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Review Article

Integrating Unmanned Aerial Vehicle Remote Sensing With Internet of Things Frameworks: A Survey of Methods and Applications

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Abstract

Remote sensing has gained significant attention in recent years due to the increasing availability of cloud computing platforms for geographically dispersed sensor sites. Within the Internet of Things (IoT) paradigm, data generated by sparsely deployed sensor networks in remote locations is transmitted through various telemetric communication channels. One of the most effective and widely adopted approaches for data collection and transmission from IoT-based sensor environments is the use of Unmanned Aerial Vehicles (UAVs), which provide high mobility, cost-effective surveillance, low deployment cost, and time efficiency. In addition to conventional cloud support, the recent convergence of Edge Computing and Artificial Intelligence has further enhanced UAV-enabled remote sensing by enabling real-time data processing, intelligent analytics, and reduced latency in distributed environments.

This review article examines the advancements, challenges, and emerging opportunities associated with integrating UAVs into IoT-driven remote sensing systems. It explores the diverse range of sensing technologies and their applications across domains such as agriculture, smart cities, natural disaster monitoring, infrastructure management, and search-and-rescue operations. Furthermore, critical challenges, including regulatory constraints, data privacy concerns, scalability requirements, and interoperability issues, are discussed in the context of evolving intelligent and edge-enabled architectures. The objective of this survey is to provide practitioners and researchers with a comprehensive understanding of UAV-assisted remote sensing within IoT ecosystems while highlighting open research issues, technological trends, and future directions.

Categories: IoT Applications and Use Cases, IoT Integration with Emerging Technologies, Machine Learning (ML)

Keywords: unmanned aerial systems, communication, security, surveillance, iot, sensors, machine learning

Introduction And Background

The Internet of Things (IoT) represents a rapidly developing paradigm in which networks of sensors observe physical environments, embedded systems perform local data processing, and communication modules forward the collected information to centralized cloud platforms for storage and analysis. These sensors are often deployed in remote or widely distributed locations, such as agricultural fields, roadside transportation systems, or along riverbanks for hydrological semonitoring. Data gathered from such distant areas is delivered to a central system through remote sensing (RS) infrastructures, which employ various types of sensors selected according to the specific application domain.

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Multiple transmission technologies can be used to relay data from the sensing sites to cloud servers or processing units. These include satellite links, next-generation wireless systems such as 6G and beyond, and aerial data collection platforms like Unmanned Aerial Vehicles (UAVs). UAVs are highly suitable for RS due to their flexible deployment, seamless integration with 6G networks, and ability to cover large geographical regions. This makes them effective in applications such as precision agriculture, climate and environmental studies, urban traffic observation, industrial automation, and healthcare services [1]. Their usefulness is especially evident in locations where human access is unsafe, labor-intensive, or impractical, for instance, during flood surveillance, earthquake assessment, volcanic activity monitoring, glacier observation, or operations in avalanche-prone areas [2,3]. UAVs also excel in scenarios requiring rapid response or high accuracy, such as search-and-rescue tasks and advanced industrial monitoring.

In situations where conventional telecommunication infrastructure is damaged, inaccessible, or costly to restore afterdisasters, UAVs provide an efficient alternative for timely data acquisition, such as in flood tracking and environmental assessment. They are equally effective for monitoring continuously changing environments, including traffic flow, crowd movement, and river dynamics. Their key advantages include high mobility, fast deployment, and minimal configuration requirements.

Given the diversity of application fields, the nature and format of collected data vary significantly, as shown in Figure *1*. Sensors positioned at different locations may rely on heterogeneous communication protocols for forwarding information to central processing systems. A notable technological trend is the fusion of IoT with RS frameworks, in which IoT-derived data is transmitted to cloud computing platforms for further analysis. UAVs can acquire information independently, such as through onboard cameras for imaging and video capture, or through passive sensing technologies like Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR). Additionally, IoT-based systems positioned on the ground can supply data that UAVs collect and transport for analysis.

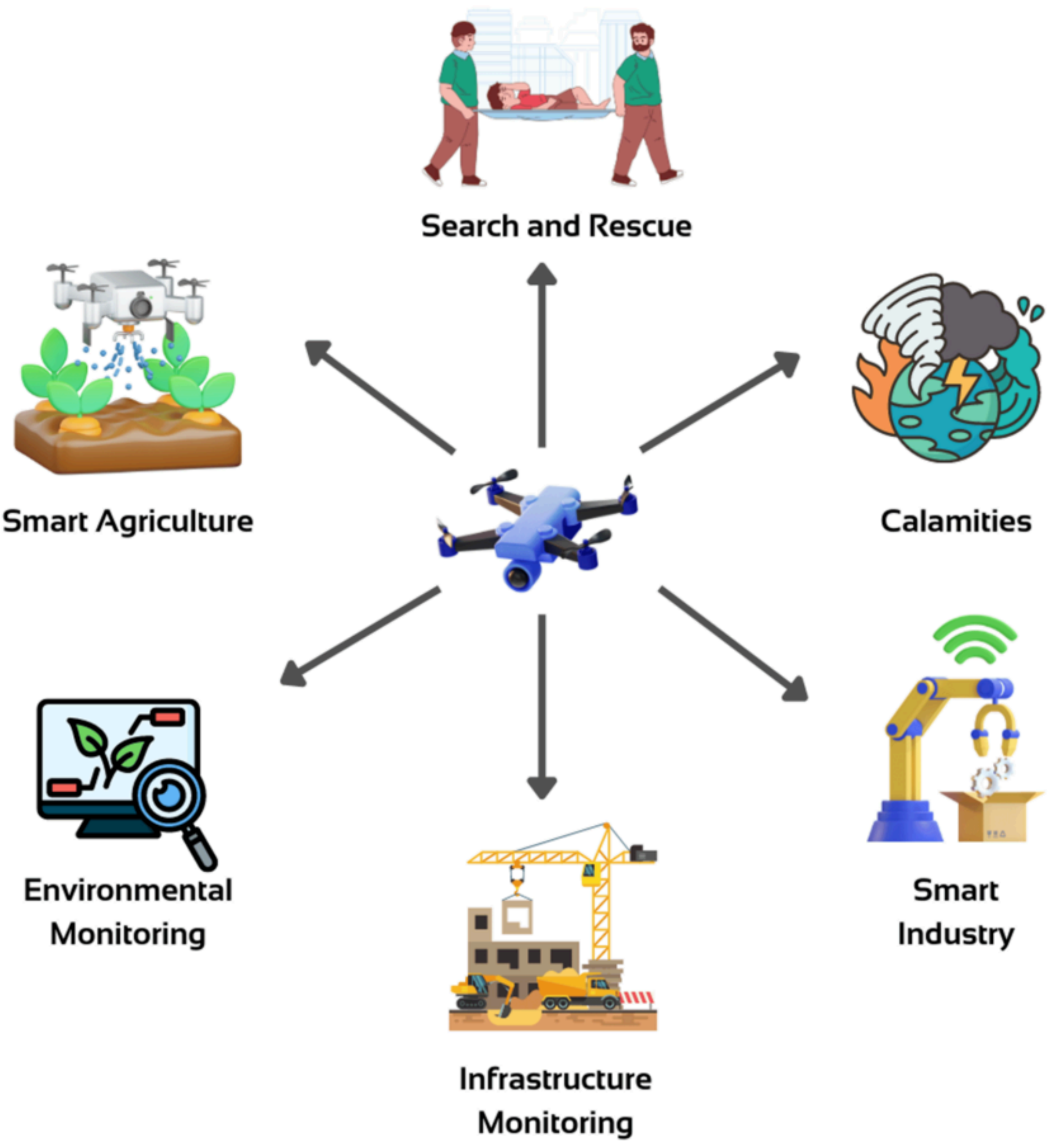

FIGURE 1: Application of UAV in remote sensing

UAV, Unmanned Aerial Vehicle

An IoT-based system typically gathers data from distributed sensors and forwards it to an aggregation node. In smart agriculture (SA), for instance, ground sensors may first transmit information to a relay node, after which a UAV collects the aggregated data. This information is then sent to a centralized cloud platform via existing mobile communication networks , where it is processed for event detection and other analytical tasks. Figure *2* illustrates the complete flow of sensing, data dissemination, and computation.

RS generally falls into two categories: passive and active sensing. Passive sensing relies on naturally available signals such as sunlight, meaning aerial and satellite images are captured without transmitting any dedicated signal. Active sensing, in contrast, emits radio waves, laser pulses, or other forms of energy and measures the reflected response. Technologies such as Radar and LiDAR fall under this category.

As noted earlier, 5G and 6G communication standards play a major role in RS systems. UAVs can be integrated with additional emerging technologies to enhance data rates, minimize latency, and reduce their energy consumption. Examples include device-to-device (D2D) communication and intelligent reflecting surfaces (IRS). Large-scale RS deployments often involve numerous sensors, resulting in significant traffic. D2D, a key feature of 5G and beyond, enables nearby devices to communicate directly in point-to-point mode, which lowers traffic within the sensor network and reduces the burden on aggregation nodes.

D2D can also operate within traditional base station (BS) networks. In this setup, the BS performs device discovery, obtains channel state information, and allows devices to communicate directly through D2D links [4]. This reduces BS congestion and improves its ability to handle UAV-collected RS data. The combined use of UAVs and D2D enhances BS processing capacity, saves energy, and strengthens wireless network performance for RS tasks.

Since UAVs have limited battery capacity, their flight paths must be optimized to conserve energy during sensing missions. RS targets often cover wide geographic areas, making it difficult for a UAV to complete its mission in a single flight. Integrating IRS with UAVs can extend communication range because IRS panels consist of passive reflective elements that redirect signals from relay nodes toward the UAV, even when the UAV is not directly above the sensing site. IRS also helps mitigate line-of-sight issues by reducing multipath fading, which lowers noise during data collection and improves the quality of analytics.

