remote sensing

Review

A Review of Flying Ad Hoc Networks: Key Characteristics, Applications, and Wireless Technologies

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Abstract: Recent advances in unmanned aerial vehicles (UAVs), or drones, have made them able to communicate and collaborate, forming flying ad hoc networks (FANETs). FANETs are becoming popular in many application domains, including precision agriculture, goods delivery, construction, environment and climate monitoring, and military surveillance. These interesting new avenues for the use of UAVs are motivating researchers to rethink the existing research on FANETs. Therefore, this paper provides a comprehensive and thorough review of the different types of UAVs used in FANETs, their mobility models, main characteristics, and applications, as well as the routing protocols used in this type of network. Other important contributions of this paper include the investigation of emerging technologies integrated with FANETs.

Keywords: unmanned aerial vehicles; UAVs; drones; flying ad hoc network; cloud-based UAV systems; cellular networks

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1. Introduction

Recently, Unmanned Aerial Vehicles (UAVs), or drones, which can be either remotely piloted by a human on the ground or autonomously controlled by on-board computers, have been widely used for wireless communication objectives [1,2]. UAVs perform many different missions, ranging from military tasks to agricultural applications. An ad hoc network can be created with a group of flying UAVs; this is called a Flying Ad hoc Network (FANETs) of UAVs [3]. The different types of UAVs employed in various FANET scenarios can be classified based on such different factors as UAV size, weight, range, endurance, altitude, application, flying mechanism, ownership, airspace class, level of control (autonomy), and type of engine [4]. Recently, several studies have shown the importance of FANETs by investigating the integration of FANETs of UAVs with different technologies, including Virtual Reality (VR), [5–9], IoT [10–12], flying edge computing [13], flying fog computing [10,14,15], cellular networks [16–19], and flying cloud computing [20]. Although such integration brings many advantages, many issues may arise as well, ranging from UAV deployment issues to regulations on using these devices. These interesting new avenues for the use of UAVs and the growth of the UAV market ae motivating researchers to rethink existing studies on FANETs. Therefore, this paper provides a comprehensive overview of the main aspects of FANETs, the different types of UAVs used in FANETs, their mobility models, their main characteristics and applications, the routing protocols used in this type of network, and the main technologies integrated with FANETs which can open new perspectives for the use of these devices. The main contributions of this paper can be summarized as follows:

- In addition to an extensive study of the existing academic research, this paper presents a comprehensive UAV classification taxonomy covering gaps not considered in previous surveys.
- A comprehensive effort specifically discusses FANET characteristics and applications, connecting them to the most commonly used routing protocols, UAV mobility models, and Cloud-based UAV Managing Systems (CBUMS).
- A prospective discussion is presented on current investigations of emerging technologies integrated with FANETs and the possibilities they can open for future applications.

The overall structure of this paper is as follows: A comprehensive UAV classification based on UAV size, weight, range and endurance, altitude, flying mechanism, airspace class, degree of autonomy, engine, and applications is provided in Section 2. Section 3 discusses the main characteristics of FANETs. Sections 4–6 address the main applications of FANETs, routing protocols in FANETs, and UAV mobility models, respectively. The main technologies integrated with UAV-networked systems and the main components of cloud-based UAV-networks are discussed in Sections 7 and 8, respectively. Section 9 discusses the various simulation tools used to design UAV-based networks. Section 10 discusses possible future directions, including the challenges of new technologies integrated with FANETs. Finally, Section 11 concludes the paper by highlighting the main findings of this review.

2. UAV Classification

There are different types of UAV classifications in the literature. As shown in Figure 1, in this SLR, a comprehensive UAV classification is provided based on different factors such as UAV size and weight, altitude, range, application, flying mechanism, ownership, airspace class, level of control autonomy, and engine type [21], all of which are shown in Figure 1. Size is often a major factor in deciding which UAV is appropriate for a mission. As shown in Figure 1, box *A*, UAVs can be classified into *Very small* sizes with very light weight, such as Micro Aerial Vehicles (mUAVs) and Nano Aerial Vehicles (NAVs), *Small* sizes such as Mini-UAVs, and *Medium* and *Large* UAVs that are heavy or super heavy [22]. The classification of UAVs based on weight, endurance, and altitude is provided in Figure 1, boxes *B*, *C*, and *D*, respectively. Table 1 classifies types of UAVs by their different sizes, altitudes [23–28], weight, range, and Eendurance.

Depending on their flying mechanisms, as shown in Figure 1, box *E*, UAVs can be classified into Fixed-wing drones, Multi-rotor UAVs (rotary-wing), and Hybrid fixed/rotary wing UAVs [16].

Fixed-wing UAVs that can be controlled either autonomously using onboard computers or remotely by the pilot can fly using wings in the same way as aeroplanes. Multi-rotor UAVs have at least four rotors to keep them flying, and hybrid models combines the benefits of two.

Another possible classification of UAVs is that shown in Figure 1, box *F*, which is based on the airspace class; very low altitude UAVs operate in Class G airspace, with the possibility of the aircraft being flown beyond the line of sight of the operator. Medium and very high altitude UAVs operate in Class A through E airspace and Class E airspace, respectively.

The International Civil Aviation Organization (ICAO) classifies UAVs based on the degree of autonomy in their flight operations into two main categories, namely, fully autonomous and remotely piloted aircraft, as shown in Figure 1—box *G*.

As shown in Figure 1, box *H*, UAVs can be classified based on their ownership as public or private, that is, whether they are operated and owned by public parties such as local law enforcement and federal agencies or by private entities or industry.

