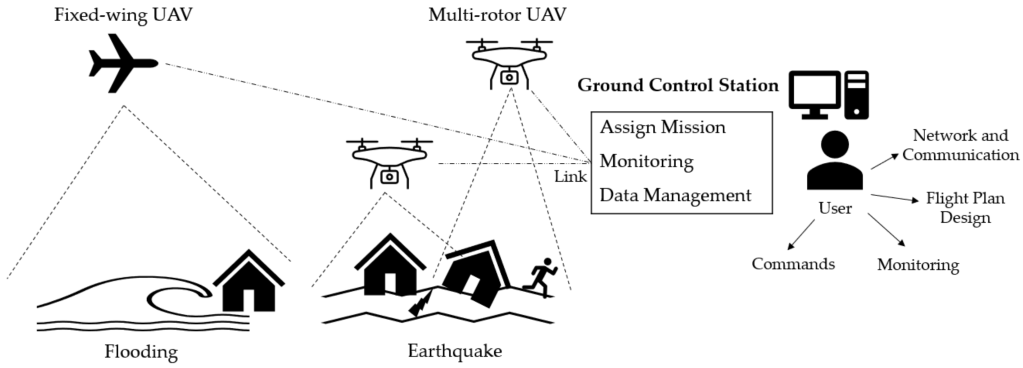

Figure 8. Post-disaster mapping mission, and user and ground control station use case [68].

3.2. Challenges and Opportunities

UAVs seem invaluable to the transportation industry in reducing time, cutting costs, increasing work quality, and even saving human lives. Topographic surveys for site visualization can be carried out ten times faster and with better precision by UAVs than the traditional manual surveys [98]. UAVs have also been reported to reduce infrastructure health assessment costs up to 90%, in some cases [99]. Search and rescue UAVs have played a crucial role in saving lives during a disaster, and various emergency scenarios, with more than 500 lives reportedly saved so far [100]. These are some of the many contributions of UAVs, and these statistics are only going to improve further with the advancement of UAV technology. However, the use of UAVs in the future transportation sector comes with certain challenges and limitations.

A current technological shortcoming regarding UAVs for logistics and delivery is that the battery life of UAVs is limited, which constraints the operational range. Commercial UAV batteries currently offer a flight time of around 10 to 20 min, rarely up to a couple of hours. Flight time and battery life are also dependent on the UAV's weight as well as the weight of the shipment [101]. Due to the energy limitation, UAVs are often used for temporary or short time purposes. The long-term mission of UAVs remains a challenge.

Although the technological advancement of lithium-ion batteries is increasing as the year progresses and the average battery life is predicted to double by 2025, it will still be some time before a fleet of UAVs can replace the ground transportation delivery trucks that can operate for a full day, and beyond. Thus, the current opportunity for UAVs is to complement the delivery truck to reduce operating costs and minimize the delivery time.

In addition to the onboard battery capacity, similar to other autonomous ground vehicles, UAVs also suffer from a longer charging time compared to refueling time in traditional manned aircraft. However, there is no doubt that the flight time of commercial UAVs will improve without recharging, enabling them to deliver more goods along with the advancements in the energy sectors, such as renewable energy sharing, faster-charging process, and more extensive portable energy storage.

For continuous operation of battery-based UAVs, swapping, laser-beam inflight recharging, and tethered technologies are being investigated [102]. Swapping enables the UAVs to recharge their batteries using docking stations. Laser-beam inflight recharging technology includes the transfer of light energy to UAVs in-flight and the conversion of that energy to electricity. Tethering refers to the continuous power supply through power lines. A hybrid power supply system is also preferable for UAVs for increasing their endurance and operating times. The hybrid power system typically involves combining the UAV battery with various energy sources such as fuel cells, solar cells, and supercapacitors.

Many researchers studied the trade-offs between shorter flight time and UAVs' operating and maintenance costs to overcome the previous issue and make UAV delivery more practical. More research is needed to address certain UAV aspects like localization and navigation, UAV coordination, and UAV designs towards implementing drones in the logistics sector [103]. UAV-enabled surveillance works much better with multiple UAVs rather than a single UAV. Due to this, efficient and accurate multi-UAV cooperation algorithms for more advanced data collection and sharing should be developed [103]. Sah et al. identified UAV regulations challenges and threats to privacy and security as one of the most critical barriers to realizing the UAVs for logistics purposes [104].

