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REVIEW

A Survey on Surveillance and Intelligent Secure Applications of UAVs

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ABSTRACT: Recently, unmanned aerial vehicles (UAVs), or drones, have attracted considerable research interest across diverse fields, encompassing public and private domains, industrial and academic fields, transportation areas, disaster and harsh environments, reliable delivery services, digital twin-enabled space, and smart cities. In particular, UAVs play a critical role in surveillance and security applications. In this paper, we investigate recent advances in surveillance and intelligent security applications using UAVs. This study covers a wide range of practical tasks and missions including intelligent traffic monitoring, disaster environments, forests and national parks, large-scale events and patrols in public circumstances. Also, we study security, privacy, and ethical issues in regard to UAV-enabled technologies. Then, we describe how UAVs can deliver rapid services and reliable performance, while also achieving efficient resource allocation across various applications through cooperative deployment.

KEYWORDS: Surveillance; UAVs; traffic monitoring; disaster environments; forests and national parks

1 Introduction

Unmanned Aerial Vehicles (UAVs) have rapidly attracted significant attention from researchers in both academia and industry, as they have become essential sensing platforms equipped with intelligent processing and surveillance capabilities. For a wide range of application domains, including intelligent transportation, disaster monitoring, and large-scale public events, UAVs are able to provide high-resolution, on-demand tracking and resilient services. Therefore, it is necessary to investigate a comprehensive review of recent advances in UAV-enabled surveillance [1,2].

For intelligent transportation systems (ITS), UAVs can take a role in dynamic sensing as well as provide a cooperation with ground components (i.e., camera, roadside unit (RSU)). Also, UAVs are capable of adapting to three dimensions appropriately so that UAVs can cover complex urban circumstances, numerous intersections and congested highways. And, when integrated with connected vehicles, RSU, edge server and cloud services, UAVs can contribute to multi-layer infrastructure which are composed of traffic status monitoring, accident recognition and digital twin-enabled construction. Recent technologies support advanced computer vision objectives such as object detection, tracking and semantic segmentation on the aerial side. Also, a group of multi UAVs and specific fleets can utilize optimization and reinforcement learning to maximize coverage as well as minimize response latency in harsh environments [3,4].

For disaster monitoring and emergent missions, UAVs can use rapid movement to accomplish critical tasks for natural catastrophes, earthquakes, floods, and wildfires. When it is equipped with multimodal sensors, UAVs are able to recognize victims, hazards and structural damage in harsh environments. Moreover, deep learning and reinforcement learning techniques allow UAVs to achieve autonomous search, recognition and mapping with a consideration of redundancy. In particular, UAVs can take the role of aerial connection points with seamless connectivity when UAVs build emergency communication infrastructures in terrestrial networks to pursue critical conditions with reliability and energy efficiency. Furthermore, UAVs in forests and national parks have been utilized widely from academic investigation to ecological conservation because UAVs equipped with optical, thermal and multi-purpose sensors allow wildlife detection, movement tracking and anti-poaching monitoring. On one hand, UAVs support fine-scale analysis and recovery analysis for forest circumstances. On the other hand, UAV-assisted image data are incorporated into the training of intelligent neural models for fire detection and segmentation, providing adaptive coverage of large protected areas and sustainable management through a group of multiple UAVs.

For massive events and crowd monitoring, including religious pilgrimages, public meetings and concerts, UAVs can be applied to improve crowd safety and security. Basically, aerial imagery gathered from multiple sensors equipped on UAVs can support accurate crowd counting, density estimation, and behavior analysis in congested environments. Deep learning-enabled schemes using UAV-gathered image data perform robust crowd counting and anomaly detection with wide-area coverage for massive events under dynamically changing circumstances. Also, a fleet of UAVs is utilized in public safety systems using edge computing and robust connectivity. Moreover, it is possible for UAVs to provide safeguard estimation while considering privacy preservation, trustworthy services, and cyberattack threats [5,6].

1.1 Contributions

Based on the above motivations, the summary of the main contributions for the paper is described as follows.

- We investigate recent works and technologies of UAV-enabled surveillance across several application domains, including intelligent transportation systems, disaster circumstances, environmental surveillance in national parks, and massive events with crowd monitoring.
- Also, we provide a unified taxonomy by considering sensing, coordination, and communication within UAV surveillance frameworks. Then, we introduce recent technological advances from various perspectives, including aerial sensing payloads, deep learning-enabled procedures, edge computing, and cloud services.
- Moreover, we discuss application-specific challenges, as well as security and privacy concerns, across surveillance domains and intelligent secure applications using a fleet of UAVs. Fig. 1 shows a brief overview of UAV-enabled surveillance and application domains, including Intelligent Transportation Surveillance (ITS) with UAVs, UAV surveillance in disaster environments, UAV surveillance for forests and national parks, UAV surveillance for mass event venues and crowd monitoring.

Fig. 1 represents an overview of UAV-enabled surveillance and application domains, including ITS with UAVs, UAV surveillance for disaster environments, forests and national parks, mass event venues and crowd monitoring. Also, Fig. 2 shows a description of multi-layer network architecture for UAV-to-UAV, UAV-to-Edge-UAV-to-Cloud for research issues including dynamic configuration and topology construction, interference management and resource efficiency, swarm configuration optimization, energy harvesting and sustainability, 3D mobility using multi-UAV coordination, distributed inference and intensive AI models, energy harvesting and sustainability, cloud offloading and integration with future networks, big data management and processing delay, data privacy and authentication.