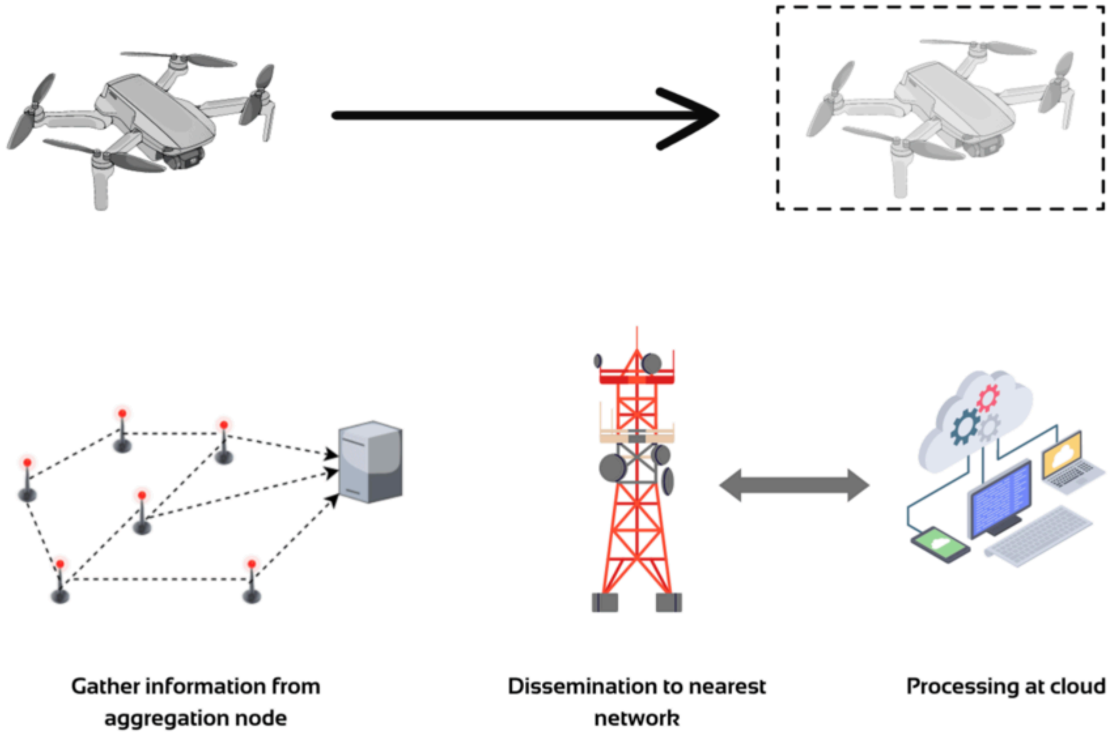

FIGURE 2: Information processing steps for UAV-based RS

RS, Remote Sensing; UAV, Unmanned Aerial Vehicle

Machine-to-machine (M2M) communication is another important technology within 5G systems, enabling devices to exchange data directly without relying on a BS or centralized controller. As a core component of IoT, it allows machine-type communication devices (MTCDs) to interact autonomously. However, when IoT infrastructure becomes damaged or inaccessible, MTCDs in remote areas struggle to maintain connectivity on their own. In such situations, UAVs can be deployed to restore communication links and ensure secure, valid data transmission. UAVs can also perform periodic data collection from isolated M2M networks where traditional communication systems cannot reach.

From an architectural perspective, a taxonomy of UAV-IoT integration can be defined based on the functional role assumed by the UAV within the IoT network. In this taxonomy, a UAV may operate as (i) an IoT node, (ii) an aerial gateway, or (iii) a cluster head.

Taxonomy of functional roles of UAV in IoT-enabled RS

Figure *3* presents a taxonomy of UAV operational roles within IoT-enabled RS systems. The classification is organized according to the functional responsibility assumed by the UAV inside the sensing architecture.

UAV as IoT Node: In this role, the UAV acts as an autonomous sensing entity equipped with onboard sensors such as cameras, LiDAR, thermal sensors, or environmental detectors. The UAV directly generates sensing data and participates similarly to conventional IoT devices.

UAV as Aerial Gateway: Here, the UAV serves as a communication bridge between distributed ground sensors and centralized infrastructure. It aggregates information from heterogeneous IoT devices and forwards data to cloud platforms, edge servers, or BSs, particularly in remote, disconnected, or disaster-affected environments.

UAV as Cluster Head: In this configuration, the UAV coordinates groups of IoT nodes, manages local resource allocation, performs preliminary data aggregation, and may execute edge-AI or lightweight analytics before forwarding processed information upstream.

This taxonomy highlights the multifunctional nature of UAVs in modern IoT ecosystems, extending their role beyond aerial sensing toward communication orchestration, edge intelligence, and distributed system coordination.

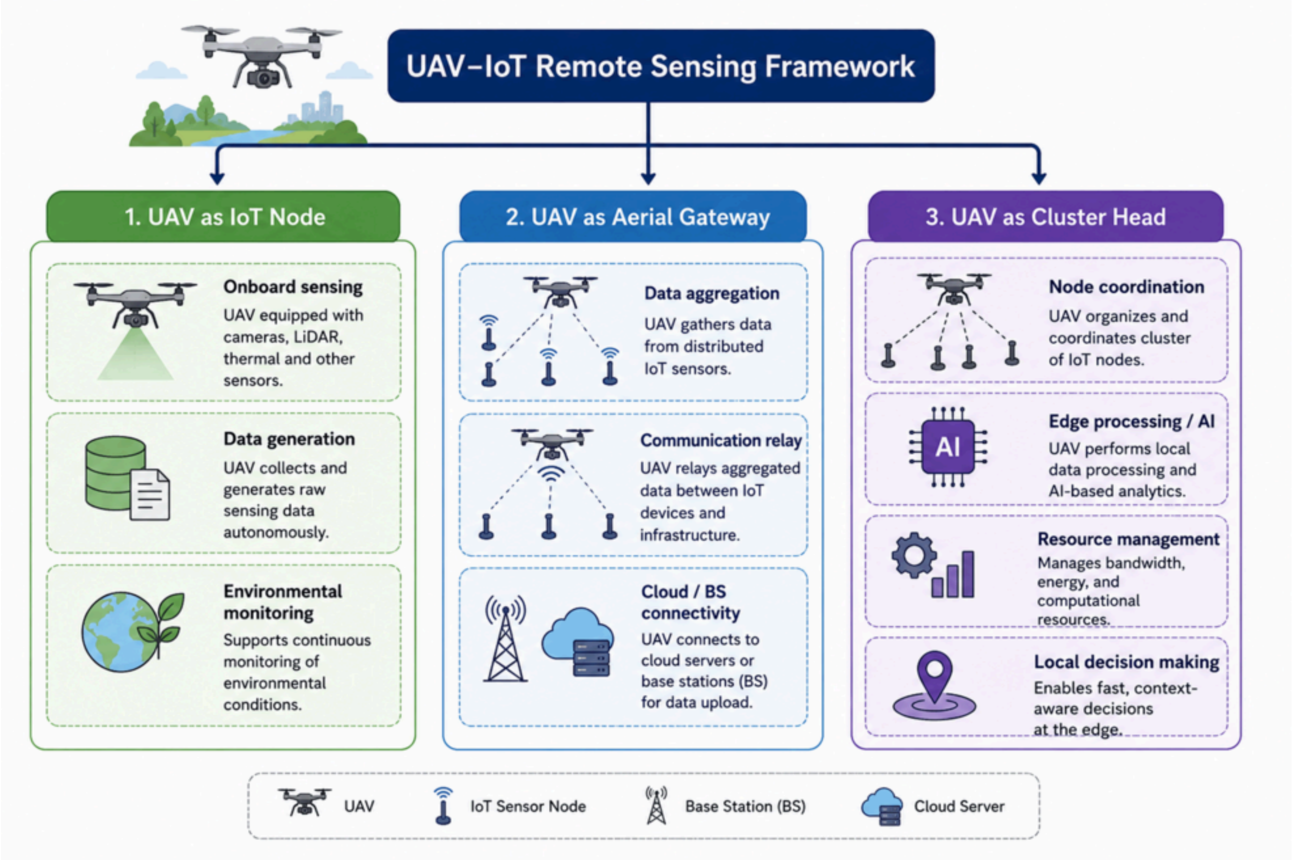

FIGURE 3: Taxonomy of roles of UAV in IoT-enabled RS systems

IoT, Internet of Thing; RS, Remote Sensing; UAV, Unmanned Aerial Vehicle

When acting as an IoT node, the UAV is equipped with onboard sensors and directly participates in sensing and data generation, similar to ground-based MTCDs. In the aerial gateway role, the UAV serves as a relay between distributed IoT devices and the core network, aggregating and forwarding data to a BS or cloud platform, particularly in areas with damaged or absent infrastructure. As a cluster head, the UAV coordinates a group of IoT nodes, manages local data aggregation, and performs preliminary processing or edge intelligence before transmission. This taxonomy clarifies that UAVs are not merely communication relays but flexible network entities whose role depends on mission requirements, network topology, and resource availability.

Different types of UAVs are selected depending on the mission requirements and RS application. Fixed-wing (FW) UAVs resemble conventional aircraft and rely on aerodynamic lift, making them well-suited for long-range surveillance and imaging tasks, although they lack maneuverability. Rotary-wing (RW) or vertical take-off and landing UAVs are lightweight, energy-efficient, and capable of hovering by adjusting rotor speeds. These platforms are typically used for short-range RS applications such as inspecting power lines or towers. A third category, hybrid UAVs, combines the advantages of FW and RW designs, offering long-endurance flight alongside vertical takeoff, landing, and hovering capability. Their versatility comes at the cost of increased structural complexity and higher manufacturing expenses.

In RS missions, FW UAVs are ideal for long-distance operations that require quick data collection passes rather than stationary monitoring. RW UAVs, in contrast, can remain fixed over a target area, making them suitable for tasks that require prolonged observation, though their flight duration and range are limited due to higher power consumption. In some scenarios, deploying a fleet of UAVs delivers better performance than relying on a single vehicle. Multiple UAVs can collaboratively capture spatiotemporal data more efficiently, and a coordinated fleet equipped with application-specific sensors simplifies large-scale data acquisition. Complex RS missions may also use mixed fleets with different UAV types operating in formation.

Networked surveillance UAVs function as autonomous platforms equipped with sensors and communication capabilities. Research in UAV deployment spans numerous active topics, including motion control, path planning, and trajectory tracking.