In disaster scenarios, scouting the area with automated UAVs might not be apt as disaster situations require time-critical actions and UAVs have limited battery life. In these situations, the use of partial external inputs to guide the UAVs might be recommended [15]. For efficient healthcare and relief operations, UAVs and UGVs can be integrated and automated for seamless and faster operations [105]. UGVs can be used for bulk transportation of heavy goods and people. UAVs can be deployed to deliver relief supplies like medicine, hygiene products, food, and water to the affected regions. Additionally, it is not easy to fly UAVs in harsh natural environments, with high wind and obstacles. Some UAVs are now equipped with collision technology to prevent UAVs from colliding with trees, buildings, or other obstacles [106]. However, the inherent problem of controlling UAVs in harsh weather conditions remains a challenge, although a lot of effort has been directed towards the advancements of robust UAV controllers in these situations.

In response to traffic congestion, an urban transportation system that moves passengers or cargo by air via highly automated aircraft is being envisioned. This system is known as 'Urban Air Mobility' (UAM), and it will mainly consist of electrical VTOL UAVs [107]. Advanced Air Mobility (AAM) is conceptualized as an extension of UAM that will encompass transportation to longer distances and geographically distant regions. FAA is working towards identifying infrastructure needs and operational frameworks for UAM and AAM, and these systems will become an essential part of our transportation system in the near future [108].

In addition to the technological advancements, a lot of new policies and regulations have to be carefully developed. There is a need to implement a safe, reliable, and efficient use of UAVs in the airspace. In the future, the airspace will be crowded with UAVs for multiple purposes and applications. Additionally, UAVs need to share airspace with current manned aircraft and spacecraft. The current traffic management systems for the ground, water, and rail are not adequate for managing airspace. Preliminary research on the UAV traffic management (UTM) system is actively being conducted in various countries—the US, China, Taiwan, Korea, Sweden, and India, to name a few; but these research works are still at a prototype stage [5,107,109–112]. The goal of UTM is the safe integration of UAVs in the low-altitude air traffic, and it focuses on strategic deconfliction of multiple aircraft [107]. This can be achieved by employing digital sharing of planned flight details of the UAVs present in the airspace for situation awareness of all the operators. Ideally, UTM should be fully autonomous, and direct human input in busy urban UTM operations should be minimal [113]. Figure 9 represents a conceptual diagram of low-altitude UTM, adapted from Ref. [114].

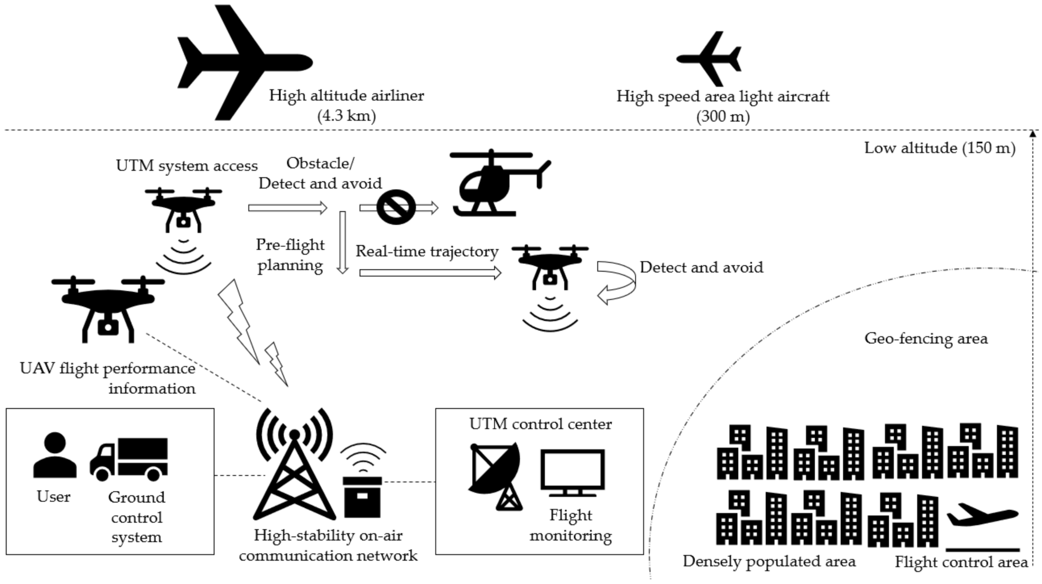

Figure 9. Conceptual diagram of UTM system [114].

