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Involvement of Surveillance Drones in Smart Cities: A Systematic Review

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ABSTRACT Drones, or unmanned aerial vehicles (UAVs), are among the most beneficial and emerging technologies, with a wide range of applications that can support the sustainability concerns of smart cities and ultimately improve citizens' quality of life. The goals of this systematic review were to explore the involvement of surveillance drones in smart cities in terms of application status, application areas, proposed models, and characteristics of drones. We conducted this systematic review based on the preferred reporting items for systematic reviews and meta-analyzes (PRISMA) guidelines. We systematically searched the Web of Science and Scopus for journal articles and conference papers written in English and published up to August 2021. Of the 323 records identified, 43 met the inclusion criteria. Findings showed that surveillance drones were used in seven distinct research fields (transportation, environment, infrastructure, object or people detection, disaster management, data collection, and other applications). Air pollution and traffic monitoring were the dominant application areas. The majority of reviewed models were based on the application of rotary-wing single-drones with the camera as the aerial sensor. Reviewed models showed that the adoption of a single or multiple UAVs, either as a stand-alone technology or integrated with other technologies (e.g., internet of things, wireless sensor networks, convolutional neural networks, artificial intelligence, machine learning, computer vision, cloud computing, web applications), can offer efficient and sustainable solutions compared to conventional surveillance methods. This review can benefit academic researchers and practitioners.

INDEX TERMS Applications, drone, smart city, surveillance, sensor, review.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), or drones, are high-end cyber-physical systems (CPSs) for numerous data collection and monitoring tasks because of their capability to perform complex computations via wireless communication channels, high mobility, and automated operation [1]. UAVs can serve as internet of things (IoT) devices for data sharing, provide real-time data for input into 'big data' applications, and enable efficient decision-making [2]. UAVs are one of the advanced technologies that, along with the other eleven technologies, are used to manage smart cities [3]. Bouassida *et al.* [4] classified UAV applications into data covering, e.g., surveillance and event covering, data relaying, e.g., delivery and emergency services, and data dissemination, e.g., cartography and precise agriculture. The surveillance task is about monitoring a target, which can be a person, a group of people, behaviors, activities, air pollutants, infrastructure, or buildings, and its typical applications are border patrol, construction management, power grid inspection, traffic monitoring, environmental monitoring, etc. [5]. When compared to traditional surveillance methods, using UAVs to perform complex surveillance tasks is a more beneficial and sustainable option because they can cover

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large and difficult-to-access areas in a short amount of time, reducing human intervention and manpower requirements, operating during and after natural disasters, positioning in precise locations, and so on.

Population growth is occurring in several cities around the world. On this note, statistics provided by the United Nations show that the world's urban population reached 4.2 billion (55% of the world's population) in 2018 from 751 million in 1950. Furthermore, the United Nations projects that the world's urban population is expected to increase by 68% by mid-century and that there will be 43 megacities with at least 10 million people by 2030. This population's rapid surge in megacities urges city planners and municipalities to develop strategically sustainable solutions to meet the demands of increasing citizens (e.g., including infrastructure improvement and expansion, providing adequate services, generation of new jobs, etc.). In this regard, the relatively new concept of the smart city can assist city management authorities in dealing with urbanization growth issues more efficiently and sustainably. A smart city is a large and complex system (or framework) that enables the improvement of the quality of life and overall safety of the city residents by leveraging multiple heterogeneous technologies, mainly based on information and communication technologies (ICT) and the IoT. Indicators of a smart city are smart government, economy, environment, people, living, and mobility. It is worth mentioning that, however, a successful smart city strategy would be more dependent on the identification and utilization of a wise methodology that could address the values, needs, and expectations of all actors and residents of the city than on technological solutions.

A few review studies on the applications and challenges of drones in the smart city context exist in the literature. Mohammed *et al.* [6] and Mohammed *et al.* [7] reviewed UAV opportunities and related issues such as privacy, safety, and ethical use, respectively, for Dubai smart city and its general form. Vattapparamban *et al.* [8] presented the cybersecurity, privacy, and public safety challenges of drones in future smart cities. Guvenc *et al.* [9] reviewed UAVs' associated threats (cyber and physical) and different techniques for detection, tracking, and interdiction of malicious drones. Haouari *et al.* [10] presented a comparative overview of fog and cloud computing plus applications of fog computing in smart cities. Alsamhi *et al.* [11] comprehensively reviewed various methods and implications of collaborative UAVs and IoT for the smartness improvement of smart cities. Al-Turjman *et al.* [12] reviewed drone applications in software-defined networking (SDN)-enabled drone base stations (DBS), surveillance monitoring, and emergency networks, as well as performance assessment approaches and related cybersecurity issues. The SDN is an infrastructure option for robust and secure management of multiple UAV communications. The applications, implications, challenges, and regulations of drones in smart cities were discussed by Mohamed *et al.* [13]. Dilshad *et al.* [14] surveyed the video surveillance operations of drones equipped with vision sensors for various applications in smart cities. In another study, Outay *et al.* [15] systematically reviewed developments in computer vision (CV) algorithms along with applications of drones in intelligent transport systems (ITSs) and future smart cities. Alsamhi *et al.* [16] presented the involvement of drones in greening IoT for sustainable smart cities plus its associated potential opportunities and barriers. Finally, Pakrooh and Bohlooli [17] classified different UAV-assisted services in IoT for smart cities and discussed the design of UAV-assisted IoT systems. These studies, however, have not systematically reviewed the literature on the involvement of surveillance drones in smart cities. Conducting a systematic review enables a thorough examination of current literature and the drawing of conclusions based on previous research. This review is thus aimed at exploring the applications of surveillance drones in smart cities and seeks to answer the following questions:

- RQ1: What is the application status of surveillance drones in the context of smart cities?
- RQ2: What application areas of surveillance drones have been addressed in the literature associated with smart cities?
- RQ3: What solution models are proposed, and what UAV characteristics are used for each application area of surveillance drones in the literature associated with smart cities?

The remainder of this review article is organized and presented as follows. Section II explains the different stages of the implemented method to select the eligible articles for this research. In Section III, we revealed the results of the bibliometric analysis to investigate the status of applications of surveillance drones in smart cities (RQ1). This section also contains the classification of different application areas into distinct categories (RQ2). Section IV provides a comprehensive review of proposed methods and developed systems (RQ3). Section V discusses the characteristics of UAVs in terms of number, types, and aerial sensors being used (RQ3). The conclusion of the paper is described in the last section.

II. METHODOLOGY

The methodology of this review article was designed based on preferred reporting items for systematic reviews and meta-analyzes (PRISMA) to answer the research questions. The flow diagram of this strategy includes identification, screening, eligibility, and inclusion stages [18].

The PRISMA-based flowchart process of our systematic review is shown in Figure 1. To collect relevant academic papers in the identification stage, the Scopus and Web of Science (WoS)-clarivate analytics databases were searched on August 27, 2021. For this purpose, we used an advanced search tool and the search string in their title, abstract, and keywords. The complete used search string was (“*drone**” *OR* “*unmanned aerial vehicle**” *OR* “*uav**” *OR* “*unmanned aircraft system**” *OR* “*uas**” *OR* “*remotely piloted aircraft**”) *AND* (“*surveillance*” *OR* “*monitoring*” *OR* “*inspection*”) *AND* (“*smart cities**”

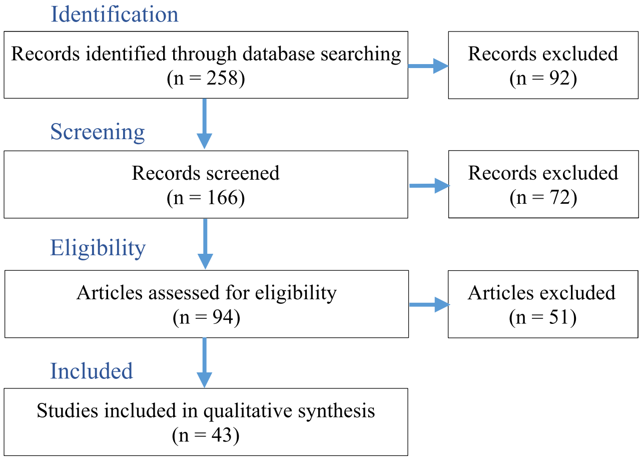

FIGURE 1. The flowchart process of the current systematic review.

