A SURVEY ON THE USE OF DRONE TECHNOLOGY IN ADVANCING SUSTAINABLE CONSTRUCTION PRACTICES

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Abstract

The integration of drone technology in the construction industry has revolutionized traditional practices, enhancing efficiency, sustainability, and safety. Data collection, surveying, and site monitoring have all been transformed by the use of drones in the construction sector. The research examines various UAV technologies, including sensor-equipped drones, 5G connectivity, and IoT integration, to improve data acquisition and processing. Key challenges such as regulatory limitations, technical constraints, and data security are discussed alongside potential solutions, including cloud computing and AI-driven analytics. The findings highlight how UAV-based systems optimize resource management, reduce operational costs, and provide enhanced visualization for project stakeholders. Creating energy-efficient UAVs, enhancing wireless communication protocols, and using AI for sophisticated site analysis are some future research avenues. The study concludes that UAV technology is a transformative tool that significantly contributes to the modernization in the construction industry.

Keywords: Aerial Imaging, Artificial Intelligence, Autonomous Drones, Construction, Machine Learning, Safety Assessment, sensor, Unmanned aerial vehicles.

1 Introduction

Unmanned aerial vehicles (UAVs), also referred to as drones, have become increasingly popular in a variety of sectors and uses in recent years [1]. Drones can be programmed or operated remotely to take pictures of scenes from a distance. This method is economical and doesn't require skilled workers. Drones are widely used in many different fields, such as security surveillance [2], search and rescue operations [3], geographic surveying [4], industrial and infrastructure inspection [5], agricultural and environmental monitoring [5], and many more.

Advanced sensors such as visible cameras, infrared thermal imaging, GPS (Global Positioning System) technology, light detection and ranging (Li-DAR), synthetic aperture radar (SAR), and multi-spectral imaging can be installed on unmanned aerial vehicles [6]. These transportable aerial imaging devices offer useful information for real-time monitoring, research, and development in a variety of industries. Drones operate in a more dynamic and resource-constrained environment than fixed and ground-based sensors, which poses special issues. However, the ability to take high-resolution photos, create precise 3D models, and perform remote inspections improves project coordination, streamlines processes, and reduces risks. This is especially true in the construction and infrastructure management industries, where full use of drone-acquired data intelligence analysis is essential to producing better operational outcomes and effective decision making [2].

According to [7], unmanned aerial vehicles have rapidly evolved from novelty to indispensable instruments in the construction sector. Construction professionals can streamline their operations, promote cooperative project teamwork, and lower potential dangers by deploying a variety of drone types. Drone use in the construction sector represents a significant advancement in sustainability, safety, and efficiency. Construction professionals may make well-informed decisions, enhance project outcomes, and maximise resource utilisation by utilising data collecting, monitoring, and inspection capabilities. Its drone technology is still developing. It will increasingly play a key role in transforming the building sector, encouraging creativity, and advocating for the use of intelligent, robust construction techniques.

Section 2 introduces the various types of drones used in the construction industry, highlighting their unique capabilities and roles. Section 3 delves into how UAVs are transforming construction through applications like aerial photography, surveying, mapping, safety monitoring, and material tracking, helping professionals make informed decisions in real time. Section 5 examines the integration of advanced sensors, including optical cameras, LiDAR, thermal imaging, multi-spectral sensors, and GPS, showcasing how sensor fusion enhances accuracy and automation. Section 6 discusses the challenges of using drones in construction, such as battery life limitations, regulatory restrictions, weather conditions, data security risks, and the need for skilled operators. Lastly, Section 8 looks ahead to the future of UAV technology, focusing on AI-driven automation, 5G connectivity, swarm coordination, and the integration of drones with cloud computing and IoT to improve efficiency and site management.

2 LITERATURE REVIEW

2.1 Types of Drones Used In The Construction Industry

Drones exist in various forms and are utilized for diverse applications within the construction field, as indicated by Figure 1. Research carried out by [6] involved administering questionnaires to different construction firms in order to identify the applications of drones and concluded that the most widespread application of drones was capturing progress photos, followed by the production of marketing videos, performing inspections, and improving site management. The most widely used types of drones are fixed-wing drones, rotary-wing drones, and hybrid drones, which find extensive usage in numerous applications, particularly in the construction sector. There are advantages and drawbacks to each drone type, thus selecting the correct drone is prudent when considering particular factors, e.g., how large the area is to be mapped, payload capacity, and under what environmental conditions the drone will be flying. Fixed-wing unmanned aerial vehicles are well-suited to the rapid scanning of large areas, as reported by a case study in [8]. However, [8] state that rotary-wing unmanned aerial vehicles are better suited to performing close-up inspection and activities in restricted spaces. In comparison to fixed-wing or rotary-wing counterparts, hybrid drones provide a more adaptable and flexible solution; however, they may also be costly and complex, as presented in [9].

