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Review

Towards the Unmanned Aerial Vehicles (UAVs): A Comprehensive Review

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Abstract: Recently, unmanned aerial vehicles (UAVs), also known as drones, have come in a great diversity of several applications such as military, construction, image and video mapping, medical, search and rescue, parcel delivery, hidden area exploration, oil rigs and power line monitoring, precision farming, wireless communication and aerial surveillance. The drone industry has been getting significant attention as a model of manufacturing, service and delivery convergence, introducing synergy with the coexistence of different emerging domains. UAVs offer implicit peculiarities such as increased airborne time and payload capabilities, swift mobility, and access to remote and disaster areas. Despite these potential features, including extensive variety of usage, high maneuverability, and cost-efficiency, drones are still limited in terms of battery endurance, flight autonomy and constrained flight time to perform persistent missions. Other critical concerns are battery endurance and the weight of drones, which must be kept low. Intuitively it is not suggested to load them with heavy batteries. This study highlights the importance of drones, goals and functionality problems. In this review, a comprehensive study on UAVs, swarms, types, classification, charging, and standardization is presented. In particular, UAV applications, challenges, and security issues are explored in the light of recent research studies and development. Finally, this review identifies the research gap and presents future research directions regarding UAVs.

Keywords: UAVs; charging; challenges; security; applications

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1. Introduction

Unmanned aerial vehicles (UAVs), also known as drones, have received momentous consideration in different disciplines of military and civilian services due to their enhanced stability and endurance in several operations. Applications of UAVs are expanding exceptionally due to their advanced use in the internet of things (IoT), 5G and B5G. UAVs have been used in a variety of applications over the last decade, including object detection and tracking, public security, traffic surveillance, military operations, exploration of hidden or hazardous areas, indoor or outdoor navigation, atmospheric sensing, post-disaster operations, healthcare, data sharing, infrastructure management, emergency and crisis management, freight transportation, wildfire monitoring and logistics [1].

A UAV is commonly referred as a pilotless aircraft with the capability to fly and stay airborne without requiring any human onboard operator, providing more cost-efficient operations than equivalent manned systems, and performing cost-efficient critical mission without risking human life. UAVs can be remotely piloted, whereby control commands are provided from a ground base station (BS) through a remote control. The UAVs are also capable of performing the control operations onboard through autopilot and different sensors, including global positioning system (GPS) and inertial measurement units (IMU).

In particular, UAVs have gained significant attention from leading online retailers, including Walmart, DHL, Google, and Amazon [2,3]. Because of the constantly growing popularity of online shopping, which may have a substantial impact on client purchases, users are increasingly demanding high speed delivery services. As a result, online retailers are looking for ways to improve delivery times. Retailers, on the other hand, face a major challenge in offering ecofriendly, cost-effective, and efficient last-mile delivery. UAVs have emerged as promising solutions in this sector, with quick and innovative designs that ensure last-mile delivery while being environmentally friendly. UAVs can be deployed easily and quickly, are scalable and flexible, have the self-organization ability, are cost-efficient, and possess high maneuverability. UAVs vary widely in configuration, size, range, weight, engine type and performance characteristics in order to carry several payloads including communication gadgets, navigation equipment, sensors, and cameras. There are different classifications of UAVs according to various parameters such as configuration, engine type, weight, range and size.

However, there are several crucial factors limiting the performance of UAVs. Some of these factors are limited battery endurance, restricted mobility, limited autonomy, and limited flight time. Limited flight time is due to various factors including sensor accuracy, harsh atmospheric conditions, fixed-wing size and battery endurance. UAVs have several vulnerabilities that increase the rate of being exposed to malicious attacks. Several studies are devoted to assess UAVs vulnerabilities, attacks, threats and have suggested viable solutions to overcome these challenges, such as using high quality devices including batteries, wing, geometry, manufacturing materials and motors etc. Some studies have reported optimization algorithms to find shortest route for UAVs to reach their intended destination [4,5].

1.1. Scope and Contributions

This review is intended for readers who are inclined to read about UAV technology. This work is a comprehensive review on UAV's critical existing challenges, security concerns, applications and future research directions. This review aims to assist the readers get an overview of the state-of-the-art UAV technology in several aspects. The readers will have a good overview of UAV types, charging, autonomous swarms, and different application scenarios. It provides a complete review of anticipated attacks on UAVs. It also investigates realistic recommendations to improve UAV architecture to ensure secure communication. Extensive analyses are carried out for various viable solutions to empower the utility of UAVs in different applications. It provides an assessment of existing challenges, security issues, and future research directions to develop secure UAV communication.

1.2. Organization of the Paper

We have organized this paper as follows. Section 2 describes the related research contributions to UAVs. Section 3 provides basic information about UAVs in different aspects, such as types, classifications, swarms, flight time, payload, and standardization. Section 4 addresses the UAV's battery charging. Section 5 is devoted to UAVs for 5G and internet of things (IoT) technology. Section 6 focuses on different applications of UAVs. Security challenges and solutions are briefly explained in Section 7. Section 8 highlights future research directions. Finally, Section 9 concludes the paper.

2. Related Work

In this section, we highlight various research contributions to enhance the utility of UAVs in different applications. Several leading companies, including Skycatch, Yuneec, DJI, and Amazon, are focusing on UAVs in terms of load carrying efficiency, parcel delivery, and monitoring etc. "Amazon Prime Air" was initiated by Amazon to deliver packages of five pound within thirty minutes at a distance of 10 miles [6]. After introducing UAVs, the company is ambitious to achieve 50% of zero-impact shipment till 2030. DHL also started its drone "Parcelcopter" to deliver medicine [7]. Later, the DHL Trend Research Team also published a report on new trends, applications, and limitations of UAVs. In 2017, Walmart started drone service and later requested permission from the Federal Aviation Administration (FAA) for commercial delivery drones in 2019 [8]. Similarly, in 2017 UPS started a battery powered drone service for home package delivery [9]. In February 2017, a Chinese-made autonomous flying drone taxi named "Ehang 184" was tested in Dubai. It has a top speed of 63 mph and can transport a passenger weighing up to 100 kg as well as a small luggage [10]. In 2019, Zipline International used UAV medical service to distribute life-saving medicines, blood, and vaccines to 2000 healthcare centers in the south of Ghana [11]. Several countries have started promoting drone research and development for multiple services [12,13].

Several research studies have focused on multiple aspects of drones. For instance, authors in ref. [14] have addressed mobile charging feature to increase the battery life of drones. Aldhaher et al. [15], proposed a model to decrease the weight of a drone by integrating a wireless powered receiver. Lu et al. [16] suggested several techniques to enhance the flight time of drones through wired as well as wireless media. Kim et al. [4] proposed a method to decrease drones congestion at the charging station through an algorithm for queuing time and charging time. The authors in [17] proposed a model for landing and charging of drones on the roof of a building. In this study, the authors have also addressed misalignment losses and possible solutions to overcome them. Rohan et al. [18] proposed a mechanism comprised of multiple transmitters and a single receiver for drones charging. Similarly, Shin et al. [19] proposed a model for the allocation of time slots to the drones through an auctioning process. Besides these studies, there are several research surveys that highlight different issues and challenges of UAVs, as shown in Table 1.

Table 1. Surveys of UAVs issues and challenges.

Reference	Year	Research Focus
[20]	2015	This study surveys major collision avoidance mechanisms discussed in different publications. These mechanisms are based on sensing, detection and collision avoidance. Authors briefly explained various characteristics, benefits and drawbacks.
[21]	2016	This survey addresses the characteristics of UAVs for civil applications over the period 2000 to 2015 considering networking and communication aspects. Authors surveyed the data requirements, network mission parameters and quality of service requirements. Moreover, they elaborated common networking requirements including scalability, security, privacy, safety, adaptability and connectivity.
[22]	2017	This study discusses open-source flight controllers, which are being used for academic research. It also introduces UAV along with required components. This study fully addresses software and hardware open-source flight controller platforms.
[23]	2018	The study focuses on UAV cellular communication and bridges the gap between 3GPP standardization status quo and the future research. Specifically, it addresses downlink command and control (C&C) channel for aerial users.
[24]	2019	This study presents a comprehensive survey of UAV developments and its integration into cellular networks. It highlights consumer UAVs, interferences challenges and mitigative solutions, UAV prototype and testbed activities, regulations, challenges and security issues of UAV-aided cellular communications.
[25]	2019	This study provides a comprehensive tutorial on applications and advantages of UAVs in wireless communication. It investigates potential challenges and important trade-offs in UAV-assisted wireless networks. It highlights key factors including energy efficiency, channel modeling, performance analysis and 3D deployment. It also describes several mathematical tools and analytical frameworks including game theory, transport theory, stochastic geometry, machine learning, and optimization theory.