In this section, the recent UAV research and applications in the transportation sector are discussed and summarized, and some of the key challenges are identified. UAVs are slowly being integrated and deployed in the transportation sector with promising results, and the potential to expand UAV applications in this sector keeps on increasing.

4. Potential Research Directions

As the current ground transportation system becomes more congested with more cars and failing old infrastructures, UAVs are deemed the future of transportation. UAVs will be employed as the new generation of transporting people and goods from one location to another that will occur in the sky [115]. Although there are many complex problems to be solved before this future transportation system can be realized, these problems are solvable by researchers from multidisciplinary areas. In recent years, significant advancements have been achieved by UAVs application in the transportation domain. However, there are some challenges and limitations in the current developments that need to be investigated and solved in the near future. In this section, some potential research areas related to the advancement of UAVs towards future transportation are discussed as follows.

4.1. Artificial Intelligence (AI) and Autonomous UAVs

The use of UAVs for transportation system automation is a new research paradigm considered among transportation experts. One of the key elements of future ITS would be the integration of AI with autonomous UAVs in the transportation system. Autonomous UAVs are operated by software without any human intervention. The integration of AI with autonomous UAVs enables automated regulation of UAVs for traffic monitoring and collection of traffic data. AI enables real-time data streaming, which provides continuous monitoring and feedback. Although AI facilitates the overall automation of ITS, the regulation and navigation of autonomous UAVs are quite challenging. There are several highly populated areas with large infrastructures where autonomous UAV regulation can be very complicated to implement. In the future, this issue should be addressed.

To achieve the automation of the overall transportation system, automating only UAVs might not be sufficient. Other transportation system components, including the field support team, traffic police, traffic monitoring, and emergency rescue teams, can also be automated and AI-assisted. A future transportation system that includes UAVs and other automated vehicles is not a simple transportation system to be developed. Many multidisciplinary practices and perspectives should be considered before the actual implementation in reality.

4.2. UAV Deployment Optimization

There are a number of UAV deployment challenges that are still under investigation. The existing regulation and air traffic policies for UAVs restrict the full utilization of UAVs in ITS. Although it might be possible to regulate the conventional UAVs under national policies, it can be complex and unpredictable with autonomous UAVs. As the main aim in the future is to use autonomous UAVs for ITS, introducing collision avoidance systems in autonomous UAVs should be first investigated to ensure that the UAVs are safe to be employed in the shared airspace with current aircraft and spacecraft.

Another potential challenge of UAV deployment is coordinating UAVs and vehicles for maximum coverage. Both UAVs and other ground (man and unmanned) vehicles will be very dynamic in their operating state. Although several optimization problems had been developed to achieve maximum coverage and path planning, these efforts often do not consider the automated UAVs.

Moreover, the deployment of swarms of UAVs is another sector that needs extensive attention. In future transportation system scenarios, as a larger scale of UAV swarms will be deployed simultaneously in a different part of the cities, all deployment optimization problems should include constraints regarding the swarms of UAVs capability and operating conditions as well as the safety factors.

4.3. Design UAVs for ITS

To establish a robust UAV-based ITS, the design of UAVs should follow all the ITS requirements. Although there has been immense progress in UAV technology, there are still some limitations in both UAVs and the infrastructure design related to ITS applications. One of the main concerns of conventional UAVs is their capacity to fly as long as the monitoring requires. UAVs are primarily still battery-operated and have operating time constraints. However, the ITS also requires continuous monitoring of the traffic. The use of alternative energy resources and charging time optimization can be a potential research direction. This can enable a longer flying time for UAVs to ensure uninterrupted traffic monitoring.