Several surveys have analyzed UAV challenges, applications, and RS-related techniques. Osco et al. [5] provide a comprehensive overview of UAV-based RS with a focus on deep learning methods. Liu et al. [4] discuss RS for SA enhanced by UAVs and edge intelligence. A related survey in [6] explores UAV and IoT-assisted smart farming, covering aspects such as fertilization, pesticide application, and crop health monitoring. Bagwari et al. [7] investigate land-monitoring use cases involving IoT systems and UAV-mounted sensors. Additional reviews include infrastructure and construction monitoring using camera and laser-based sensors [8], and remote health monitoring supported by smart devices and body area networks (BANs) [9].

Several surveys have explored UAVs, IoT, and RS from different perspectives, including deep-learning-enabled UAV RS, SA, infrastructure inspection, and healthcare monitoring. However, most existing reviews remain application-specific or emphasize a limited subset of enabling technologies. In contrast, this survey adopts a cross-domain perspective, integrating UAV-enabled IoT RS across multiple application areas including SA, smart cities (SCs), healthcare, search-and-rescue, disaster management, infrastructure monitoring, and smart energy systems.

In addition, this work introduces a functional taxonomy of UAV participation within IoT ecosystems, where UAVs operate as IoT nodes, aerial gateways, or cluster heads, depending on sensing, networking, and computational requirements. The survey further examines the influence of emerging technologies such as edge computing, AI, blockchain-based security, 5G/6G communication, D2D networking, and IRS on UAV-assisted RS architectures.

Therefore, rather than focusing on a single application domain, this review aims to provide a unified understanding of UAV-IoT-RS integration, summarize major technical challenges and opportunities, and identify future research directions spanning heterogeneous sensing environments.

- A cross-domain survey framework for UAV-enabled IoT RS is presented, integrating applications spanning SA, SCs, healthcare, search-and-rescue, disaster management, infrastructure monitoring, and smart energy systems. Unlike domain-specific reviews, this work provides a unified perspective across heterogeneous RS environments.

- A functional taxonomy of UAV participation within IoT ecosystems is introduced, classifying UAV operation as (i) IoT node, (ii) aerial gateway, and (iii) cluster head, thereby clarifying their sensing, communication, coordination, and edge-computing roles in RS architectures.

- A comprehensive review of enabling technologies for UAV-IoT RS is provided, including edge computing, AI/machine learning, blockchain security, 5G/6G communication, D2D networking, and IRS, together with their role in enhancing system intelligence, scalability, and connectivity.

- A broad collection of real-world UAV-assisted IoT RS applications is compiled and comparatively analyzed, covering use cases such as precision agriculture, environmental monitoring, infrastructure assessment, healthcare, and disaster response.

- Major technical limitations, deployment challenges, and open research directions are identified, including issues related to power constraints, communication reliability, multi-modal data fusion, security, scalability, environmental robustness, and autonomous coordination in large-scale UAV-IoT systems.

Review

UAV-assisted RS

This section presents an in-depth review of major RS applications, encompassing land and avalanche monitoring, infrastructure assessment, and emerging smart systems. With continuous technological advancements, urban environments and healthcare infrastructures are increasingly benefiting from modern RS solutions, leading to improved citizen welfare, enhanced precision in healthcare services, and more reliable control systems [7-13]. To ensure a comprehensive and objective analysis, the studies included in this review were selected using a systematic literature review methodology. A structured search was conducted across leading scientific databases, including IEEE Xplore, Scopus, Web of Science, and Google Scholar, covering publications from 2015 to 2024. The search strategy employed relevant keywords and Boolean combinations such as UAV RS, avalanche forecasting, LiDAR snow monitoring, GPR-based snow profiling, IoT-enabled SA, and AI-driven precision farming. Peer-reviewed journal articles and conference papers reporting validated methodologies, experimental evaluations, or real-world deployments involving UAVs, IoT, and RS technologies were included. Studies were excluded if they were purely review-based, lacked methodological rigor or validation, focused solely on simulations, or fell outside the scope of environmental hazard monitoring and SA. Following title, abstract, and full-text screening, the final set of studies was selected to ensure relevance, technical robustness, and alignment with the objectives of this review, particularly highlighting the transformative role of UAV-enabled IoT and AI in SA and industrial applications. Most of the selected studies report experimental evaluations or real-world deployments of UAV-enabled RS and IoT systems across domains such as agriculture, disaster monitoring, SCs, and infrastructure inspection. A smaller portion of the literature includes simulation-based studies, mainly focused on communication protocols and UAV coordination, which were included only when supported by rigorous methodological validation.

Avalanche Forecasting and Risk Management With the IoT

Continuous monitoring of snow is essential to reduce avalanche risks in mountainous regions. It supports the management of water resources, the forecasting of snowstorms, and the prediction of avalanche hazards. Avalanches and landslides are among the most significant natural disasters in mountain areas, posing threats to both local residents and tourists. Accurate forecasting is therefore critical for safety and disaster mitigation. Traditionally, snow and soil layers were monitored using upward- and downward-looking radar systems.

In recent years, UAV-based RS has emerged as a practical solution for avalanche monitoring due to its wide coverage and cost-effectiveness. Various types of UAVs, including quadcopters, hexacopters, and octocopters - collectively referred to as multi-copters - are commonly used. Multi-copters are particularly valued for their aerial stability, which generally increases with the number of rotors, making them suitable for precise and steady data collection, as detailed in Table *1*.

Avalanche monitoring relies on a range of sensors, such as cameras, infrared systems, LiDAR, photogrammetry, and ground-penetrating radar (GPR). Cameras offer an economical approach to monitor snow surfaces, though they are limited in estimating snow depth and layering, especially under low-light conditions. Infrared sensors provide information about surface conditions but do not capture subsurface characteristics. LiDAR systems allow detailed monitoring of snow surfaces, detection of cracks that could trigger avalanches, and accurate estimation of snow depth and volume [7]. Photogrammetry provides a cost-effective alternative to LiDAR for measuring surface conditions, snow depth, and volume. GPR-equipped UAVs can precisely assess snow layers and volumes, often deployed on octocopters due to their superior hovering stability.

Detecting snow layers is crucial for forecasting avalanches, as these events typically occur when a weak layer detaches from the snowpack [8]. UAVs equipped with optical or multispectral sensors, combined with high-precision positioning systems, are effective for validating photogrammetry results in avalanche-prone regions. The integration of IoT sensors and AI algorithms further enhances monitoring by enabling real-time prediction of potential snow slides.

The choice of UAV type depends on the monitoring requirements and sensor payload. For instance, fixed-wing UAVs are advantageous in extremely cold environments or when long flight durations with wide-area coverage are necessary. Multi-copters, on the other hand, are preferred for their stability when carrying heavier or more sensitive sensors. This combination of UAV platforms and diverse sensors provides a flexible and effective approach to avalanche forecasting and risk management. In addition to sensor-specific characteristics, UAV operations can also be affected by environmental and weather conditions. For example, sub-zero temperatures can significantly reduce battery efficiency and flight endurance, while strong winds, rain, or fog may affect flight stability and the accuracy of sensors such as cameras and LiDAR. These environmental constraints should therefore be considered when deploying UAV-based sensing systems in real-world environments.

UAV Type	Sensor Type	Surface Condition	Layers	Volume	Depth	Cost
Multirotor	Electric Visual Camera	✓				Lower
Fixed Wing	Electric & Infrared	✓				Lower
Fixed Wing	Photogrammetry	✓	✓	✓		Higher
Octocopter	GPR	✓	✓	✓	✓	Higher
Hexacopter	LiDAR	✓	✓	✓		Costly

TABLE 1: Comparison of sensors used for avalanche monitoring

GPR, Ground-Penetrating Radar; LiDAR, Light Detection and Ranging; UAV, Unmanned Aerial Vehicle

Smart Agriculture

SA integrates modern technologies into traditional farming to enhance crop yield, addressing challenges such as rapid population growth, urbanization, and shrinking arable land. Conventional high-yield methods often rely on chemical inputs, which can harm the environment and contribute to climate change. SA offers solutions to monitor environmental toxins, optimize resource use, and reduce the negative impacts of agriculture on ecosystems [10,14-21].

RS plays a central role in SA by enabling crop monitoring, disease prevention, and environmental management using diverse sensors and data-processing devices [10]. For instance, computer vision-based systems are employed for disease detection and growth monitoring, often using Wi-Fi-enabled platforms like Arduino [14,15]. Environmental monitoring, such as irrigation control and soil management, relies on Narrowband (NB)-IoT, LoRa, Sigfox, NFC, and cellular networks with hardware platforms including Arduino and FORLINX OK6410 [16-18], as detailed in Table *2*.

Among the various low-power, wide-area network technologies, LoRa has gained significant adoption in UAV-assisted IoT RS, particularly in SA and environmental monitoring. This is primarily due to its operation in unlicensed spectrum, which enables low-cost and infrastructure-independent deployment in remote areas where cellular coverage is limited. Additionally, LoRa provides long-range communication with ultra-low power consumption, making it well-suited for energy-constrained IoT nodes and UAV-based data collection systems. Its compatibility with LoRaWAN gateways further enables flexible and scalable network deployment, including UAV-mounted gateways for data aggregation. In contrast, NB-IoT, while offering improved reliability and quality of service through licensed cellular infrastructure, is less suitable in infrastructure-scarce or rapidly deployable scenarios. Therefore, LoRa is generally preferred in rural and large-scale RS applications, whereas NB-IoT is more appropriate for urban environments with established cellular support.

Chemical analysis, including nitrate and nitrogen monitoring, is performed with IoT-enabled ZigBee sensors, while temperature, moisture, and humidity data for disease prevention are collected using cellular-connected devices such as ESP8266 [17,19]. Pest control applications leverage machine learning algorithms over cellular networks [20], and waste management monitoring - including humidity, temperature, and sunlight intensity - is handled using IoT gateways and Ethernet-connected Raspberry Pi platforms [21].