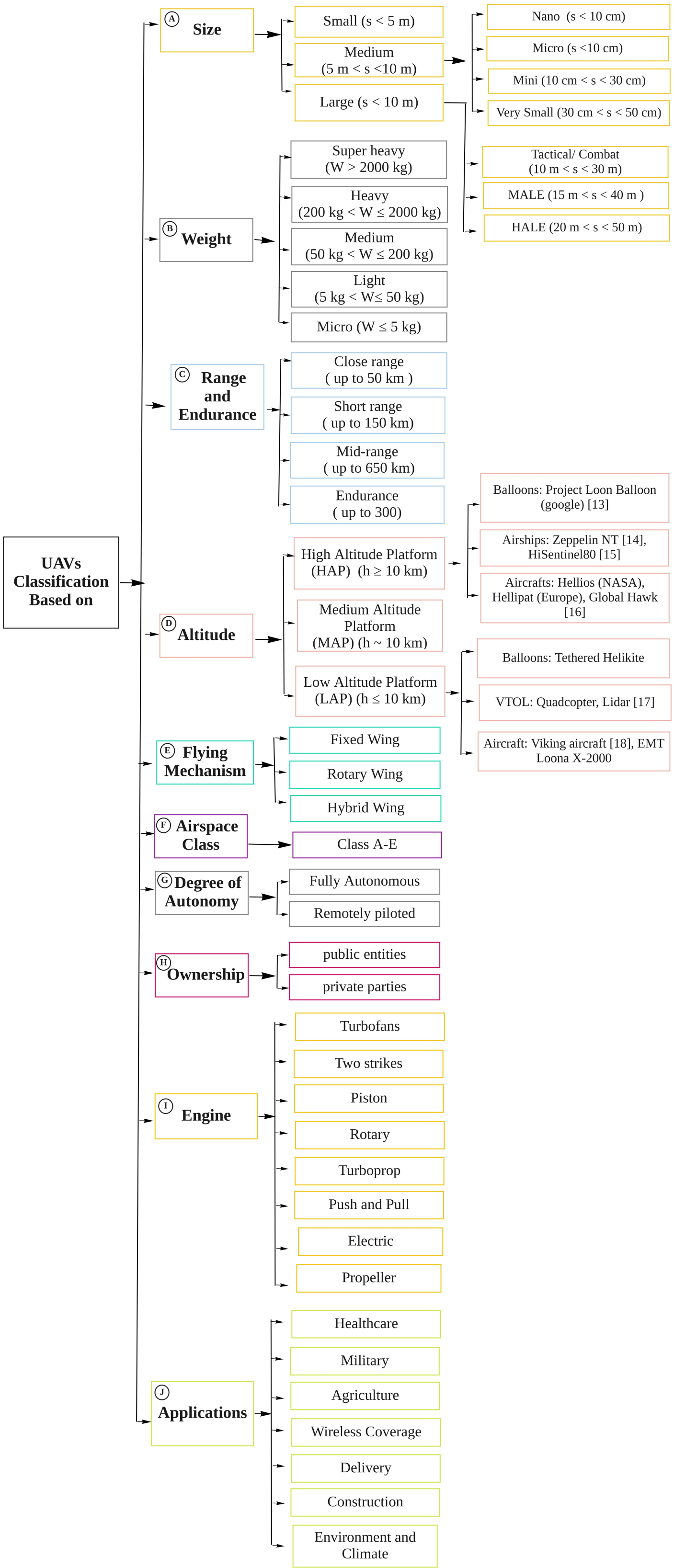

Figure 1. UAV Classification based on different features such as size, weight, range and endurance, altitude, flying mechanism, airspace class, degree of autonomy, ownership, type of engine, and application.

Table 1. UAV Classification based on size, weight, altitude, coverage, range, and endurance.

Type	Size (inch)	Weight (gram)	Max Altitude	Coverage Range (kilometer)	Endurance (hour)
Nano	around 3	$W \leq 0.2$	$h \leq 15$	$0.05 < r < 0.1$	$E < 0.6$
Micro	$s \leq 4$	$0.2 < W \leq 2$	$h \leq 15$	$0.1 < r < 0.5$	$E < 1$
Mini	$4 \leq s \leq 12$	$2 < W \leq 20$	$h \leq 30$	$0.5 < r < 1$	$E < 1$
Very Small	$12 \leq s \leq 20$	around 20	$h \leq 300$	$1 < r < 5$	$1 < E < 3$
Small	$20 \leq s \leq 80$	$20 \leq W \leq 150$	$300 \leq h \leq 1500$	$10 < r < 100$	$0.5 < E < 2$
Medium	$200 \leq s \leq 400$	$50 \leq W \leq 200$	$3000 \leq h \leq 4500$	$500 < r < 2000$	$3 < E < 10$
Large	$900 \leq s \leq 2500$	$4500 \leq W \leq 13{,}000$	$6000 \leq h \leq 12{,}000$	$1000 < r < 5000$	$10 < E < 200$
Tactical	$4000 \leq s \leq 11{,}000$	$150 \leq W \leq 600$	$3000 \leq h \leq 1000$	$500 < r < 2000$	$5 < E < 12$
MALE	$600 \leq s \leq 1500$	$W > 2000$	$4500 \leq h \leq 9000$	$20{,}000 < r < 40{,}000$	$10 < E < 200$
HALE	$800 \leq s \leq 2000$	$450 \leq W \leq 4500$	$15{,}000 \leq h \leq 21{,}000$	$2000 < r < 4000$	$30 < E < 50$

In addition, according to Figure 1, box *I*, UAVs can be categorized based on the different types of engines they have, including turbofan, two-strike, electric, piston-driven internal combustion, rotary, turboprop, push–pull, and propeller. Out of these engine types, piston and electric engines are the most commonly used types, especially for small UAVs and heavier UAVs, respectively.

According to Figure 1, box *J*, UAVs can be classified based on their applications. Figure 2 presents several applications in which UAVs are employed that can be used for classification, as detailed below.

- *Military (Figure 2, box A):* With continuing advancements in UAVs technology, defence forces around the world increasingly use UAVs for a variety of applications, including logistics, surveillance, communications, attack, and combat. Figure 2, box *A* shows military applications of UAVs. Famous drone types used in military applications include the RQ-4 Global Hawk, RQ-2A PioneerRQ-2A Pioneer, QF-4 Aerial TargetQF-4 Aerial Target, R-MQ-8 Fire ScoutR/MQ-8 Fire Scout, RQ-7B ShadowRQ-7B Shadow, RQ-11B RavenRQ-11B Raven, MQ-9 ReaperMQ-9 Reaper, and MQ-1B Predator (https://www.military.com/equipment/drones accessed on 21 July 2022).
- *Medical Applications (Figure 2, box B):* Recently, UAVs have begun to be employed in medical startups. According to Figure 2, box *B*, they have been used for search and rescue when a natural disaster suddenly happens, for transport and delivery of medications, first aid kits, and laboratory samples, and for remote telemedicine and teleradiology services [29–33]. The most promising UAVs for near-future applications in healthcare are Seattle's *VillageReach* (https://www.villagereach.org/ accessed on 21 July 2022), used for transportation of blood samples from one hospital to another; *Flirtey* (https://getskydrop.com/ accessed on 21 July 2022), used for delivery of first aid kits; *EHang* (https://www.ehang.com/index.html accessed on 21 July 2022), used to transport donated organs to people for use in emergency situations; *ZipLine* (https://flyzipline.com/ accessed on 21 July 2022), used for blood transportation; *TU Delft* (https://www.tudelft.nl/io/onderzoek/research-labs/applied-labs/ambulance-drone accessed on 21 July 2022), which is an ambulance UAV sent to bystanders near a patient to teach them how to perform CPR and use its in-built automatic defibrillator until emergency services arrive to take over; and *Google Drones*, which can provide people in distress with medical aid before an ambulance can arrive there; other autonomous UAVs for use in healthcare applications include *Project Wing* (https://x.company/projects/wing/ accessed on 21 July 2022), *Healthcare Integrated Rescue Operations (HiRO)* (https://ieee-aess.org/hiro-healthcare-integrated-rescue-operations

accessed on 21 July 2022), and *Vayu Drones* (https://www.engineeringforchange.org/solutions/product/vayu-drones-for-medical-delivery/ accessed on 21 July 2022).