Table 1. *Cont.*

Reference	Year	Research Focus
[26]	2019	This study surveys UAV communication towards 5G/B5G wireless networks. It discusses space-air-ground integrated networks and associated challenges. It also identifies several open research problems and future research directions.
[27]	2019	This study presents a comprehensive survey on the integration UAV-enabled wireless networks and of 5G mmWave communication. It highlights existing research problems and cutting-edge solutions. This study also points out open issues and sheds new light on future research directions.
[28]	2020	This article presents a comprehensive study on UAV regulations, potential applications and challenges. Particularly, it addresses challenges including security, energy harvesting techniques, optimal trajectory, collision avoidance, interference mitigation, channel modeling and UAV standardization. Finally, it presents several problems and future research directions.
[29]	2020	This study focuses on Network Function Virtualization (NFV) and Software-Defined Network (SDN) technologies. In addition, it presents an in-depth analysis of use cases, classifications and challenges of UAVs. It also discusses NFV/SDN-assisted UAV systems along with different case studies and issues. Finally, it outlines open research problems, high level insights, and future research directions.
[30]	2020	This study is dedicated to the safety of UAVs from three different aspects such as communications, sensors and multiple UAVs.
[31]	2020	This survey presents a generic review on several applications of multi-UAV systems. Moreover, it provides architectural and nomenclature taxonomy. Finally, it discusses UAV challenges and current trends.
[32]	2021	This article carries out a comprehensive survey on green UAV communications for future 6G networks. In particular, it introduces the typical UAVs and their energy consumption models. It also discusses the typical trends and typical applications of UAVs. Finally, it investigates open research issues and several promising techniques.
[33]	2021	This study presents general architecture of UAV prototype along with experimental demonstration for UAV energy consumption model and air-to-ground channel models. In the end, it highlights some promising future directions for UAV prototype and experimental verifications.
[34]	2021	This study provides deep learning techniques for vehicle detection from UAV aerial images. It focuses on accuracy enhancement, computation overhead reduction and optimization objective. This study will help researchers in the area of traffic surveillance and artificial intelligence.

3. Unmanned Aerial Vehicles (UAVs)

In recent years, UAVs have gained significant attention. Generally, UAVs refer to controlled aerial vehicles without carrying a human pilot on them. It can be autonomously controlled and operated through sensors, microprocessors and other electronic gadgets [35]. Figure 1 depicts a typical UAV system architecture, showing how UAVs interact with satellites, ground control systems (GCS), smart phones, and computers via communication links. A human operator is used to control and operate a UAV remotely. UAVs can perform autonomous tasks in situations where human intervention is difficult or dangerous [36].

At present, UAVs have become a very convenient approach for logistics. In particular, there is a notable upsurge in the civilian market for UAVs. The key applications of UAVs include remote operations such as search and rescue, disaster monitoring, environmental monitoring, and delivery of airmail, medical items, and packages. Figure 2 presents the growing revenue of USA for commercial UAV market in different sectors.

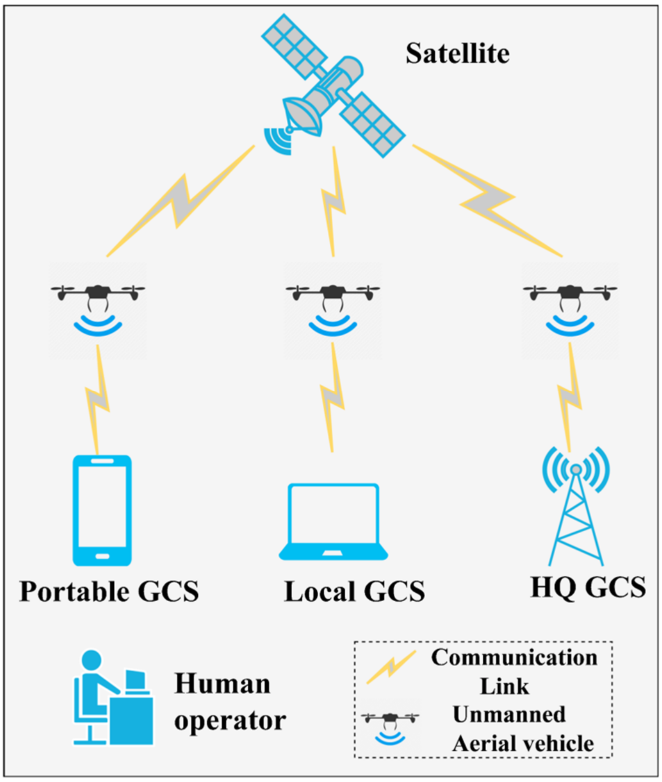

Figure 1. Architecture of UAV system.

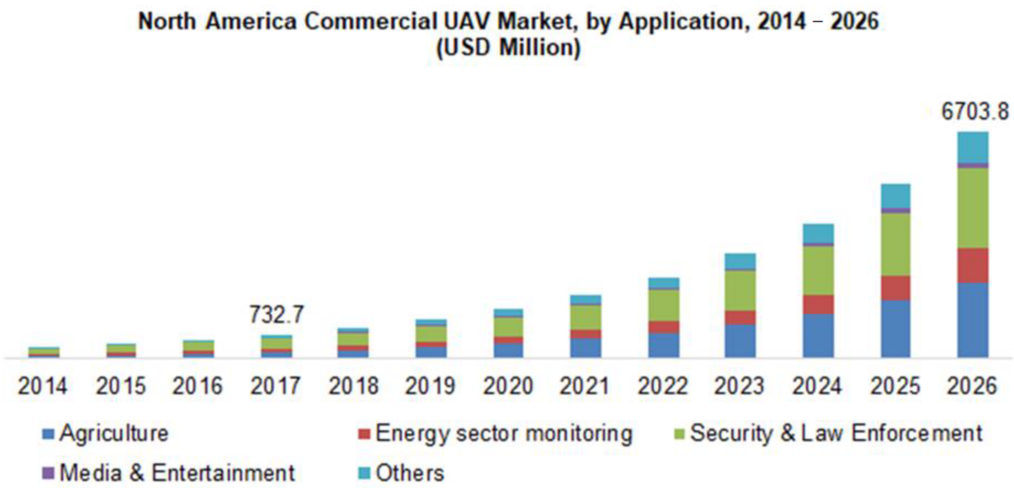

Figure 2. Commercial UAV market of North America [37].

Despite increasing attention, mostly UAVs are being controlled by human-aided remote controls. Generally, UAVs' characteristics, configurations, and mechanisms vary according to the application, speed, weight, and operation. Figure 3 shows different types of aircraft in terms of thrust forces and flight principles [38]. Piloting a UAV is hard for human beings while manual controls are vulnerable to inconvenience, inefficiency, and human error. In most of the cases, laborious, expensive, and intensive training is needed for UAV piloting. Even though autopilot features have been integrated into existing UAVs, they still face challenges such as limited battery life, limited autonomy, landing accuracy, limited mission time and distance. Although landing accuracy can be significantly enhanced through computer vision techniques, it still needs resources and protocols that are not available for commercial drones. Vertical takeoff and landing (VTOL) is a key feature of UAVs. VTOL-capable UAVs have high speed, high efficiency, and vertical hanging capability in the air. The aircraft under the "Motorized" section on the left side of Figure 3 are UAVs with VTOL features.

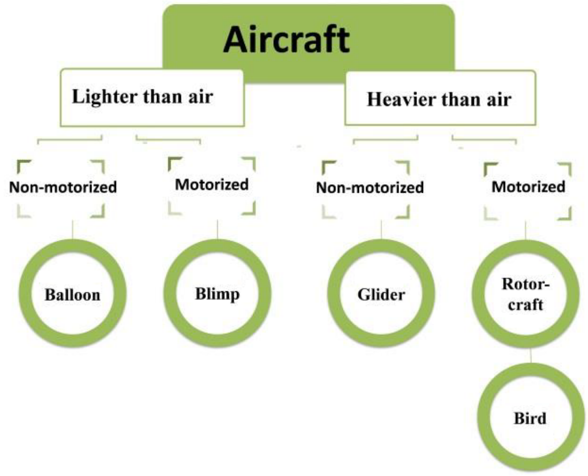

Figure 3. Classification of UAVs [38–43].