OR "*smart city**"). The initial search results revealed that the respective populations of academic publications covered by the Scopus and WoS databases are 197 and 125. The initial search results of both databases showed a similar source (Mohammed *et al.*, [6] published in 2014) as the oldest published article. Therefore, 323 records appeared as the cumulative search results of both databases from 2014 to August 27, 2021. Then, we limited the Scopus results (197 records) based on document type (article and conference paper), source type (journal and conference proceeding), and language (English). The respective results of these limitations indicated 159, 146, and 145 records. Regarding WoS search results (125 records), they were limited based on document type (article and meeting), database (WoS core collection), and language (English), which resulted in 118, 114, and 113 records, respectively. Thus, a total of 258 records (Scopus (145) and WoS (113)) remained. Checking these records showed that 92 out of 258 records were duplicated, which were then removed. Thus, 166 records were identified in the identification stage. In the screening stage, the authors checked the titles and abstracts of the 166 records and found that 72 records (survey and review (19) and not the actual application (53)) were irrelevant to this study. Thus, a total of 94 records remained. In the eligibility stage, we carefully screened the full text of all 94 articles. Among them, 51 articles addressed different technical and non-technical issues of drone operations, which are out of the scope of this review. Consequently, a total of 43 articles were included in our systematic review.

III. STATUS OF APPLICATIONS AND APPLICATION AREAS OF SURVEILLANCE DRONES IN SMART CITIES

The bibliometric analysis of all included articles was performed to demonstrate the current applications of surveillance drones in smart cities in terms of the annual number of publications, conference and journal papers, publishers, and countries. The annual number of publications was distributed between 2017 (1 article), 2018 (8 articles), 2019 (15 articles), 2020 (10 articles), and 2021 (9 articles). The total number of 43 published articles from 2017 to August 2021 reflects the rising interest of researchers in the topic. However, it can be considered an early-stage research area. Journal and conference (or proceeding) articles constitute 20 and 23 out of 43 articles, respectively. More than half of the journal articles were published by IEEE Xplore (6) and MDPI (5) outlets, followed by Elsevier (4) and Springer (3). The "Personal and Ubiquitous Computing" journal contained the maximum number of publications (2 articles), and the remaining articles were published in 18 different journals. Ten out of 23 conference articles belonged to eight IEEE international conferences and proceedings, and the "Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience" and "2020 IEEE International Smart Cities Conference" conferences contributed the highest number of publications (2 each). Thus, it can be concluded that more than one-third of all articles (16 out of 43) were published by IEEE. The top 3 countries in terms of article publication rate are the United States (10), China (8), and India (6), followed by Spain (5) and Philippines (2), as well as Italy, the United Kingdom, Saudi Arabia, Jordan, Tunisia, Poland, Bangladesh, Thailand, Brazil, Pakistan, Taiwan, and Mexico (1 each).

In recent years, the use of surveillance drones in smart cities has been addressed in several disciplines. The authors of this review classified the 43 included papers into seven distinct categories. Transportation, environment, infrastructure, object or people detection, disaster management, data collection, and others are among the categories. Notice that some articles could be considered in multiple categories. We picked the most related category among alternatives to assign a single category to each article. For instance, research into condition monitoring of road pavement is more suitable for the infrastructure category than transportation. Table 1 shows the classification and distribution of included articles based on application areas. The results showed that most of the included articles belong to the transportation and environment categories (20.9% each), followed by infrastructure (16.2%). Furthermore, the included articles addressed thirty different application areas of surveillance drones in smart cities. Air pollution monitoring gained the highest population (7) among other application areas, followed by traffic monitoring (6), power line inspection and traffic safety (2 each), and each of the remaining application areas addressed in one article.

IV. APPLICATION AREA DEVELOPMENTS OF SURVEILLANCE DRONES IN SMART CITIES

This section contains our review of all 43 proposed models and consists of 7 sub-sections. The detailed information (application area, aim, research gap/problem, results, future recommendation studies, and evaluation type) of the proposed models for transportation, environment, infrastructure, object or people detection, disaster management, data collection, and other categories are respectively presented

TABLE 1. Articles distribution based on application areas.

Category	Application area	Number of articles	Total number of articles	Percentage
Transportation	1. Traffic monitoring	6	9	20.9%
	2. Traffic safety	2		
	3. Parking management	1		
Environment	4. Air pollution monitoring	7	9	20.9%
	5. Waste incineration management	1		
	6. Weather monitoring	1		
Infrastructure	7. Bridge inspection	1	7	16.2%
	8. Bridge and pavement inspection	1		
	9. Bridge deck condition monitoring	1		
	10. Power line inspection	2		
	11. Road pavement condition monitoring	1		
	12. Building inspection	1		
Object or people detection and tracking	13. Tracking people and objects	1	6	13.9%
	14. Urban tree detection	1		
	15. Runways trees detection	1		
	16. Night-time pedestrian detection	1		
	17. Foreign object debris detection	1		
	18. Criminal tracking	1		
Disaster management	19. Humans body detection	1	5	11.6%
	20. Evacuation map building	1		
	21. Fire detection	1		
	22. Firefighting management	1		
	23. Search and rescue	1		
Data collection	24. General	1	3	6.9%
	25. Data collection and fusion-city monitoring	1		
	26. Multimedia streaming	1		
Others	27. 3D spectrum mapping	1	4	9.3%
	28. 3D city modeling	1		
	29. Farming	1		
	30. City and extensive ocean monitoring	1		
Total		43	43	100%

in Tables 2-8. Note that these tables are sorted based on the publication year of the articles.

A. TRANSPORTATION

Nine of the 43 (20.9%) included articles were about surveillance drone applications in transportation. Of those, 6 articles (66.6%) reported the usage of surveillance drones for traffic monitoring in smart cities. In this direction, one article addressed the concept of cooperative intelligent transportation systems (C-ITS). De Frias *et al.* [19] proposed a cooperative system for traffic monitoring in urban areas by implementing drones and a lightweight semantic neural network. This system enables the generation of a segmented image of the vehicles from the RGB images, the 2D real-world position of the detected vehicles, and the dissemination of information about surrounding vehicles. The evaluation results showed the applicability of the proposed model for traffic monitoring purposes since it includes a low mean error in vehicle position estimation. Two articles addressed the utilization of multiple drones. In the SwarmCity project, Roldan *et al.* [20] explored the effectiveness of using aerial swarm instead of placing sensors in fixed locations or in public transportation systems, which have the respective problems of blind zone production and non-controllable sensor movement, to monitor the traffic in a simulated city (SwarmCity). The results showed that aerial swarms are suitable for data collection and traffic modeling in smart cities. In a similar project, Garcia-Aunon *et al.* [21] proposed an approach to monitor the traffic by developing and utilizing a behavior-based surveillance algorithm that allows the control of multiple aerial agents (drones). They argued that the configured algorithm has acceptable performance with low standard deviation, is suitable for different traffic volumes, and is scalable. Two articles presented integrated drone applications with web applications and CV methods. Hossain *et al.* [22] proposed a model to reduce the congestion on roads in urban areas by offering a path with a minimal number of vehicles to the users. In their model, drones are utilized in every junction in the area to record real-time video from the covered path and transmit the collected information (the number of vehicles) to a local cloud server. The collected data is then transmitted to the main server, which processes the collected data from all drones to select the path with the fewest vehicles among all potential paths upon receiving a request from a user. The authors evaluated the model's performance. However, the data collection and