- *Agriculture (Figure 2, box C):* Recently, UAVs integrated with the IoT paradigm have found wide use in intelligent agriculture. As shown in to Figure 2, box *C*, UAVs are employed in many agriculture applications. UAVs equipped with flight planning software automatically take pictures using onboard sensors and the built-in camera to allow users to perform mapping analyses of an area. UAVs are capable of planting seeds and seedlings, harvesting crops, and detecting infestations and weed. In addition, they can spray crops more accurately than a traditional tractor [34–36]. By applying ML techniques to real-time data gathered by UAVs, parameters such as plant disease detection and soil moisture [37], minimum and maximum temperatures at field level [38], and the level of phosphorus in the soil [39] can be predicted. Using UAVs in agriculture can reduce costs as well as potential pesticide exposure to workers. Of the numerous types of agricultural drones on the market, among the most widely used are the *PrecisionHawk DJI Matrice 200 v2* (https://www.dji.com/br/matrice-200-series-v2 accessed on 21 July 2022), the *senseFly eBee SQ* (https://www.sensefly.com/blog/talking-ebee-sq-agriculture-drone/ accessed on 21 July 2022), and the *Sentera PHX Complete System* (https://sentera.com/data-capture/phx/ accessed on 21 July 2022).
- *Wireless Coverage (Figure 2, box D):* UAVs that are equipped with directional antennae are used to provide wireless coverage for both indoor and outdoor users in dense environments or when terrestrial BSs are out of service due to bad weather conditions [40]. However, there are outstanding issues, such as finding the minimum number and optimal deployment of aerial wireless BSs or cellular-connected UAVs to maximize the total coverage area. Moreover, providing an optimal A2G path loss model is required for aerial wireless BSs [41–43].
- *Environment and Climate (Figure 2, box E):* UAVs can be used to help the environment in a wide variety of way; Figure 2, box *E* shows applications of UAVs in the mining industry [44,45], aerial mapping, nature monitoring [46–48], wildlife protection [49,50], forest fire detection [51], prediction of rising sea levels [52,53], renewable energy maintenance, disaster relief [54], climate change forecasting [55], the potential of space drones for exploring other planets [56], marine drones that can study marine organisms and identify the location of oil spills [57], tree-planting, clean energy, and solar power generation [58,59].
- *Delivery and transportation (Figure 2, box F):* As shown in Figure 2, box *F*, delivery UAVs can be used to transport food, medical supplies, household items, and packages, as well as for ship resupply [40,60]. The Federal Aviation Administration (FAA) has proposed airworthiness criteria for type certification of delivery drones for commercial operations, which in 2020 covered ten drone manufacturers, Amazon Prime Air, Zipline, and Wingcopter among them (https://www.faa.gov/newsroom/faa-moving-forward-enable-safe-integration-drones?newsId=96138 accessed on 21 July 2022).
- *Construction (Figure 2, box G):* In construction applications, UAVs can be utilized for technical inspection, painting, safety, and delivery. *Inspector UAVs* equipped with high-resolution digital cameras are employed for progress monitoring, technical inspection of construction sites and buildings, and quality control [60,61]. *Delivery UAVs* with high-performance rotors and robust frames are used to carry material, tools, and payloads to workers at heights. *Builder UAVs* can be connected to paint reservoirs and onboard compression pumps for painting applications, and *Safety UAVs* with infrared and visual sensors are used to monitor and detect safety issues in construction [62–64].

The type of UAV for a selected particular application must meet various requirements, such as energy capacity, endurance, payload, and compliance with local regulations.

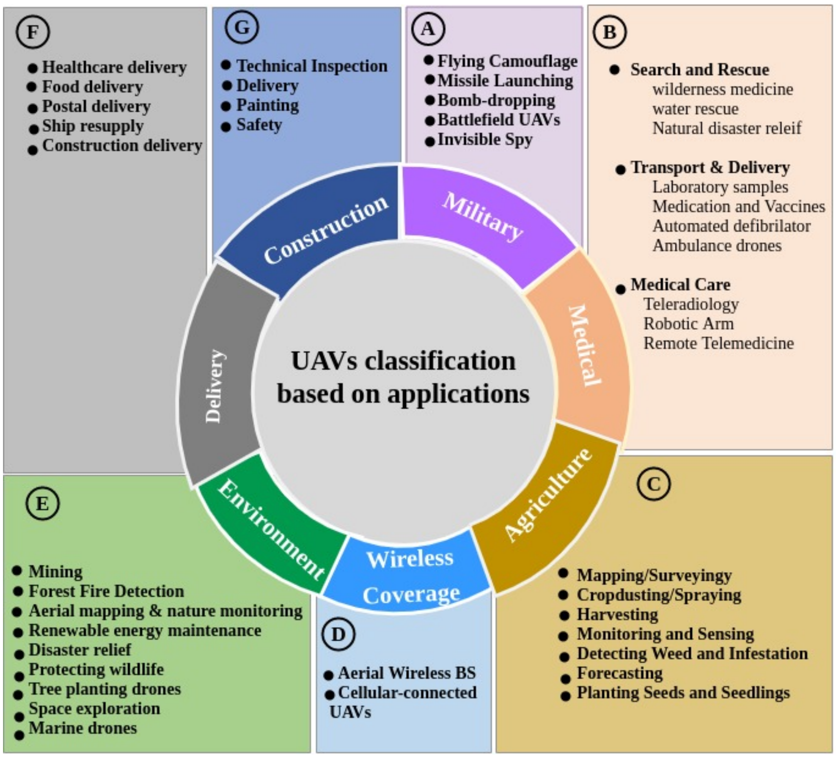

Figure 2. UAV Classification based on application domain: delivery, construction, military, agriculture, wireless coverage, and environmental monitoring.

3. Main Characteristics of FANETs

As shown in Figure 3, the main characteristics of FANETs are node density, node mobility, changing network topology, communication range, radio propagation model, localization, power consumption, frequency band, cost efficiency, versatility, agility, and network lifetime [65–68], as detailed below.

- *Node Density:* The average number of UAVs per unit volume is the node density. The node density of UAVs in FANETs is less than in other ad hoc networks such as MANET and VANET. The node density can be varied according to the objective of the UAVs mission.
- *Node Mobility*: Node mobility is one of the main features of FANETs; it is very high compared to VANET and MANET. UAV speed varies from 30 to 460 km/h depending on the type of UAV. This can causes issues, including disruptions, link failure, and more [69].
- *Changing network topology*: The network topology in FANETs undergoes frequent changes due to the rapid movements of UAVs. Possible FANET topologies under conditions of frequent topological fluctuation include star topology, in which all UAVs directly communicat with the ground control station (GCS), and mesh topology, in which dynamic routing is necessary. Both the star and mesh network topologies have advantages and disadvantages; for example, with star network topologies, the dedicated link between each UAV and GCS fluctuates due to the high speed of UAVs, which can affects data exchange [66,70,71].
- *Radio propagation model*: A crucial element when designing and simulating any communications system is the radio propagation model employed in the network. The simplest and most popular propagation model used in simulation tests is the Friis free space model. This model only uses the distance and frequency of the signal, which has corresponding limitations [72]. A UAV-to-Ground (U2G) communication channel is a widely used channel model in the literature. The different types of propagation models can be categorized [73] as follows:

  - *Theoretical models*: These models provide a detailed propagation model of U2G or U2U channels for UAV network scenarios.
  - *Empirical models*: These models are obtained from a series of measurements made in various rural or urban scenarios.
  - *Semi-empirical models*: These models are initiated as theoretical models and then varied according to a set of measures to match reality.
  - *Well-known models*: These models attempt to verify the sufficiency of already-known propagation models in UAV network scenarios.
- *Localization*: FANETs take advantage of low-latency global positing (GPS) to locate UAVs to compensate for their high speed and mobility and the resulting network topology changes. Localization in FANETs can be based on network positioning, height, assisted GPS (AGPS), or differential GPS (DGPS) [66,74] .
- *Power consumption and network lifetime*: Energy constraints represent a critical issue in ad hoc networks. Power consumption in FANETs depends on the size of the UAVs, the distances involved, the communication hardware of the FANET and the link, and other hindrances. Sensor and actuator nodes play a vital role in the power consumption of FANETs; lowering the requirements of power-sensitive devices in FANETs can directly improve network lifetime and reduce network breakdowns [66,74].
- *Frequency band*: Unlicensed bands such as 0.9 GHz and 2.4 GHz are widely used in UAV communication systems. However, using these bands can cause congestion. The frequency of 5 GHz integrated with IEEE 802.11a provides the best result for UAV-to-Ground links. Avoiding interference with other bands is best at 5.9 GHz with IEEE 802.11p [66].