3.1. Classification of UAVs

UAVs are available with different specifications, equipment, sizes, range, and shapes. In the market, UAVs are present with a different number of rotors or propellers as shown in Table 2 [44]. UAVs have been developed with different engines and wing structures. UAVs can communicate using both short and long range wireless technologies, and their sizes can be classed as nano, micro, or large. They are excellent possibilities for providing cellular connectivity due to continuing and developing advances. Drones are equipped with First Person View (FPV) goggles, a Global Positioning System (GPS), sensors, stabilizers, and cameras. In this study, four different UAV categories are termed as fixed-wing, fixed-wing hybrid, single rotor, and multirotor as shown in Table 3 [45]. Fixed-wing UAVs are based on wings, main body, motor, and propeller. These UAVs require extensive skills-based training to operate and can vertically balance in the air for about sixteen hours, but they cannot move backward, hover, or rotate. Thus, they are not useful for some tasks such as aerial photography. Figure 4a shows an example of a fixed-wing UAV [46]. These UAVs are commonly used for power line inspections and aerial mapping. On the other hand, fixed-wing hybrid UAVs are based on automation and manual gliding. These UAVs are not good at forward flight and hovering. Figure 4b presents fixed-wing hybrid UAV [47]. Furthermore, single rotor UAVs are expensive and require skill training for operation. These UAVs are mechanically complex and vulnerable to challenges like vibrations. Figure 4c shows an example of a single rotor UAV [48]. Moreover, the cheapest and most easily fabricated UAVs are multirotor UAVs. These UAVs are commonly used for imaging and video surveillance. Multirotor UAVs can be tricopters, quadcopters, hexacopters, or octocopters as shown in Table 2. Quadcopters are the most commonly used UAVs, as illustrated in Figure 4d. Quadcopters have gained attention due to their vertical landing, fast maneuverability, high agility, and takeoff capabilities, along with their simple structure, cost-effectiveness, and small size.

Table 2. Categories of UAVs based on number of propellers.

Types of UAVs	Number of Propellers
Octocopter	8
Hexacopter	6
Quadcopter	4
Tricopter	3

Table 3. Key features of different categories of UAVs.

Types of UAVs	Key Features
Fixed-Wing	High speed, long endurance
Fixed-Wing Hybrid	Long endurance, VTOL
Single Rotor	Long endurance, hovering, VTOL
Multirotor	Short endurance, hovering, VTOL

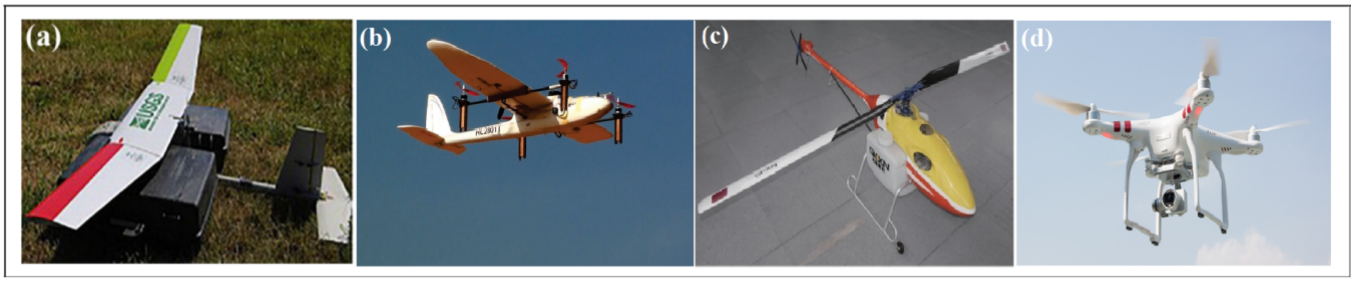

Figure 4. (**a**) fixed-wing, (**b**) fixed-wing hybrid, (**c**) single rotor, and (**d**) multirotor UAV.

3.2. UAV Swarms

As illustrated in Figure 5, UAV swarms can be classified as semi- or fully autonomous. This classification can also be categorized as single-layered and multi-layered swarms. In single-layered swarms, each UAV is a leader drone. Each layer of a multi-layered UAV swarm is occupied by a dedicated layer of drones, which operate and report to specific leader drones at each layer. In every swarm, each drone has data collection and processing capabilities in real-time, while the central processing occurs at the cloud or base station. The swarms of UAVs with intelligent monitoring mechanisms can reliably and quickly cover an intended area by using different parallel operating drones. Several research studies have focused on the role of UAV swarms. For example, ref. [49] considers swarms of drones to address the charging mechanism of several drones in parallel. It features UAV swarms for smart energy management. Some studies have suggested prioritization algorithms in case of swarms of UAVs, where UAVs with high priority will be recharged first as compared to UAVs with low priority. Swarms of UAVs also impact the hovering performance. UAV flight synchronization and hovering stability are essential when we consider the mission execution of swarms of UAVs such as quadcopters. In addition, communication reliability of the quadcopter swarm is also crucial for a successful mission. The authors in ref. [50] proposed an efficient multi-robot coordination method to address the issue of real-time UAV swarm coordination on a broad area network. Swarms of UAVs have been studied in the past for surveillance purposes. For instance, the authors in ref. [51] describe quadcopter swarms for object tracking and localization.

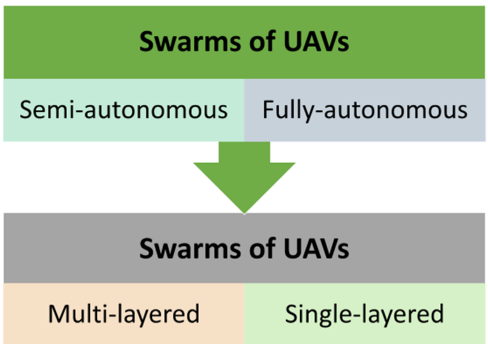

Figure 5. Classification of swarms.

3.3. UAV Characteristics

3.3.1. Speed and Flight Time

Smaller UAVs can fly at a speed lower than 15 m/s. In contrast, large UAVs can fly at a speed up to 100 m/s. When any UAV follows any intended trajectory to enhance its spectral or energy efficiency, its speed must be properly checked at different turning points of this trajectory. In ref. [52], the authors focused on trade-off between UAV's turning agility and speed.

While the flight time of a UAV refers to maximum time, it can fly until its battery drains out. Size, weight, and weather conditions have a strong impact on battery life of UAVs. Large UAVs can travel for hours, while smaller UAVs can fly for a limited time of 20–30 min. Flight time is also affected by the autopilot system and GPS. The flight time of a UAV is of paramount importance along with cost and price. The research fraternity should investigate innovative solutions to overcome the limited endurance of UAVs, which plays a crucial role in their full-scale deployment and successful mission accomplishment.

3.3.2. Payload

Payload refers to lifting capability of any UAV to carry any load. The lifting capability varies from a few grams to hundreds of kilograms. A larger payload can carry more accessories at the cost of short flight time, high battery consumption, and larger size. Common payloads are sensors and video cameras used for surveillance, reconnaissance, or commercial applications. UAVs can also carry cellular user equipment (UE) including mobile phones or tablets of weight less than 1 kg [53]. It is considered that heavy payloads reduce the flight time of UAVs. However, if a UAV has more surface area and carries more motors, then it can store more power which ultimately enhances flight time. Thus, the quality of the payload can assist to travel longer for the same accuracy and resolution.

3.3.3. Range and Altitude

UAV's range refers to the distance from where it can be controlled remotely. The range differs from a few meters for small drones to hundreds of kilometers for larger drones. On the other hand, altitude refers to the height at which a drone can fly. Usually, aerial platforms are divided into two categories on the basis of altitude.

- Low altitude platforms (LAPs): LAPs are usually deployed to support cellular communication as they offer fast-deployment and cost-effectiveness. In addition, LAPs offer line-of-sight (LoS) path which can substantially improve the communication performance [54].
- High altitude platforms (HAPs): HAPs like balloons are also used for cellular connectivity. HAPs offer wide coverage as compared to LAPs. HAPs deployment is complicated and they are mostly considered as a vehicle to support Internet connectivity. Table 4 presents UAV categories based on altitude. Table 5 summarizes a comparison of different UAV types considering three different parameters. Figure 6a–d show different UAV projects implemented in different countries.

Table 4. UAV categorization on altitude [55].

Category	Endurance (h)	Flight alt. (m)	Range (km)	Mass (kg)
Low altitude deep penetration (LADP)	0.5–1	50–9000	>250	250–2500
Low altitude long endurance (LALE)	>24	3000	>500	15–25
Medium altitude long endurance (MALE)	24–48	3000	>500	1000–1500
High altitude long endurance (HALE)	24–48	20,000	>2000	2500–5000

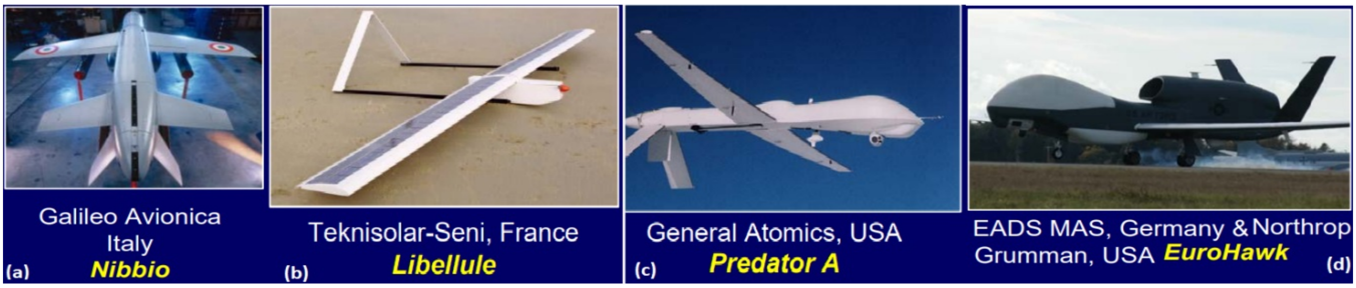

Figure 6. Different examples of UAVs on altitude (**a**) LADP, (**b**) LALE, (**c**) MALE, and (**d**) HALE [56].