Area	Sensors/Data Collected	Domain/Application	Network Protocol	Hardware/Platform	Ref.
Crop Monitoring	Disease prevention	Computer Vision	Wi-Fi	Arduino	[14]
Growth	Growth measurement	Computer Vision	Wi-Fi	–	[15]
Environmental Monitoring	Irrigation control	NB-IoT/Sigfox/LoRa/NFC	Arduino	–	[16]
Luminosity	Light intensity	Internet of Things	Cellular	Arduino	[17]
Substrate Monitoring	Soil temperature and moisture	Artificial Intelligence	Cellular	FORLINX OK6410	[18]
Chemical Elements	Nitrate, nitrogen, and other chemicals	Internet of Things	ZigBee	Arduino	[17]
Disease Prevention	Temperature, moisture, and humidity	Computer Vision	Cellular	ESP8266	[19]
Pest Control	–	Machine Learning	Cellular	–	[20]
Waste Management	Humidity, temperature, sunlight intensity	Internet of Things/Gateway	Ethernet	Raspberry	[21]

TABLE 2: Comparison of state of the art for crop growth in smart farming

LoRa, Long Range; NFC, Near Field Communication; NB-IoT, Narrowband Internet of Things

UAVs further enhance SA by providing aerial support for tasks such as weed management, planting, spraying pesticides and fertilizers, disease and pest monitoring, and automated irrigation. UAVs can map fields, track spraying operations in real time, and assess crop ripeness, making farm management more precise and efficient. Wireless connectivity allows

UAVs to collect data from remote sensor nodes and transmit it to ground control stations, which then forward the information to cloud servers for analysis and decision-making. This UAV-assisted IoT framework supports decision support systems, enabling timely interventions in crop management, irrigation, fertilization, and pest control.

Despite these advantages, SA faces challenges including equipment maintenance, limited power resources, security and privacy concerns, and connectivity issues in remote areas. Solutions include deploying distributed UAV networks equipped with BLE, meshed LoRaWAN gateways, and satellite communication systems to overcome connectivity constraints, as shown in Figure *4*. This figure illustrates a UAV-assisted wireless sensor network architecture for SA. In this framework, distributed ground sensors collect environmental data such as soil moisture, temperature, and crop conditions, which are gathered by a UAV acting as a mobile gateway. The collected information is then transmitted to a ground control station or cloud platform for analysis and precision farming decision support.

Advanced approaches such as hyperspectral imaging enhance data accuracy, while dynamic planning algorithms and sensor calibration protocols reduce false detection probabilities, ensuring reliable monitoring and management in smart agricultural systems.

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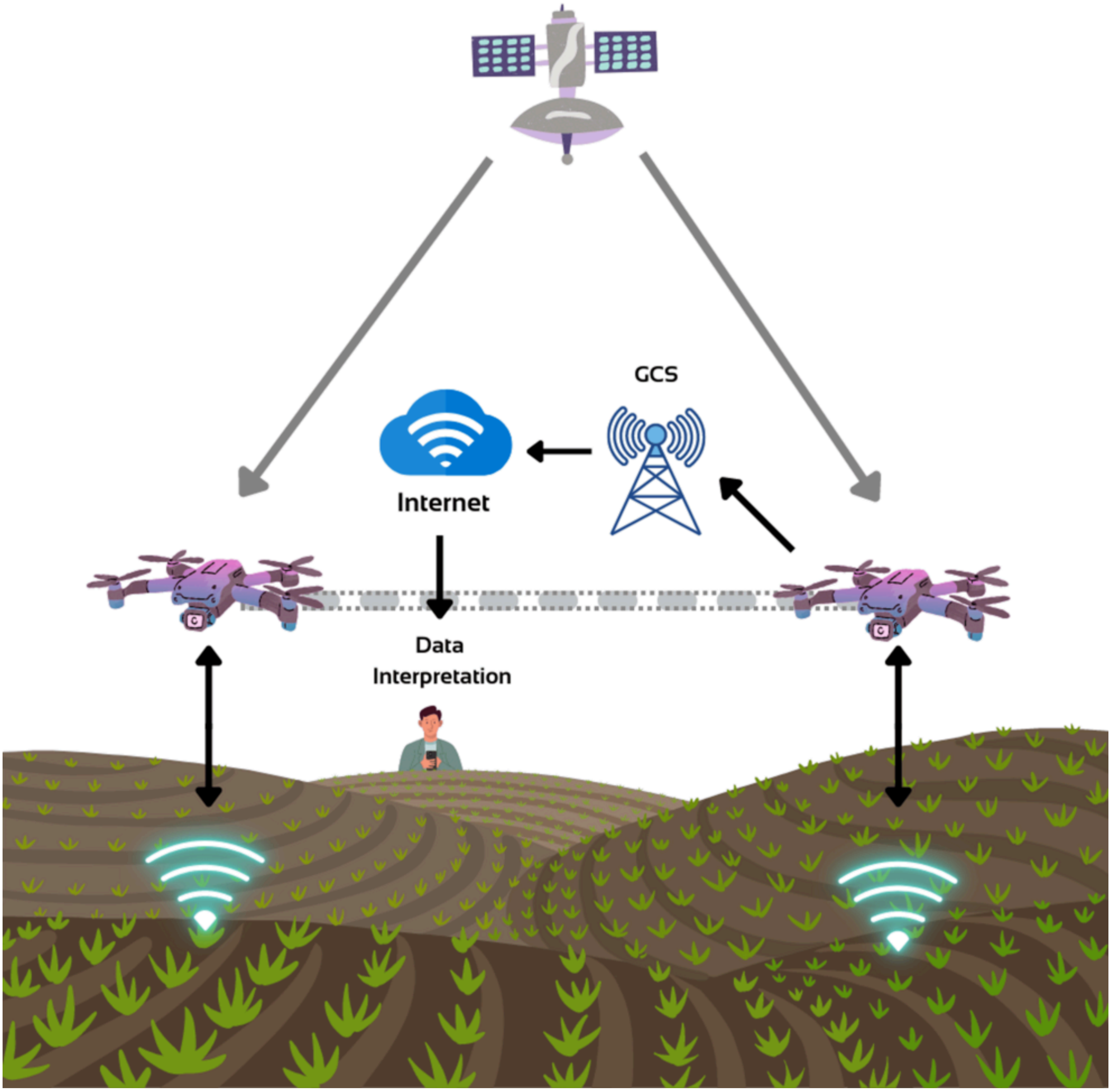

FIGURE 4: Agriculture monitoring using UAV WSN system

GCS, Ground Control Station; UAV, Unmanned Aerial Vehicle; WSN, Wireless Sensor Network

Smart Cities

An SC transforms traditional urban environments by integrating digital technologies to create innovative, efficient, and sustainable urban services that benefit both residents and businesses [11]. Data collected from a wide array of sensors, processed using IT algorithms and signal processing techniques, enables efficient city resource management. This data-driven approach informs decisions on infrastructure and services, enhancing urban operations and improving overall quality of life. SCs also provide enhanced security and safety systems [12], energy-efficient utilities, and sustainable resource management while reducing ICT costs and resource consumption. Furthermore, SC frameworks facilitate improved interactions between citizens and government institutions.

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Applications of SCs encompass various domains, including urban transportation networks, secure smart homes, efficient water supply management, enhanced waste disposal facilities, and energy-efficient lighting and heating systems. In all these scenarios, connected devices enable remote monitoring and management, ensuring effective resource utilization. Additionally, supply chain systems have demonstrated their effectiveness in disaster management, such as wildfire detection and control. UAVs, in combination with IoT systems, extend coverage to hard-to-reach areas, enabling UAV-based RS. Figure *5* illustrates how UAVs collect data from various IoT devices, which is then transmitted to a centralized node for real-time processing.

UAV-enabled RS applications within SCs are broad and diverse, including crowd surveillance, smart residences and commercial buildings, public safety enhancements, urban governance, intelligent educational institutions and workplaces, and advanced healthcare systems, as summarized in Table *3*. Crowd surveillance, for instance, relies on UAV-based RS and AI for real-time analysis of large volumes of data. Machine learning and deep learning algorithms are critical in processing unstructured data efficiently, enhancing the performance and oversight of UAV-IoT systems. The integration of AI with UAV-enabled IoT also ensures effective governance of the urban ecosystem, supporting both specialized applications and large-scale operations. Future developments aim to implement autonomous and intelligent UAV-IoT systems for supply chain applications, demonstrating the fusion of AI and big data analytics in SC evolution.

Application	UAV Type	Number of UAVs	Sensor	Objective	Ref.
Traffic monitoring	Rotary wing	Multiple	Camera	Minimize traffic congestion	[22]
Traffic monitoring	Rotary wing	Single	Camera	Improve road safety	[23]
Air pollution monitoring	Rotary wing	Single	LoRa based PM2.5	Reduce air pollution	[24]
Air pollution monitoring	Fixed wing	Single	PM (OPC-R1)	Used in public transport to obtain real-time PM data	[25]
Object/criminal detection or tracking	Rotary wing	Multiple	Camera	Monitoring	[26]
Object/criminal detection or tracking	Rotary wing	Single	Camera and Passive Infrared	Detect urban green areas with high accuracy	[27]

TABLE 3: Comparison of state of the art for smart cities

LoRa, Long Range; PM, Particulate Matter; UAV, Unmanned Aerial Vehicle

The deployment of UAVs for RS in SCs offers both cost and operational benefits. Their inherent reliability makes them ideal for geospatial analysis, land surveying, and GIS applications, reducing human labor requirements and overall costs. Multi-agent systems and M2M communication provide a robust framework for addressing challenges related to scalability and interoperability [11]. Limitations such as energy constraints and speed can be mitigated through in-flight recharging strategies or higher-altitude operations. Finally, reliability and communication failures are managed through adaptive fault-tolerant control designs, ensuring effective coordination between UAVs and ground control resources.