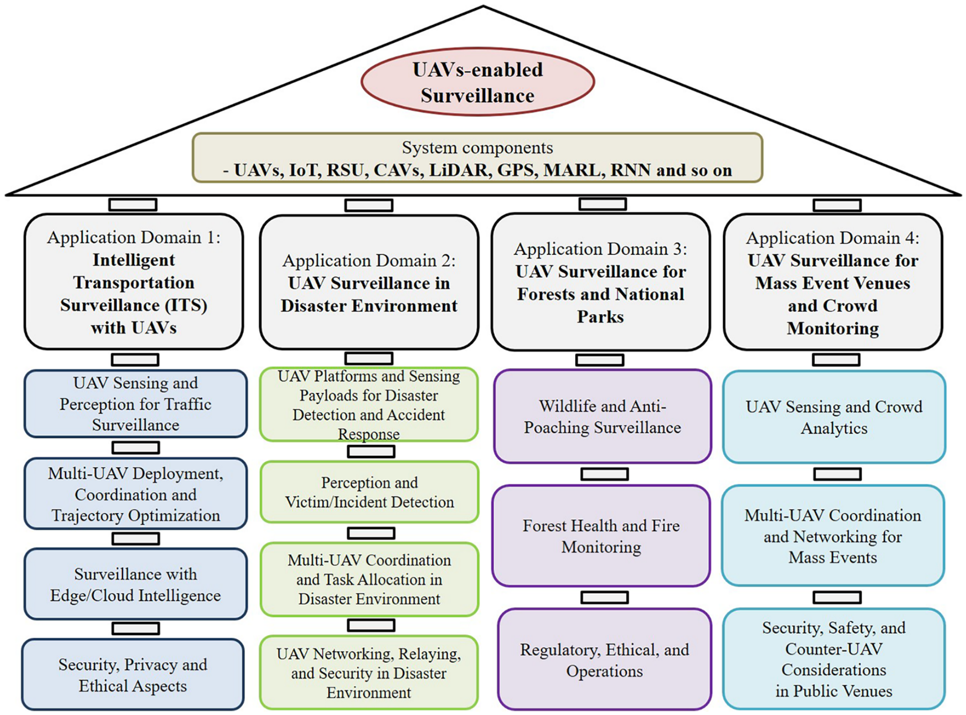


Figure 1: An overview of UAVs-enabled surveillance and application domains including ITS with UAVs, UAV surveillance for disaster environment, forests and national parks, mass event venues and crowd monitoring.

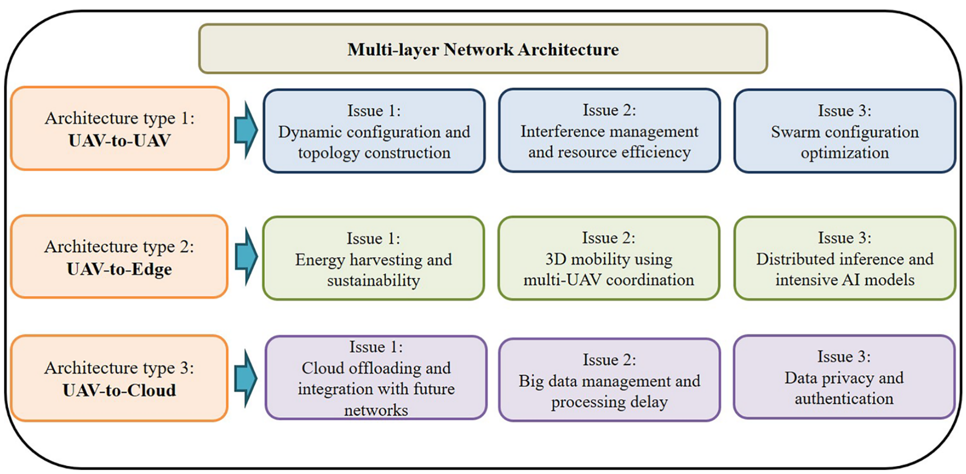


Figure 2: A description of multi-layer network architecture for UAV-to-UAV, UAV-to-Edge-UAV-to-Cloud for research issues.

1.2 Organization

The organization of this paper is as follows. Section 2 reviews UAV surveillance studies and relevant issues in Intelligent Transportation Surveillance (ITS). Section 3 investigates UAV surveillance in a disaster environment with a consideration of UAV Platforms for disaster detection and accident response. Also, Section 4 describes UAV surveillance for forests and national parks to cover wildlife surveillance, forest health and fire monitoring. Furthermore, Section 5 investigates UAV surveillance for massive events and crowd monitoring to perform crowd analytics, multi-UAV coordination and networking for mass events in public venues. Section 6 describes research challenges and future issues for UAV surveillance domains. Finally, the conclusion of the paper is described in Section 7.

2 Intelligent Transportation Surveillance (ITS) with UAVs

Unmanned Aerial Vehicles (UAVs) are increasingly considered as an integral sensing and operation component in Intelligent Transportation Systems (ITS) [7,8]. Their capability with rapid reposition sensors in three dimensions provides a proper coverage of occluded regions, adaptation to dynamic traffic patterns as well as timely manner response to correspond to incidents in congested urban areas with various interchanges [9]. In such environments, mobile aerial sensing allows more comprehensive situational perception than ground-assisted methods that rely solely on static components, such as fixed cameras [10]. Recent studies have evolved from single-UAV use to system-level designs that utilize UAVs for wide-area sensing, communication, and operation services [11,12]. Essentially, several systems consider that UAVs are integrated with various components and devices, such as connected and autonomous vehicles (CAVs), roadside units, edge computing platforms, and cloud servers, to aggregate data from both the aerial and ground sides. Based on the collected and trained data, appropriate decisions can be made, thereby supporting signal controllers and routing engines [9]. Consequently, UAVs can be deployed to specific locations where static sensors are installed to implement the required management policies for special events, work zones, and natural disasters [13,14].

Moreover, civil aviation and transportation authorities define formal standards and procedures for line-of-sight UAV operations, autonomous flight, and low-altitude UAV operations in urban airspace. In addition, the concepts of Urban Air Mobility (UAM) and Unmanned Traffic Management (UTM) are increasingly being applied to ITS environments [11,12]. These advances influence the design of UAV traffic surveillance frameworks covering allowable corridors, altitude status, cybersecurity, privacy, fairness and operational procedures [8,9,15]. Recently, deep learning-assisted UAVs are capable of accomplishing real-time transportation surveillance and accident detection in ITSenvironments. Generative adversarial networks (GANs) are utilized to achieve vehicle path estimation and traffic pattern analysis [16–18]. If GAN-enabled UAVs are incorporated into ITS, generative artificial intelligence (AI) can provide aerial videos and images for traffic status evaluation and the training of perception models in ITS environments.