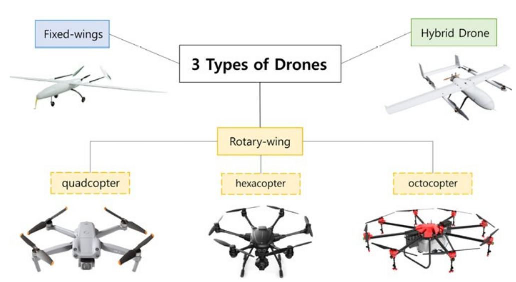

Figure 1: Types of Drones [10]

2.2 Applications of Drones Used In The Construction Industry

2.2.1 Aerial Photography

Traditionally the construction industry has relied on aerial photography captured using cranes, manned fixed wing aircraft, or helicopters to provide an overhead perspective of construction sites. These images and videos are valuable for tracking object's progress and are often utilized in marketing efforts to attract future business opportunities. UAV's, due to their compact size and height maneuverability, offer a more cost-effective and efficient alternative. Unlike conventional aerial methods, UAV's can operate at various altitudes from ground level to overhead flyovers capturing comprehensive site data from multiple viewpoints [6] . These images and videos collected can be processed, significantly reducing operational costs compared to traditional aircraft imaging techniques. Additionally, UAV's generated aerial imagery can be captured daily aging inside planning, material storage arrangements, the cut in vehicle movement optimization and the early detection of potential construction these are challenges related to planned installations [11]. Equipped with GPS technology UAVs are increasingly being deployed with preprogrammed waypoints to capture consistent area images over time. This approach enables precise monitoring of actual construction progress in comparison to the planned schedule [6]. Advanced planning software allows users to define flight routes, speeds, altitudes, and camera focal points, ensuring consistent data collection some UAV systems are also equipped with automated lending capabilities, further enhancing operational efficiency [6].

2.2.2 Surveying And Mapping

Traditional surveying and mapping methods have changed as a result of the integration of UAVs with construction. providing a more economical and effective method of gathering data. An essential component of construction is mapping, which offers vital data for site planning, design, and implementation. UAVs with high-resolution cameras and sophisticated sensors have become effective instruments for gathering topographical data, allowing for accurate evaluation of side features, existing structures, and border delineations ([6]).

The overall workflow of applying surveying and mapping techniques on a construction site includes numerous critical steps. It starts with pre-flight planning, where the survey area is delineated, flight routes are planned, and required permits and safety protocols are ensured [12], [13]. The drone acquires images and information of the area using onboard sensors during flights. When's the data is collected it is processed using specialized software to generate accurate maps and models [14]. It has been discovered that GPS enabled UAV's follow pre-programmed flight paths systematically capture high resolution aerial imagery, ensuring consistency and accuracy in data acquisition. According to [15] photogrammetric techniques process overlapping images to mosaics, which are then transformed into detailed 3D surface models. They enable topographic mapping, three-dimensional site and volumetric analysis representations, incorporating project cleaning into decision making. Furthermore, the combination of photogrammetry with light detection ringing technology increases mapping accuracy, allowing the creation of contour maps, volumetric surveys and high-fidelity 3D building models. The accuracy of UAV based mapping has been widely acknowledged existing literature. According to [11], UAV's provide precise measurement of distances, elevation, contributing to the development of highly detailed topographic models. The author further stated that the capabilities are enhanced through the establishment of control savvy control points for georeferencing and ensuring the ability of mapping output [2]. All that has been discovered that the UAV acquired area imagery undergoes photogrammetry processing to generate also rectified 2D and 3D maps which accurately represent site features, including elevations slopes and terrain variations. According to [6], the geometrical accuracy of these maps facilitates precise distances calculations, yeah estimations and in-depth spatial analysis, making UAV based mapping and essential tools in construction and execution beyond. Beyond traditional mapping applications UAVs equipped with thermal imaging sensors have demonstrated significant potential in energy efficiency assessments. According to [16], thermal imaging enables the identification of heat loss and insulation deficiencies through building envelope surveys providing valuable insights the improving energy conservation measures. It has been discovered that UAVs also contribute to asset inventory management by mapping existing structures, utilities and vegetation, thereby supporting site development planning in infrastructure integration [17]. The use of UAV in construction mapping and surveying has led to increased efficiency, cost savings and enhanced accuracy in site assessments. According to, [11] UAV's generate high resolution geospatial data in real time, improving project monitoring and decision making while also facilitating sustainable construction practices. The author stated that its technological advancements continue to enhance UAV capabilities, their role in construction site management is expected to expand further, optimizing efficiency and precision in the built environment [6].