TABLE 2. Distribution of articles for transportation category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Hossain et al. (2019) [22]	Traffic monitoring	Proposed a model based on UAV and a web application	Monitor and control traffic in real-time to minimize the traffic congestion problem in urban areas	The model enable users to select the path with minimum vehicles	Use CNN in the model to improve data collection and image processing	Simulation
Roldan et al. (2019) [20]	Traffic monitoring	Answer the question: "Can an aerial swarm monitor the traffic in a Smart City?"	Need to develop an algorithm to fuse the data collected by the drones and build a traffic map of the city	*Aerial swarms can be used as tools to collect data and model traffic *The best strategy for data processing is computing a weighted mean of the last measurements	*Using Gaussian processes for data fusion and traffic modelling *Adapt the algorithms for crowds, climate, and pollution monitoring	Simulation
Garcia-Aunon et al. (2019) [21]	Traffic monitoring	Proposed a first approach for using aerial swarm in a simulated city	Utilizing aerial swarm for data collection to solve sensor position issues (blind areas and non-controllable)	The developed algorithm showed good performance, can be applied on different traffic levels, and it is scalable	*Evaluate the algorithm for bigger city size with more cars and drones *Implementing a control strategy that enables continuous move of drones	Simulation
De Frias et al. (2020) [19]	Traffic monitoring	Proposed a cooperative system based on UAV and a lightweight semantic neural network	Using UAV to solve issues related to sensors mounted in fixed locations	The proposed method is robust and effective	Proposing a model that able to distinguish all the elements in the road to obtain a full coverage of the roads	Simulation
Gogoi et al. (2020) [26]	Parking management	Proposed a system using multiple sensor nodes and a drone	Increase the accuracy of parking monitoring with utilizing a UAV	The proposed system is an efficient system with low power consumption and high accuracy	Improve the scalability of the proposed system enabling management of multilevel parking slots	Simulation
Shirazi et al. (2020) [23]	Traffic and intersection monitoring	Proposed a system by integration of UAV and CV techniques	Fixed cameras are no longer suitable for continuous monitoring of intersections	The presented system able to successfully track vehicles and providing traffic measurements	Adoption of the system for robotics and business intelligence usages	Experiment using UAVDT data
Yang et al. (2021) [24]	Anomaly detection	Presented a novel method for safety-related anomalies detection	Previous risk level assessment studies could use only safety-related data as summary statistics	Majority of the functional outlier detection measures achieve good separation from anomalies to non-anomalies	*Investigate how traffic videos and the quantified traffic conflicts can be used for proactive safety monitoring *Further research to validate the method	Experiment
Beg et al. (2021) [25]	Traffic monitoring and policing	proposed an intelligent and autonomous solution using UAV	There is a need of an improved, dynamic, and autonomous solution to solve problems of conventional methods	The system abeles to detect real-time emergency traffic situations, to investigate potential accidents situations with rapid response units, to issue emergency response units on the occurrence of an incident	Develop the system for detection of driving while intoxicated drivers, parking violations, and accident detection	Simulation
Bouassida et al. (2021) [4]	Traffic monitoring and road safety	Study how using drones may improve road safety and energy efficiency	Need to tackle the problem of using drone signaling in a crosswalk scenario	using UAV in such a scenario causes reduction in rate of accident, braking distance, energy consumption, and occasional visibility	*The effect of communication delays on the drone signalling performance *Considering a scenario that car arrivals and pedestrian presence at the crosswalk	Simulation

TABLE 3. Distribution of articles for environment category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Hernández-Vega et al. (2018) [32]	Air pollution monitoring	Proposed a prototype based on UAV-GCS communication	Fixed monitoring units are limited in scope range and height	*Electrocatalytic sensors are not useful due to their high current usage *Mq sensors are ideal for this study. However, their accuracy is low in humid and temperature change condition	*Investigate more advanced aerodynamic design of UAV *Compare the estimation results with results obtained from fixed monitoring stations *Using high precision sensors adaptable with the data acquisition card for contaminant estimation	Experiment
Chen et al. (2018) [27]	Air pollution monitoring	Design LoRa-based PM2.5 sensor to be integrated with UAV	*PM2.5 sensor is not able to monitor dynamic air pollution emission *Environmental protection needs effective air pollution monitoring in terms of real-time information and minimum human intervention	Using UAV with this particular sensor allows to measure PM 2.5 on air in a real-time manner with least human intervention	Not specified	Experiment
Mayuga et al. (2019) [28]	Air pollution monitoring	Implement an aerial sensor system to measure particulate matter	Need for risk assessment of air pollutants in urban areas	The highest PM concentration for heavy and light traffic conditions found at respective elevation of 50m and 120m	Conduct the experiment with additional gas sensors	Experiment
Hu et al. (2019) [29]	Air pollution monitoring	Proposed a system that enable measuring and monitoring from air and ground	The air quality is not similar even in very small area specifically in urban areas	*Effects of incomplete measurement and data latency eliminated *Quality of the collected data improved *Balance availability between power consumption and data accuracy	Not specified	Experiment
Gu and Jia (2019) [33]	Air pollution monitoring	Presented a consumer UAV-based air monitoring system with all off-the-shelf consumer components, inclu –ding hardware and software.	Address challenges including Multiple air pollutants, energy efficiency and flight time, synchronization of monitoring sensor data and GPS data, safety and restrictions in city	*On-board devices have no influence on the UAV's power consumption and flight time *Sensor readings can be affected by UAV operations	Explore how to shield on-board sensors from UAV's electronic interference and the development of area coverage of UAV flight missions	Experiment
Lu et al. (2019) [34]	Waste incineration managemen t	proposed a CPS for quick respond to key operating conditions and managing waste incineration emissions	Need to implement CPS to overcome problems of conventional CEMS	The system can be used by stakeholders as a solution for semi-structured and poorly structured issues	Not specified	Experiment
Yadav et al. (2020) [30]	Air pollution monitoring	Proposed a solar-powered UAV with potential ability of perpetual flight	Static sensors are not effective and air quality need to be monitored continuously and the data need to be available in real-time manner.	The module can be utilized in various public transport systems in cities to obtain real-time PM data	Test the proposed prototype to perform perpetual flight in autonomous style with real-time sensing capability	Experiment
Gao et al. (2021) [31]	Air pollution monitoring	Proposed a system based on 360-degree aerial images with low error and energy use	Need to use vision-based approach to overcome problems associated with other methods	*Implementing the system in large areas causes energy consumption saving *The systems is able to perform the recognition task with high accuracy	Not specified	Simulation
Chodorek et al. (2021) [35]	Weather monitoring	Proposed an open, universal platform for urban and industrial areas monitoring	A UAV-based system needs to meet the requirements such as high temporal and spatial resolution of measurements	*The WebRTC application is fast enough to serve fast-response sensors *High temporal and spatial resolutions have been achieved in the field-test	Considering multiple air stations served by a single ground station, and single air station served by multiple ground station	Experiment