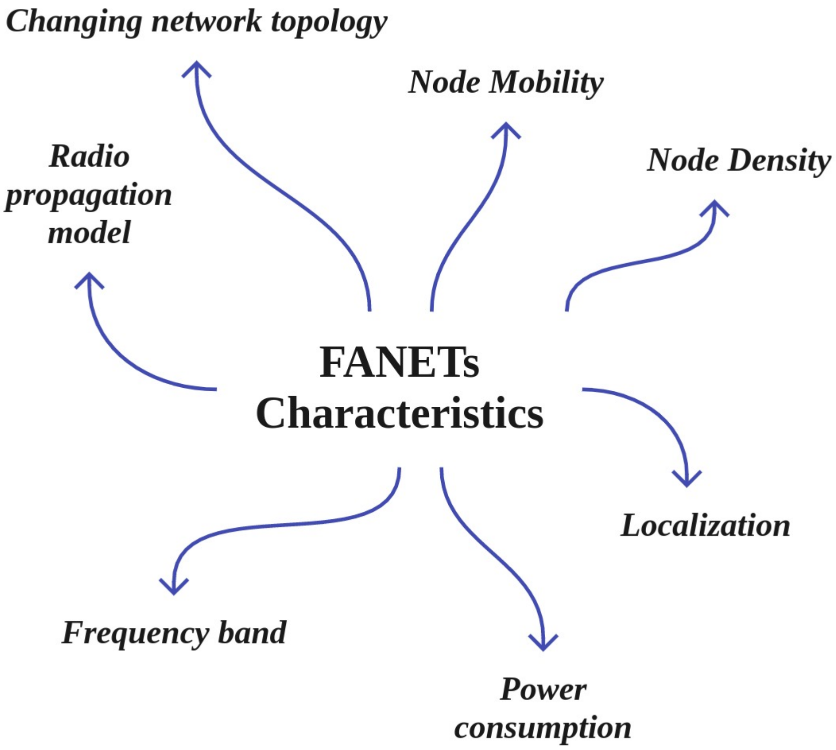

Figure 3. FANET characteristics, including localization, power consumption, frequency band, radio propagation model, changing network topology, node mobility, and node density.

4. Main Applications of FANETs

Three main applications of FANETs can be distinguished as follows [40]:

- Multi-UAV cooperation: Figure 4, box *A* shows the following applications, which can be categorized as multi-UAV cooperation:

  - *Target detection*: Target detection technologies such as thermal and vision cameras can be employed in UAVs to detect objects and persons [43,75].
  - *Tracking and monitoring in disaster situations*: UAVs can help to assess the direction in which a flood is moving, then predict what buildings are exposed to damage. Similarly, they can be used for rescue operations in the aftermath of earthquakes, identifying collapsed population-dense buildings such as hospitals and schools so that these areas are given a higher priority in rescue operations [76,77].
  - *Emergency situations*: UAVs are used in the construction industry to check safety and to monitor the progress of construction and buildings. UAVs can be used to provide temporary wireless coverage in cellular networks during emergencies when the ground base stations are out of service, as well as in many other emergency scenarios [33,54].

- UAV-to-Ground tasks: Figure 4, box *B* shows the following applications for UAV-to-ground cooperation:
  - *Public and civilian applications*: UAVs have been widely used for public and civilian domain applications, especially in the form of small quadcopters, as their cost effectiveness and flexibility provide advantages over ground-based infrastructure [78].
  - *Search and rescue missions*: UAVs play a vital role in search and rescue missions (SAR). FANETs are considered an immense advantage in guaranteeing public safety, performing SAR missions, and managing man-made or natural disasters such as floods, earthquakes, forest fires, tsunamis, terrorist attacks, and checking the safety of critical infrastructure such as power and water utilities. It is important to provide communications coverage in such situations. In situations when public communications networks are disrupted, UAVs can provide timely disaster warnings and help to speed up rescue and recovery operations. UAVs can carry medical equipment to inaccessible regions. They can make SAR operation much faster in situations such as avalanches, wildfires, searching for missing persons, and more.
- UAV-to-VANET collaborations between UAVs and vehicles: As shown in Figure 4, box *C*, the following applications involve cooperation between UAVs and vehicles:
  - *Roadway traffic monitoring*: FANETs can be employed instead of intensive labour and complex observational infrastructure to carry out road traffic monitoring. In roadway traffic monitoring, UAVs are able to detect traffic crashes and then report these incidents easily. Using UAVs is much faster than using the incident commander's vehicle. In addition, UAVs can be used to provide road safety by capturing real-time videos from various security scenarios and situations in road networks [79].
  - *Data packet delivery*: Data delivery to mobile ad hoc nodes is a challenging task, as it is difficult to find a reliable forwarding path to ensure that data is delivered from one user to another. In this respect, UAVs are widely used as airborne communication relays to deliver data collected by ground devices to distant control centres. In other words, UAVs deliver packet data based on the load-carry-and-delivery (LCAD) paradigm, in which data is loaded from the source node and forwarded to the destination node utilizing multiple UAVs [80,81].
  - *Route guidance*: In VANETs, the high mobility of vehicles leads to inadequate routing. In UAV-assisted VANETs, vehicles and UAVs transmit data to each other using multi-hop relays. UAVs are used to provide route guidance and routing improvement in VANETs [82,83].

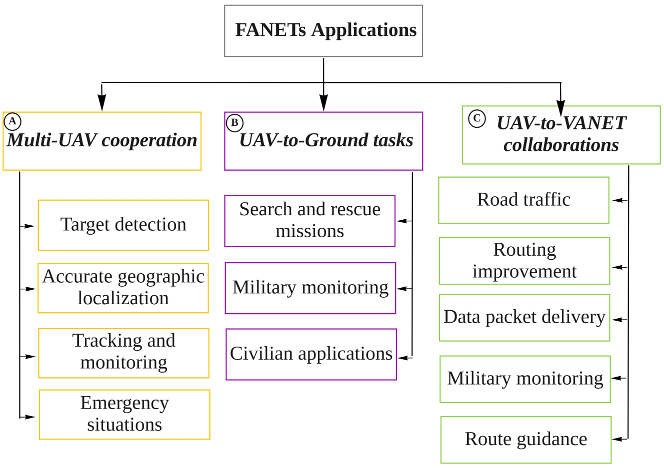

Figure 4. FANET applications: Multi-UAV cooperation, UAV-to-Ground cooperation, and UAV-to-VANET cooperation.