Table 5. Feature-based comparison of UAVs [57].

UAV Type	Altitude (km)	Avg. Control Range (km)	Avg. Airspeed (m/s)
Multi-rotor UAVs (DJI Agras MG-1P [58])	2	3–5	7
Fixed-wing UAVs (AgEagle RX60 [59])	0.125	2	18.8
Single rotor (Alpha 800 [60])	3	30	15.2
Fixed-wing-multi-rotor hybrid UAVs (Jump 20 [61])	4	500–1000	30

3.4. UAV Standardizations

3.4.1. UAVs 3GPP Standardization

In this modern era of technology, UAVs have gained significant attention in LoS and NLoS environments [28,62]. In 2017, the third-generation partnership group (3GPP) conducted several studies and issued Release-15 to acknowledge LTE-empowered UAVs. The main objective of these studies was to focus on UAV traffic requirements, channel modeling techniques for air-to-ground propagation perspectives, reuse of current cellular networks to enable UAV communication, LTE support and developments required to integrate LTE into UAVs. The 3GPP objectives also include the identification of traffic types for which the existing cellular networks must cater for UAV flight over 300 m from ground. Table 6 summarizes these UAV communication requirements which are classified as: (i) synchronization and radio control; (ii) command & control; and (iii) application data [24].

Table 6. UAV communication requirements [24].

Link	Data Type	Data Rate	Critical
Downlink	Radio control (PDCCH)	N/A	Yes
	Synchronization (SSS/PSS)		Yes
	Command and Control (C&C)	60–100 kbps	Yes
Uplink	Command and Control (C&C)	60–100 kbps	Yes
	Application data	Up to 50 Mbps	No

3.4.2. UAVs Standardization Outside the 3GPP

Besides 3GPP standardization, there are several other regulatory bodies that define various specifications of UAVs to ensure efficient, reliable, and uniform communication.

- In 2015, the Institute of Electrical and Electronics Engineers (IEEE) introduced the Drones Working Group (DWG). The main aim of this group was to develop the taxonomy for consumer drones with the objective of highlighting security and privacy issues. For this purpose, the DWG establishes methods, systems, requirements, testing, and validation needed for consumer drones to preserve the security and privacy of the public and their properties.
- The European Telecommunications Standards Institute (ETSI) aims to identify UAV applications, use cases, and understanding regarding Internet Protocol (IP) suite

architecture to be developed and spectrum rules required to facilitate UAVs in current LTE networks [63].
- The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) defined work item (WI) Y.UAV.arch to support a reliable and functional architecture of UAVs and UAV controllers through IMT-2020 networks [64].

3.5. Unmanned Traffic Management (UTM)

It is envisioned that urban airspace will be congested with several types of autonomous aerial vehicles, consequently leading to complex air traffic management. Existing human centric, monopolistic and centralized air traffic control systems are not feasible to cope with UAVs congestion and cannot provide immediate legal solutions for autonomous aerial missions [65]. The aforementioned elements became the rationale for dedicated UTM systems to strategically de-conflict multiple UAV flights in the shared and segregated proximity. UTM systems are fully autonomous, where controllers can decide trajectories, traffic density and risk calculations. UTM has proven its stature in a wide variety of higher-tier applications including surveillance, communication, agriculture, aerial mapping and remote sensing. It has the capability to operate in both LoS and beyond the visual LoS (BVLoS) links. The existing UTM systems operate on very-low-level (VLL) airspace along with offering BVLoS links. Most UTM systems have similar concepts of operations and objectives. Various UTM systems are based on federated, distributed and service-oriented architecture [66]. Three levels of connectivity based on ground stations, airborne vehicles and satellites are required for communication in UTM systems. UTM systems offer following potentials features:

- Safe and secure UAV missions,
- Flexible operations for several types of UAVs,
- Provides real-time monitoring based on integrated sensors,
- High level control providing prediction of other piloted UAVs,
- A key unifying element of reliance on a more automated and competitive system.
- Operates on national and international standardizations.

4. UAV Battery Charging

Drones are currently being used for several applications such as military operations, power lines inspection, forest monitoring, disaster prevention and smart agriculture [57,67,68]. Drones carry different types of payloads such as GPS, infrared cameras, batteries and sensors as a delivery vehicle. These drones usually carry high energy batteries e.g., lithium batteries that support flight time ranging from 20–40 min [69]. However, range and endurance are a critical challenge in UAVs due to limited battery capacity. It is not feasible to increase battery size of UAV as it will increase weight, which is another critical concern. Several research studies have addressed battery charging of UAVs but still it requires intensive investigations by research fraternity [16]. Jawad et al. [67] suggested three ways to enhance flying time: (i) drones can be equipped with high battery capacity but it can increase the drone weight. (ii) The battery swapping can be achieved after the landing of drone. However, it also causes complexity and high cost of swapping system. (iii) Recharging can be done at the base station of the drone. Charging can be achieved through wired or wireless power transfer (WPT) system [70]. Next, we have briefly discussed WPT techniques.

4.1. Wireless Power Tranfer (WPT)

According to [71], it is envisaged that WPT has generated 12,000 million dollars of revenue in 2020. The statistics of drones and WPT market growth can be seen in Figure 7. It is expected that drone market will hit $43 billion in total sales with a Compound Annual Growth Rate (CARG) of 13.8% by 2025, as shown in Figure 7 [10]. It is due to diverse applications in the electronic industry with several key benefits in terms of safety, convenience, reliability and a fully automated charging mechanism. These benefits can be attained through different WPT techniques. Another key feature of WPT is that it is very essential in different environments where wired power transfer technique is dangerous, difficult and impossible, such as harsh underwater environments and high voltage power applications. Research fraternity has been exploring trade-offs and evaluated different WPT techniques. These techniques are categorized as: radiative electromagnetic (EM) and non-EM techniques. Figure 8 shows these WPT techniques which are further divided into nine categories. In non-EM, power is transferred using acoustics or optical sources such as laser. EM is further classified into radiative far-field, non-radiative and mid-filed radiative and non-radiative. RF is used for power transmission in radiative, while capacitive coupling; inductive coupling and magnetic resonance coupling are used in non-radiative. Currently, these WPT techniques are commercially available for different applications such as smart phone charging and charging implantable medical devices etc. and still being developed for different applications. Next, we have highlighted some WPT techniques and some research contributions on WPT.

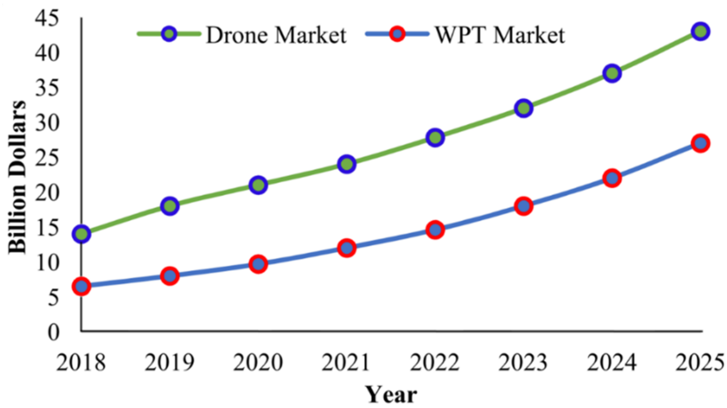

Figure 7. Statistics of Drones and WPT market growth (Data Source: Drone Industry Insight Report [72]).