2.2.3 Suitable Imagery For Site Selection

The use of UAVs for producing 3D photographs of locations and visual surveys has rapidly gained relevance in recent years [11]. Drones play a significant role in this process by providing valuable data and insights through aerial imagery and data collection with their ability to capture high-resolution aerial imagery. They have cameras that can take in-depth images and videos of the potential locations from various viewpoints and heights. With the use of these imageries, project managers, architects and engineers may evaluate the site's features and possibilities in detail. Drone photos allow for the assessment of variables like accessibility, closeness to transit hubs, and surrounding infrastructure [17]. This allows for the efficient collection of photographs from a large site, and the extraction of texture and geometry data from UAV images [12]. Moreover, construction professionals may enhance project results, maximize resource use, and make well-informed decisions by leveraging their data collecting, monitoring, and inspection capabilities [11].

2.2.4 Earth Working And Grade Monitoring

Drones equipped with their greatest feature of high-resolution cameras and advanced sensors offer increased efficiency [18], [19], improved accuracy [20] as well as enhanced safety. Drones are incredibly precise and accurate. They capture precise measurements and detailed images of the site, allowing for accurate volume calculations [21]. According to a study by [22], and [23], drones can also be used for slope monitoring and cut and fill studies. This degree of precision promotes resource allocation, reduces the need for rework, and guarantees adherence to design criteria.

Figure 2: Drone data processing results of 3D point cloud (left) and orthomosaic (right) [21]

2.2.5 Safety And Monitoring

Safety monitoring using with the application of drones in construction has emerged as a valuable tool for enhancing safety practices and mitigating potential hazards [2]. Because of their sophisticated cameras, sensors, and data processing capabilities, drones provide tools and uses for safety monitoring in construction. They can detect dangerous situations like falling structures, debris, broken equipment, or inappropriate usage of personal protective equipment since they are able to obtain high-resolution photos and videos [24]. Inspectors can evaluate the site's overall safety, spot possible hazards, and take appropriate precautions thanks to the airborne perspective [25] and [26].

Figure 3: UAV images for safety monitoring at a construction site in Chile: (a) lack of guardrails; (b)worker without safety rope; and (c) lack of guardrails [27]

2.2.6 Damage Detection

The use of drones equipped with cameras for structural damage detection has gained significant attention in recent years due to its efficiency and accuracy. As shown in Figure 7777, the process begins with capturing high-resolution images of structures using a drone-mounted camera. Once the images are collected, they are transferred to a computer for image processing, where various techniques are applied to enhance quality, improve contrast, and reduce noise or distortion. After pre-processing, advanced image analysis algorithms are employed to automatically detect and locate cracks in the processed images [28]. These algorithms typically use edge detection, texture analysis, or pattern recognition techniques to identify regions indicative of cracks. The detected cracks can then be classified based on characteristics such as length, width, orientation, or severity. The effectiveness of high-resolution cameras for crack detection depends on several factors, including image quality, lighting conditions, surface texture, and the expertise of the image analysts. To ensure accurate and reliable crack detection results, it is crucial to establish appropriate standards and guidelines for image capture, processing, and analysis. Furthermore, integrating advanced technologies such as artificial intelligence (AI) and machine learning can significantly enhance crack detection capabilities by training algorithms to recognize and classify cracks more accurately. This, in turn, improves the overall efficiency and effectiveness of the damage detection process [29].