2.1 UAV Sensing and Perception for Traffic Surveillance

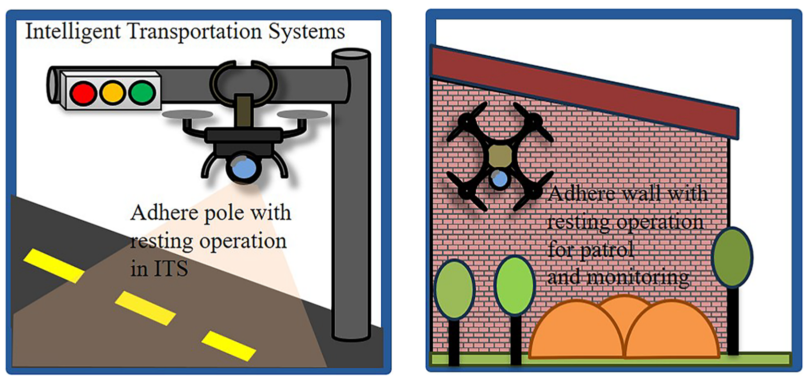
UAVs should be an airborne sensor framework that accomplish several roles with multi spectral cameras, thermal sensors, lightweight LiDAR (Light Detection and Ranging), transmitters and receivers [10]. For traffic surveillance, UAVs equipped with the high-resolution video cameras are able to provide the wide observation of road sides, road intersections so that UAVs can monitor critical traffic circumstances and situations including vehicle states, traffic volume, speed distributions and road utilization [13,19]. Recent studies in computer vision and deep learning enable UAVs to enhance the robustness of UAV-enabled tasks and applicable objectives through perception. In addition, object detection networks with multi-object tracking using aerial images and datasets are able to support perspective variations, including tiny objects, lane-changing rates, and cluttered backgrounds. Also, semantic segmentation frameworks can present road states, vehicle lanes, and sidewalks, which enables contextual reasoning [20]. Furthermore, temporal modeling frameworks based on recurrent neural networks can generate traffic state classification, including traffic congestion, traffic signal control, and adaptive traffic signal control, with consideration of various speed limits and traffic restrictions [21].

For multi-modal with multi-view fusion in traffic surveillance, UAVs can be utilized in combined environments with fixed ground sensors and in-vehicle devices so as to perform continuous coverage of specific areas [22]. Also. feature-level fusion gives the trained representations from aerial images and ground views, while decision-level fusion covers independent estimations for traffic flows [23]. In addition, multi-UAV fusion allows the cross-validation of recognition results, thereby facilitating improved depth estimation and robust tracking across occlusions in dense urban environments [7]. Persistent sensing can contribute to higher-level applications, including digital twins for road communications. For corridors and interchanges in transportation areas, UAVs are able to build the 3D geometry of roadside digital twins with updated lane markings and pavement defect information, thereby enabling long-term planning [12,20]. It is well known that perception quality depends on environmental conditions, such as motion blur, vibration, and weather conditions. Furthermore, large vehicles and buildings may cause occlusions, which require edge offloading and computational complexity reduction [24]. On the other hand, it is indispensable to consider privacy requirements, including privacy-aware sensing and anonymity. On-board blurring of license plates and the generation of aggregated heatmaps instead of raw video are recognized as critical approaches for privacy preservation. These challenges can be addressed by detection and tracking schemes operating at reduced resolution, together with perception–privacy co-design strategies [8].

2.2 Multi-UAV Deployment, Coordination and Trajectory Optimization

When UAV traffic surveillance in isolated flight scenarios is considered, monitoring extensive areas necessitates coordinated operations among multiple UAVs [7]. The optimal deployment and motion planning problem depends on determining the movement of each UAV at an appropriate altitude while satisfying several constraints, including limited battery resources, collision avoidance, privacy-preserving operation, and secure communication [25]. The essential objectives or goals include maximizing coverage, maximizing information gain regarding traffic states, and minimizing accident or event detection delay [23]. Those optimization problems should be resolved with a consideration of combinatorial and dynamic conditions because both traffic flows and states of UAVs are changed frequently during a specific time duration [26]. It is necessary to determine the optimal deployment of multiple UAVs for coverage, patrolling, and vehicular communication tasks over a network graph, where road segments are assigned weights according to traffic volume and accident risk, enabling high-priority segments or trajectories to receive more frequent surveillance [27]. It is possible to apply mixed-integer optimization formulations with satisfying required constraints including limited flight time, mandatory returns to charging locations with different network sizes [23]. To handle the issues, there are various works of genetic algorithms, particle swarm optimization, ant colony optimization which can be alternative solutions when near-optimal routes with complex limitations are found [10]. Furthermore, the issue of traffic-aware and learning-based coordination should be handled carefully. Instead of static patrol patterns, UAVs have the capability to adapt their movements with traffic predictions which are derived from collected measurements and trained data [22]. And, multi-agent reinforcement learning (MARL) has attracted much interest of researchers so as to learn cooperative strategies (i.e., each UAV determines the movement trajectory and sensing operations according to local edge circumstances with constrained communication among neighbors) [28]. The reward functions can be utilized to support surveillance, robust coverage with required timelines, safety, network connectivity and so on [27]. Also, the 3D placement with traffic status and proper altitude of UAVs can affect the flexibility with a consideration of trading off between resolution and line-of-sight transmission [26].

On the other hand, hierarchical control frameworks can operate large fleets of UAVs. For instance, a centralized controller at the roadside, which divides the monitored area into several zones, can assign different tasks, including monitoring hotspots, verifying accidents, and investigating work zones, so that UAVs are allocated appropriately to satisfy those task objectives at the upper level [28]. On the contrary, at the lower level, each UAV can accomplish local trajectory planning to consider avoiding collisions and the given local constraints [7]. The communication between UAVs and connected vehicles can alleviate serious situations, including conflicts, as well as perform cooperative behaviors, such as seamless handover, for surveillance purposes under battery limitations [27]. Moreover, there are critical issues to be addressed, such as battery recharging operations, charging optimization, and the optimal placement of charging stations [9,25]. Human operators can be involved in the loop for supervision of abnormal detections [14]. It is necessary to resolve the problem of multi-UAV coordination in a manner that is robust, interpretable, and compatible with variations of UAVs, such as Urban Air Mobility (UAM) [11]. In [29], a surveillance and secure monitoring framework using resting drones (or resting UAVs) has been devised for intelligent transportation systems and smart cities. The new concept of *resting drone* was introduced, which is capable of adhering to or detaching from poles, walls, trees, and smart infrastructures to provide resting opportunities for drones, thereby extending their maximum lifetime when performing specific operations, including movement, monitoring, and resource charging with improved energy efficiency. Fig. 3 depicts a brief overview of the resting UAV and its applicability in ITS, which includes its ability to hang on poles in ITS and adhere to walls for patrol and monitoring. Also, Fig. 4 shows a snapshot with hardware prototype of the resting UAV.



(a) An example of resting UAV applicability to hang pole in ITS.

(b) An example of resting UAV applicability to adhere wall for patrol and monitoring surveillance.

Figure 3: Resting UAV with applicability: (**a**) An example resting UAV to hang pole and (**b**) An example of resting UAV to adhere wall for patrol and monitoring surveillance in ITS.