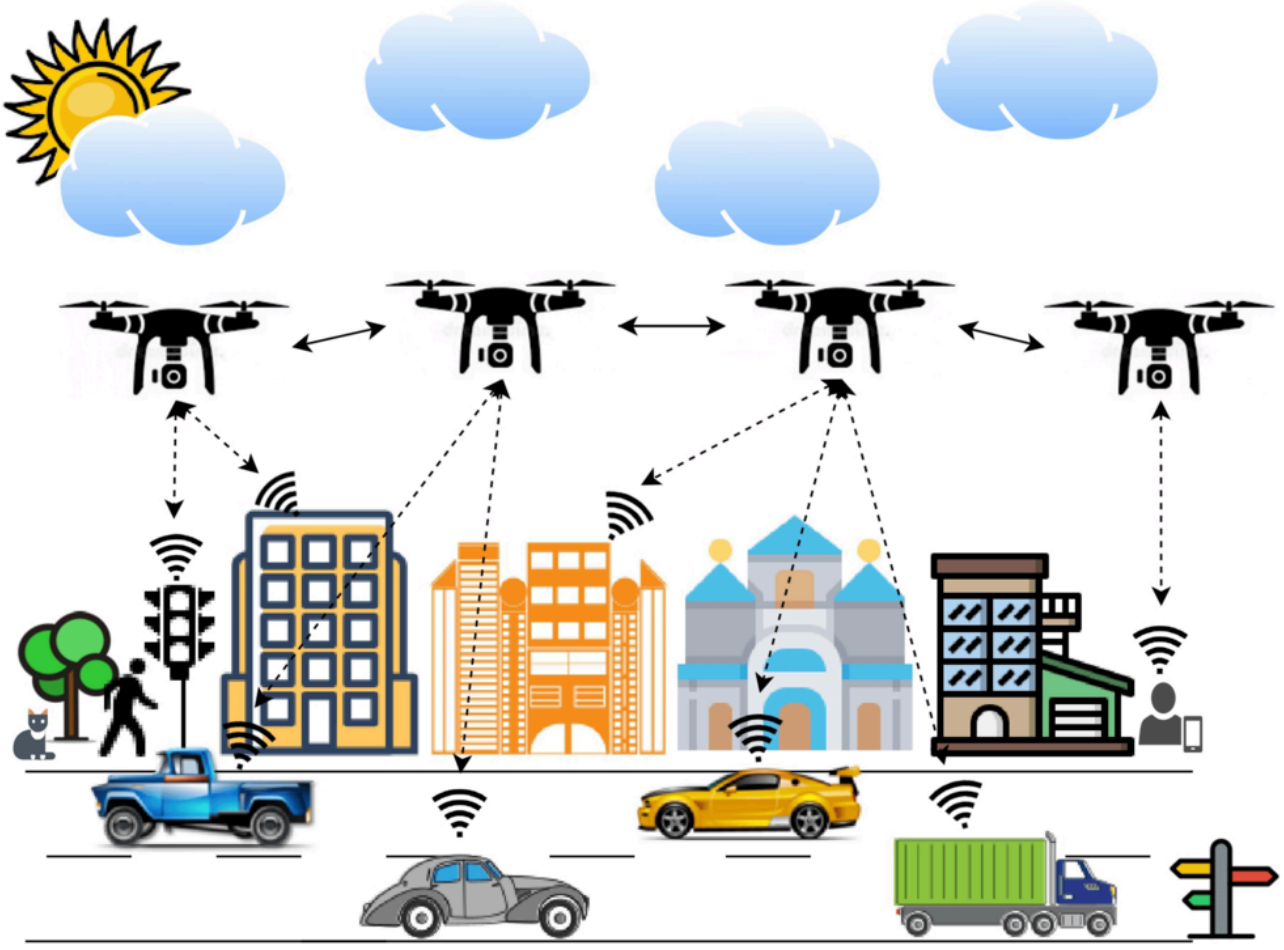

FIGURE 5: UAV-enabled smart cities

UAV, Unmanned Aerial Vehicle

Future SC development is moving toward autonomous UAV-IoT systems supported by AI and big-data analytics, especially in urban operations and supply-chain management. UAV-enabled RS offers several advantages, including reduced human labor, cost-effective geospatial analysis, land surveying, and broader GIS applications. Multi-agent frameworks and M2M communication enable scalable, interoperable platforms for SC environments. Challenges such as energy limitations and restricted flight speed can be addressed through mid-air recharging or higher-altitude operation [13]. Connectivity issues in remote or under-served regions can be improved using higher-frequency communication, LoRa-based long-range networks, and edge-cloud video processing. Reliability and fault tolerance are strengthened through adaptive, robust control mechanisms and efficient communication between UAVs and ground-control resources.

The range of UAV-assisted applications within SCs is broad, and the table highlights how different UAV types, sensor configurations, and mission objectives align with real urban needs, as shown in Table *3*. For example, RW UAVs equipped with cameras are used in traffic-monitoring studies to minimize congestion [22] or improve road safety [23]. Air pollution monitoring benefits from RW UAVs carrying LoRa-based PM2.5 sensors to support pollution reduction strategies [24], while FW UAVs carrying particulate-matter sensors provide real-time particulate matter data useful for public-transport planning [25]. In security-oriented applications, RW UAVs with multiple cameras assist with object or criminal detection through continuous monitoring [26]. RW platforms equipped with both visual cameras and passive infrared sensors have also been shown to accurately detect urban green areas [27].

Remote Health Monitoring

Advances in technology are transforming traditional healthcare systems into smart healthcare (SHC) frameworks that enable remote patient monitoring through wearable devices and implanted sensors. By integrating IoT, big data, AI, and blockchain-based solutions [6], SHC ensures secure, accessible, and effective care for patients, even during critical periods like the COVID-19 pandemic.

Electronic health record systems have evolved from basic digital repositories into “linked health” platforms, combining wireless sensor networks smartphones, mobile apps, and wireless technologies such as Bluetooth, Wi-Fi, and LTE. This approach provides a comprehensive record of a patient’s health history, including medications, vaccinations, test results, and ongoing diagnoses, which can be shared among multiple healthcare professionals to facilitate collaborative care while reducing the need for frequent hospital visits.

The Web of Things extends IoT capabilities, streamlining interactions among devices and integrating new data to support emergency response. IoT-driven solutions can incorporate patient information in emergency situations, improving response times and reducing mortality risks. Semantic and ontological frameworks allow extensive medical data exchange and processing, while indirect emergency healthcare infrastructures ensure continuous data availability. However, IoT ecosystems also face challenges, including interoperability, privacy, and data authenticity issues.

UAVs offer significant benefits to SHC-enabled RS networks, including real-time patient monitoring, data collection and analysis, alert generation, remote assistance, and support for research applications (Figure *6*).

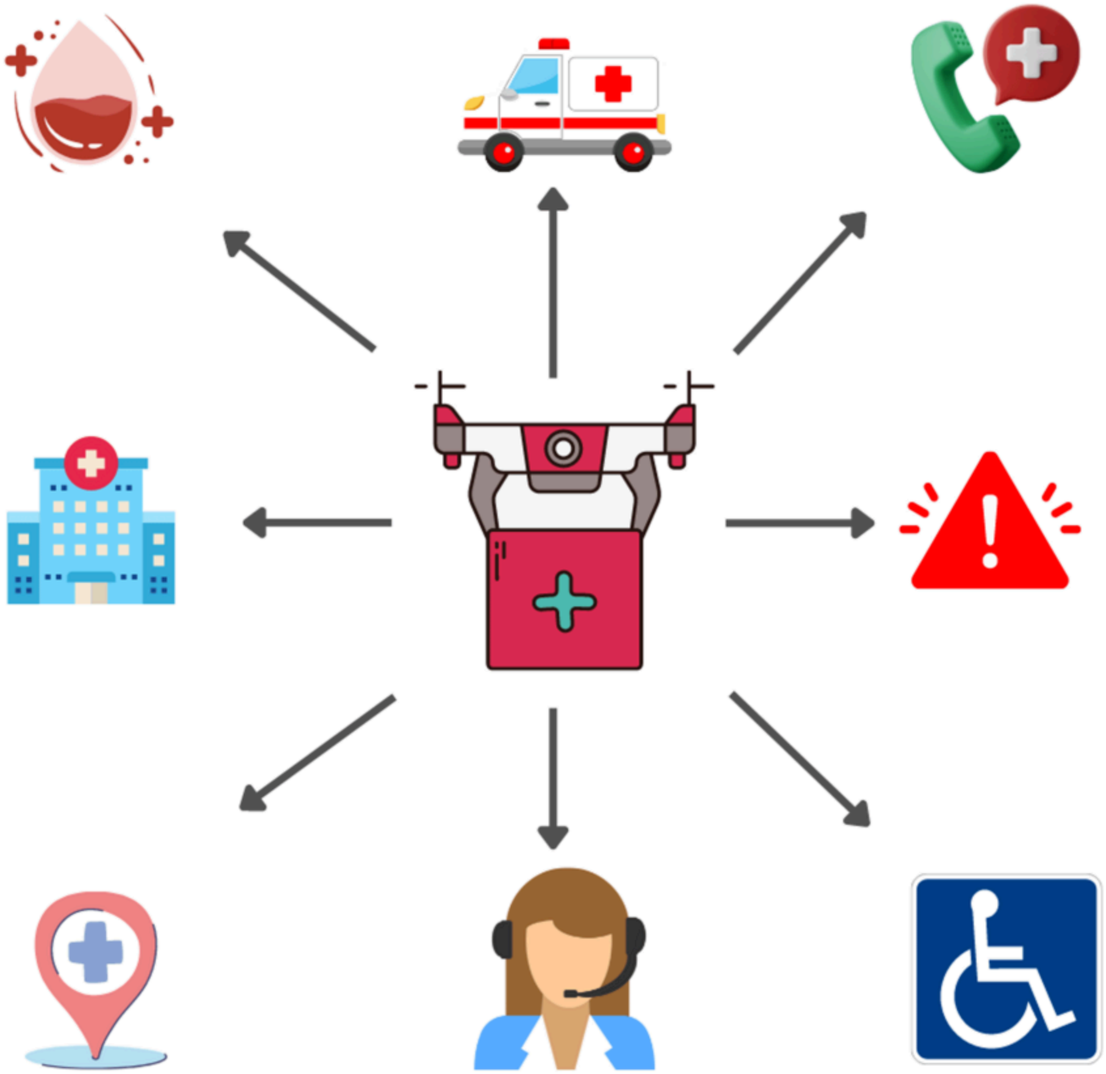

FIGURE 6: UAV-enabled IoT devices in smart healthcare

IoT, Internet of Thing; UAV, Unmanned Aerial Vehicle

Despite these advantages, data security and privacy remain critical concerns. Many IoT devices lack standardized data formats and compliance with data rights, making patient information vulnerable to cyberattacks. Unauthorized access can compromise pharmaceuticals, medical devices, and personal health information.

Beyond data privacy, UAV-enabled healthcare systems must address critical cyber-physical security challenges, particularly in securing the command-and-control (C2) communication links between UAVs and ground stations. These links are vulnerable to attacks such as jamming, which disrupts communication through signal interference, and spoofing, where malicious actors inject false signals (e.g., GPS spoofing) to mislead UAV navigation.

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To mitigate these risks, several technical solutions are employed. Encryption and authentication mechanisms ensure that only authorized entities can access and control UAV operations. Techniques such as frequency-hopping spread spectrum and adaptive channel selection improve resilience against jamming by dynamically varying communication frequencies.