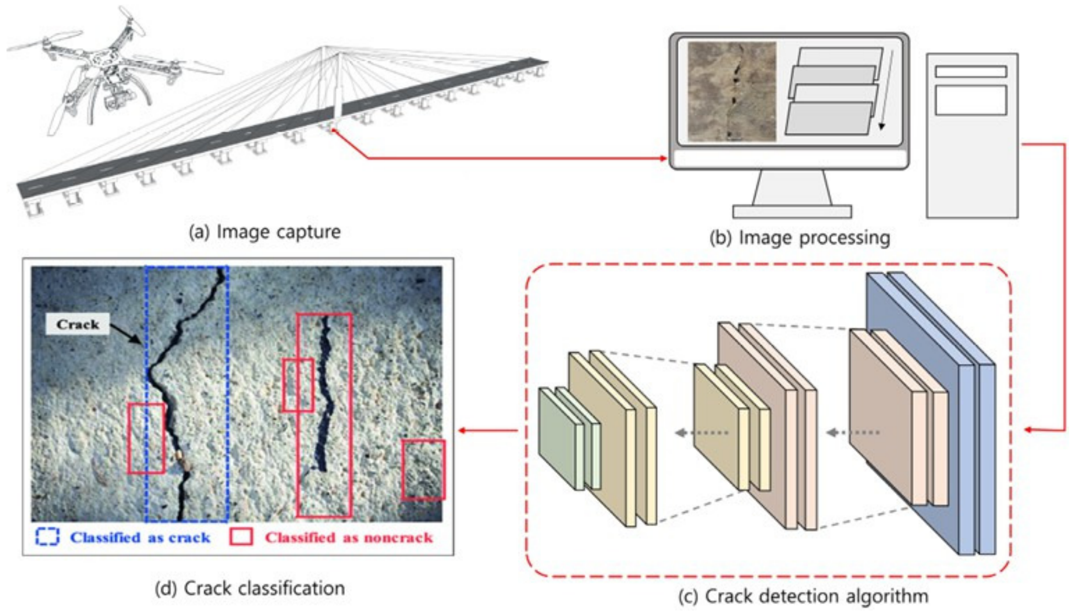

Figure 4: General concept of crack damage detection using a drone [10]

2.2.7 Material Tracking And Delivery

Drones are also being used in various industries for delivering materials, including the construction industry. They can deliver materials quickly and efficiently, reducing the time and the cost associated with traditional delivery methods. This is particularly useful in areas with limited access or where heavy machinery cannot be used [11] - [10], [30]

2.3 UAVs Equipped With Sensors Used In The Construction Industry

The integration of onboard sensors in unmanned aerial vehicles for the purpose of monitoring and evaluating construction sites in real time is displayed in the table below. concentrating on GPS/GNSS modules, optical cameras, thermal sensors, and multispectral sensors. This section looks at how various technologies can improve safety, structural health monitoring, and shaking during building. Along with the significance of sensor fusion approaches for enhancing data accuracy, the function of machine learning algorithms in object recognition, defect detection, and personal identification is also covered. Drones with thermal cameras, LiDAR technology, and high-resolution cameras can identify damage and flaws in structures that may not be apparent to the human eye. The figure below shows the difference between drones equipped with cameras, LiDAR and thermal sensor.This can help maintenance teams detect problems early,before they become major issues. The paper section highlights the advancements in UAV based sites assessment, emphasizing their potential in streamlining construction operations, including safety and optimizing.

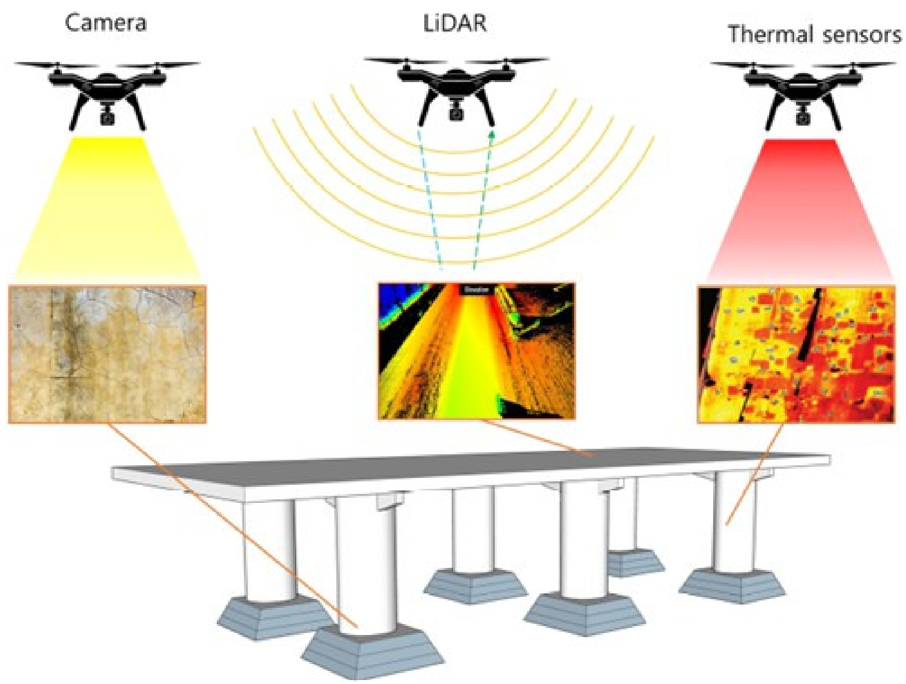

Figure 5: Difference of drone equipped with camera, LiDAR, and thermal sensor [31] - [32]