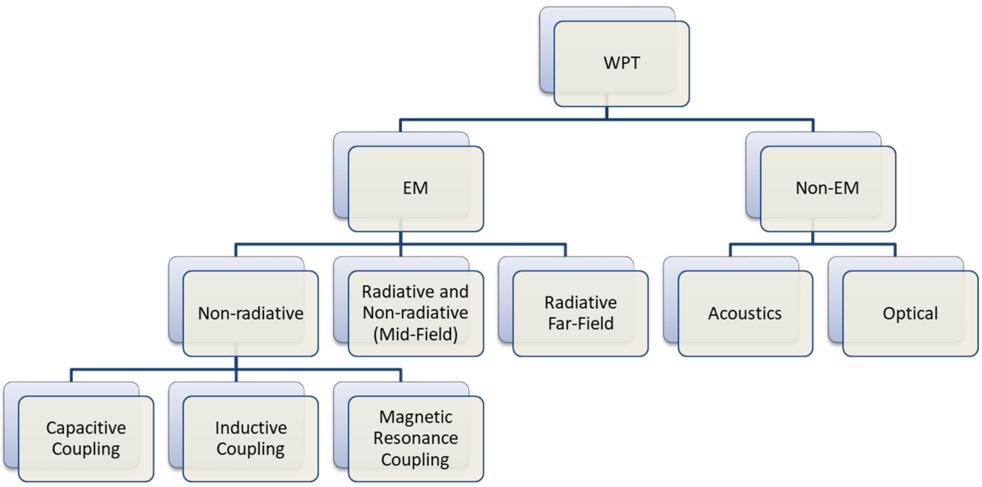

Figure 8. Different WPT techniques.

The aforementioned WPT techniques ensure efficient and reliable wireless power transmission between UAV and the base station. The application of WPT technology to UAVs should take on some critical issues such as misalignment, interference and payload into consideration. UAV-based WPT system must be lightweight to avoid payload reduction. Furthermore, the WPT techniques must ensure misalignment tolerance between coils, high landing precision and efficient power transfer. Among these challenges, misalignment affects are a dominant issue as landing accuracy is low in the case of UAVs. Consequently, it affects coupling factor, transfer efficient and power transfer. Several research studies have reported these major issues about recharging UAV batteries through WPT techniques [70,73,74]. UAV charging can be achieved through inductive coupling WPT to enhance both range and flight time for inspection, monitoring and surveillance tasks. UAV-empowered inspection technique can overcome several limitations of existing inspection techniques, such as expensive task and hazardous operation through manned helicopters. In ref. [75], the authors demonstrated magnetic resonance coupling (MRC) WPT to recharge drone and performed testing of proposed system for different distances and misalignment topologies. Authors reported 90% transfer efficient at 10 cm distance. Junaid et al. [76] presented a vision-based, closed-loop target detection through UAV for outdoor applications. Authors designed a charging station that prolongs the flight time and enhances endurance of UAV. In ref. [77], Blain proposed a novel mid-air inductive charging mechanism to charge multiple drones at the same time without any need of landing using global energy transmission (GET). It is worth mentioning that most studies in the literature focused on UAV charge scheduling while taking into account centralized architecture. Only a few studies looked at the peer-to-peer network of UAVs charging through blockchain technology [78,79]. Table 7 summarizes some reported studies in the literature on the charge scheduling of UAVs.

Table 7. Studies on charge scheduling of UAVs.

Reference	Year	Research Focus
[15]	2017	Lightweight WPT system for the mid-air charging of drones.
[16]	2018	WPT techniques for UAVs. A review, extensions and reconceptualization.
[18]	2018	Designing of drone battery charging system through wireless power transfer (WPT).
[70]	2018	WPT system to charge autonomous electric UAV using a small secondary coil.
[80]	2018	WPT technology-based drone charging stations to charge drone over the buildings.
[19]	2019	Auction-enabled charge scheduling using deep learning framework for a network of multiple drones.
[67]	2019	WPT based sleep/active method for a drone charging station in smart agriculture.
[81]	2019	Neural blockchain-empowered assistance for drone swarms.
[82]	2020	Energy-efficient UAV crowd-sensing through multiple charging stations using deep learning.
[83]	2020	Novel application of a distributed network of charging stations and UAVs through advanced blockchain.
[84]	2021	Blockchain-empowered charge scheduling for UAVs in smart cities.

4.1.1. Photovoltaic Cell-Based UAV Charging

The PV cells are commonly utilized to charge batteries and enhance flight time of UAVs. PV cells make use of sunlight to charge batteries of UAVs. Whenever sunlight is present, the required power is provided by PV cells and in the absence of sunlight batteries are used to deliver required power to UAV. Research works on solar-powered UAV report that several parameters play a key role such as temperature intensity, angle of incidence of sunlight, geometry, orientation and position of PV cells [85]. This technique is not suitable in scenarios with insufficient sunlight. There is a need to adopt alternative strategies whenever sunlight is not present to continue UAV flight. These strategies include additional power supplies, enhanced battery power, PV cells size and automatic position adjustment according to sun position. As PV cells require certain payload capacity and wing length on the UAV, so it is feasible for fixed-wing UAVs. Moreover, environmental conditions such as humidity, temperature, fog, clouds reduce the system efficiency and reliability. Thus, these atmospheric conditions must be kept into consideration.

Solar energy-based UAVs have gained the attention of several research groups. Solar-powered aircrafts are currently being used for power line inspection, forest fire fighting, border surveillance and high altitude communication. This technology can be used to supersede environmental, scientific and communication satellite to be used for military and civilian applications. Sufficient flight power can be achieved through appropriate selection of PV cells and taking account of efficiency and weight is the key factor to ensure long flight time and high endurance in solar-powered UAVs. To achieve cost-effectiveness and great efficiency, several materials are used in solar cells. Some studies suggest mono-crystalline silicon PV cells due to affordable cost and high efficiency [86]. Furthermore, mono-crystalline silicon PV cells offer high flexibility that supports easy integration in the UAV wing. Table 8 summarizes a comparison of mono-crystalline silicon PV cells from various manufacturing companies. It is still important to investigate PV cells with novel designs, energy management strategies and manufacturing material to ensure high efficiency and high availability [85]. Research fraternity should focus more on material science developments as low photoelectric efficiency is a major limiting factor in this research domain [87]. Some studies propose an effective approach to optimize solar-powered UAV flight trajectories in order to gain more solar radiation along with low consumption of mechanical energy [88].

Table 8. PV cells comparison [86].

Company	PV Cell	Dimension (mm)	Weight (g/m^3)	Flexibility	Efficiency (%)
Gochermann Solar technology	SunPower C60	125 × 125	950–1000	Semi-flex	22.6
Gochermann Solar technology	SunPower E60	125 × 125	-	Semi-flex	23.8
Bsolar	TG18.5BR	156 × 156	-	-	17.5–18.39
Delsolar	D6F	156 × 156	-	-	18–20
Gochermann Solar technology	SunPower A300	125 × 125	-	-	20 min
IXYS (IXOLAR)	KXOB22-12X1	27 × 7	2645	Semi-flex	22
Bosch Solar Energy	M3BB	156 × 156	1027	No-flex	18.43
SunOWE	156 MM	156 × 156	1027	No-flex	18.2

4.1.2. Charging with Laser Beaming

Laser power transfer (LPT) is another method used to charge UAVs and is mostly considered in space and military applications [89]. In this charging technique, a laser beam of specific wavelength and frequency feeds PV cells mounted on UAV. These PV cells are used to harvest energy from laser transmitter to power UAV and charge its batteries. Laser beaming technique is used for rotary wing and fixed-wing UAVs. It has become a viable solution to offer unlimited endurance. It has the capability to deliver high energy to the receiver using narrow beam divergence [90]. Laser power transfer is envisaged to empower several energy-hungry missions of UAVs over a long distance. Some studies [91,92] have reported the feasibility of laser power transfer for UAVs. In ref. [93], authors presented results pertaining to current, voltage and efficiency based on laser wavelength in a laser PV cell and material type. In ref. [94], authors discussed results pertaining to wavelength and temperature output of PV cells used for charging system through laser beams. In ref. [92], authors proposed a controller design strategy based on laser PV module output characteristics to control the power converter of a laser power transfer system. In LPT, some critical concerns are blockage, mobility and performance in long range flights. This method is restricted in certain areas such as military areas, airports and scenarios where laser beam is hazardous to human health and living environments. Figure 9 illustrates an overview of multi-UAV WPT system using laser beams. Table 9 summarizes efficiencies of different PV materials when illuminated with laser light of different wavelengths. As given in Table 9, GaAs PV cell gives highest efficiencies around 850 nm wavelengths.

Table 9. Efficiencies of various PV materials.

PV Material	GaAs		Si		InGaAs	InGaP	CIS
Laser Wavelength	810 nm		950 nm		>1000 nm	>1000 nm	>1000 nm
PV Cell Efficiency (%)	60	53.4	28	27.7	40.6	40	19.7
Laser Intensity (kW/m^2)	110	430	110	10	2.37	2.6	10

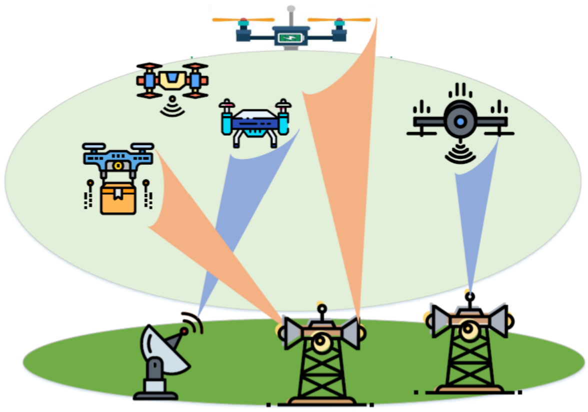

Figure 9. Recharging of multiple UAVs through laser beams [95].