2.3 Surveillance with Edge/Cloud Intelligence

It is verified that the effectiveness of UAV-enabled traffic surveillance framework depends on communication and networking performance [9]. Essentially, the high-bandwidth links are necessary to send high-rate sensing data information between UAVs and ground servers or edge devices. At the same time, it is necessary for low-latency control channels to be maintained for navigation which is operated by a group of UAVs [12]. Also, UAVs can be connected through terrestrial cellular networks, aerial-vehicular networks, public and private buildings to satisfy the requested coverage and the low interference [30]. For UAVs on cellular links, the rapid changes for altitude and locations of UAVs may affect signal strength and handover patterns, video interruptions [26]. It is possible for vehicle to take a role of relay positions with high speeds, which can cover frequent topology changes [21]. Also, there is a study on predictive link-quality estimation and adaptive modulation to support quality-of-service for surveillance service [24]. Edge computing and cloud services are essential to manipulate the massive volume of data which is collected or created by UAVs with surveillance tasks. For intensive missions, the deep neural inference for detection and tracking can be handled by edge devices along the roadside when the tiny UAVs are operated with restricted resources. There are several issues to be handled on the local side, which include task offloading, server load, low latency, and dynamic scheduling. Given intermittent connectivity, the hybrid strategy can provide lightweight processing and low compression onboard so that the cloud performance with connectivity can be enhanced [10].

Figure 4: A snapshot with hardware prototype of resting UAV.

Also, it is crucial to consider the joint optimization between communication and computation in bandwidth-constrained environments. And, instead of streaming raw video, it is possible to extract features or representations while privacy-preserving requirement with reducing bandwidth is satisfied for downstream analytics. Also, the issue of joint optimization between UAV trajectories and communication should be handled (i.e., the location of UAVs should be decided optimally so that UAVs can take roles of aerial relays to avoid coverage holes for communication and transmission) [26]. The integrated role for network slicing and QoS (Quality of Service) allows the traffic processing and information control for safety over massive data information in 5G and 6G communications [11]. Distributed strategy with federated learning expedites model training among a groups of UAVs and edge computing devices in distributed processing for raw data [31]. For those distributed circumstance, UAVs locally train for fine-tune for aggregated data. Then, there are several issues to be handled such as bandwidth consumption minimization, privacy improvement, efficient aggregation, robustness among heterogeneous components and devices [15]. The distributed strategy with intelligence enables UAVs to move from simple remote cameras to collaborative sub-systems in complex transportation area.

2.4 Security, Privacy and Ethical Aspects

The traffic surveillance using UAVs should address serious cybersecurity concerns and attack variations, including eavesdropping, jamming, spoofing, man-in-the-middle attacks, and data transmission attacks on wireless links [8,32]. And, there are control-link attack types and compromised threats, such as hijacking UAVs, falsification, injection, and selective blocking of the surveillance system. Therefore, secure solutions and countermeasures should be developed to cover robust authentication, secure encryption, key management, and intrusion detection when the resource constraints and mobility patterns of UAVs are considered [15,33]. Because sensors and navigation systems are vulnerable, GPS (Global Positioning

System) spoofing and malware flight attacks can be operated on UAVs, which may affect locations and unintended operations in restricted spaces, misbehavior, detection failures, and wrong classification of certain vehicles [14,32]. To reduce these risks, there are several studies to introduce anomaly detection, sensor consistency, redundancy improvement for multiple navigation sources, secure hardware modules, assurance enhancement and so on [8,34].

Privacy should be one of the major concerns in traffic surveillance, particularly because UAVs periodically collect sensing information, including identifiable data about drivers, passengers, and pedestrians [8]. Essential traffic-related information, such as traffic flows and high-resolution video, can be utilized for the re-identification or tracking of individuals and objects. Therefore, it is indispensable to develop privacy-preserving solutions that support the protection of identifiable information and strict retention restrictions [8]. For secure traffic management, on-board blurring, masking of license plates and encrypted storage can be considered for efficient traffic tasks. Furthermore, there are ethical and legal issues for data protection, and distributed surveillance in UAV-enabled neighborhoods [35]. The issue of benefits and burdens of surveillance should be handled fairly with a consideration of transparent policies, public engagement in distributed manner [14]. Legal frameworks satisfying aviation regulations and data-protection laws has been devised for secure flight operations with effectiveness and data processing with flexibility [11,34]. In addition, Table 1 represents a brief summary for ITS category, main focus and key issues for UAV-enabled intelligent transportation systems.

Table 1: Summary of UAV-based traffic surveillance in ITS environment.

ITS Category	Main Focus	Key Issues
UAV sensing and perception for traffic surveillance	Use of UAV-enabled sensors to extract traffic states with flow, speed, trajectories and infrastructure features	Deep learning-assisted detection, tracking and segmentation on aerial side; multi-view and multi-modal fusion with ground sensors; building digital twins; privacy-aware perception
Multi-UAV deployment, coordination and trajectory optimization	Coordinated use of multiple UAVs for large-area, persistent traffic surveillance under resource and safety constraints	Coverage and patrolling formulations; mixed-integer and meta-heuristic optimization; traffic-aware and MARL-based coordination; hierarchical control and intention-based communication; routing–charging co-optimization
Communication, networking and edge/cloud intelligence	Networking architectures enabling real-time video, control, and analytics for UAV-based traffic surveillance	5G/6G aerial–vehicular networking; mobility link management; edge offloading and hybrid cloud processing; joint communication–computation optimization

(Continued)

Table 1 (continued)

ITS Category	Main Focus	Key Issues
Security, privacy and ethical aspects	Risks and safeguards related to cyberattacks, data misuse, and social impacts of UAV traffic surveillance	Attack surfaces on communication, control, and sensing; intrusion and anomaly detection; GPS spoofing and malware threats; fairness, transparency and legal compliance

3 UAV Surveillance in Disaster Environment

Natural and man-made disasters, including earthquakes, floods, wildfires, industrial accidents, and frequent traffic accidents, require rapid situation assessment for time-critical decision-making and resource allocation [36,37]. UAVs are appropriate for situations that require rapid response and movement, since they can be operated with heterogeneous sensors for real-time surveillance and monitoring in obstructed areas [36,38]. Existing disaster management mainly depends on manned aviation and fixed sensor networks, which can be slow and expensive [39,40]. UAVs are capable of providing reliable trajectories, rapid data aggregation, and integration with multi-agent systems and edge computing devices [38,41]. Thanks to strong advantage of UAVs, it is necessary to support UAV-enabled surveillance with a consideration of perception, coordination and reliable communication for disaster and accident response [36,38,42].