5. FANET Routing Protocols

In this section, different sets of routing protocols in the network layer are defined for FANETs. One possible classification of FANET routing protocols is depicted in Figure 5, and is discussed in the following.

- *Position-based (Figure 5, box A):* In these protocols, the geographic information of the nodes is known from GPS, and the positions of the sender and receiver are determined in advance using *reactive*, *predictive*, *greedy* [84], and *hierarchical* [85–87] methods, as shown in Figure 5, box *A*. The position-based hop by hop protocols usually dynamically select relay nodes. The packets are broadcast blindly by the node, and the selection of the relay is postponed until the neighbours of the node receive the packets. After the neighbours receive the packets, they calculate the dynamic forwarding delay (DFD) values according to their local position information in a distributed manner and then forward the packets to the destination greedily.The nodes closest to the destination then acquire the minimum DFD value and become the next forwarder [88].
- *Topology-based (Figure 5, box B):* In topology-based hop by hop routing protocols, the senders forward packets through an optimal path using the network's topology information along with link- state information such as IP address [89]. As shown in to Figure 5, box *B*, these can be classified as *static* [90], *proactive* [91], *reactive* [92], and *Hybrid*.
- *Delay-tolerant networks (DTNs) (Figure 5, box C):* In DTNs, the mobile nodes are intermittently and unstably connected. As the mobile nodes experience high latency and low data rates, new routing protocols are needed to address the DTN characteristics [66]. The three main DTN-based routing protocols studied for FANETs are *deterministic*, *social network*, and *stochastic* [66], which are depicted in Figure 5, box *C*.
- *Heterogeneous (Figure 5, box D):* FANETs interact with various ground networks, such as VANETs, MANETs, or fixed nodes, in which heterogeneous routing protocols are required for exchanging data between moving users. Routing protocols with heterogeneous techniques can support both mobile and fixed nodes in FANETs [93]. This technique can provide sub-network assistance coverage for both nodes on the ground and UAVs, network extension, and more [94]. The classification of heterogeneous routing protocols is shown in Figure 5, box *D*.
- *Cluster-based (Figure 5, box E):* In the clustering technique, nodes with similar characteristics and features are combined to form clusters. There is a cluster head in each cluster that carries out communication processing [95]. As shown in Figure 5, box *E*, cluster-based routing protocols in FANETs can be classified into two main categories, namely, probabilistic and deterministic. A full classification of cluster-based routing protocols in FANETs is shown in Figure 5, box *E*.

- *Swarm-based (Figure 5, box F):* This routing technique takes advantage of the social behaviour of fish, birds, and insects to find the optimal path and topology management approach [96–99].

Selecting the best routing protocol for different UAV-based scenarios depends on a variety of characteristics, including the routing approach (dynamic, static, on-demand, hybrid), mobility models, simulation tools, and performance metrics. Although UAV routing protocols are in the early stages of development, the reactive and proactive routing approaches have thus far performed better in highly dynamic FANETs compared to other protocols. In addition, hybrid protocols appear to be better for employment in monitoring applications in large-scale FANETs [100].

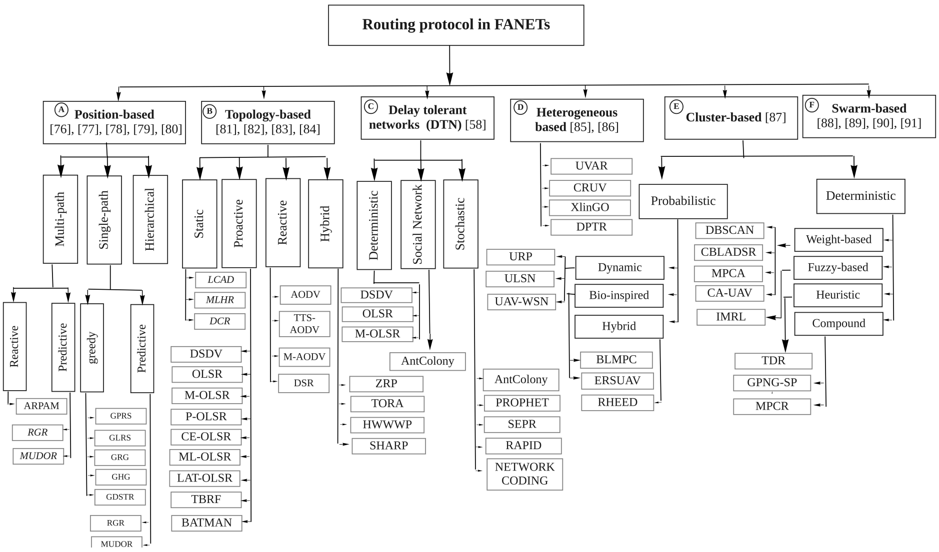

Figure 5. FANET Routing Protocols: position-based, topology-based, DTN, heterogeneous, cluster-based, and swarm-based.

6. UAV Mobility Models

This section describes the different UAV mobility models supported in FANETs. Typical mobility models used in FANETs include pure randomized mobility models (the random way (RW), random waypoint (RWP), random direct ion (RD), and Manhattan grid (MG) models), time-dependent mobility models (the Gauss Markov (GM), boundless simulation area (BSA), and smooth turn (ST) models), path-based mobility models (the semi-random circular movement mobility model (STCM), and paparazzi (PPRZM) models), group mobility models (the reference point froup (RPGM), exponential correlated (ECR), column (CLMN), nomadic community (NC), pursue (PRS), and particle swarm (PS) models), and topology control mobility models (the pheromone base (PB), distributed pheromone repel (DPR)-based, mission plan-based (MBP), and self-deployable point coverage (SDPC) models) [66,73,79,88]. The chosen model relies on the network to keep the entire system working as a unity. There are several parameters, including the altitude, path and directing of flying, and atmospheric conditions, all of which impact UAV mobility. In addition to these parameters, other important aspects should be considered when select a mobility model for UAVs in different scenarios. These aspects include avoidance of connections that control the distance between UAVs, controlling sudden changes in the UAVs' direction, and the safety standards and deployment that need to be considered in order to prevent collisions between UAVs [100].

7. Integration of Technologies with the UAV-Networked Systems

Recently, UAVs have begun to be integrated with several technologies, several of which technologies are discussed in this subsection, as shown in Figure 6.

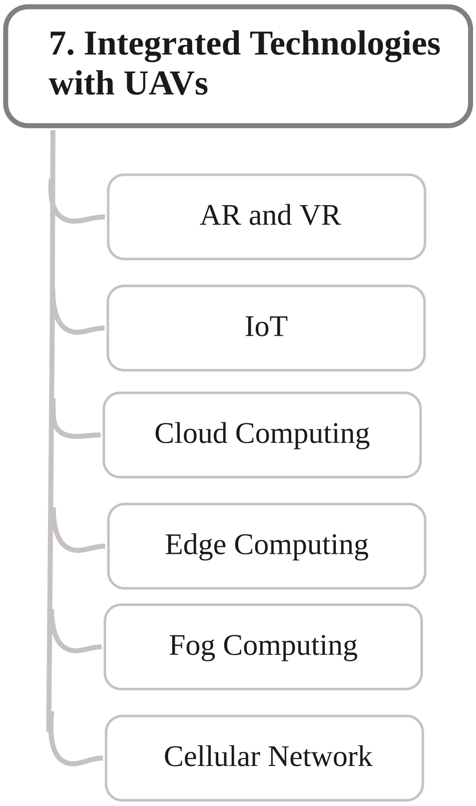

Figure 6. The main technologies integrated with UAVs: augmented and virtual reality (AR and VR), IoT, cloud, edge, and fog computing, and cellular networks.