Table 1: Summary of Sensor Technologies in Construction

Sensor type	Description	Application in construction	Key findings	References
Optical cameras (RGB)	High-resolution cameras capturing visual site progress, personal tracking, and structural assessment	Construction progress tracking, structural assessment, personal tracking, quality control	Visual insights into progress and structural assessment, crucial for real-time monitoring	[33], [30]
LiDAR	Uses laser pulses to generate 3D point clouds for depth measurements and terrain modeling	Excavation monitoring, volumetric analysis, terrain modeling, surveying	Accurate depth measurement, terrain modeling, useful for excavation and material analysis	[34], [35], [36], [37]
Thermal cameras	Captures infrared radiation to detect heat variations	Safety monitoring, overheating equipment, identifying structural issues	Enhances safety monitoring by detecting heat variations, indicating potential equipment failure	[11], [10], [37], [38] [39]
Multi-spectral sensors	Captures different wavelengths for environmental and material analysis	Material composition, quality control, environmental monitoring, aging analysis	Provides insights into material properties, quality aging, and sustainability assessments	[40], [40], [41]
GPS/GNSS Modules	Provides real-time positioning and geotagging of UAV data	Georeferencing, site survey, building information modeling	Enhances spatial accuracy of UAV surveys, supports integration with BIM systems	[30], [42], [43]
Edge detection and image	Algorithms used for cracks, defects, and site features in images	Structural defect detection, crack identification	Enhance image clarity by detecting edges	[33], [44], [45], [45], [46], [47]
Sensor fusion	Integration of multiple sensor data for improved sensor accuracy in mapping and monitoring	Accurate depth measurement, object detection, site assessment	Techniques like EKF, Particle Filtering, Bayesian Inference improve multi-sensor integration and data accuracy	[40], [48], [49], [50], [51]

2.4 Benefits Of Drones In Construction

Drones are gaining popularity in the construction sector since they can give a bird's eye view of a site at a relatively low cost [52]. They are less expensive than operating a manned aerial vehicle. Drones, according to construction agencies, improve conditions for workers by providing surveying, inspection, safety and security monitoring, 3D rendering services, and precise mapping [11]. Besides, [12] argues in his study that unmanned aerial vehicles minimize safety risks and ensure structural integrity through the utilization of advanced sensors for inspection, communication, and logistic optimization. "As drones become more part of construction operations, they can aid in enhancing accountability in the development process," a case study by [8] added. Since the drone can monitor the location every day, it can provide various documents for reference to prevent errors, their precise activity tracking can help monitor and capture accurately. According to [41], drones can be used to play a significant role in tracking the progress of engineering projects. Through aerial video capture of the construction site, drones provide stakeholders—regardless of their location—with the ability of seeing live updates [51]. This provides a timeline framework of data that can be utilized for regulation and verification of work, assist in quality control, and enable comparison of actual progress with initial plans to ascertain any difference between planned targets and ongoing developments. Further, video recording using drone technology may hamper the development of a lasting record of the project that can be viewed as and when required [41]. The author highlights how common conflicts are in the construction industry and how the stakeholders can utilize drone footage to get the full overview of the circumstances when disputes arise. Apart from that, drone footage serves as helpful evidence in lawsuits, since it "can clarify or explain oral testimony or documentary narrative in concrete terms" [53].

Drones as known for their good feature of the bird's eye view that drones can provide, [52], shares they are beneficial in map inaccessible and hazardous areas, more especially with their ability to enter areas and reach certain heights that can be hard to capture manually or by laser scanners Drones can be used in conjunction with cutting-edge scanning technology to give stakeholders access to 3D representations of existing structures, including historical sites. Also, for business enterprises, the unique vantage point provided by drones allows property owners and real estate agents to create distinctive visual content for their constructed properties for sales, marketing, and advertising campaigns [11]. The fact that drones can soar over hazardous zones and sloping terrain for critical operations like inspection or surveying renders the technology a safer option compared to traditional human resources. Rather than personally undertaking their surveying or inspection tasks and exposing themselves to potential hazards, land surveyors and inspectors can deploy drones to conduct aerial surveys over specific areas of interest. Drones can be employed to rapidly identify deviations from established parameters or incursion into forbidden zones, thereby adding an extra layer of safety to the work environment [54]. This is made necessary for the people visiting the site and for the pedestrians walking around the area of the construction site. Additionally, traffic management issues could be reduced by the use of drones in inspecting transport infrastructure such as roads, bridges, and tunnels. From the economic point of view, different applications of drone use illustrate that drones can augment reporting by enabling real-time capture and footage for off-site and on-site project stakeholders [55]. Drones can enhance decision-making through remote site access by providing accurate calculation tasks and, from an economic standpoint, simplify reporting for project stakeholders present both inside and outside the job site. They can also track progress on construction sites with high accuracy and compare it to design to develop as-built statuses [55]. Additionally, they facilitate the mobility of resources and materials throughout the project site [56]. By doing so, they eliminate the need for truck cranes, elevating platforms, and heavy machinery to check dangerous areas. They also lower liability by settling disputes more quickly. Additionally, drones have an advantage on the environmental factors. Drones do not rely on fossil fuels and are mostly electric motor driven; Thus, drones release significantly lower levels of carbon dioxide emissions when compared to construction equipment, making them an environmentally friendly alternative for aerial work i.e. land mapping, photography, and surveying [6]. Further environmental benefits are also perceived through reducing congestion, for drones will decrease the amount of human labor and equipment needed to perform critical tasks [54] and hence the use of drones can contribute to sustainable development and construction when monitoring energy projects like pipelines, wind turbines, or solar farms. All these benefits result in effective job sites with effective stakeholder communication and collaboration as well as significant time and cost savings for their projects [51]. Additionally, using drones gives businesses a competitive edge when submitting bids for projects or looking for new customers.