3.1 UAV Platforms and Sensing Payloads for Disaster Detection and Accident Response

There are a variety of recent studies on UAV platforms covering multi-rotor, fixed-wing, and hybrid types for different disaster situations, such as earthquake response, wildfire monitoring, and maritime search and rescue [41,43]. UAVs with Multi-rotor can be operated in dense urban and indoor-near environments due to their hovering capability and maneuverability. Also, fixed-wing platforms allow sustainable operation and persistent communication relaying [40,44]. For maritime search and rescue, UAVs are often utilized and cooperated with unmanned surface vehicles in order to build mobile edge computing networks and a visual coverage graph among aerial vehicles. On the other hand, there are several works for three-dimensional operation of UAVs to offer wireless services and coverage according to different disaster regions to perform specific objectives (i.e., minimizing the number of UAVs while continuing service quality) [43]. And, there is a surveillance system using multimodal UAVs equipped with RGB (Red, Green, Blue) cameras, thermal cameras and LiDAR to detect or track victims, fires, infrastructural damage, or hazardous leaks [37]. We identify that the thermal cameras are useful for alarming humans in smoke-filled or low-visibility situations. And, UAVs equipped with LiDAR, embedded GPUs (Graphics Processing Unit), and edge accelerators can offer three-dimensional mapping, on-board processing, object detection, semantic segmentation, anomaly detection and damage assessment [38,45]. Then, UAVs can be operated as edge nodes when offloading heavy computation to ground stations or cloud platforms is estimated with a minimum local computation for safety-critical missions [38]. In [46], the authors provided a comprehensive evaluation of lightweight deep learning models for UAV-based surveillance, which focuses on the trade-offs between detection accuracy, latency, GPU utilization and energy consumption on edge platforms.

3.2 Perception and Victim/Incident Detection

The detection of victims and hazards with applicable robust computer vision scheme should be critical issue in UAV-enabled disaster surveillance [47]. The search and rescue systems for extensive area utilize sensors and images on UAVs using detection schemes to search for injured people in disaster areas [36]. Furthermore, machine learning-enabled UAVs with detectors (i.e., YOLO (You Only Look Once) and convolutional methods) can be trained on aerial images and monitoring data to detect objects, groups of people, vehicles, and disaster situations at various altitudes [45]. The method with YOLO and optical flow can accomplish rapid detection and tracking of moving victims using continuous localization and autonomous target tracking on the ground side [38,45]. Reinforcement learning approaches can be applied to find safe flight paths while avoiding obstacles in unknown circumstances [45]. Also, there are mapping systems which are combined with simultaneous localization to generate real-time disaster scenes as well as path planning and coverage map optimization. Recent studies on emergency communication and monitoring introduce the integrated perception with communication and control loops to provide reliable detection and reporting for time-critical tasks [39,42].

3.3 Multi-UAV Coordination and Task Allocation in Disaster Environment

The coordination among a fleet of UAVs and multiple drones allows large-scale coverage and redundancy in disaster environments with surveillance [38,48,49]. Multi-UAV-enabled frameworks utilize several architectures, including hierarchical formation or decision-making in a distributed manner, so that every UAV can locally perform information sharing and data aggregation to achieve full-area coverage, cooperative tracking, and matching between fixed sensors and mobile actors. There are studies on multi-UAV applications with disaster-oriented tasks for wildfire monitoring, urban search and rescue operation, inspection to target areas [38,49]. A group of multiple UAVs combined with wireless sensor networks is able to achieve cooperative surveillance, task allocation and trajectory planning with reliable sensor deployment, efficient coverage and urgent victim detection [48,50]. In particular, Multi-UAV task allocation pursues multi-objective optimization with critical constraints, including flight time, communication range, and no-fly zones in disaster environments. There are studies to handle joint task allocation, three-dimensional deployment, optimal movement, quality of service and path planning regarding cooperation among multiple UAVs in dynamic emergency rescue scenarios [38,43]. In [51,52], the authors studied heterogeneous UAVs, UAV-enabled multi-access edge computing, coordination overhead, fault tolerance, time-varying disturbances, for multi UAVs-enabled systems.

3.4 UAV Networking, Relaying, and Security in Disaster Environment

The disasters affect terrestrial communication configuration to require emergent coordination and information sharing while UAVs can take the roles of relay nodes or temporary backup coverage points to cooperate with ground networks [44,53]. There are several studies on UAV communication, emergent configuration, energy-efficient operation, resource allocation, reliable connectivity and quality of service (QoS) [39,40,44]. Multi-UAV network architectures have been introduced to perform disaster monitoring, routing protocols and integrated implementation with Internet-of-Things and vehicular networks on the ground side [38,43,54]. On the other hand, UAV-enabled emergency surveillance should deal with security and privacy-related issues. For example, unauthorized access issue, data privacy [38,40]. Several attacks, including jamming, spoofing and eavesdropping may disrupt UAV communications [40,44]. For trust and integrity in search and rescue tasks using UAVs, blockchain-based UAV systems have been devised to cover consortium blockchains to massive groups of UAVs so that the flexible and mission-specific access control can be provided [55]. It is necessary to resolve authentication, lightweight cryptography and intrusion detection for secure UAV networks while the issue of resource constraints and mobility patterns of UAVs should handled in disaster environments [38,53]. In addition, Table 2 represents a brief summary of category, main focus and key points for UAV surveillance for disaster environment.

Table 2: Summary of the UAV surveillance for disaster environment.

Category	Main Focus	Key Points
UAV platforms and sensing payloads	Frameworks, deployment and sensors	Recent UAV platforms for urban rescue, wildfires and maritime incidents; multimodal payloads; on board edge computing for real-time detection, mapping, and decision support
Perception and incident detection	Sensing to datasets pipeline	Visual victim detection methods using aerial imagery; autonomous search, tracking and mapping strategies; SLAM (Simultaneous Localization and Mapping)-enabled environment modeling; reliable hazard localization
Multi-UAV coordination and task allocation	Cooperative surveillance and scheduling	Multi-UAV systems; task allocation and trajectory planning for area coverage, energy usage and task priorities, coordination of UAVs with communication constraints and dynamic disaster conditions
UAV networking, relaying and security	Emergency communication and reliability	UAV-assisted emergency communication networks; networking functions for QoS, interoperability, routing; security and privacy issues with attacks on UAV links

4 UAV Surveillance for Forests and National Parks

For forests and national parks, there are several issues and environmental situations, including multiple, intertwined threats, altered fire regimes, and invasive species, as well as unregulated resource extraction. So, it is highly necessary to proceed with surveillance to provide early detection in heterogeneous regions and send the detected information to administrators or managers safely so that the administrators do not need to enter danger area directly. Because UAVs equipped with RGB, LiDAR, gas sensors and spectral cameras are capable of high-resolution, on-demand sensing over terrain and harsh environments with flexible deployments on ground, it is possible for UAVs to perform various surveillance tasks, including wildlife monitoring, fire detection, animal tracking, search and rescue in forests and national parks.