- *Augmented reality (AR) and Virtual Reality (VR) technologies (Figure 6, box A):* VR, which is shown in Figure 6, box *A*, has been integrated with UAV-networked systems for greater integration of the virtual and real worlds. Such integration can create a virtual environments for multiple purposes, including marketing, agriculture, entertainment, education, and more, by taking over people's vision and making them feel as if they are somewhere else. AR is considered a variation of VR; VR technology, there is an essential need for 3D data on a large scale. In this regard, UAVs that can freely fly in the sky are excellent tools for collecting 3D data. Several studies have investigated the use of VR technology and UAV networks [5–9]. The main challenges of UAV-enabled VR include the low battery lifetime and computing capacity of VR users, which in turn cause issues with content caching and transmission. VR applications need a high data rate and low latency. In this regard, AI and ML techniques bring together novel NN ideas from echo state networks (ESNs) and the liquid state machine (LSM), which can enable user reliability prediction in order to find the optimal content level for transmission and caching [7,101,102].
- *IoT-enabled UAV communication system (Figure 6, box B):* The integration of UAVs with IoT is called the Internet of Flying Things (IoFT) [10,11] or Internet of Drone Things (IoDT) [12]. IoFT or IoDT represents a new research topic related to IoT, cellular networks, cloud, fog, and edge computing, big data, intelligent computer vision, and security techniques. IoFT or IoDT can efficiently support different applications in various fields ranging from disaster management to smart industry, providing high connectivity, scalability, flexibility, and availability. Although integrating UAVs with IoT improves the scalability, connectivity, stability, reliability, and security of real-time IoT applications, there are several open challenges, including interference and collision, UAV selection and placement, UAV control and management, security issues, the power limitations of IoT devices, path planning, and more [66,103–108].

- *Integration with Cloud Computing (Figure 6, box C):* As shown in Figure 6, box *C*, cloud computing has been integrated with FANETs; known as cloud-based UAV or flying cloud computing, this can improve and increase storage, network bandwidth, and processing. Such an integrated system includes three main layers: a UAV layer, a cloud server layer, and a ground control system (GCS)/client layer. The UAV layer collects sensor data such as pressure, temperature, etc., while flying and transmits the collected data to the cloud for storage and processing using 3G/4G/5G cellular communication devices or other technologies such as WiMAX, WiFi, etc. The communication layer is responsible for providing wireless connectivity for the UAVs and GCS any time and anywhere without any limitations on communication range. The last layer contains the cloud servers that store and process different types of data, such as geographical location parameters, environment variables, sensor data, images, etc., received from the UAVs to detect various events [10,109–111]. Although flying cloud computing provides many advantages in addition to the existing challenges in traditional FANETs, new issues arise as well. The major challenges that appear in cloud-based applications include large bottlenecks, latency due to centralized processing, lack of offline processing, and security issues. These challenges can be mitigated by edge and fog computing in a distributed manner, with storage and processing of the data carried out near the places where the data are generated. Therefore, integrating edge and fog computing with UAVs can provides better results in certain cases [14].
- *Flying Edge Computing (Figure 6, box D):* Edge computing allows data storage and computing closer to the sources of data. Edge computing has been integrated with FANET (flying edge computing) to mitigate the hardware limitations of UAVs and improve the performance of UAV networks [13]. Flying edge computing is employed to support real-time IoT applications such as video streaming surveillance, VR and AR, and smart transportation [112]. In flying edge computing, UAVs are associated with edge IoT devices such as GBSs to offload and migrate part of the data computation to the edge layer; the other parts of computation tasks are locally managed by the UAVs [113] without the intervention of the cloud [114]. Integrating UAVs with edge computing provides low latency and response time for different IoT real-time applications. However, certain applications require storage and computing of voluminous data such as video streams. The local resources of edge IoT devices cannot efficiently support such cases. Therefore, flying fog computing can be expanded to the core network to provide low latency for storage and processing of huge amounts of UAV data [10].
- *Flying Fog Computing (Figure 6, box E):* Flying fog computing, which is located at the edge of the network, provides an intermediate level between the cloud and UAV layers. The fog layer communicates with the UAV layer through wireless connection and the cloud layer using the internet. The integration of fog computing and UAVs provides low latency for real-time UAV-assisted IoT applications along with high capacity in terms of computing and storage. Although the flying fog computing paradigm provides enough computing power for IoT nodes, a major issue involves the integration of the UAVs in the edge computing layer with the cloud computing layer [10,14,15]. Figure 7 shows the cloud, fog, edge, and IoT layers.
- *Integrating UAVs into cellular networks (Figure 6, box F):* Agile UAVs are a special class of lightweight fixed-wing UAVs with small control surfaces [115]; they can be used as flying base stations, mobile relays, users, sensors, network controllers, and even as a scheduler in a cellular network [16], providing high reliability and low latency in communications. In UAV-based cellular networks, UAVs are mostly equipped with small BSs to provide temporary required communication links and cover the hard-to-reach regions. These flying BSs are more adaptive, flexible, and cost-effective than conventional towers or pole-mounted or rooftop BSs [17]. However, cellular networks have limitations in terms of supporting UAV communications. For example, optimally deploying UAVs is one of the most challenging issues in this context [18,19].

Therefore, new communication technologies such as 5G and 6G that support aerial and satellite communication are needed to manage UAV traffic in very dense air traffic scenarios [77,103,116,117]. There are challenges with integrating 5G and 6G with FANETs, which can suffer from issues and is a very complex task with many technical issues which need to be addressed [66].

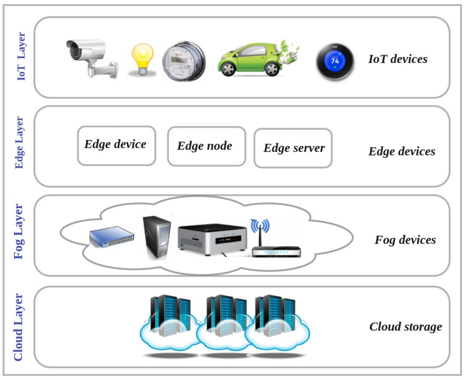

Figure 7. The basic model of cloud, fog, and edge computing.

8. Main Components of Cloud-Based UAV Managing Systems (CBUMS)

As already mentioned, CBUMS include three main layers, the UAV layer, cloud layer, and control layer [20], as shown in Figure 8.