Additionally, more challenges lie in collecting valuable data through UAVs. This requires the addition of a variety of sensors in UAVs. Currently, GPS and visual data can be collected through UAVs. These data are processed to retrieve useful information. In the future, the research should focus on developing an in-built image processing unit in UAVs so that the data processing time can be reduced. Also, multi-sensors data processing capability can be included in the UAV design.

4.4. Security in ITS

Although security issues relating to UAV-enabled systems have been extensively addressed in many research works, ensuring the ultimate security is still under investigation. The future ITS will involve interconnected systems of UAVs, vehicles (air, ground, water, and rail), and roadside infrastructure. The UAVs can carry, generate, and transfer valuable data and sensitive information about both vehicle users and UAV operators. This information includes vehicle information, location, and traffic data. As UAVs and vehicles are connected to a communication network, they can be tracked, and the information can be leaked for malicious purposes [37]. Besides, some UAVs can be manipulated to execute attacks on sensitive ITSs data. Any of these data needs to be adequately protected against unknown intruders. Providing security to prevent any unexpected intrusion would be a significant challenge. Moreover, the privacy of the users should be ensured with the emerging ITS technology. Although cybersecurity has always been a widely explored area, it still needs more advancements as the future ITS will build upon a UAV-vehicle network.

4.5. Energy Optimization

The energy limitations of UAVs are a great challenge to establish a long-term UAV-monitoring system in ITS application due to short battery life. The battery life of conventional UAVs is usually less than half an hour, which could create significant challenges for ITS operations with autonomous UAVs. Because of the short battery life, the average flight time also decreases. Although various energy consumption models for UAVs are developed, the energy consumption of autonomous UAVs is still to be explored.

In future ITS, UAVs should consist of long flight time, more sensor operation capacity, continuous connection with the communication network, and emergency response capacity. All these operations require a considerable amount of energy, which is limited in typical UAVs. In addition to advances in battery materials and options, the investigation of maximizing the flight time, operability, and coverage of autonomous UAVs by optimizing energy can be explored in the future. In addition, the use of solar and renewable energies can also be investigated further.

4.6. Limitations in Information

Future ITS is a complex domain of research that is still under investigation. Although extensive development has been made in this area, the amount of available information is limited as most system components are still not implemented widely. Many researchers have proposed the layering of the system, which provides an idea of the UAV-based future ITS. As it is not implemented yet, many limitations and challenges are still unknown. It is difficult to assume the everyday challenges of UAV implementation in future ITS. There will be a lot of unforeseen risks, as well as opportunities. More experiments implementing UAV applications in ITS can be explored in future research.

With the advancements in global technology, the overall current transportation system is indeed changing towards the ITS concept. As UAVs are one of the essential elements of future ITS, significant improvements, retrofits, and upgrades must be made in the current transportation system infrastructure. These efforts require rigorous research and experiments of UAVs on a smaller scale prior to the actual implementation. Popular research areas that are currently under investigation are UAV-assisted ITS, data routing and communication, energy-efficient ITS, load transportation, and emergency response.

Although significant technology development of incorporating UAVs in ITS has been observed, other areas such as policies, management, and security issues need to be investigated to achieve the ultimate goal of employing UAVs in the future ITS. This study provides an overview of the current state of the art and directs toward future development. The identified challenges can help both the transportation researchers and the Department of Transportation (DOT) understand the underlying improvements necessary for the ITS development.

5. Conclusions

UAVs are potentially one of the fundamental elements of the future ITS. This paper summarized the recent advances of the research on UAVs and their roles in the current and future transportation systems. An overview of the fundamentals of UAVs, including their specifications, performance measures, network and communications, software architecture, and privacy and security concerns, have been provided. The state-of-art of current and potential applications of UAVs are also discussed. UAVs are currently employed in surveillance, logistics services, urban planning, transportation management, and disaster management. From this discussion, some key challenges of using UAVs are identified. With the advancements in UAV applications in transportation, various research areas have also emerged towards the vision of developing ITS. Some of the current research areas are discussed in this paper. Based on the current research areas, few potential research areas are identified. This paper provides an overview of the advancements and limitations in research on UAV technology in future ITS, which will help achieve a robust and resilient ITS in the future.

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