2.5 UAVs And IoT Integration In Construction

Unmanned Aerial Vehicles (UAVs) provide value-added services including automation, site evaluation, and real-time monitoring, making them indispensable in Internet of Things frameworks. As a specialised subset of the Internet of Things, the Internet of Drones (IoD) relies on robust IT infrastructure, including cloud computing, edge computing, and advanced communication protocols, to facilitate seamless interaction between UAVs and other systems [57]. Because it enables efficient data collection, improved decision-making, and enhanced worker safety, this connectivity is essential for UAV applications in the construction industry. Security, privacy, and communication concerns remain the main challenges when integrating UAVs with IoT. The most important factors, such as secure data transmission, encryption techniques, and access control rules to safeguard sensitive construction site information, are highlighted by the IoD taxonomy as covered by [58].

IoT-enabled UAVs are transforming manual surveys in the construction industry, drastically lowering human error while increasing productivity. Comprehensive 3D mapping, structural analysis, and real-time reporting are made possible by UAVs outfitted with high-resolution cameras, LiDAR sensors, and thermal imaging [59]. AI-based techniques that automate picture processing, anticipate possible structural weaknesses, and optimize UAV flight paths further improve these capabilities. The best UAV positioning and mobility in 3D space for efficient data collecting have been investigated in recent research. As data relays, UAVs collect data in real time from Internet of Things sensors that are integrated into building supplies, machinery, and structural elements [58]. By enabling predictive maintenance, site progress tracking, and hazard detection, this sensor-UAV synergy increases project efficiency overall. Moreover, a power-efficient communication framework has been proposed to optimize uplink transmissions between UAVs and ground-based IoT devices, ensuring minimal energy consumption while maintaining reliable data exchange [60].

According to [61], the integration of cloud and edge computing enhances UAV capabilities in construction by facilitating real-time data analysis and decision-making. By processing critical data locally rather than relying on remote cloud servers, edge computing, for instance, reduces latency. Additionally, swarm intelligence, in which multiple UAVs cooperate autonomously, offers new opportunities for automated inspections, materials delivery, and large-scale surveying [59]. As construction sites become more digitalized, the combination of UAVs, IoT, and AI-driven analytics will shape the future of smart construction and make projects safer, faster, and more economical [62].

2.5.1 Cloud Computing For UAV-Based Construction Monitoring

Due to their limited processing and storage capabilities, UAVs are unable to execute complex computations while in flight. Cloud computing provides a practical substitute that enhances UAV-based construction monitoring by enabling real-time data processing and storage. By moving computational tasks to cloud platforms like AWS, UAVs can move vast volumes of data from construction sites for efficient analysis and decision-making [42]. Cloud-based optimisation techniques, such cloudlet solutions and mobile edge computing, enhance UAV communication and resource management even further by reducing latency and processing overhead [63]. Combining these technologies allows UAVs to operate effectively without being constrained by their internal computing power. The UAV-Edge-Cloud model is one hybrid approach that shows promise for solving the computing issues of UAVs. This idea combines cloud and edge computing by having edge servers handle data closer to the UAVs before transmitting it to remote cloud platforms. By reducing the need for real-time cloud communications, edge computing significantly lowers latency, making it suitable for time-sensitive applications such as flight route optimization, automated reporting, and structural integrity research [64]. UAV swarms can also share computational tasks via ad hoc cloud networks, which enhances resource efficiency and lessens the strain on individual UAVs [65].

One of the biggest challenges in cloud-based UAV operations is the significant latency required to deliver large datasets to distant cloud servers. Delays might hinder effective decision-making since real-time applications require instant processing [66]. Edge computing helps to improve response times and lessen this issue by processing data at the network edge before sending it to the cloud. The authors of 66 introduced UAV Map, a cloud-based UAV management tool that enables users to remotely access UAVs, schedule missions, and coordinate multiple UAVs. The MovieLink protocol forms the foundation for automatic reporting, structural analysis, and real-time flight path synchronization, while a cloud-based proxy server facilitates seamless communication between UAVs and human operators [64]. The substantial latency needed to send massive datasets to remote cloud servers is one of the main obstacles to cloud-based UAV operations. Since real-time applications need to be processed instantly, delays could make it more difficult to make wise decisions [66]. By processing data at the network edge before delivering it to the cloud, edge computing helps to reduce this problem and improve reaction times. UAV Map, a cloud-based UAV management application that allows users to remotely access UAVs, plan missions, and coordinate multiple UAVs, was introduced by the inventors of 66. A cloud-based proxy server enables smooth communication between UAVs and human operators, while the MovieLink protocol serves as the basis for automatic reporting, structural analysis, and real-time flight path synchronization [64].