In addition, sensor fusion-based validation, combining GPS data with inertial navigation systems, can detect inconsistencies caused by spoofing attacks. Machine learning-based anomaly detection methods are also increasingly used to identify abnormal communication patterns or control behaviors in real time.

These cyber-physical security mechanisms are essential for ensuring safe and reliable UAV operation, particularly in healthcare scenarios where system failures or malicious interference can have critical consequences.

As shown in Table *4*, current research spans multiple wearable form factors and technologies tailored to different medical and monitoring needs. Head-mounted wearables such as wireless headphones have been used for stress and cardiovascular monitoring, with a focus on improving energy efficiency through Bluetooth-based signal-processing methods [28]. Smart-eyewear systems contribute to cost-effective location tracking, especially for Alzheimer's patients, using Wi-Fi networks and machine learning models to improve safety and mobility support [29].

Skin-based wearables, including electronic tattoos, enable out-of-hospital patient monitoring for chronic pain management by relying on Bluetooth connectivity and machine learning algorithms for continuous assessment [30]. Patch-type sensor devices offer a cost-effective solution for real-time patient monitoring using RFID technology and lightweight signal-processing techniques [31]. Handheld wearables, particularly wristwatches, provide cloud-connected tracking and heart-rate-variability analysis using AI approaches over Bluetooth networks [32]. Wristband-based systems further support low-power, multi-parameter monitoring of heart rate, electroencephalogram, electrocardiogram, and pulse oxygen levels, typically using ZigBee-enabled signal-processing algorithms for reliable long-term operation [33].

Together, these technologies highlight the growing integration of BAN-based health monitoring into broader SC ecosystems, where UAVs, IoT platforms, and wearable sensors collectively enhance situational awareness, emergency response, and personalized healthcare delivery.

Technology Type	Device Type	Research Problem Addressed	Objective	Network Protocol	Algorithm Used	Ref.
Head-Mounted Wearable	Wireless Headphones	Energy efficiency	Stress monitoring, cardiovascular health	Bluetooth	Signal Processing	[28]
	Smart Eyewear	Cost-effective location tracking	Monitoring Alzheimer's patients	Wi-Fi	Machine Learning	[29]
Skin-Based Wearable	E-Tattoo	Out-of-hospital patient monitoring	Chronic pain relief	Bluetooth	Machine Learning	[30]
Sensor Patches	Patch Device	Cost-effective sensing	Real-time patient monitoring	RFID	Signal Processing	[31]
Handheld Wearable	Wristwatch	Cost-effective sensing	Cloud-based tracking, heart rate variability	Bluetooth	Artificial Intelligence	[32]
Wristband	Wristband Device	Low power consumption	Heart rate tracking, pulse oximeter, EEG tracker, ECG tracker	ZigBee	Signal Processing	[33]

TABLE 4: Comparison of state of the art for smart healthcare

EEG, Electroencephalogram; ECG, Electrocardiogram; RFID, Radio-Frequency Identification; UAV, Unmanned Aerial Vehicle

The IoT streamlines the delivery of urgent medical supplies by drawing on data collected from bionic sensors and physiological monitoring systems. This leads to faster, more efficient, and more cost-effective distribution. UAVs further strengthen this system by transporting medicines, blood units, and essential medical tools directly to hospitals, ambulances, and high-risk or remote locations. When UAVs are integrated into SHC infrastructures, both access to treatment and emergency response times improve significantly.

Search and Rescue

Search and rescue is a critical, time-sensitive application of RS, often operating in challenging and inaccessible areas. UAVs play a crucial role in SAR by quickly reaching remote locations, providing real-time aerial imagery, and enabling rapid decision-making for emergency response. In addition to surveying disaster sites, UAVs assist in assessing the scale of the disaster, estimating necessary medical supplies, life-saving equipment, and food for affected populations. Beyond disaster response, UAVs deployed for aerial surveillance, border monitoring, anti-poaching, and maritime surveillance can provide immediate alerts, supporting SAR operations and preventing illegal activities.

Integrating IoT with UAV-based SAR enhances operational efficiency through real-time data collection, communication, and automation [26]. Key IoT-enabled functionalities in SAR include:

Smart Sensors: Deployed on UAVs, rescue personnel, or disaster-prone locations, these sensors provide real-time environmental data, including temperature and weather conditions.

Location Tracking: IoT devices enable continuous tracking of both rescuers and victims, improving coordination and response times.

Remote Control: UAVs and robotic rescue equipment can be operated remotely, ensuring safer and more efficient missions.

Predictive Maintenance: IoT systems forecast maintenance needs for SAR equipment, ensuring vehicles and UAVs remain operational.

Communication: IoT-enabled networks facilitate seamless communication between rescue teams for coordinated action.

During disaster situations, UAVs play a critical role in locating survivors and delivering support, particularly in areas where conventional communication infrastructure is unavailable or damaged. The use of multi-UAV systems enables coordinated search and rescue operations, where centralized task allocation and scheduling strategies improve efficiency and reduce communication delays. Various transportation and routing approaches have been developed for UAV networks to minimize energy consumption and latency, making them suitable for time-critical disaster recovery missions. In addition, UAV-assisted evacuation guidance systems can analyze real-time disaster conditions to identify and recommend optimal escape routes for affected populations.

UAVs offer wide-area coverage and rapid real-time data collection through onboard sensors such as cameras and thermal imaging devices. Thermal sensors are especially effective in detecting survivors in low-visibility conditions, including darkness, smoke, or hazardous environments. Fixed-wing UAVs equipped with imaging systems have been successfully deployed in offshore search and rescue operations, where they complement manned helicopters and help reduce risks to human personnel. These UAVs can be programmed with specialized algorithms to monitor helicopter movements while ensuring continuous surveillance of the ground area.

The Integrated Components for Assisted Rescue and Unmanned Search (ICARUS) system, developed by the Royal Military Academy of Belgium, demonstrates the effective use of UAVs in marine search and rescue operations. By integrating GPS coordinates with real-time aerial imagery, ICARUS provides rescuers with enhanced situational awareness, including terrain conditions, victim locations, and potential environmental hazards. This integrated information supports safer navigation and more effective mission planning during complex rescue scenarios.

Recent research has increasingly emphasized the role of unmanned systems and UAV-assisted SAR operations in crisis management and emergency response. The OPARUS system established an open architectural framework for UAV-based surveillance, enabling large-scale air-to-ground monitoring and improving coordination in SAR missions [34]. The AIROBOTS system focused on the development of flexible and reconfigurable UAV platforms capable of close-contact inspections, which are particularly useful for emergency infrastructure assessment in hazardous environments [35].

The DARIUS system introduced an integrated and deployable SAR chain using unmanned systems for marine, urban, and forest fire scenarios, allowing rapid and coordinated response in diverse operational conditions [36]. AIRBEAM further enhanced emergency response capabilities by combining UAV-mounted sensors with satellite systems to support real-time monitoring and situational awareness during crisis situations [37]. CRISMA contributed to improved disaster preparedness and response by providing crisis modeling and RS tools to support humanitarian organizations in assessing long-term structural and economic impacts of disasters [38].

Additional advancements were achieved through the DITSEF system, which improved first responder efficiency by enabling real-time data collection, sharing, and visualization during emergency operations [39]. The CLOSE-SEARCH system addressed navigation challenges in UAV-based SAR missions by employing EGNOS-supported positioning and thermal imaging, enabling accurate and low-cost rescue operations in remote or restricted-access areas [40]. A comparative summary of these UAV-based research initiatives is presented in Table *5*.

System Name	Scope/Year	Impact on UAVs/SAR Operations	Ref
OPARUS (Open Architecture for UAV-based Surveillance System)	FP7-SEC-2009	Established a framework for unmanned air-to-ground monitoring over large regional areas in Europe, enhancing SAR coordination.	[34]
AIROBOTS (Innovative Aerial Service Robots for Remote In-Inspections by Contact)	FP7-ICT-2015	Developed expandable and flexible UAV test models for inspection and remote monitoring.	[35]
DARIUS (Deployable SAR Integrated Chain with Unmanned Systems)	FP7-SEC-2016	Designed for marine, urban, and forest fire SAR operations, enabling rapid deployment in diverse scenarios.	[36]
AIRBEAM (AIRborne Information for Emergency Awareness and Monitoring)	FP7-SEC-2017	Combined UAV-mounted sensors and satellites to support crisis management and emergency response.	[37]
CRISMA (Modeling Crisis Management for Improved Action and Preparedness)	FP7-SEC-2018	Assisted NGOs and humanitarian organizations by providing remote sensing for areas affected by long-term disasters with structural and economic impacts.	[38]
DITSEF (Digital & Innovative Technologies for Security & Efficiency of First Responder Operations)	FP7-ICT-SEC-2019	Enhanced first responder efficiency by collecting and sharing critical situational data in real time.	[39]
CLOSE-SEARCH (Accurate and Safe EGNOS-SoL Navigation for UAV-Based Low-Cost SAR Operations)	FP7-Galileo-2020	Supported SAR missions in remote or restricted-access areas using thermal imaging and sensor-based UAVs for timely response.	[40]

TABLE 5: Summary of UAV-based systems and search and rescue domain

SAR, Synthetic Aperture Radar; UAV, Unmanned Aerial Vehicle

Infrastructure Monitoring

Infrastructure development covers systems such as bridges, roads, ports, dams, and other civil works. Monitoring these infrastructures is crucial for tracking system progress, ensuring quality, and gathering information for planning and management. RS enables continuous monitoring across different system phases. However, acquiring data for infrastructure systems is challenging due to their large scale and, in many cases, inaccessible terrain where manual inspection is difficult or impossible [7].

RS in infrastructure monitoring involves gathering, managing, and analyzing information about people, activities, and physical assets, including buildings, roads, and other infrastructure components. Techniques commonly used include camera-based surveillance, GPS tracking, radio monitoring, and biometric sensing. Traditional inspection approaches are often labor-intensive, repetitive, costly, and limited in their ability to access hard-to-reach or hazardous locations.

The use of UAVs in infrastructure monitoring has become increasingly practical due to advancements in computer vision, sensor technologies, and aerial platforms. UAVs provide stable, efficient, and flexible support for on-site monitoring, fault detection, and structural inspections. Several UAV applications in this domain demonstrate their versatility and effectiveness.