5. UAVs in 5G and IoT Networks

With the rapidly growing advancements of UAV technology, the UAVs have proven their great stature in an extensive range of applications such as environmental monitoring, wireless communication and public safety. Apart from this, UAVs are extensively explored in conjunction with wireless networks and have shown promising solution to enhance the energy and spectrum efficiencies of the fifth generation (5G) wireless networks as they offer on-demand flexible platform to deploy aerial base stations. The unique attributes of UAVs, such as adaptive altitude, scalability, flexibility, mobility, high resilience, high reliability, and low cost, motivate their use for many applications. Orders of magnitude performance enhancement is envisaged to be attained in UAV-assisted networks as compared to conventional terrestrial system without UAVs. UAVs can be smartly controlled and remotely operated when needed. UAVs offer high probability of LoS communication which significantly enhances the transmission rate. Swift maneuverability of UAVs can ensure reliable and broadband wireless coverage during live stream events and natural disasters. Thus, UAVs can be used in 5G networks to offer offloading services with stringent requirements [96] in case of emergency operations. With aforementioned potencies, it is plausible to integrate UAVs into 5G networks. Extensive research endeavors are being performed on UAV-assisted 5G technology to reduce latency and extend network coverage, capacity and energy efficiency. However, there are certain challenges for this coexistence such as UAV's vulnerability to interference, dynamic network topology and mobility causing spatial and temporal dynamics. These challenges can lead to frequent intermittent connections or even transmission failures [97]. Moreover, UAVs are used to perform wireless energy transfer (WET) and wireless information transfer (WIT) to power ground terminals such as IoT terminal which are integral parts to develop flexible and sustainable 5G networks [98].

With the continuous development of UAVs in terms of maneuverability, agility, degree of autonomy, flying speed, flight time and mechanical performance, UAVs have emerged as attractive platforms to support various IoT applications [52]. For instance, UAVs can be incorporated with IoT terminals to get information about water, gas and power meters from sky, offering an unprecedented benefit to IoT regulators. UAVs equipped with specific sensors can gather information about air quality in a smart city and deliver this real-time data using machine type communication or LoRa. In ref. [99], the authors proposed an open-source smart IoT platform through UAV to support different smart city services. UAV has been considered as a promising enabler to support IoT vision due to its reliability, scalability and agile usability [100]. In contrast to other applications of 5G networks, IoT devices are randomly scattered and energy limited. These challenges will severely aggravate the connectivity issue for IoT networks. By leveraging the UAV's maneuverability and agile mobility, it is viable to get close to IoT terminals and gather the sensing information from them. Hence, UAV-assisted IoT networks can substantially reduce the overhead of IoT network and can solve the coverage issue. Moreover, cost-effectiveness of UAVs makes them promising candidates for emergency on-demand operations in IoT applications.

Despite these appealing advantages, using UAV in an IoT networks still suffers from several challenges of channel modeling, prior information of channel state and energy constraints of IoT terminals. Any small maneuverability error can significantly affect entire mission of UAV. UAV's maneuverability limitations have been experimentally analyzed in [52]. For IoT terminals, both total energy constraint and peak transmit power constraint must be kept into consideration while optimization of the communication strategy as recharging the battery equipped with IoT devices is hard. Moreover, another critical concern is the amount of sensing data which may alter dynamically. Accordingly, the communication strategy should support the data sensing status. Practically, both budget transmission duration constraint and budget power constraint can be incorporated to link data sensing condition and communication strategy optimization. A comprehensive study on UAV related challenges including sky pollution, physical collision, safety, privacy and regulations is presented in [101].

6. UAV Applications Areas

The advancements in the potentials of deployed sensors on UAVs support the creation of a new breed of services and various applications for unmanned operations. In this section, we have briefly discussed some prominent applications of UAVs.

6.1. Security, Monitoring, and Surveillance

UAVs are playing an integral role in military surveillance missions. Several countries have added UAVs in their defense strategic plans. Countries are using these flying robotics machines for enemy detection, anti-poaching, border control and maritime monitoring of critical sea lanes. Low cost, reliable and versatile UAVs are currently playing a significant contribution in aerial surveillance, monitoring and survey of any specific area to prevent any illegal activity. For instance, surveillance for any threat can be detected through drones and they can be used to monitor any movement activity in any restricted area. UAV can provide these services by sensing an automatic alert with minimal manual efforts.

6.2. Disaster Management

In the case of a man-made or natural disaster such as terrorist attacks, tsunami and floods, UAVs can gain access to disaster truck locations that are hazardous for manned activity. These disasters can severely damage telecommunication infrastructure, transportation, power and water utilities. UAVs can help to collect information, necessitate rapid solutions and navigate debris. Radars, sensors and high quality cameras incorporated in UAVs can assist rescue teams to identify damage and immediately start recovery operations and send resources such as first aid medical kits and manned helicopters. UAVs can assist in finding timely disaster estimation, providing disaster alerts and help in finding efficient countermeasures. In case of wildfire, a swarm of drones containing fire extinguishers can monitor, examine and trace any area without endangering human lives. Thus, UAVs can assist in real-time coverage of large areas without risking the safety and the security of the personnel involved. Early warning through UAVs can help to rescue human beings and wildlife at risk.

6.3. Remote Sensing

Currently, amateur drone technology has been used to get high resolution imagery data of remote areas, islands, mountaintops and coastlines. UAV technology bridges the gap between airborne, spaceborne and ground-based remote sensing data. Low cost and lightweight characteristics of UAVs support quality observation with high temporal and spatial resolutions. The remote sensing capabilities of UAVs can support in disease detection, water quality monitoring, drought monitoring, oil and gas, yield estimates, hydrological modeling, biodiversity conservation, geological disaster survey, terrain survey, forest mapping, and crop monitoring. This technology can also be used for crowd sourced mapping and creation of 3D environmental maps and has become an active part of archaeology and cartography. Affordable drones can help to provide latest data that can fit land planning budget without relying on outdated mapping sources. UAVs applied to remote sensing for different applications are shown is shown in Figure 10.

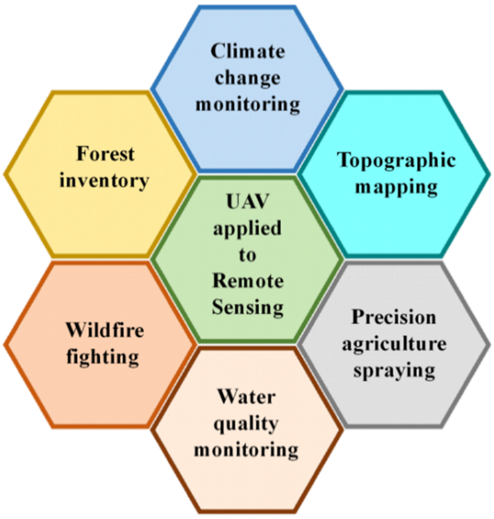

Figure 10. UAV and remote sensing applications.

6.4. Search and Rescue (SAR)

UAVs are considered to be of pivotal importance in critical scenarios such as disaster management, rescue operations and public safety. UAVs can save a lot of manpower, resources and time by offering real-time imagery data of intended locations. Consequently, a SAR team can timely detect and decide where accurately the assistance is urgently required. UAVs can speed up SAR operations in disastrous situations like missing persons, avalanches, wildfires and poisonous gas infiltration. For instance, drones can be used to track mountaineers who are lost during any mission or protect human lives lost in any remote desert or forest. Thus, drones can assist in tracing unfortunate victims or any challenging terrains or hard atmospheric conditions. Drones can provide necessary medical supplies before the arrival of any ambulance or medical team. Drones can be equipped with medical kits, life-saving jackets and food supplies to disaster-stricken areas and remote location. Such drones can provide cloth, water and necessary items to stranded human beings in inaccessible areas before the arrival of rescue crews.

6.5. Construction and Infrastructure Inspection

As-built mapping, construction monitoring and site inspection have become efficient, easy and fast through UAVs. Monitoring of construction projects from start to finish ensures quality progress of site work. It can provide reports containing imagery, video and 3D mapping to potential stakeholders. This technology can significantly support infrastructure and construction inspection applications. There is rapidly expanding interest in UAVs used for GSM towers inspection, gas pipeline monitoring, power lines inspection and construction projects monitoring [102].