TABLE 4. Distribution of articles for Infrastructure category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Seo et al. (2018) [36]	Bridge inspection	Inspect different damages of a bridge type using a UAV	Need to use UAV since this task is time consuming, and involve safety risks	*different types of bridge damages can be recognized when UAV is used for inspection *This method is applicable for bridge areas that are not visible to inspectors	*Apply this method to other bridge types *Identify bridge damages using image analysis-based quantification methods	Experiment
Barreto et al. (2018) [40]	Power line inspection	Introduced a system that allows autonomous inspection of utilities	Need to develop a UAS for energy-related assets includes of aerial and land platforms, sensors, and information systems	Using the proposed project is beneficial for utility companies in terms of inspection productivity, keeping (or increase) the safety level, and comfort of the teams	Design the new architecture that enables real-time analysis	Experiment
Wu et al. (2018) [38]	Bridge and pavement inspection	Application of UAV and deep neural network in concrete crack and asphalt pavement distress classification	Image processing are challenging and time consuming	The results demonstrated preliminary utilization of UAV and deep neural network which can be used by inspection engineers	Conduct bridge inspection and pavement surface rating in real-time and autonomous manner	Experiment
Shang et al. (2019) [37]	Bridge deck condition monitoring	Proposed a platform that provides defects detection based on aerial and ground inspecti-on images	Need to develop a data fusion platform to fuse multi-scale images	The proposed platform allows to detect the surface and subsurface bridge's deck defects, describe and locate them	Develop the platform so that can be used for pavement and tunnel applications	Experiment
Latha et al. (2019) [42]	Building inspection	Presented an automatic building information method using UAV	Need to use a method for automatic building detection to overcome scene complexity, incomplete cue extraction and sensor dependency of data	The method of this study can be applied in smart city applications	Using RTK mode UAVs and improved sensors for respective higher location accuracy of the UAVs and spatial accuracy	Experiment
Pan et al. (2020) [41]	Power line inspection	Proposed a system that enables efficient usage of the big image data for broken power strand detection	There is a need to detect broken power strand	Random Forest (RF) shows better performance in homogeneous views, while neural network related algorithms are better in heterogeneous and semi heterogeneous scenarios	Increase the accuracy and stability of the proposed system by some model details adjustments	Experiment
Roberts et al. (2020) [39]	Road pavement condition monitoring	Proposed a method to analyse paveme-nt's condition	Need to develop a low-cost method	The method is a reliable, affordable, and flexible solution for pavement condition monitoring	Apply the method for analysis of a wider network	Experiment

analysis were performed using software (sky software and PTV Vissim 2020) instead of actual drones. Shirazi *et al.* [23] developed a deep visual tracking system for intersection monitoring (vehicle detection and tracking) using drones and CV techniques. The tracking system is also improved using the optical flow method. The authors evaluated the performance of the proposed system using unmanned aerial vehicle benchmark object detection and tracking (UAVDT) video data. The outcomes showed the capability of the proposed system for vehicle tracking and providing traffic measurements.

Furthermore, two articles have addressed traffic safety issues. Yang *et al.* [24] proposed a method to accurately and automatically detect traffic safety anomalies. A UAV is used to provide traffic video data, and the functional data analysis (FDA) technique is implemented for safety indicator time series modeling. The authors used a rotary-wing drone with an on-board camera to perform the field test of the proposed method at the signalized intersection of a roadway. They found a good separation between safety-related anomalies and non-anomalies. However, more research is required to validate the proposed functional method. Bouassida *et al.* [4] investigated the effectiveness of using a drone for improving road safety and energy efficiency in a case (car-pedestrian accident) that may happen in C-ITS and smart cities. A UAV was implemented at the

TABLE 5. Distribution of articles for object or people detection category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Wan et al. (2017) [48]	Criminal tracking	Proposed a system to deal with threats and emergencies management	Need to use an intelligent system since installed surveillance camera method is inefficient and labor-intensive	Compared to previous methods, the system has more flexibility, wider data collection, larger area coverage, and communication abilities	Pursue the proposed structure as a reference for construction of such a system	Not specified
Surinta and Khruahong (2019) [43]	Tracking people and objects	Proposed an algorithm allowing people and object tracking for an autonomous UAV	Need to use a proper surveillance method since traditional methods such as CCTV includes blind-spots in the coverage	*Less computation time is needed for object detection than the human detection *Small objects can be detected *Orange color recognition is an issue of this model	*Perform this experiment with camera's angle change *Using deep learning method in the proposed model	Experiment
Yadav et al. (2019) [44]	Urban tree detection	Proposed an algorithm to detect green areas including all kind of trees	Majority of UAV-based algorithms address only certain tree types	The system successfully extracts urban green areas with high accuracy rate when multiclass logistic regression classifier is used	Not specified	Experiment
Kim et al. (2019) [45]	Runways trees detection	Proposed a method regarding field test of runway inspections	How airport inspections using UAS and visual assets can lead to work efficiency increment and human error reduction	Logistics information of airports and runways, information of obstructions around runways, and condition of airport light and beacon operations can be gained respectively from UAS-based 2D still images, UAS-based point cloud data, and infrared images	*Compare the result of UAS-based and manual inspections *Assess and evaluate the crack and obstruction method for different conditions when PCL is used	Experiment
Wang et al. (2021) [46]	Night-time pedestrian detection	Developed a method to increase the quality of pedestrian images taken by a UAV at night time	Earlier introduced methods cannot be directly adopted in UAV image processing or unsuitable for the real-time processing of the UAV images	Adopting this method can result in higher rate of image quality improvement and accuracy of detection.	*Optimize the algorithm to improve processing efficiency for real-time pedestrian detection *The algorithm needs to adaptively obtain the image processing paramet-ers to solve differe-nt detection issues with different illum-ination conditions	Experiment
Munyer et al. (2021) [47]	Foreign object debris detection	Developed a dataset of FOD to evaluate a potential system for light-weight automated detection	Lack of a proper and available dataset for complex research applications in this field	Application of this method on real-world experiment showed the capability of the method with more than 99% precision and accuracy	*Improve this process for auto-removal of FOD after inspection *Automated UAS navigation and item retrieval *Perform FOD detection by adopt-ing enhanced CV-UAS based system	Experiment

scene (where there was a crosswalk, vehicle, and pedestrian) for information collection and communication with the vehicle (U2V) and infrastructure (U2I) to avoid potential accident occurrences. Their findings show that using a UAV in this situation reduces accident rates, braking distance, and occasional visibility while saving energy. In another study, Beg *et al.* [25] presented a system based on existing traffic policing infrastructure and autonomous UAV-enabled solutions to address the inadequacies of traditional traffic monitoring and policing tactics. Their simulated results indicate that the proposed system could effectively and intelligently handle different tasks (e.g., congestion and accident detection, traffic rerouting, traffic light violations, autonomous emergency response, etc.).