In such inspection tasks, machine learning serves as an enabling layer for intelligent interpretation of UAV-collected data rather than a standalone component. Recent approaches increasingly rely on deep learning-based semantic segmentation architectures to achieve pixel-level identification of structural defects such as cracks, corrosion, and surface degradation. Common models include Fully Convolutional Networks, U-Net, and DeepLab variants, which are well-suited for analyzing high-resolution aerial imagery.

To evaluate the performance of these models, the Intersection over Union (IoU) metric is widely used. IoU measures the overlap between predicted defect regions and ground truth annotations, providing a quantitative assessment of detection accuracy. The integration of semantic segmentation with IoU-based evaluation enables more reliable, automated, and scalable infrastructure monitoring using UAV systems.

Inspection of construction sites: UAVs provide a safe and efficient solution for inspecting construction sites and complex structures such as bridges. Equipped with high-resolution cameras, thermal imaging systems, and LiDAR sensors, they capture detailed visual data and precise geometric measurements for structural assessment.

In such applications, a key technical consideration is the trade-off between Structure from Motion (SfM) techniques and LiDAR-based point cloud generation. SfM reconstructs 3D structures using multiple overlapping images acquired from cameras, offering a cost-effective approach with rich texture and visual detail. However, its performance is sensitive to lighting conditions, surface texture, and image quality, which can affect reconstruction accuracy and consistency.

In contrast, LiDAR systems directly measure distances using laser pulses, producing highly accurate and geometrically consistent point clouds. Two critical performance metrics in this context are point cloud density and registration accuracy. Point cloud density determines the level of structural detail captured, which is essential for detecting fine defects such as cracks and deformations. Registration accuracy reflects how precisely multiple scans or datasets are aligned, directly influencing the reliability of structural analysis.

While LiDAR provides superior geometric accuracy and robustness, it typically involves higher cost, increased payload requirements, and greater energy consumption. SfM, on the other hand, remains a lightweight and cost-efficient alternative but often requires additional processing and calibration to achieve comparable accuracy. As a result, hybrid approaches that combine SfM and LiDAR data are increasingly being explored to balance accuracy, cost, and operational efficiency.

Using these sensing and reconstruction techniques, engineers can identify structural issues such as cracks, corrosion, and deformations with high precision. UAVs can access areas that are difficult or hazardous for human inspectors, including the undersides of bridge decks, tall piers, and elevated frameworks. Furthermore, UAV-based inspections are faster and can be conducted more frequently than traditional methods, enabling early detection of potential failures and supporting timely maintenance and repair.

Land survey: UAVs are highly effective for surveying land and infrastructure, providing accurate and detailed data for planning and construction. Equipped with high-resolution cameras, LiDAR, and other sensors, UAVs can capture images and measurements used to generate up-to-date maps and 3D models.

Key applications include:

Planning and Design: UAV data helps create detailed topographical maps and models for roads, bridges, buildings, and other systems.

Site Preparation and Excavation: UAV surveys identify underground utilities, drainage systems, and other critical infrastructure for safe and efficient site preparation.

System Progress Monitoring: UAVs can regularly capture site images and data, enabling continuous monitoring and early detection of potential issues.

Volume Calculation: UAVs provide precise measurements of stockpiles, quarries, and excavation sites for material volume estimation.

Using UAVs reduces the need for human surveyors, saving time and cost while increasing accuracy and coverage. For large-scale systems, multiple UAVs can operate in coordination, monitoring different components or overlapping areas to provide a comprehensive view of the site, as illustrated in Figure *7*.

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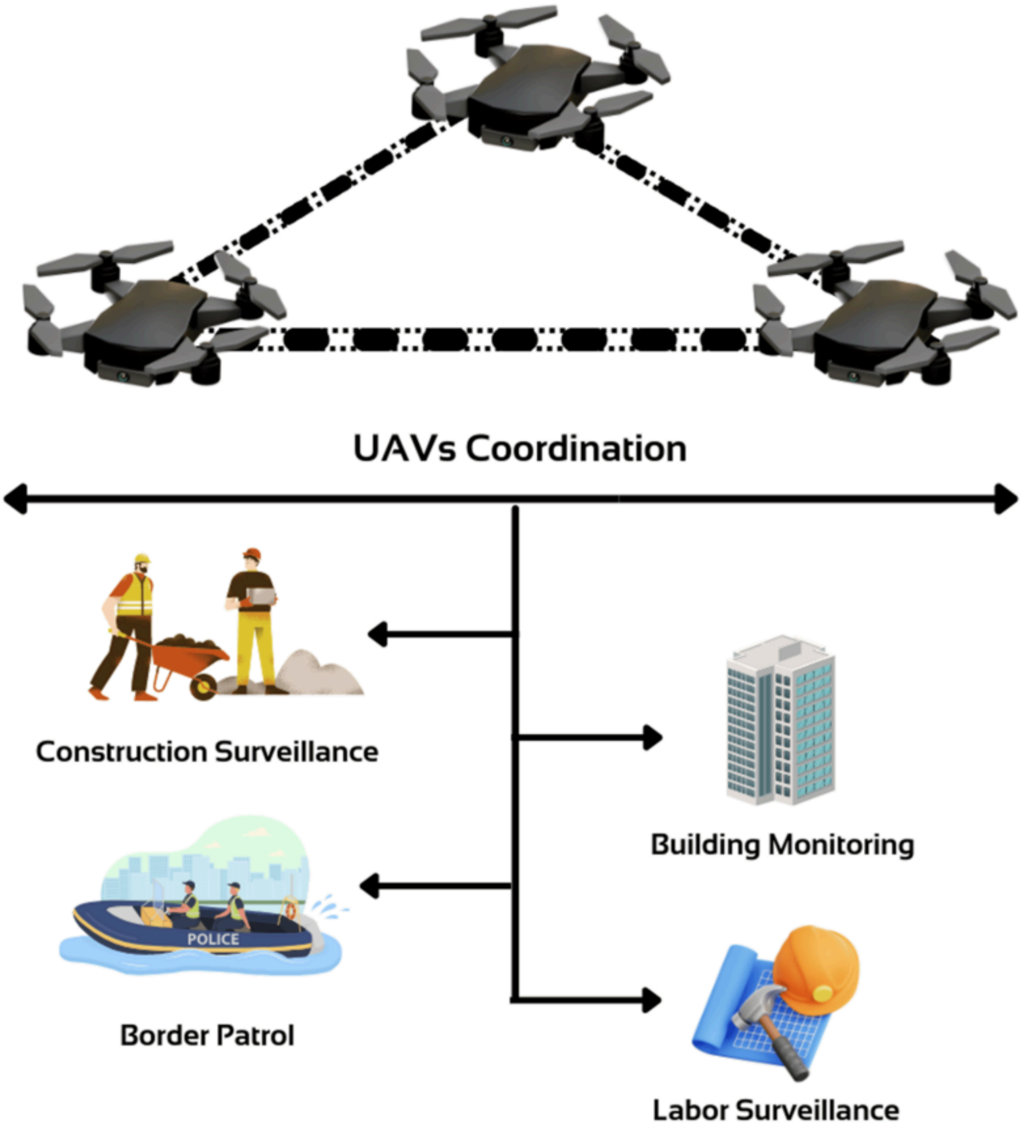

FIGURE 7: UAV-enabled infrastructure monitoring

UAV, Unmanned Aerial Vehicle

Assessing the condition of roads, railways, and pipelines: UAVs provide an efficient and economical solution for assessing the condition of roads, railways, and pipeline infrastructure. Their ability to conduct aerial inspections enables rapid data collection over large and complex areas, supporting comprehensive infrastructure health monitoring. UAV-based inspections serve several key functions, including the detection of surface and structural defects such as cracks, potholes, erosion, subsidence in transportation networks, and leaks or corrosion in pipeline systems.

Routine UAV surveys facilitate continuous condition monitoring by capturing temporal changes in infrastructure assets. This longitudinal data enables early identification of degradation trends, allowing timely intervention before failures occur. Furthermore, UAV-acquired imagery and sensor data support informed planning of repair and maintenance

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activities by accurately identifying defect locations, severity levels, and maintenance priorities. This targeted approach improves maintenance efficiency while reducing operational costs.

UAVs also significantly enhance inspection safety by accessing hazardous or hard-to-reach areas, such as elevated bridges, railway understructures, and remote pipeline corridors, thereby minimizing exposure risks for human inspectors. When equipped with advanced sensing technologies, including thermal cameras, gas sensors, and hyperspectral imaging systems, UAVs can deliver detailed insights into pipeline networks and water distribution systems. Thermal sensors reveal abnormal temperature patterns associated with leaks, gas sensors detect escaping or accumulated gases, and hyperspectral imaging identifies chemical variations that may indicate contamination or structural deterioration. The collected data can be processed using cloud-based platforms, computer vision algorithms, and machine learning techniques to enable near real-time analysis and decision support.

Inspection and Maintenance of Smart Grids and Energy Sources

The growing global demand for reliable and sustainable energy has intensified the need for efficient energy management and infrastructure optimization. Power shortages, increasing consumption, and the transition toward renewable energy sources necessitate advanced monitoring and control strategies. Effective management of conventional energy assets, along with the integration of renewable sources such as solar, wind, and hydroelectric power, plays a critical role in ensuring system reliability and sustainability.

Energy efficiency measures, including the use of energy-efficient appliances, improved insulation, and routine system inspections, contribute to reduced energy losses and enhanced operational performance. Smart grids provide a flexible and adaptive framework for managing modern energy systems by incorporating secure communication, automation, and real-time monitoring technologies. These capabilities enable smart grids to accommodate fluctuating energy demands while supporting the integration of distributed and renewable energy sources.

Traditional manual inspection methods for energy infrastructure involve significant safety risks, particularly in high-voltage environments, and often lack accuracy when applied to large-scale networks. The integration of UAVs and IoT technologies offers a safer, more precise, and efficient alternative by enabling RS, continuous monitoring, and predictive analytics.

UAVs in energy management: UAVs equipped with high-resolution cameras, sensors, and LiDAR systems have transformed the surveillance and monitoring of energy infrastructure. Their ability to autonomously cover large areas with high accuracy makes them well suited for a variety of energy management applications.