4.1 Wildlife and Anti-Poaching Surveillance

There are various studies to reinforce wildlife monitoring by UAVs which are able to provide flexible and repeatable coverage with reduced risk to field personnel [56,57]. And, existing studies focus on different issues regarding wildlife disturbance, including the shift of conservation practitioners in flight, nest and den detection, habitat mapping, behavior observation, and operator training [58–60]. It is necessary to deal with deployment issue in national park between static monitoring to active surveillance to provide real time management responses [61]. Also, some works showcase the use of UAVs equipped with thermal cameras, which are able to recognize poachers at night along park borders. The critical function of UAVs allow users to detect illegal campfires in remote campsites, as well as to manage high-risk access corridors, ground ranger patrols, which can be cooperated with camera traps and acoustic sensor. Then, it is possible to consider the integration of UAV-enabled surveillance for anti-poaching, smart park using static sensor, human patrols based on data-driven framework.

There are several works to utilize visible light-assisted UAVs with sensing-modality function to monitor daylight wildlife since those visible light-assisted UAVs can generate interpretable imagery which can be analyzed for a massive number of mammals, birds and marine species around the surface area [56,62]. When visible light-assisted UAVs with thermal imaging are used with high contrast status, the issue of how to support the detection of cryptic animals in dense forests or at dawn [61,63]. The UAVs with multi-sensor functions using RGB, thermal and LiDAR can give complementary perspectives for the equal environment and scenes. The advanced technology of UAVs with computer vision, deep learning and machine learning has been improved to a wide range of tasks such as UAV imagery into usable wildlife surveillance information, variants of YOLO, the reinforced object detection schemes to make airborne datasets based on detection information for various species including deer, seals, sea turtles, large herbivores in protected areas so that the high prevision tasks can be achieved [61,63,64]. And, aerial-wildlife datasets and repositories for various background and flight configuration information can relax the limitation of labeled data for rare specifies across geographic areas [64–66]. Recent studies deal with the concepts and roles of multi UAVs and swarm for wildlife surveillance where different types of UAVs are operated to provide continuous tracking of moving objects [67]. These studies also suggest decentralized coordination approaches using a fleet of UAVs, with consideration of communication constraints and the balance between coverage, energy consumption, and disturbance in remote environments [63,67,68].

4.2 Forest Health and Fire Monitoring

UAVs can support forest-health surveillance which covers early detection of stress and damage that may not be visible in coarse satellite imagery or infrequent areas [69–71]. The UAVs equipped with multispectral RGB and convolutional neural models can be utilized to categorize tree species, quantify defoliation, detect disease outbreaks and so on [70,71]. Those functions of UAVs with data-driven state can achieve different types of detection missions, including small patches, storm damage, pest infestation for targeted areas. Recent works show the results of experimental deployments which can be applied to operational forest-health monitoring with standardized workflows for UAV path planning, image capture and model training [69,70]. It is also critical to study the issue of how UAVs can be connected with satellite networks, LiDAR, and multi-scale datasets to accomplish secure validation and reduction of vertical complexity with a consideration of habitat quality, and fuel structure [72].

It is indispensable for UAVs to be used for minimizing wildfire risks and fire regimes in UAV-based fire detection and tracking. Furthermore, forest-fire UAV datasets with high resolution allow the training of deep learning models for fire classification, detection, and segmentation using aerial monitoring information to provide early warning and secure firefighting [69,73–75]. The forest-fire datasets through UAVs can cover different situations and environments including smoke conditions, fire disaster scenarios. Also, there are recent studies for the design of mobile edge-computing frameworks using UAVs so that the capture imagery, reduction of communication load and preliminary processing can be performed properly by a group of UAVs, edge devices and ground servers in remote forest areas and harsh environment with limited bandwidth [73,75,76]. On the other hand, there are several works that use image-fusion techniques which can be applied to UAVs and edge devices to improve detection robustness to endure smoke, variable lighting constraints [73,74]. It has been explored for UAVs to consider how multiple or groups of UAVs can move around complex and three-dimensional terrain to satisfy several system conditions such as maximum coverage in high-risk area, efficient battery usage, safety, maximum communication link connection to ground servers and devices [77,78]. Then, UAVs can take a critical role of fire management cycle and risk evaluations for early fire detection and rapid response handling [69,72,75].

4.3 Regulatory, Ethical, and Operations

The applicability of UAV surveillance in national parks allows them to provide data sharing, liability, and visitor safety, privacy with legitimate management and services in national parks and adjacent community lands [79,80]. For example, the operation of UAVs (i.e., landing or launching UAVs) is prohibited within national park boundaries except the controlled operations by park authorities [79,80]. It is possible for UAVs to operate two different modes: the first is recreational mode within restricted area and the second one is administrator mode with standard management [59,79]. The ethical issues of UAVs are related to surveillance practices, UAV conservation, illegal logging, militarized imagery, volumetric geographies, data justice, and territorial control [60]. From a wildlife ethics perspective, UAV disturbances caused by UAV noise, visual presence, and proximity may affect animal behavior and stress responses during specific periods (i.e., breeding or migration) [60]. There are studies to deal with standard operation guidelines for UAVs' flight altitude, resting angle, flight speed so as to minimize disturbance which can be conformed with park regulations and long-term monitoring appropriately. Also, it is necessary to resolve the persistent issues including battery endurance, flight time trade-offs, reliable operations for harsh mountain, forest or coastal areas where GPS signal strength can be degraded due to dynamic weather status [69–71]. The robust communication infrastructure should be improved for real-time data streaming, autonomous decision-making, reliable operations with edge computing and delay-tolerant networking, coordination of multi-UAVs, safety protocols, data-management policies [73,80,81]. In addition, multi-UAV cooperative surveillance with the enhanced autonomy and visual-line-of-sight operations can be operated by an integration of geographic information systems and decision-support systems [67,72,77]. Furthermore, Table 3 shows a brief summary of category, main focus and key points for UAV surveillance in forest and national parks environments.

Table 3: Summary of the UAV surveillance for forests and national parks environment.