When it comes to UAV-based cloud computing, security and communication dependability are also crucial factors. Advanced communication protocols and cloud-based proxy servers are integrated to provide safe and easy data transfer between end users, cloud platforms, and UAVs. Using cloud computing to improve site management and decision-making capabilities, UAV-based construction monitoring can get access to AI-driven analytics, real-time 3D modelling, and predictive maintenance solutions [42].

[65] claims that by resolving computational limitations, increasing productivity, and lowering latency, cloud computing greatly enhances UAV-based construction monitoring. When cloud and edge computing are combined, real-time data processing is optimised, energy consumption is reduced, and cooperative data exchange across UAVs is made possible. Future research should focus on refining task scheduling algorithms, improving QoS guarantees, and addressing security challenges to further advance UAV-based construction monitoring systems [64], [67].

2.6 Cognition in 5G Oriented UAVs

Deep reinforcement (RL) techniques in UAVs applications and challenges regarding UAVs cognitive channel modeling is important. deep learning techniques have a significant role in dealing with UAVs complex problems, e.g optimization of UAVs trajectories, energy efficiency, and landing on the mobile platform.

2.6.1 Deep learning

LTE and next-generation cellular networks supporting UAVs face several challenges. One major issue in LTE is that radio signals are not widespread enough to support UAV operations at high altitudes or beyond the line of sight (BLoS). LTE base station (BS) antennas are primarily designed to serve ground-based users, with downtilted orientations that maximize throughput for terrestrial devices [68]. Similarly, in mmWave-based 5G and beyond (B5G) networks, directional antenna beams are also tilted downward to enhance data rates for ground users. This network architecture makes it difficult to achieve full sky coverage, limiting UAV operations. Moreover, UAV-based communication systems face limitations due to antenna design constraints, signal path loss models, frequent handovers, environmental terrain challenges, and complex optimization problems. Addressing these issues effectively requires advanced techniques such as machine learning (ML), particularly Deep Reinforcement Learning (DRL).

Several studies highlight the effectiveness of ML and DRL in UAV-related challenges. For instance, [69] introduced a DRL framework using an echo state network (ESN) to optimize UAV trajectories. Their approach minimized data latency and interference at ground base stations (GBSs) by enabling UAVs to learn their flight paths, adjust transmission power, and update their network associations dynamically. [70] explored cost-effective 5G/B5G network coverage using an optimal number of UAVs. They demonstrated that simulated annealing (SA) and genetic algorithms could be effective for optimizing UAV deployment. Meanwhile, [71]addressed UAV trajectory optimization using a reinforcement learning (RL) approach based on the temporal difference method, which modeled the problem as a Markov Decision Process (MDP).

[72] proposed a Q-learning framework to maximize UAV sum-rate performance while serving as aerial base stations. Likewise, research in [73]used an ESN-based DRL method to navigate UAVs and minimize interference at GBSs, whereas [74] leveraged radio mapping methods to find the best airborne positions for UAVs. Security-specific UAV issues have been investigated as well. For example, the research in [75] proposed the use of k-order Bessel functions to detect UAV types (single rotor or multi-rotor). Additionally, [76] employed Random Forest and Extreme Learning Machine techniques to assess soil moisture content using UAV-based hyperspectral imagery.

[77] presented a DRL-based framework that jointly optimizes the trajectories of UAVs and data transmission schedules of GTs. Another research [78] solved UAV landing issues on dynamic surfaces, using the Deep Deterministic Policy Gradient (DDPG) algorithm and the Gazebo simulation platform. Agricultural inspection has also been implemented using DRL, as can be seen in [79] with the use of a neural network and image processing techniques for citrus crop phenotypes inspection. For UAV collision avoidance, [80] proposed a DRL-based SARSA protocol to enable UAVs to learn adaptive and collision-free flying patterns. A three-step ML-based solution was proposed to optimize UAV trajectory and power consumption for enhancing sum-rate performance. The solution predicts optimal UAV positions relative to users using Q-learning first, followed by an ESN-based optimization process.

2.7 Modeling Cognitive Channels

A significant difficulty is maintaining ubiquitous, reliable, and seamless data connectivity between UAVs and ground-based stations (GBSs)/users with low latency and large data speeds. Because of their increased efficiency, accessibility, quick and safe navigation, and smooth transition to 5G and beyond (B5G) connection, cellular-connected UAVs perform better than traditional UAVs.