- *UAV Layer*: As shown in Figure 8, in the UAV layer (i.e., the physical layer), UAVs that are connected with the IoT cloud using short- and long-range wireless technologies can perform different tasks, ranging from traffic monitoring to delivery. The cloud layer sends control information and signals about the traffic situation to the UAV layer to guide responses based on the desired GBS in the control layer. In the UAV layer, multiple network components such as drone-to-target (D2T) and drone-to-drone (D2D) are attached [20,118].
- *Cloud Layer*: The cloud layer, which is the heart of CBUMS, transfers the data between the UAV and control layers. As can be seen in Figure 8, the storage, computation, ML techniques, and interface are the main components of the cloud layer [20,118].
  Storage: The cloud layer captures streams of data about the location, environment, and UAV mission information, storing the captured data in a regular SQL database or NoSQL database based on the application's requirements.
  Calculations and ML techniques: Several computation algorithms, such as map/reduce, data analytics, image processing, ML techniques (including supervised and unsupervised learning algorithms), RL and DRL-based algorithms, and FL-based techniques are executed in the cloud to improve the system performance and fix existing open issues.
  Interface: The interface contains web and network services that make connections between control and UAV layers. Interfaces in the cloud layer take advantage of various communication protocols, including wireless personal area networks (WPAN), wireless local area networks (WLAN), low-power wide-area networks (LPWAN), and cellular networks. In applications that require UAVs to directly communicate with the central station, a WiFi transmission system is used. However, long-term evolution (LTE) and long-range area networks (LPWAN) provide lower-latency communication systems than WIFi.
- *Control Layer*: As Figure 8 shows, the control layer includes GCSs that remotely register, control, manage, and monitor UAVs from a location close to or inside the flying field. The GCS contains application software that receives collected data from UAVs and sends control signals to them. The users can monitor UAVs, set task parameters, and modify them through the data analysis implemented by the cloud based on the application software [20,118].

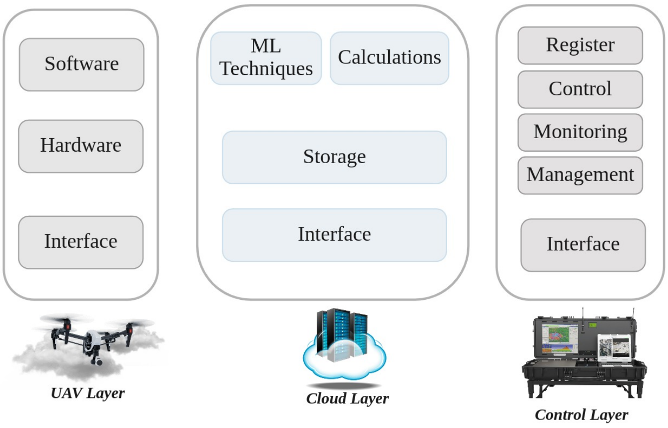

Figure 8. Cloud-based UAV managing system including the three main layers: UAV, cloud, and control.

9. Simulation Tools

Evaluating the performance of UAV-based communication networks in the real world is a difficult task that requires a remarkable amount of time and resources. Frequent topology changes and the high degree of mobility of the UAVs in FANETs make the practical evaluation of UAV performance a challenging, costly, and time-consuming task. In addition, due to regulations around using UAVs in most countries, certain types of cyber-attack resistance evaluation tests for UAV networks are not allowed [2]. Therefore, many flexible simulation tools, frameworks, emulators, and testbeds have been developed to make it possible to create, implement, test, and evaluate schemes virtually without requiring real-world implementation. The available FANET performances analysis tools include *AVENS*, *CUSCUS*, *Simbeeotic*, *UAVSim*, *UTSim*, *FANETSim*, *Netsim*, *OMNeT++*, *NS2,NS3*, *OPNET*, *ROS-NetSim*, *MATLAB*, *TOSSIM*, *QualNet*, *GloMoSim*, *YANS*, *ONE*, *SSFNet*, *FlynetSim*, *J-Sim*, *BonnMotion*, *GAZEBO*, *AirSim*, *RoboNetSim*, *Mininet-Wifi*, and *SUMO*, each of which supports different mobility models, operating system, and programming languages [119–122]. Table 2 shows additional details about each simulator.

Table 2. Simulation tools and testbeds for UAV systems performance analysis.

Name	Type	Mobility Model	Operating System	Programming Language	More Description
AVENS (http://hdl.handle.net/10125/41924 accessed on 21 July 2022)	Simulator	Linear Mobility	Linux, Windows, MacOS	N/A	A flight control simulator that implements co-simulation between the XPlane Flight Simulator and an OMNeT++/INET simulation for modeling UAV communication.
CUSCUS [123]	Simulator	micro-mobility	> Ubuntu 14.04	N/A	A simulation architecture for networked control systems which is based on two well-known solutions in the fields of networking simulation (the NS-3 tool) and UAV control simulation (the FL-AIR tool).
Simbeeotic [124]	Simulator and Testbed	N/A	Linux	Java	Used to evaluate Micro-aerial vehicle (MAV) swarms.
UAVSim [125]	Testbed	well-defined mobility framework	Windows, Linux and MacOs	C++	An OMNeT++ based UAV simulator; useful for cyber security analysis in UAV-based networks.
UTSim [126]	Simulator and a framework	N/A Linux	Windows	C#, JavaScript, Unity Script, or BOO coding languages.	Useful for air traffic sumulation and capable of simulating UAV physical specification, control, navigation,sensing , communication, and avoidance in environments with stationary and mobile objects.
FANETSim [127]	Simulator	Grid	Linux Distribution	Java	Java software able to consider a set of flying UAVs in the sky, providing connectivity to the users inside the considered map.
Netsim [128]	Simulator	RW, RWP	Windows , MacOS or Debian-based Linux.	C	Provides three different versions: NetSim Pro, Standard, and Academic, with a very intuitive GUI interface
OMNeT++ [129]	Simulator	FP, RWP, RW	Linux, MacOS. and Windows	C++, high-level language (NED)	A modular and extensible component-based network simulator used for research and commercial purposes.
NS2 [130]	Simulator	RW, RWP, GM, MG, RPGM	Linux, Windows, MacOs	C++, with an OTcl interpreter as a front-end	A discrete event simulator used for networking research which simulates TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks.
NS3 [87]	Simulator	RW, RWP, RD, GM, MG, RPGM	Linux, Windows, and MacOS	C++, Python	Allows simulation of both IP and non-IP-based networks. It is suitable for performance evaluation of mobile ad hoc and TCP networks

Table 2. *Cont.*

Name	Type	Mobility Model	Operating System	Programming Language	More Description
OPNET [131]	Simulator	RW, Group mobility, RWP, RD	Windows, Red Hat and CentOS	C, C++	Provides a powerful GUI and animation that involves significant costs.
ROS-NetSim [132]	Simulator	N/A	Linux	C++, Python	An ROS package that acts as an interface between robotic and network simulators.
MATLAB [133]	Simulator	SRCM, PSMM	Windows, Linux, and MacOs	C, C++	Provides different example applications involving both fixed-wing and multirotor UAVs, along with a UAV Toolbox and the ability to integrate AI/ML through its Statistics and ML Toolbox.
TOSSIM [134]	Testbed	RWP	Linux, and it is compatible with Windows	C++, Python	A BSD-licensed OS designed for low-power wireless devices, it is widely used in both academia and industry.
QualNet [135]	Simulator	RWP, Group mobility	MacOs, Linux UNIX, Windows,	C++	A powerful simulation tool for UAV research focusing on network security.
GloMoSim [136]	Simulator	RWP, Group mobility	Linux, Windows	C, Parsec	Widely used for research purposes and very scalable; does not offer good documentation, however, which makes it less user-friendly.
YANS [137]	Simulator	N.A	MacOS, Ubuntu	Python, C, C++	A lightning-fast Docker-based network simulator.
ONE [138]	Simulator	RWP	Linux, Windows and MacOS	Java	Generates node movement using different movement models and visualizes both mobility and message passing in real-time in its graphical user interface. ONE can import mobility data from real-world traces or other mobility generators.
SSFNet (http://www.ssfnet.org/ accessed on 21 July 2022)	Simulator	MG, RPGM, RW, RWP, GM	Linux, Solaris, and Windows NT using JDK1.2 and higher	java, C++	A scalable simulation framework network model designed for expansion of networks, including topology, protocols, traffic, etc.
FlynetSim [139]	Simulator	GM, MG, RPGM, RW, RWP, RD	Ubuntu Distributions	Python	An open-source synchronized UAV network simulator based on NS3 and Ardupilot.
J-Sim (https://sites.google.com/site/jsimofficial/downloads accessed on 21 July 2022)	Simulator	RWP	Linux, Windows, and MacOS	Tcl, Python, and Perl	A powerful tool, although it is relatively complicated to use and has a longer execution time than NS3.