Besides, one study focused on smart parking management applications. Gogoi *et al.* [26] proposed a system to monitor

TABLE 6. Distribution of articles for disaster management category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Tariq et al. (2018) [51]	Humans body detection	Proposed a real-time autonomous system to detect humans body for rescue purpose	In disastrous condition, victims cannot be rescued due to unidentified exact location of them	The system could successfully identify the location of human body under the debris of collapsed building	Not specified	Experiment
Alsamhi et al. (2019) [52]	Data collection (disaster management)	Presented a public safety network based on UAVs and IoPST	Need to use space wireless communication technologies since terrestrial solutions could be missing, Unavailable in congested areas, or damaged	The system can efficiency solve the wireless communication problem when ground-based infrastructure not functioning	Not specified	Simulation
Sahil and Sood (2020) [2]	Smart disaster management	Proposed a Fog-Cloud centric IoT-based cyber physical framework for evacuation of the panicked stranded individuals	In smart cities, disaster-related risks need be prevented and controlled using fast and accurate emergency response methods	Efficiency of evacuation map building using UAVs, and panic health sensitivity monitoring using Bayesian Belief Network (BBN)	*Improve energy efficiency of the sensors, device failure management, and fog layer computation offloading *Tracing the panic health of individuals in various distressing scenarios	Simulation
Sharma et al. (2020) [49]	Fire detection	Proposed an early fire detection system using senor network and UAV	Need to utilize simultaneous approaches to prevent and protect forests from fires and spread awareness and quick response	*The system offers cost-saving method for real-time data collection and monitoring *Using the system enables accurate fire event detection and emailing warning alerts	*Improve the capability of the system by enabling smoke detection *Use the system for detection of hidden fires (because of dense fog, etc.)	Simulation
Zadeh et al. (2021) [50]	Firefighting management	Proposed a UAV-based method to assist firefighters and individuals in exterminating fire	Firefighters need to reach the top floors of high-rise buildings fast and efficiently	The field-test results showed successful application of the method	Investigate the utilization of 3D printing to increase the number of balls carried by a UAV in flight attempt	Experiment

and manage parking spaces smartly and accurately. The system includes wirelessly interconnected sensors (magnetic and ultrasonic distance) assisted by a UAV equipped with a camera. The proposed system could accomplish the task with low power consumption and high precision.

B. ENVIRONMENT

Drone utilization for environmental applications in smart cities was described in 9 (20.9%) of the 43 eligible articles. Five articles addressed the measurement of airborne particulate matter (PM), which is the mixture of solid particles and droplets in the air. Chen *et al.* [27] designed a LoRa-based air quality monitor mounted on a UAV to measure PM2.5 in the air, which is an irregular and uncertain air pollutant, and a web user interface that enables the user to configure the UAV's route and view the sensed data with no delay. Their field test showed that the UAV with a LoRa-based PM2.5 sensor could successfully perform data collection and transmit the data to the server in real-time with minimum human intervention. In another study, Mayuga *et al.* [28] tested their aerial sensor system (which consists of a UAV with PM, temperature, and humidity sensors) to measure the PM in different elevations in high and light traffic conditions. Hu *et al.* [29] implemented an IoT-based 3D system to measure and monitor air quality using a combination of aerial and ground sensing. The system has different layers (sensing, transmission, processing, and presentation), and it is capable of providing information in a real-time, fine-grained, and power-efficient manner. The sensing layer of the system consists of several tiny sensors on the ground and a UAV equipped with sensors to address the issue of changing air quality from meter to meter in city areas. Yadav *et al.* [30] presented a system consisting of a solar-powered UAV prototype capable of performing perpetual flight and a data fusion module. They conducted a practical test by integrating the module into a UAV to obtain the PM2.5 real-time data. They also tested the module when mounted in a car to demonstrate how this low-cost module may be widely used on public transportation systems in urban areas. Finally, Gao *et al.* [31] presented a novel system to measure PM in urban areas. The framework of the system includes three layers (data collection, processing, and presentation), and it uses a visual approach that uses a UAV with the on-board camera to provide 360-degree aerial panoramic

TABLE 7. Distribution of articles for data collection category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Garge and Balakrishna (2018) [54]	Data collection (Multimedia streaming)	Examine the effectiveness application of UAVs in multimedia streaming	In most of multimedia rich applications, computing and storage resources are not located at the edge of networks which causes inefficiencies	Using a UAV with on-board MEC that hosts a TCP proxy can improve QoS in terms of connection delay and throughputs to TCP-based applications	*Evaluate different hardware options for on-board use *Estimate the working memory requirements for a TCP proxy *Simulate data transfers across 4G and 5G radio access networks	Not specified
Roldán-Gómez et al. (2020) [55]	Data collection and fusion (city monitoring)	Proposed a system for smart city monitoring based on city simulator, drone swarm, behaviour and data fusion algorithms, and immersive interface	Installed sensors in the city have limitations to obtain relevant and updated data	The system capable of providing the relevant information of a city and the operator can understand the city state, behavior of different variables and detecting the most relevant events	*Adapt the behavior-based algorithm to perform different tasks *Increase quality of maps using popular data fusion modes	Simulation
Khalifeh et al. (2021) [53]	Data collection	Presented a framework based on WSNs for remote sensing and monitoring in smart city applications	Available new technologies for monitoring networks need to be properly designed to address reliability and interoperation with other systems	Found that the performance of XBee-PRO wireless module is better than the XBee S2 wireless module	*Deploy more sensor nodes to maximize the network range *Develop mobile sensor nodes to be used in the method *Design nodes with multi-radio interfaces with different technologies and frequency bands	Experiment

TABLE 8. Distribution of articles for others category.

Author(s)	Application area	Aim	Gap/problem	Findings	Future work	Validation process
Marín et al. (2018) [56]	Farming	Proposed a system for grass state monitoring	Need to use a technique for efficient use of water for urban lawns	Using UAV for lawn monitoring of an area bigger than $1000m^2$ result in time saving	*Add moisture soil sensors to control the irrigation regime *Use the system to study different plant diseases and analyze different plant species	Simulation
Kim et al. (2018) [57]	Urban and ocean area monitoring	Proposed different frameworks for monitoring of smart city and ocean based on their specific requirements	Need to consider efficient recharge solutions for heterogeneous small-scale UAVs in city infrastructures	The frameworks presented needs further research and improvements to better utilize UAV technology	Not specified	Not specified
Pannozzi et al. (2019) [58]	3D city modelling	Presented a 3D simulated city environment	A close-to-reality simulated environment is needed to test detailed mission profiles and related risk analysis	The presented environment enables to study UAV's urban monitoring with different piloting modes	*Numerous future works are presented, however, target detect - ion, HIL simulation, advanced obstacles avoidance and the use of a fleet of UAVs are some of them	Simulation
Wu et al. (2020) [59]	3D Spectrum Mapping	Proposed a framework for spectrum mapping and management in smart cities	Lack of 3D spectrum mapping since majority of models addressed only 2D ground spectrum mapping	Considering performance and energy consumption criteria, respective ROI-only UAV deployment and 3DTV-SMR method are the best options	*Highly accurate algorithms for spectrum situation estimation *Considering the size of high-rise buildings *An efficient algorithm for UAV's power allocation for spectrum mapping	Simulation

haze images. Evaluation of the system performance showed that high-level recognition accuracy can be achieved using a small-scale pre-training dataset. Also, deployment of the system in a large-range area can reduce its energy consumption since it benefits from the provided genetic-based location selection algorithm. Two articles addressed the measurement of multiple air pollutants. Hernández-Vega *et al.* [32] proposed and evaluated a prototype model to monitor different air pollutants (sulfur dioxide, nitrogen dioxide, particulate material, lead, carbon monoxide, and ozone). They used a quadcopter drone equipped with a data acquisition system (DAQ) that communicates with the ground control station (GCS). The DAQ includes a board card that converts, filters, and amplifies the signal emitted by the sensors. The data is then transmitted from the DAQ to the GCS using Radio Frequency (RF) technology for further processing. Gu and Jia [33] proposed a consumer UAV-based air monitoring prototype that enables us to provide real-time information on multiple air pollutants. The components of the system are a UAV, a data fusion module, and two sensors mounted on the UAV platform. They performed a field test to monitor PM and nitrogen oxide pollutants.