One primary application is asset inspection and maintenance. UAVs can inspect power transmission lines, substations, wind turbines, and solar panels to identify defects, thermal hotspots, structural damage, and potential safety hazards. Early detection of such issues supports proactive maintenance strategies, reducing system downtime and operational risks.

UAVs also support RS by collecting environmental data, such as solar irradiance levels, temperature, and weather conditions. This information is valuable for optimizing energy generation and forecasting power output, particularly in solar and wind energy systems. Additionally, UAVs play a critical role in emergency response scenarios by rapidly assessing damage caused by natural disasters or system failures, identifying critical fault locations, and supporting timely restoration efforts to enhance grid resilience.

IoT in energy management: IoT technologies enhance energy management through the deployment of interconnected sensors and embedded devices that enable real-time monitoring, communication, and control across energy systems. One of the most significant applications of IoT is smart metering, where intelligent meters continuously track energy consumption, demand patterns, and grid performance. This data supports demand forecasting, load balancing, and demand-response programs aimed at optimizing energy usage.

Distributed IoT sensors also facilitate grid monitoring and control by continuously measuring voltage levels, equipment health, and environmental conditions. These measurements enable predictive maintenance and automated control actions, improving grid reliability, stability, and operational efficiency. In addition, IoT devices deployed in buildings, hospitals, industrial facilities, and residential environments monitor energy usage at the device level, enabling automated energy-saving actions that reduce waste and operational costs.

Predictive maintenance is another key benefit of IoT-based energy management. Sensors installed on solar panels, inverters, transformers, and other critical components detect anomalies and early signs of failure. Data-driven analytics allow maintenance activities to be scheduled proactively, extending equipment lifespan and maximizing energy production.

Integration of UAVs and IoT

The integration of UAVs with IoT technologies enables advanced monitoring and management capabilities for energy and infrastructure systems. UAVs equipped with IoT sensors and communication modules can perform aerial inspections while transmitting real-time data to centralized platforms for analysis and visualization. This integration supports autonomous monitoring, faster decision-making, and proactive maintenance strategies.

The seamless integration of UAVs within IoT frameworks is enabled by lightweight and efficient communication protocols designed for resource-constrained environments. Among these, Message Queuing Telemetry Transport and Constrained Application Protocol are widely adopted in UAV-IoT systems.

Message Queuing Telemetry Transport operates on a publish-subscribe model, allowing UAVs and IoT devices to exchange data through a broker with minimal communication overhead. This makes it particularly suitable for real-time monitoring applications where efficient data dissemination is required. In contrast, Constrained Application Protocol follows a request-response architecture optimized for low-power devices and constrained networks, enabling direct and lightweight communication between nodes.

These protocols support reliable and low-latency data transmission while minimizing bandwidth and energy consumption, thereby facilitating scalable and efficient integration of UAV platforms with distributed IoT sensor networks.

For example, IoT sensors deployed in solar power plants can identify abnormal temperature variations in photovoltaic panels, triggering UAV-based thermal inspections to pinpoint inefficiencies or faults. Data collected from both UAVs and IoT devices can be fused within energy management platforms to provide comprehensive insights into energy production, consumption patterns, grid performance, and asset health [41]. The combined use of UAVs and IoT technologies enhances operational efficiency, resource utilization, system reliability, and sustainability in smart energy systems.

Data security and integrity

Ensuring data security and integrity is essential in UAV-based monitoring networks. Blockchain technology provides a robust framework for securing UAV data through decentralized and tamper-resistant mechanisms.

While blockchain provides strong guarantees for data integrity and secure data sharing, its practical implementation in UAV-enabled IoT systems is constrained by the limited computational resources and energy capacity of UAV platforms. Traditional consensus mechanisms such as Proof of Work are computationally intensive and require significant processing power and energy, making them unsuitable for resource-constrained aerial systems.

To address this limitation, recent research has focused on lightweight consensus mechanisms that reduce computational overhead while maintaining security. Approaches such as Proof of Stake, Delegated Proof of Stake, and Practical Byzantine Fault Tolerance offer lower latency, reduced energy consumption, and improved scalability compared to Proof of Work-based systems. Additionally, hybrid and permissioned blockchain models are being explored to further optimize performance in UAV-IoT environments.

These lightweight approaches enable the integration of blockchain-based security frameworks in UAV-assisted RS systems without exceeding resource constraints, making them more suitable for real-time and large-scale deployments.

Decentralized Data Integrity

Blockchain employs a distributed ledger that stores UAV-generated data across multiple nodes, eliminating dependence on a centralized server. This decentralized architecture enhances system resilience and prevents single points of failure, particularly in remote or hostile environments.

Immutable Data Storage

Once data such as sensor readings, flight logs, or control commands are recorded on the blockchain, they cannot be altered. Each block is cryptographically linked to the previous one, creating a reliable and verifiable historical record.

Decentralized Control

By distributing control and data validation across network participants, blockchain significantly increases resistance to cyberattacks. Compromising the system would require control over a majority of network nodes, which is computationally and practically challenging.

Data Verification and Consensus

Consensus mechanisms ensure that only verified and authentic UAV data is added to the blockchain. This prevents malicious data injection and maintains trust in the monitoring system.

Secure Data Sharing

Blockchain enables secure and encrypted data exchange among multiple UAVs and ground stations. Participants can verify data authenticity without exposing the system to unauthorized modifications.

Smart Contracts for Automation and Access Control

Smart contracts automate data access, validation, and compliance rules, reducing the need for centralized oversight while improving operational efficiency and security.

Auditability and Traceability

Blockchain maintains a complete and traceable history of UAV operations, enabling operators to track data origin, collection times, and transfer paths. This enhances accountability and supports effective incident investigation.

Limitations, challenges, and open issues

Despite significant advancements in UAV-enabled RS within IoT ecosystems, several limitations and challenges continue to exist in current research and practical implementations. This section summarizes key issues identified in the literature while also highlighting corresponding future research directions to address these challenges. The discussion covers power constraints, communication reliability, data processing complexity, multi-modal data integration, security concerns, and scalability issues in large-scale deployments.

Integration of Digital Twins

Digital twin technology enables the creation of real-time virtual representations of UAVs, reflecting their physical state, behavior, and environmental interactions. This approach supports predictive maintenance, performance optimization, and operational safety. However, current implementations are limited by high computational complexity and the lack of lightweight models suitable for UAV platforms.

Future Direction: Future research should focus on developing lightweight and online machine learning models for digital twin systems that can operate efficiently on resource-constrained UAVs. Real-time synchronization between physical UAVs and their digital counterparts remains an open challenge.

Power Limitations

UAVs are constrained by limited battery capacity, necessitating efficient flight planning, energy-aware routing, and effective recharging strategies. Similarly, RS sensors often operate under strict power limitations, although solar-powered sensor deployments offer improved energy availability.

Future Direction: Promising directions include energy-efficient UAV design, wireless power transfer, and AI-driven trajectory optimization. Hybrid energy solutions and in-flight charging mechanisms require further investigation.

Coordination and Flight Planning

Swarm-based UAV operations require advanced coordination and route optimization techniques. Challenges include navigating unknown environments, avoiding dynamic obstacles, and preventing collisions in real time. Reliable large-scale coordination remains difficult.

Future Direction: Future work should emphasize distributed, intelligent coordination algorithms, including reinforcement learning-based swarm control and fault-tolerant multi-UAV systems [42].

Multi-Modal Data Fusion

Modern UAV-based RS systems increasingly rely on multi-modal sensor fusion, combining data from LiDAR, optical cameras, thermal sensors, and IoT devices to improve accuracy and situational awareness. However, integrating heterogeneous data sources in real time remains a major challenge due to differences in data formats, resolutions, sampling rates, and sensor alignment requirements. Additionally, fusion algorithms are often computationally intensive, making real-time implementation difficult on resource-constrained UAV platforms [43,44].

Future Direction: Future research should focus on efficient and scalable fusion frameworks, including deep learning-based fusion models and edge-assisted processing techniques. Developing low-latency, real-time fusion algorithms and standardized data integration pipelines will be critical for enabling practical deployment of multi-modal UAV sensing systems.

Privacy and Security

UAV systems are vulnerable to cybersecurity threats due to open communication channels and frequent interaction with ground stations. Privacy concerns also arise when UAVs operate over sensitive areas.

Future Direction: There is a need for lightweight and robust security frameworks, including blockchain-based solutions, secure communication protocols, and privacy-preserving machine learning techniques.

Sensor Environment and Safety

UAV sensors must function reliably under extreme environmental conditions, including harsh weather and hazardous terrains. Maintaining accuracy and reliability under such conditions is challenging.

Future Direction: Future work should explore adaptive sensing systems, robust calibration techniques, and intelligent fault detection mechanisms to ensure reliable operation.

Big Data and Communication

RS applications generate large volumes of data, creating challenges in storage, processing, and transmission. UAV mobility introduces PHY-layer issues such as Doppler shifts, carrier frequency offsets, and reduced channel coherence time. Frequent handovers further increase latency and signaling overhead.

Future Direction: Future research should focus on AI-driven data management, edge computing integration, and mobility-aware communication protocols. Advanced techniques such as adaptive beamforming and predictive handover strategies are essential.

Meteorological Conditions and Accidents

Adverse weather conditions such as strong winds, heavy rainfall, and fog negatively impact UAV stability, sensor accuracy, and flight safety.

Future Direction: Developing weather-resilient UAV systems, real-time environmental awareness models, and adaptive flight control strategies is essential for safe and reliable operation.

Conclusions

The integration of UAVs with RS technologies provides an effective solution to meet the growing demand for data acquisition in IoT applications. UAV-RS enhances traditional sensing platforms by offering superior mobility, flexible deployment, and efficient data collection. Despite ongoing advancements, several challenges - such as regulatory restrictions, data privacy issues, and the need for scalable infrastructure - remain unresolved. However, the continued development of AI and machine learning algorithms, coupled with improved sensor technologies for autonomous UAV operations, positions UAV-RS as a highly promising approach for future IoT applications. This work also highlights the key challenges and limitations that practitioners, researchers, and policymakers must address to fully leverage the potential of UAVs within IoT ecosystems.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Acquisition, analysis, or interpretation of data: Farzana Kulsoom , Hassan Nazeer Chaudhry, Farzana Arshad, Zahid Mehmood

Critical review of the manuscript for important intellectual content: Farzana Kulsoom , Hassan Nazeer Chaudhry, Farzana Arshad, Zahid Mehmood

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