6.6. Precision Agriculture

UAVs can be used in precision agriculture for collecting data from ground sensors (water quality, soil properties, moisture, etc.), pesticide spraying, disease detection, irrigation scheduling, weed detection and crop monitoring and management. The incorporation of UAVs in precision agriculture is a time-saving and cost-efficient technology that can enhance profitability, productivity and crop yields in farming systems. In addition, UAVs assist pest damage, weed monitoring, chemical spraying and agriculture management, thereby they effectuating a better yield of the crops to meet specific production requirements. UAVs along with remote sensing can be a game-changer for precision farming.

It provides temporal, spatial and spectral resolution, but can also offer multi-angular observation and detailed vegetation height data. UAVs can put a significant impact on agriculture industry by performing smart aerial mapping. UAVs equipped with right sensors and appropriate cameras can monitor health of crops in terms of leaf thickness, foreign contaminants, chlorophyll level and temperature [103]. In ref. [104], WH Maes et al. briefly discussed the progress on remote sensing with UAVs in growth vigor assessment, nutrient status, pathogens and weed detection and drought stress. In the future, image processing techniques can be used to investigate plants diseases and other traits from UAV captured high resolution images.

6.7. Real-Time Monitoring of Road Traffic

Road traffic monitoring (RTM) system constitutes a domain where the integration of UAVs has captured great interest. In RTM, the complete automation of transportation sector can be achieved through UAVs [105]. It will include the automation of rescue teams, road surveyors, traffic police and field support teams. Reliable and smart UAVs can assist in the automation of these elements. UAVs have emerged as new promising tools to gather data about traffic conditions on highways. In contrast to conventional monitoring devices such as microwave sensors, surveillance videos cameras and loop detectors, cost-efficient drones can monitor huge road segments [102]. Drones can be operated by local police to get a sharp vision of road accidents or massive security crackdown on highway criminal activities such as car theft. Other applications include vehicle identification, raids on suspect vehicles, chasing armed robbers and hijackers or anyone who violates traffic rules. It can also detect vehicle over-speeding, accidents and can assist in avoiding traffic jams and mass congestions [106]. An overview of UAV services on highway is presented in Figure 11.

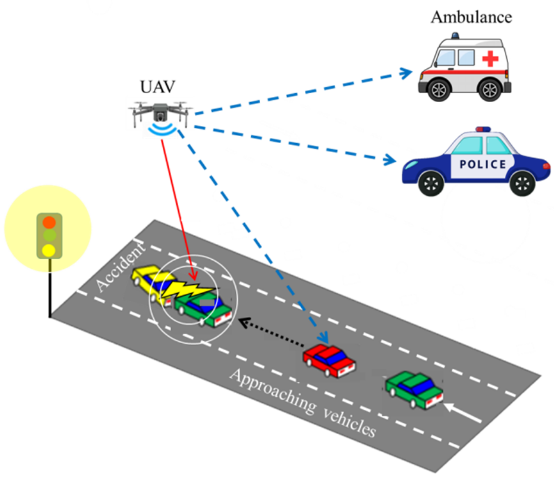

Figure 11. UAV assistance on highway.

UAVs can be used for road conditions monitoring such as indicating any cracks and giving an early warning to avoid possible accidents and reduce damages. Currently, road monitoring and inspection are implemented through manned vehicles and its automation level must be improved. The integration of road inspection technology and UAVs can significantly reduce road damages. Moreover, target detection algorithms can be implemented on road cracks images taken from UAVs for effective detection.

6.8. UAVs for Automated Forest Restoration

Another emerging research domain is to utilize UAVs for automated forest restoration (AFR). UAVs can be deployed to assist in several tasks needed for the implementation of forest restoration such as site survey, restoration strategy, site infrastructure, seeds supply, site management (fertilizing and weeding etc.), and biodiversity survey following restoration interventions [107]. Existing available technologies such as positioning and imaging sensors help UAVs to perform certain tasks including rudimentary pre-restoration site surveys and monitor several aspect of biodiversity recovery. UAVs can monitor changes in climate, ecosystem composition, and functions of forests as well as supporting inspection of forest restoration [108]. High resolution cameras installed in UAVs can provide appropriate data on forest ecosystems to assist forest restoration projects. The adequate resolution of UAV cameras can support characterizing and analysis of forest areas due to their ease in acquiring data and versatility. Furthermore, optical sensors installed in UAVs are also being utilized to attain geometric features of forests e.g., canopy diameter and height [109]. Similarly, remote sensing operations from UAVs are also reliable and efficient substitutes for traditional forest measures.

6.9. UAVs for Inspection of Overhead Power Lines

Detection and prevention of faults from power lines is crucial for the availability and reliability of electricity supply. The drawbacks of traditional techniques include high cost, cumbersome deployment and hazardous risks. Therefore, UAV-aided power line distribution and transmission lines inspection as shown in Figure 12 have gained significant interest by researchers. Inspection of power lines also refers to the safety of a power transmission grid. UAV equipped with digital camera to take images of power lines corridors is a convenient approach to support these inspection tasks [110]. UAVs can be used to trace power pylons for damaged bolts, corrosion or rust and lightning strikes. Short-circuiting of these power lines usually occurs due to harsh weather conditions, bush fires and tree falls. In a recent study [111], authors discussed the installation of UAVs in the overhead power lines to identify faults. Both UAVs and climbing robots can be used to locate faults. UAVs can perform these inspection operations at lower cost than helicopters and low risk associated to conventional foot patrol. Among different UAVs, fixed-wing UAVs that can fly faster and higher are mostly preferred for rough inspection and vegetation monitoring. In contrast, multi-rotor UAVs are utilized to get images by hovering in the air at a closer position to the objects. Multi-rotor UAVs are suitable due to high 3D maneuverability. Despite these potentials, use of multi-rotor UAV in a confined or complex environment is challenging for the autonomous mission plan and pilot. In the future, advanced data gathering, sharing and processing algorithms should be investigated for cooperative UAVs network to support reliable, efficient and faster inspections.

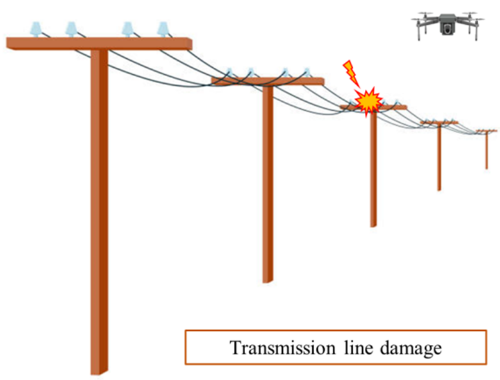

Figure 12. Inspection of power lines through UAV.

7. Security Challenges and Solutions

The security and privacy concerns are rarely addressed in the design consideration of small UAVs. UAVs often include onboard wireless communication modules that use open, unencrypted, and unauthenticated channels, rendering them exposed to a variety of cyber-attacks [112–114]. An intruder wishing to disrupt drone communication has several options for carrying out their malicious aim. For example, the attacker may send out many reservation requests, eavesdrop in on control communications, and/or falsify data. Hacking of drones is another major concerns of using UAVs for data collections and wireless delivery. In military operations, UAVs contain sensitive-information and may become victim of malicious attacks and data theft. Hackers can usurp control of UAV for illegal activities including smuggling, invasion of privacy and stealing stored information. Liability for UAV includes an enormous risk to individual privacy. UAVs are installed with cameras or any device that can capture images or videos; it can violate the privacy of communities or people. To overcome this issue in USA, Center of Democracy and Technology (CDT) informed Federal Aviation Administration (FAA) to implement certain rules to ensure privacy. In this regard, Privacy by Design (PbD) was proposed, which offers remedies for security and privacy breaches [115]. PbD rules significantly limit the privacy intrusion. Additionally, continuous UAVs flights can reveal trade secrets of concerned companies and can severely affect their business.

Denial-of-service (DoS) and distributed DoS are the most common attacks on UAVs that occur due to the absence of proper DoS/DDoS resistant mechanisms. DoS attacks cause severe availability challenges as the attacker sends several requests to cause UAV network congestion. DoS attacks are performed by depleting the batteries, overloading the processing units and flooding the communication links to cause huge interruptions. In DDoS, UAV systems faces unreachability issues as the attacker can overwhelm it through traffic from multiple sources. Moreover, signal spoofing through hijacking can damage the nature of certain UAVs. GPS Signal spoofing attack can be performed by inserting or passing false data through GPS channels by the miscreant as shown in Figure 13. In hijacking, the attacker can take complete control of UAV by injecting extra commands. Communication links of UAVs also suffer from session hijacking. These attacks can be mitigated through direction-of-arrival sensing, detection of signal distortion and strong authentication.