One article addressed waste incineration management. Lu *et al.* (2019) [34] proposed a CPS for dealing with waste incineration pollution effectively. It benefits from UAVs equipped with micro-sensors for verification and post-evaluation purposes. The system enables pollution avoidance by controlling the whole life cycle of waste incineration from pre-treatment to pollutant emission, and it is not limited to on-site pollution monitoring. The authors argued that the adoption of this method overcomes conventional continuous emission monitoring systems (CEMS) shortcomings. The application of surveillance drones in weather monitoring is presented by Chodorek *et al.* [35]. They proposed an open universal system for continuous monitoring of urban areas and industrial regions based on UAV integrated with IoT measurements and web real-time communications (WebRTC), which is for the transmission of reliable data and real-time video. The system architecture consists of a network that connects an air station to a ground station. The field-test results showed the capability of the system to perform the task with high temporal and spatial resolution and in poor visibility conditions.

C. INFRASTRUCTURE

The usage of surveillance drones for infrastructure fields in smart cities has been reported in 7 (16.2%) articles. Two studies addressed bridge inspections. Seo *et al.* [36] analyzed the effectiveness of drones for bridge inspection in terms of image quality and damage identification on a specific bridge type (three-span glued-laminated timber girder with a composite concrete deck). The method includes bridge information review, site risk assessment of surrounding areas, pre-flight setup, drone-enabled bridge inspection, and damage identification stages. The results suggested the utilization of a drone (equipped with a digital camera) and photogrammetry software for the highly detailed bridge inspection tasks. Shang *et al.* [37] presented a data fusion platform capable of bridge deck condition monitoring and defect detection. It is made up of three parts: data collection (UAV and ground inspection), image processing (perspective projection and image stitching), and a web-based user interface (map and defects layer). The platform can fuse multi-scale aerial and ground images to identify, describe, and locate the surface cracks and sub-surface delamination. One study addressed both bridge and pavement inspections. Wu *et al.* [38] proposed a framework based on the combined use of UAVs and deep learning for infrastructural crack and damage detection and classification. High-resolution pictures and infrared thermal images taken by a UAV are used to train deep convolutional neural networks (CNNs). The authors have successfully applied the method to the concrete slab of a parking garage, road, and parking lot pavement. One study addressed pavement inspections. Roberts *et al.* [39] proposed a method for pavement distress detection by providing 3D models from images taken from the pavement's surface using UAVs and using segmentation algorithms to assess the 3D models of pavement sections. Their results from a real-case study show that the method is a reliable, flexible, and low-cost technique for pavement condition monitoring. Two studies addressed power line inspections. Barreto *et al.* [40] introduced the SIAD-AERO Project for autonomous and automatic inspection and anomaly detection in different city utilities. The project is an unmanned aerial system (UAS) consisting of different systems (decision-making system and an advanced artificial intelligence (AI) system), command and control stations (mobile and portable), and aerial platforms (fixed-wing UAS and quadcopter UAS). The impact business analysis results showed the growth of the company's capacity and reduction in operational time, human intervention, and labor risk. Pan *et al.* [41] proposed a system for automatic power line recognition and broken strand detection based on UAV images. It includes three main processes: oversampling (to provide more training data with balanced normal and broken strand samples), image transformation (to filter numerous redundant image backgrounds), and machine learning (ML) algorithms (for automatic power line recognition and broken strand detection based on UAV aerial images). Finally, building inspection is presented in Latha *et al.* [42]. They conducted a pilot study regarding automatic city-building information extraction using a UAV and cloud image processing platform. They tested the method for two types of buildings, and comparison results showed that the method has potential for urban development measure applications in smart cities.

D. OBJECT OR PEOPLE DETECTION

The deployment of surveillance drones for object or people detection was described in 6 (13.9%) of the 43 included articles. Surinta and Khruahong [43] presented a model that can be implemented in autonomous UAVs for human tracking (face recognition) and object detection (color recognition) purposes. The components of the model are face recognition (using Haar-cascade classifier and max-margin object detection with convolutional neural network (MMOD-CNN) methods), color recognition (using the HSV color space to detect the region of interest (ROI)), and tracking algorithm (using image processing and ML techniques). The experimental results showed that the model can perform object detection faster than people detection and that the model is capable of small object detection. Yadav *et al.* [44] proposed a system based on the application of UAV (real-time image and video capturing) and ML (object classification) for efficient management of urban green resources considering the various types of trees. The system architecture consists of training (image resizing, feature extraction, labeling, and classification), classification (classify image objects using a logistic regression model), and segmentation (color assignment, post-processing, and result improvement using the boundary extraction method) phases. The results of the field test confirmed the capability of the system. Also, multiclass logistic regression is the most accurate classifier. Kim *et al.* [45] proposed a method for the detection of obstructions (e.g., trees and berms) around runways based on UAS and visual assets (still images, point cloud models, and infrared photography). Three stages of the method are: data collection of 2D images using UAS, providing a 3D point cloud model using UAS photogrammetry, and running analysis using point cloud library (PCL). The field experiment showed that detailed information about obstructions around runways can be obtained using UAS-based point cloud data. Wang *et al.* [46] developed an efficient and robust method to improve the quality of images taken by UAVs at night time for pedestrian detection. Image enhancement was performed using a combination of algorithms (hyperbolic tangent curve (HTC) and block-matching and 3D filtering (BM3D)). Their comparative and experimental tests showed that the performance of the proposed method is higher than that of other methods in terms of image quality enhancement and detection accuracy. Munyer *et al.* [47] developed a dataset of foreign object debris (FOD) using CV, UAS, and machine learning technology to assess the potential of a lightweight automated detection system. The field-test results showed that the method detects the majority of FODs correctly. Wan *et al.* [48] suggested a smart system for threat detection, criminal tracking, and emergency response in urban areas. The system consists of different working layers: a central agent, UAVs, multiple robots (several independent and intelligent agents on the ground), and a sensor network (several static distributed-connected sensors). These layers can transmit the data between and within themselves. The central agent is responsible for synthesizing the data from the layers and controlling the entire system. UAVs detect threats and transport robots to the scene. Robots collect detailed data on the scene and handle emergency and security issues. Sensors are the assistants of UAVs and robots and are responsible for constant area monitoring.

E. DISASTER MANAGEMENT

The surveillance drone applications for disaster management appeared in five of 43 (11.6%) articles, 2 of which described fire-related disasters. Sharma *et al.* [49] presented a system to detect an early-stage fire around smart cities and forests using UAVs, cloud computing, wireless sensor networks (WSN), and image processing techniques. UAVs provide the region's real-time images, map, and localize the target area. The experiment conducted by the authors verified the cost-effectiveness of the method for real-time data collection and monitoring and showed its ability for accurate fire occurrence detection. Zadeh *et al.* [50] developed a UAV design with a shooting and dropping mechanism for firefighting services in urban areas. The designed UAV can shoot and drop the fire distinguisher balls to decrease fire spread. The UAV communicates with a controller using a radio frequency transmitter, and it is equipped with a night vision camera, global positioning system (GPS), servo motor, and gyroscope. The field test showed the high performance rate of the designed UAV. However, the shooting accuracy may be affected due to the UAV's sensitivity to the weather conditions.

Sahil and Sood [2] proposed a framework that provides an evacuation strategy and timely medical support for panicked stranded individuals after a disaster occurrence. It includes physical (IoT sensor layer, stranded individuals, and evacuation personnel) and cyber (fog and cloud layers) sub-systems. The outcomes indicated the functional role of a UAV in more efficient evacuation map building. Tariq *et al.* [51] presented DronAID, a real-time autonomous system based on UAV technology for detecting human bodies buried under debris as a result of natural or man-made disasters. DronAID is composed of five modules: control (microcontroller), monitor (passive infrared sensor), capture (camera), data storage (SD card), and communication (Wi-Fi). The sensor of the system detects infrared radiation generated by the human body.