Category	Main Focus	Key Points
Wildlife and anti-poaching	Real-time animal tracking and poacher recognition in remote parks	Balancing detection accuracy with minimal wildlife disturbance; Proper operations for RGB and thermal cameras and multi-UAV swarms; privacy concerns with false positives; domain shifts in datasets
Forest health and fire	Canopy stress recognition and dynamic fire-front monitoring	Operation reliability in obscured smoke circumstance and rugged terrain; multispectral CNNs (Convolutional Neural Network) with image fusion and LiDAR; resource allocation for patrols and massive data processing
Regulatory and ethical operations	Park-specific operational procedures and ethical operation guidelines	Dual-use tensions and data equity; altitude disturbance guidelines; surveillance bias and cross-agent cooperation

5 UAV Surveillance for Mass Event Venues and Crowd Monitoring

The mass events, including public campaigns, marathons, religious pilgrimages, concerts, sports games, and political demonstrations require strict the observation of dynamic crowds continuously, as well as the rapid recognition of accidents and abnormal status by UAVs [82,83]. Also, the cooperation of UAVs, CCTV (Closed-Circuit Television), cameras and ground patrols can perform flexible and elevated views with adjustable altitude and can improve the visibility for wide-range areas when massive crowds move around extensive event areas [82,84]. In this section, we review UAV-assisted surveillance frameworks for massive events, crowd monitoring, safety assurance, emergency response and detection of security threats [85,86].

5.1 UAV Sensing and Crowd Analytics

There are several studies for UAV-enabled sensing and analytics which focus on real-time crowd monitoring, including crowd counting, density estimation, tracking, and anomaly detection in massive events [82,87]. There are studies investigating overhead UAVs to address wide-area coverage and high spatial resolution while avoiding motion blur and frequent occlusion caused by umbrellas, signs, and event infrastructures [88]. Those issues can be handled by deep learning-based schemes for aerial information, event complex structures. Also, there are recent studies for crowd counting and density calculation which the convolutional and attention-based systems can be utilized to generate crowd density maps and its estimation according to aerial video views, aerial information [83,89]. For instance, UAV-assisted systems for crowd tracking provide density estimation with enhanced localization and tracking accuracy through multi-object tracking in congested aerial environments [89]. For massive event surveillance and crowd monitoring, environmental conditions such as low-light and nighttime should be considered carefully because these conditions may degrade surveillance performance, including anomaly detection and counting accuracy [83]. Also, the UAV-enabled crowd estimation and analytics can play an important role in identification, human-centric aerial surveillance with diverse altitudes and viewpoints in trained models for massive events [90]. Human detection and localization with consideration of crowd density estimation can be supported by annotated UAV images, tracking and video information for public events [91].

For static counting, there are studies combining crowd density maps into higher-level safety frameworks with sliding-time-window analysis of density distributions to evaluate overcrowding trends and enable early intervention [82,83,92]. The density estimation-enabled system is useful for large event venues where manual monitoring is infeasible [85]. It is essential for crowd anomaly detection and behavior analysis to deliberate on early identification for massive events requiring high safety [93,94]. And, UAV-enabled anomaly recognition schemes can be integrated with motion patterns, scene context, and density variations through the application of spatio-temporal deep models using aerial and ground views in public areas [93]. The issue of intelligent localization for anomaly has been studied with flagged abnormal behavior, UAV video information with geo-referenced maps and building formations, intuitive visualizations for potential accidents regarding crowds in public spaces [82,95]. Also, there exist studies for mobile crowd sensing, density estimation, circumstance assessment and anomaly detection using smartphones or wearable devices, edge computing which cooperated with the methods of binary abnormal labels, flows around obstacles based on the activity of multiple UAVs [85,88,90,96]. The aerial information collected by UAVs is able to validate distinctive patterns of motion and group movement using trajectory prediction or estimation and a graph modeling to classify crowd states in massive event venues [84,89]. Moreover, those high level behavior systems with UAVs should be helpful for accurate decision-making between proper people gathering and dangerous circumstances with back-pressure around entrance and exit [83,92].

5.2 Multi-UAV Coordination and Networking for Mass Events

Although a surveillance with a single large UAV is effective for regional monitoring and local patrol, a fleet of multiple UAVs should be useful for large events and extensive area monitoring with minimal redundancy [86,97]. There are studies on swarm coordination, stable integration and public safety communication among multiple UAVs to monitor crowds and accidents with reliable operations in dynamic topology change with interference [85,95]. The trajectory planning and resource allocation for UAV surveillance can be achieved by the coordination of multi-robot, edge devices and UAVs with both centralized administrator and distributed manner to evaluate crowd patterns and circumstance features [98]. The study of target allocation system makes a formal definition for the assignment problem of UAVs into sub-areas so that the objectives of balanced coverage with minimal overlaps, anomaly detection and rapid response are accomplished. When the trajectory planning is implemented, the issues and safety constraints of no-fly zones, safety spaces for crowds and potential obstacles should be considered carefully. Also, there are critical requirements such as event monitoring, crowd density calculation, crowd analysis, anomaly detection and alerts for dynamic task completions for crowds using UAVs [82,95]. The UAV-enabled hierarchical infrastructures can be applied so that each UAV handles collision avoidance, balanced scalability and fine-grained path adjustments [99]. For the coordination of multiple UAVs, there are several studies to deal with optimization of energy usage, flight time, maximal coverage and monitoring time for long events, energy-efficient routing, scheduling patrols by UAVs, on-site battery management, optimal deployments of wireless charging stations, stable monitoring without excessive downtime, and design of grid access-assisted structures [100].

On the other hand, there are critical challenges and issues for UAV surveillance with networking configuration and edge computing, including reliable communication, stable video manipulation, and sharing situational awareness among multiple UAVs and ground devices in public spaces [86,95]. In particular, the UAV-assisted mobile edge computing frameworks has been been studied widely because those systems can resolve heavy tasks with deep vision inference, reduction of onboard energy usage, minimal delay through the coordination among autonomous vehicles, edge servers, mobile base stations and so on [101]. Then, the issue of intermittent connectivity, reliable communication, stable bandwidth allocation and spectrum congestion in public spaces with massive number of people should be considered importantly. And, it is highly necessary to consider the integration of UAVs with public safety components where individual UAV plays a role of relay node for public services operated by police and medical institutions in aerial side for mission-critical communication including ad-hoc UAV networks, LTE, 5G and 6G backhaul, etc. [100]. There are studies for the network-oriented framework with a consideration of interoperability, quality-of-service and public safety where a fleet of UAVs can recover the lost connection rapidly due to congested or damaged communication in expansive areas with massive events. Furthermore, the reinforcement learning-assisted schemes combined with vehicular ad-hoc networks (VANETs) can improve various system performance of communication such as adaptive routing, optimal UAV positions, maximal coverage, traffic monitoring in massive event venues with several crowd flows of people [101]. Fig. 5 represents a brief overview of UAV operation and coordination for mass events and secure monitoring in public venues. UAVs can be cooperated with mobile robots, smart camera and other UAVs to perform secure monitoring, surveillance, tracking, accident warnings to citizens, terror prevention in mass events and public venues.