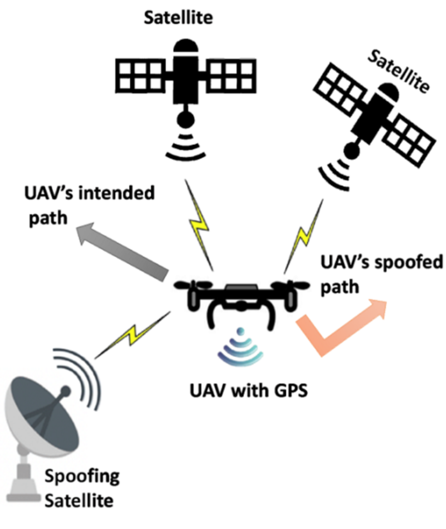

Figure 13. GPS spoofing attack.

Among different security issues, Ground Control System (GCS) attacks are very dangerous as the attacker can steal all the data from UAV by using computer running dedicated software. A compromised GCS enables adversary to send malicious and erroneous commands. These attacks are usually performed through key loggers, viruses and malwares. Malicious operating commands can be performed to take control of any victim UAV. These attacks compromise the confidentiality of UAVs through different methods such as social, engineering and malware etc. Necessary countermeasures are required to prevent UAV's data from being leaked to unauthorized processes, entities and users. It can be mitigated by using multiple GCS authentications. Possible GCS threats are shown in Figure 14.

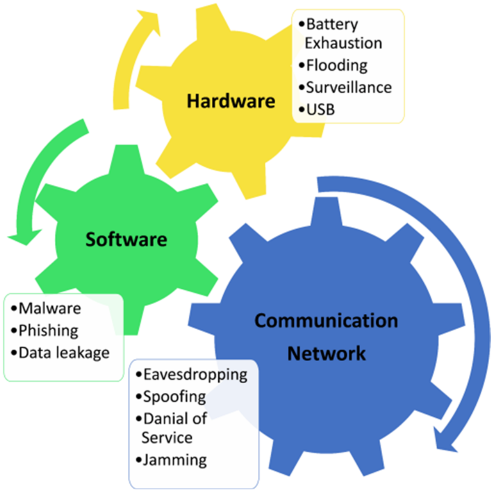

Figure 14. Ground control station (GCS) threats, inspired by [116].

In some cases, attackers send erroneous warning messages to misguide UAVs. It creates an illusion for UAVs and can degrade UAVs network performance by causing data traffic jams. These attacks can transmit corrupt data to UAVs as they mislead ground control stations. Moreover, the attacker can send false information which might impact the performance of UAVs. It occurs due to the absence of proper authentication mechanisms. In such attacks, the adversaries can masquerade as a legitimate user to send wrong instructions or commands. In the absence of authentication mechanisms, any adversary can impersonate as a legitimate user to steal information and interfere communication link of legitimate users.

In some attacks, the attacker can monitor the trajectories of UAV and can use this location information for any malicious or illegal activity. Such attacks can leverage the UAVs around the victim UAV. Another critical challenge is the eavesdropping that occurs due to the lack of protective mechanism such as encryption. In such attacks, UAV's data can be accessed by the adversary. Non-repudiation can be utilized to confirm that a node has issues specific information. This mechanism prevents from denial of behavior and strengthens various tasks [117]. The key objective of this mechanism is to inquire specific information on the emergence of any security risk. Integrity of UAV mission is of paramount importance which ensures data transmission without any interruptions and received data is accurate. In the absence of integrity protection mechanism, malicious attacks can damage original data and thus it becomes invalid.

One crucial issue is a malicious hardware attack which can tamper UAV's hardware to change its intended behavior [118]. This attack is carried out with the intention to steal confidential data or cause a failure in UAV's mission. Any attack to interrupt UAV's flight control and communication links to alter mission parameters is known as flight control computer attack. This attack can be mitigated through onboard software and hardware mechanisms. It can include real-time monitoring, instantaneous estimation of the controller, alert warning and immediate action on any alteration from the intended controller model. Some attacks can misguide the UAV's trajectory after causing an intentional tampering on onboard navigational sensors. These attacks can cause error in sending accurate location and position of UAVs to the control system.

8. Future Research Directions

According to the analysis of literature, we discuss some of the future possible directions for UAV research as follows:

8.1. Machine Learning and Deep Learning Techniques

Machine learning and deep learning techniques play a promising role in different applications related to UAVs such as battery scheduling, trajectory planning, tracking, obstacle avoidance and resource allocation. The development of new ML tools and enhancement of onboard computational power will help to develop novel UAV models that are smarter, lightweight and smaller to perform any operation without the risk of collision. Using these tools, UAVs can autonomously modify their motion, direction and location to serve ground users. Moreover, the availability of accurate data can support UAVs in smart control, trajectory planning and vision tasks. By installing different cameras on UAV, several types of images can be captured for further image processing. UAV planning, including trajectory, navigation and manipulation can be performed to find an intended path. Similarly, the movement of ground users and load sharing can be obtained for UAV trajectory planning. Although conventional machine learning methods have been implemented in UAVs, but deep learning methods have not been explored due to limited power resources and processing capabilities. Thus, research fraternity should investigate efficient and low-power deep learning methods in UAVs, especially for SAR operations [119].

8.2. Energy Harvesting Techniques

There is a need to investigate novel material for UAV's batteries and new energy harvesting solutions to get full potential of UAVs in extended time missions [120]. Battery charging time and weight are also some future concerns. Thus, there is a need to find lightweight batteries that can significantly enhance UAVs flight time and support longer distances. Efficient techniques to control battery power consumption for IoT terminals in UAVs should be addressed in future studies.

8.3. Sensing, Navigation and Localization Algorithms

More research towards sensing, navigation and localization is needed. These issues occur due to weak GPS systems to obtain the location which can create problems in accurate and timely parcel delivery. Among these, localization has a major role in safe operations of UAVs. Due to unpredictable and high mobility of UAVs, accurate localization tends to be problematic within a short time. The accuracy of UAV location is restricted by 3D mobility and obstacle-based and highly dynamic environment. Generally, GPS is used to track location, but it can add unnecessary costs and delay due to dense deployment of UAVs. Therefore, the incorporation of localization systems and low cost sensors must be investigated for proficient UAV location.

8.4. Offloading Algorithms

In various operations, multiple tasks should be conducted simultaneously. There is an increasing demand of multi-UAVs for such tasks. These tasks are divided among deployed UAVs such that each task gets proper focus in a timely manner. Owning to high mobility scenarios, commutation-sensitive and time-sensitive UAV applications, cost-efficient task offloading is a critical concern [121]. Researchers should introduce novel task offloading algorithms in order to reduce the total energy consumption for performing predefined tasks.

8.5. Mobility Models

UAV networks are vulnerable to high mobility. Frequent topology changes can damage both cooperation and communication among UAVs [122]. Several mobility models have been proposed to overcome mobility challenges but they are insufficient to deal with communication issues. These models must be designed considering network requirements. Network coverage is significantly reduced in case of UAV mobility at low speed, results in higher network delays. However, mobility models with minimal latency are required in emergency scenarios. Furthermore, continuous network connectivity leads to degraded network performance. Thus, novel mobility models should be developed for certain applications and environments to tackle mobility challenges.

8.6. Aerial Blockchain

Blockchain technology, as a decentralized solution, is projected to usher in a new era of secure and adaptable privacy protection for blockchain-based UAV systems. Aerial blockchain can prevent UAV communication privacy leaks and secure the integrity of data acquired by UAVs [123,124]. Furthermore, a block-chain-enabled UAV softwarization may be utilized to provide communication services over the UAV network with dynamic, flexible, and on-the-fly decision capabilities [125]. While there have been various study attempts on blockchain technology in UAV networks, researchers have yet to look into block-chain-enabled softwarization for UAV networks.

8.7. Novel Antenna Designs Techniques

Novel antenna designs for UAVs should be designed to ensure high data rate communication. It is suggested to utilize small, aerodynamic antennas for UAVs cruising at higher speeds. Similarly, directional antennas can be used in smalls sized UAVs to overcome space and energy limitations. Moreover, tilted–beam circularly polarized antennas are widespread due to advantage of saving space. By using such antennas, performance is envisaged to be enhanced in terms of radiation pattern, axial ratio and return losses. WPT techniques and backscatter antennas can be used to enhance network lifetime. The incorporation of multiple adaptive antennas can also support communication in highly-mobile UAVs [126].

9. Conclusions

This study investigates recent research developments of UAVs, accomplished by industrial and academic sectors. We provide comprehensive discussion pertinent to UAV types, UAV classifications, UAVs swarms and charging techniques. This study also explores UAV's standardizations. Our work reveals growing interest of business bodies, states authorities and researchers to harness and use the full potentials of UAV technology. Furthermore, UAVs characteristics such as flight time, speed, range, altitude and payload are briefly discussed. In this review, a comprehensive study on UAVs applications, potential challenges and security issues is presented. In particular, UAVs in 5G technology and IoT network are explored in the light of recent research contributions. In the end, this review identifies the research gap and presents future research directions for UAV technology.

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