Alsamhi *et al.* [52] presented an embedded system based on cooperation between UAVs and internet of public safety things (IoPST) devices for public safety purposes. It consists of multiple drones and search and rescue (SAR) responders connected via mobile ad hoc network (MANET) and ad-hoc on-demand distance vector (AODV) protocol for service routing. Evaluation of the system showed its capability to provide quick connectivity and fast data communication services in a large area while keeping high QoS and lessening economic losses.

F. DATA COLLECTION

Data collection implications are discussed in three articles (6.9%). UAVs can act as data collectors from different devices for various applications in smart cities. Khalifeh *et al.* [53] presented a framework for data collection by integrating UAVs and WSNs. In this method, WSNs are ground-static sensors responsible for data collection from a designated area. A UAV acts as a data mule by enabling covered area extension, sensing above-the-ground, collecting the collected data via WSNs, and transmitting it to a remote center. They performed three field tests with three different channel conditions between sensor and destination nodes based on two wireless sensor nodes. The results stated that high-energy, high-range wireless sensor nodes perform significantly better than cost-effective, low-range ones. Garge and Balakrishna [54] investigated how utilization of UAVs can be beneficial for high-performance needed surveillance tasks such as multimedia streaming. They found that UAVs with on-board mobile edge computing (MEC) that hosts a transmission control protocol (TCP) proxy are viable solutions for multimedia streaming applications in smart cities. Drones can act as flying infrastructure extenders, provide on-demand quality of service (QoS), and cause end-user experience improvement. Roldán-Gómez *et al.* [55] proposed an aerial robotic swarm system for city monitoring (collection of traffic, pedestrians, climate, and pollution data). The system is comprised of different modules: a city simulator that includes different models, a drone swarm that is controlled by a behavior-based algorithm, a base station that is used for data analysis and map production using a data fusion algorithm, and an operator interface for city monitoring. They have used a virtual city called SwarmCity to validate the data collection, data processing, and data presentation.

G. OTHERS

The remaining four articles presented the application of surveillance drones in farming, city and extensive ocean monitoring, 3D city modeling, and mapping. Marín *et al.* [56] proposed a system for urban lawn monitoring that facilitates decision-making regarding proper irrigation and planting. The system's architecture consists of a drone with a pre-planned flight, controlling algorithm, and image processing. Their experimental results demonstrated the usage of the algorithm in the classification of plots based on the coverage (high, low, and very low), and the proposed system is a time-efficient method to cover a large surface of urban lawns. Kim *et al.* [57] presented differential frameworks using multiple heterogeneous smart UAVs capable of simultaneous detection of multiple events in a smart city (tight plane-based framework) and monitoring and seamless surveillance over an extensive ocean (loose hierarchical-based framework). In the city framework, UAV ground stations (UGSs) are installed in possible public areas, and current public transport systems are utilized to charge UAVs. This framework includes three steps (periodic report and event detection, scheduling workable UAVs, and scheduling returning UAVs) and it supports multiple pair communications (UGS-UGS, UGS-UAV, and UAV-UAV). Pannozzi *et al.* [58] presented a 3D simulated real-world environment of a city (Turin, Italy) for city monitoring simulations and modeling. The model can pilot and navigate drones with on-board sensors either through a GCS or through manual direct piloting. It is beneficial for the development and execution of case studies before undertaking field experiments. Wu *et al.* [59] proposed a UAV-based framework for 3D spectrum mapping. It includes pre-sampling, spectrum situation estimation, iterative ROI-driven UAV deployment, and spectrum map recovery. The authors tested different schemes of UAV implementations (ROI-driven, random, and ROI-only) in a simulation environment, and found that the ROI-only scheme has the best performance. However, due to the high energy usage of this scheme, it can't be a good option when energy saving is the main criterion.

V. CHARACTERISTICS OF IMPLEMENTED DRONES

The characteristics of the drones used in earlier studies in terms of the number of UAVs, type of UAV, and aerial sensors are presented in Table 9. These results indicate that the use of multiple UAVs appeared in about 20% of the articles. The remaining articles dealt with single-UAV applications. Fixed-wing and rotary-wing types of UAVs appeared in 2 and 33 articles, respectively, which indicates the dominance of the rotary-wing type. Cameras were the most-used aerial sensors in all categories except the environment category.

Several aerial sensors for the measurement of various air pollutants were implemented. MQ7, MQ8, and MQ135 are semiconductor gas sensors for the respective detection of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2) based on the temperature cycling (high and low) method. Their sensing material is stannic oxide (SnO_2). It has low conductivity in clean air. Its conductivity rate increases when the gas concentration rises. MQ131 is a sensor for ozone (O_3) gas detection, and its sensing material is tungsten oxide (WO_3). The main advantages of these MQ sensors are high sensitivity, low cost, long lifespan, and simple drive circuits. The Adafruit HTU21D-F is a breakout board comprised of temperature and humidity sensors. It enables us to measure the temperature and humidity with high accuracy of respective $\pm$ 1° C and $\pm$ 2% within the range of −30° C to 90° C and 5% to 95% humidity. However, its accuracy drops outside of these ranges. The 4-Electrode NO_2 sensor is used for urban air quality monitoring, and it measures low-concentration nitrogen dioxide. Its benefits include accuracy, ultra-high resolution, long-term detection performance, sensitivity, and short response time.

The PM pollutant is measured by different aerial sensors: LoRa-based PM2.5, Plantower PMS3003 Laser Dust, A3-IG, OPC-N2, and OPC-R1. LoRa is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology which supports the data rate between 300 bps to 50 kbps based on the spreading factor and the channel bandwidth [60]. The LoRa PM2.5 is a sensor node for precise measurement of PM2.5 up to 600 $\mu g/m^3$ (microgram per cubic meter) with a transmission range of 2 to 5 km in urban areas. Its key advantages are low-power consumption, long-range transmission, and application in indoor and outdoor environments. Plantower's laser PM2.5 PMS3003 is a digital particle concentration sensor that operates on the

TABLE 9. UAV-implemented characteristics.