Table 2. *Cont.*

Name	Type	Mobility Model	Operating System	Programming Language	More Description
BonnMotion [140]	Mobility generator	RW, RWP, GM, MG, RPGM and more	Linux, OSX	Java, Windows	Java software that creates and analyzes mobile ad hoc network characteristics.
GAZEBO [141]	Simulator	High-speed Mobility	Linux, Linux virtual machines	C++	A robotics simulation platform for testing algorithms and building AI/ML platforms for UAV applications. It can connect to a robot control framework (ROS).
AirSim [142]	Simulator	N/A	Windows, Linux	C++, C#, Python, Java	An open-source platform for AI research experimentation, with computer vision, deep learning, and reinforcement learning algorithms for UAVs
RoboNetSim [143]	Framework C++,	It provides good mobility patterns.	MacOs, Linux, Windows,	Python	Integrates multi-robot simulators with network simulators for realistic communications simulation of networked multi-robot systems. It has been applied to interface the NS-2, NS-3, and ARGoS Player/STAGE simulators.
Mininet-Wifi (https://mininet-wifi.github.io/ accessed on 21 July 2022)	Emulator	RW, RWP, TruncatedLevyWalk, GM, Random Direction, Reference Point, TimeVariantCommunity	any Ubuntu Distribution from 14.04	C++, Python	An extension of the Mininet SDN network emulator that adds or modifies classes and scripts.
SUMO [144]	Simulator	N/A	Windows, Linux or MacOs	C++, Python	While it cannot be used directly in FANETs as it is tailored for 2D vehicles, it can be integrated with OMNeT++ and NS3.

10. Future Prospects

Although the collaborative UAVs technologies discussed in Section 7 provide a number of benefits for a variety of collaborative applications, there are a number of challenges that remain to be addressed [145].

Due to the energy limitations of UAVs, energy-efficient algorithms need to be designed for such different aspects as collaborative communication, sensing, processing, acting, and data storage [145].

Providing efficient resource management strategies that try to dynamically manage resources such as bandwidth, transmitting power, the number of UAVs, and UAV flight time is another challenging issue in UAV-assisted technologies [1]. Security provision in UAV-based communication is a complex task, as UAVs are now widely used in technologies involving domains (military, rescue services, and infrastructure inspection) that involve sensitive information. Therefore, efficient techniques are required to provide reliable and secure communications and services in the technologies associated with UAVs [145,146]. In our own future work, we plan to apply Artificial Immune System-based Danger Theory to enhance FANET security, as this is an area in which promising results have previously been found by [147].

In addition, flexible deployment of a UAVs relies on their mobility and ability to fly towards their destination and perform their mission. To prevent conflict and manage battery levels, UAVs' real-time mobility reactions and states are vital [148,149].

11. Conclusions

This paper has presented a comprehensive review of FANETs, highlighting their characteristics, routing protocols, and new applications. UAV-based communication provides many benefits, and as such many solutions are being proposed and implemented by researchers exploring their possible employment. The main objective of this article has been to provide a thorough review of overall research in the area of FANETs, describing the different types of UAVs used in FANETs along with their main characteristics, applications, and routing protocols. This comprehensive review sought to find the most relevant publications addressing each of these topics. The main findings of this review are summarized as follows:

- *UAV classification*: UAVs can be classified based on size, weight, altitude, range and endurance, application, flying mechanisms, air class, degree of autonomy, ownership, and type of engine.
- *Main Characteristics of FANETs*: Node density, node mobility, changing network topology, communication range, radio propagation model, localization, power consumption, frequency band, cost-efficiency, versatility, agility, and network lifetime are the main characteristics of FANETs.
- *Main Applications of FANETs*: The applications of FANETs can be classified into three main categories: *Multi-UAV cooperation* (e.g., target detection/tracking, area monitoring, and surveillance), *UAV-to-ground tasks* (e.g., relay networking, provision of on-demand base stations for mobile communication, intermittent networking), and *UAV-to-VANET collaborations* (e.g., roadway traffic monitoring, data packet delivery, route guidance).
- *FANET routing protocols*: FANET routing protocols can be classified into six main categories: *position-based*, *topology-based*, *delay-tolerant networks (DTNs)*, *heterogeneous*, *cluster-based*, and *swarm-based*.
- *UAV Mobility models*: The mobility models used by FANETs consist of pure randomized mobility models, time-dependent mobility models, path-based mobility models, group mobility model, and topology control mobility models.
- *Integration of other technologies with UAV-networked systems*: UAVs have been integrated with various technologies, including augmented and virtual reality, IoT, cloud computing, fog and edge computing, cellular networks, and intelligent reflective surfaces.

- *Main components of CBUMS*: Cloud-based UAV managing systems includes three main layers: the UAV layer, cloud layer, control layer.
- *Simulation Tools*: The available FANET performances analysis tools include *AVENS, CUSCUS, Simbeeotic, UAVSim, UTSim, FANETSim, Netsim, OMNeT++, NS2, NS3, OPNET, ROS-NetSim, MATLAB, TOSSIM, QualNet, GloMoSim, YANS, ONE, SSFNet, FlynetSim, J-Sim, BonnMotion, GAZEBO, AirSim, RoboNetSim, Mininet-Wifi*, and *SUMO*, each of which support different mobility models, operating systems, and programming languages.
- *Future Directions*: When integrating new technologies with UAV-based communications, there remain several significant open challenges that need to be addressed, including the energy limitations of UAVs, the need for dynamic management of various resources (bandwidth, transmitting power, number of UAVs, UAV flight time), and the FANET security.

An important contribution of this paper is our discussion of possible future UAV network application, which was made possible by a review of the main emerging technologies that are currently being integrated with FANETs. This discussion sheds light on the future of this research area and can open the path for new ideas further exploring the possibilities discussed in this article.

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Abbreviations

The following abbreviations are used in this manuscript:

Unmanned Aerial Vehicle	UAV
Flying Ad Hoc Network	FANETs
Virtual Reality	VR
Internet of Things	IoT
Drone-mounted base station	DBS
Machine learning	ML
Artificial intelligence	AI
Deep learning	DL
Software Defined Network	SDN
Network function Virtualization	NFV
Quantum Annealing	QA
Intelligent reflective surfaces	IRS

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