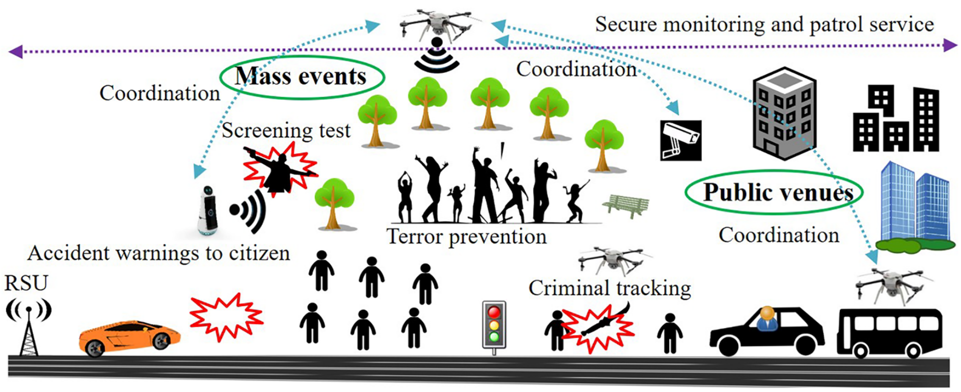


Figure 5: A brief description UAV operation and coordination for mass events and secure monitoring in public venues.

5.3 Security, Safety, and Counter-UAV Considerations in Public Venues

For UAV surveillance in public venues, there are critical issues of security and threats including malicious attack, unauthorized UAVs operations, communication links attacks, information integrity, privacy, safety against rogue UAVs, intrusion detection, secure communications [82,99,102–104]. In particular, the study of security and privacy in UAV surveillance has been conducted to address lightweight authentication, efficient key agreement protocols, privacy-preserving trajectory estimation, and so on [103,105]. For instance, the key agreement in smart UAV systems can basically be implemented by elliptic-curve cryptography and mutual authentication for secure access and data transmission among UAVs, edge devices and ground base stations with reduced computation and complexity [105]. For edge computing with lightweight authentication, the blockchain–based schemes have been proposed to enhance data exchanges and secure UAV access [99,106]. Also, there are studies for UAVs surveillance systems to deal with security and privacy threats and attacks, including spoofing, jamming, hijacking, intrusion detection, secure route decision, etc. [102]. For data transmission and aggregation using UAVs in public areas, there are several issues to be considered including false injection, eavesdropping on communication between UAVs and other system components, illegal access into system resource and control planes, counter attacks for public safety networks [99].

On the other hands, there are several studies to deliberate on counter-UAV technologies, event monitoring, secure access against unauthorized UAVs, capture, spoofing, anti-UAV technologies based on sensing communication such as RF, radar and acoustic, early detection, layered defense in crowd surveillance [102,104,107]. In the case of failures by UAVs in aerial side, the safety-oriented studies also deal with operational risks, collision avoidance of authorized UAVs, automated fail-safe behaviors and conservative flight when they are operated over massive people or are entered into restricted areas [97]. We should consolidate regulators, safety requirements and formal standards covering UAS standards, flight operations for surveillance in massive public event venues. Moreover, Table 4 describes a brief summary of category, main focus and key issues for UAV surveillance for mass events and crowd monitoring area. In [108], the adversarial attacks with GPS spoofing and denial-of-service attacks were studied in UAV-enabled non-terrestrial networks as well as proposed a framework to provide AI-enabled security solutions for privacy-preserving response. A secured privacy-preserving system for smart UAVs was devised, which utilized two-level privacy processes including blockchain and smart contract-assisted proof of work to minimize data poisoning threats.

Table 4: Summary of UAV surveillance for mass events and crowd monitoring area.

Category	Main Focus	Key Issues
Sensing and crowd analytics	Real-time aerial monitoring of crowd density, anomalies and behavior at events	CNN/attention-based density maps and anomaly detection; UAV-specific datasets; scale variation, low-light, occlusion;
Multi-UAV coordination and networking	Swarm collaboration, path planning, edge computing for wide-area event coverage	Hierarchical task allocation and routing; public safety network integration; energy optimization and dynamic topology control;
Security, safety and counter-UAVs	Threat protection, secure communication and collision avoidance over crowds	ECC authentication, RF/radar anti-UAV detection; layered defenses and standards; rogue UAV classification; privacy logging

6 Research Challenges and Future Issues

There exist major UAV surveillance domains, including military and defense with border patrol, civil infrastructure inspection. For instance, in [109], multi-sensor UAVs with enhanced accuracy were used to improve detection accuracy, reliability with artificial intelligence and sensor fusion technologies. In [110], UAV-assisted border patrol system with a consideration of wireless charging function was developed to maximize time duration between continuous flights to specific section of the border. In [111], the efficient deployment of UAVs for border patrol was devised using Stackelberg game to optimize a patrol trajectory of UAVs.

With the expansion of application areas and intelligent applicability of UAVs, this paper covers a comprehensive review of surveillance and intelligent secure applications using UAVs so that recent works and technologies on UAV-assisted surveillance are broadly investigated. Then, we provide a unified taxonomy for sensing, coordination, and communication in UAV surveillance. As future issues, it is necessary to analyze detailed quantitative metrics and comparisons, including deep learning models for crowd counting, accuracy, computational complexity, data sizes, and so on.

As future works, we plan to study the UAV surveillance with practical constraints including battery endurance, adverse weather conditions, communication failures, regulatory restrictions, data annotation challenges, model generalization challenges and deployment costs. Moreover, we will study various open research issues including autonomous multi-UAV collaboration, onboard foundation models, energy-aware AI, privacy-preserving surveillance, or regulatory issues for large-scale deployments.

7 Conclusion

In this survey, we studied various issues of UAV-enabled surveillance across multiple categories. We investigated the reviewed literature and recent studies on surveillance and intelligent secure applications of UAVs through IEEE Xplore, ScienceDirect, and Web of Science over the past five years. Firstly, we provide a comprehensive review of recent cross-domain technologies and applications in intelligent transportation systems, disaster environments, environmental monitoring, and mass event venues from an integrated UAV perspective. Secondly, we introduce several categories embracing sensing, coordination, secure communication, and standards for UAV-enabled surveillance systems. Thirdly, this paper deliberates on recent technologies and advances in UAVs, including deep learning-based perception, accurate sensing, edge computing, cloud computing, and multi-modal data manipulation in real-time environments. Fourthly, we investigate efficient cooperation among multiple UAVs to achieve various tasks, including trajectory estimation, reinforcement learning, and scalability. Furthermore, we studied integrated edge-enabled systems covering the integration of UAVs with 6G communication, crowd monitoring, security, and privacy across various domains and application scenarios. There exist the limitations of UAV surveillance for current study.

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