Category	Author(s)	Number of UAVs	UAV type	Aerial Sensors
Transportation	Hossain et al. (2019) [22]	Multiple	Rotary wing	On-board camera
	Roldan et al. (2019) [20]	Swarm (multiple)	Rotary wing	On-board camera
	Garcia-Aunon et al. (2019) [21]	Swarm (multiple)	Rotary wing	On-board camera
	De Frias et al. (2020) [19]	Single	Rotary wing	On-board camera
	Gogoi et al. (2020) [26]	Single	Rotary wing	On-board camera
	Shirazi et al. (2020) [23]	Single	Not specified	On-board camera
	Yang et al. [24]	Single	Rotary wing	On-board camera
	Beg et al. (2021) [25]	Multiple	Not specified	On-board camera
	Bouassida et al. (2021) [4]	Single	Not specified	On-board camera
Environment	Hernández-Vega et al. (2018) [32]	Single	Rotary wing	Gas (MQ7, 8, 131, 135) sensors
	Chen et al. (2018) [27]	Single	Rotary wing	LoRa-based PM2.5
	Mayuga et al. (2019) [28]	Single	Rotary wing	PM (Plantower PMS3003 Laser Dust) sensor, temperature and humidity (Adafruit HTU21D-F) sensors
	Hu et al. (2019) [29]	Single	Rotary wing	PM sensor (A3-IG)
	Gu and Jia (2019) [33]	Single	Rotary wing	PM sensor (OPC-N2) Nitrogen dioxide sensor (4-Electrode NO2)
	Lu et al. (2019) [34]	Single	Rotary wing	Micro-sensors
	Yadav et al. (2020) [30]	Single	Fixed wing	PM (OPC-R1) sensor
	Gao et al. (2021) [31]	Single	Rotary wing	On-board camera
	Chodorek et al. (2021) [35]	Single	Rotary wing	Weather sensors and on-board camera
Infrastr ucture	Seo et al. (2018) [36]	Single	Rotary wing	On-board camera
	Barreto et al. (2018) [40]	Single	Fixed and rotary	Ultraviolet camera (Ofil Swif), RGB visual camera (PointGrey Grasshopper), Infrared camera (FLIR A65)
	Wu et al. (2018) [38]	Single	Rotary wing	Built-in camera and thermal camera
	Shang et al. (2019) [37]	Single	Rotary wing	On-board camera
	Latha et al. (2019) [42]	Single	Rotary wing	CMOS sensor
	Pan et al. (2020) [41]	Single	Not specified	On-board camera
	Roberts et al. (2020) [39]	Single	Rotary wing	On-board camera
Object or people detection	Wan et al. (2017) [48]	Multiple	Rotary wing	On-board camera
	Surinta and Khruahong (2019) [43]	Single	Rotary wing	On-board camera
	Yadav et al. (2019) [44]	Single	Rotary wing	Raspberry Pi-camera and analog camera
	Kim et al. (2019) [45]	Single	Rotary wing	On-board camera
	Wang et al. (2021) [46]	Single	Rotary wing	On-board camera
	Munyer et al. (2021) [47]	Single	Not specified	On-board camera
Disaster Management	Tariq et al. (2018) [51]	Single	Rotary wing	On-board camera and Passive Infrared (PIR)
	Alsamhi et al. (2019) [52]	Multiple	Not specified	no sensors on-board
	Sahil and Sood (2020) [2]	Single	Rotary wing	no sensors on-board
	Sharma et al. (2020) [49]	Single	Not specified	On-board camera
	Zadeh et al. (2021) [50]	Single	Rotary wing	On-board camera
Data collection	Garge and Balakrishna (2018) [54]	Not specified	Not specified	no sensors on-board
	Roldán-Gómez et al. (2020) [55]	Multiple	Not specified	Camera and environmental sensors
	Khalifeh et al. (2021) [53]	Single	Rotary wing	no sensors on-board
Others	Marín et al. (2018) [56]	Single	Rotary wing	CMOS camera
	Kim et al. (2018) [57]	Multiple	Rotary wing	On-board camera
	Pannozzi et al. (2019) [58]	Single	Rotary wing	On-board camera
	Wu et al. (2020) [59]	Single	Rotary wing	Spectrum monitoring device

basis of laser light scattering. It detects PM2.5 in the air with great precision and sends serial data (in the form of a digital interface) to the host at a time interval between 200 to 800 ms (milliseconds). Real-time reaction, in-time data correction, zero false alarm rate, and detection of particles with diameters ranging from 0.3 to 10 m (micrometers) are among its key benefits. A3-IG is the digital sensor for PM2.5 measurement. This low-cost sensor has low-power consumption, high-temperature resistance between $-10°$ C and $85°$ C, a range of 6000 $\mu g/m^3$, and measuring particles with a diameter range of 0.3 to 10 μm. OPC-N2 is the Analog PM2.5 sensor that provides PM readings and real-time particle size histograms. It detects particles with a diameter range between 0.38 to 17 μm in an environment with a temperature range of $-10°$ C to $50°$ C. OPC-R1 is the digital sensor based on the laser scattering theory. It detects particles with a diameter range between 0.4 to 12.5 μm in a temperature range similar to the OPC-N2.

FLIR A651 is a thermal imaging temperature sensor based on infrared technology to detect hot spots with the underlying anomaly. The high-quality, low-noise thermal images enable easy tracking of even very small temperature changes. The sensor is suitable for process control/quality assurance, fire prevention, and condition monitoring. Ofil Swift is the ultraviolet camera to detect corona, which creates corrosive materials such as ozone and nitrogen oxides, on an asset. The utilization of ultraviolet sensors allows pinpointing corona and arcing, identifying the location and severity of the failure, demonstrating the emitting objects and the emitted radiation, and predicting the inevitable crisis. PointGrey Grasshopper is an RGB camera that uses charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS) technology to produce high-quality images. It can be used as a visual sensor to detect and locate different anomaly types.

VI. CONCLUSION

Drone technology is one of the most recent and advanced technologies that offers more efficient and sustainable solutions for solving numerous surveillance problems compared to conventional methods. In this direction, different drone-based methodologies for various surveillance tasks in the context of smart cities have been proposed by researchers recently. Conducting a systematic review is essential to highlight the current situation of the topic in the academic literature and analyze the relevant studies. The contribution of the current review lies in the classification of application areas of surveillance drones in the smart city research domain, investigation of the drone's integration with other technologies to perform different tasks, and identification of aerial sensors used in surveillance operations. In this work, eligible articles were classified into seven distinct categories, and complementary information, including application area, aim, research gap, outcome, future work recommendation, and validation method for each article, was provided. In addition, the characteristics of utilized UAVs in terms of number, type, and the type of aerial sensor were explored.

This review found that the given topic is in an early-stage status in academic research. IEEE Explore is the main outlet that publishes most of the related articles. Surveillance drones have been deployed in different application areas, including transportation, environment, infrastructure, object or people detection, disaster management, data collection, and other applications in smart cities. Transportation, environment, and infrastructure are the most attractive categories, and traffic and air pollution monitoring are the dominant application areas. Adoption of a drone (or multiple drones) either as a stand-alone technology or combined with other recent technologies (e.g., IoT, WSNs, CNNs, AI, ML, C-ITS, CV, WebRTC, cloud computing, web applications, etc.) enables us to provide real-time data and efficiently perform the complex surveillance tasks in smart cities. It also allows us to overcome the shortcomings of conventional methods and offers cost-effective, time-saving, labor-intensive, and highly accurate solutions. A minority of the proposed models were validated based on experimental and real-world scenarios, while the majority used simulation as the validation method. The real-case executions of surveillance drones in smart cities are still limited. Their large-scale use necessitates overcoming various challenges and barriers, such as operational issues, policies and legislation, and the safety and security of citizens. The rotary-wing UAV is the predominant type for surveillance operations compared to the fixed-wing type. Cameras were used as aerial sensors in most of the reviewed models for visual data collection, and a few of the models were based on laser scanners. In comparison to multiple-drone applications, majority of the examined models concentrated on single-drone applications.

The collected images from the on-board cameras on UAVs can be converted into point clouds using image-based photogrammetric methods. The point clouds generation is useful in different application areas in smart cities since it enables us to provide 3D models of the area of interest. However, the precision of the 3D models depends on the processing, analyzing, and visualizing of raw point cloud data. Thus, further studies are required to investigate the impacts of these tasks on providing accurate 3D city models. Besides, this study also suggests more research on employing vision-based approaches to assess multiple air pollutants.

Note that the outcomes derived from this systematic review were based on multiple limitations. Firstly, the relevant documents in any scholarly databases, except Scopus and Web of Science, were not taken into account in this review. The second is that this review is limited to those studies that propose methods for different applications of surveillance drones in the context of smart cities. Research works that address the challenges of drone operations were excluded (e.g., authentication security, drone communications modeling, path planning algorithms, cyber threats, data transfer, etc.). Thus, further review research to explore the technological challenges of drones in smart cities is required. Finally, we only considered articles and conference papers in English.

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