2.7.1 Control Links

For UAVs to operate safely and securely, ultra-secure and dependable communication channels are necessary. Low latency and low data rates are typical characteristics of data link communication between UAVs and GBSs/users. Ultra-reliable low-latency communications (URLLC) were suggested by the authors in citezeng2018cellular for UAV uplink (G2A) and downlink (A2G) transmission. The L-Band (960–977 MHz) and the C-Band (5030–5091 MHz) are the two frequency bands in which UAVs operate [49].

Command and control from GBSs to UAVs, UAV data transmission to GBSs/users, and sense-and-avoid information sharing during AI-driven energy-efficient UAV operations are the three categories of control link-based data communication. Furthermore, human control linkages could be implemented as an elective accident prevention strategy [81]. Data lines are extremely sensitive to security, though, since any compromise could result in unapproved UAV control. As a result, data networks are not very resilient to security flaws and signal latency problems [82].

Subsection: Data Links The data connection layer in UAV communication enables wireless backhaul communication between UAVs, data interchange between UAV base stations (UAV-BS) and UAV gateways, and direct interaction between GBSs/users and UAVs. Depending on the needs of the application, data links usually have larger capacities than control links [49].

2.7.2 UAV Channel Features

There are distinctive features of UAV communication channels. Obstacles like buildings, trees, or cliffs rarely hinder the line-of-sight (LoS) connection between a UAV and a GBS (UAV-GBS). Obstacles, however, can result in signal reflection, diffraction, and scattering during low-altitude UAV flights [69].

Compared to UAV-GBS communication, the channel is likewise LoS in direct UAV-to-UAV communication, with a lower probability of obstacles. Furthermore, Doppler shifts may be introduced by the fast motion of UAVs, especially when mmWave bands are used [71]. The path loss models for ground user equipment (GUE)-GBS interactions are different from those for UAV-UAV and UAV-GBS communications. These models are determined and classified by variables such the communication link type, altitude, and the signal propagation environment.

2.8 UAV Communication Path Loss Models

2.8.1 Air-to-Ground Path Loss Model for Low-Altitude Platforms (LAP)

The authors in [83] developed a statistical propagation model for LAP-based UAVs using InSite ray-tracing software to simulate three types of rays: reflected, diffracted, and direct. Based on simulation results, they categorized receivers into three groups: LoS/near LoS, non-LoS (NLoS) with reception through reflection/diffraction, and high-fading conditions. The authors concluded that the path loss model depends on UAV height and coverage area, presenting mathematical formulations in [84].

2.8.2 Air-to-Ground Path Loss Model for High-Altitude Platforms (HAP)

In [85], a propagation prediction model was proposed for dynamic communication from HAP-based UAVs. The probability of LoS and NLoS channels between UAVs and GBSs/users was analyzed as a function of the elevation angle. The study developed path loss models for various environments, including urban, suburban, dense urban, and high-rise urban areas, with corresponding mathematical relations provided in [85].

2.8.3 Cellular-to-UAV Path Loss Model

The authors in [84] conducted extensive research to statistically model the path loss between cellular base stations and airborne UAVs. Their findings indicated that path loss depends on the depression angle and the terrestrial coverage area beneath an airborne UAV. The corresponding mathematical relationships are presented in [84].

2.9 Communication Modules

UAV's must constantly update GCS about their position, between health, onboard sensor data and other critical information in order to enable and maintain seamless autonomous operations. The requirement for telemetry or sensed data transfer necessities the use of efficient and reliable communication technology for UAV's. The following section provides insights into some of the characteristics associated with each communication protocol so that the other user can make informed decisions about their choice of communication module to equip onboard UAV's. Furthermore, the table highlights the key contributions of various communication protocols used in UAV's.

2.9.1 LoRa

This is a low power, low range communication technology that is primarily used on the Internet of Things IoT applications. This technology is developed by Semtech Corporation. The protocol is designed and implemented in such a way that it's physical layer employs appropriately cheap spread spectrum (CSS) modulation, while its MAC Leah, known as LoRaWAN is open source and maintained by its alliance [86]. It transmits over and licensed brands at frequencies of 433 MHz, 868 MHz, 915 MHz, and 923 MHz with an approximate maximum range of about 10 to 15 km. One of the main limitations of using LoRa in UAVs is its data rate, which can reach only up to a maximum of 50 kbps [87].

2.9.2 BluetoothLowEnergy (BLE)

An improved form of the traditional Bluetooth technology, Bluetooth Smart (BLE) is intended for low-power, short-range applications [87]. The protocol was created by the Bluetooth Special Interest Group (SIG) to offer low-power solutions for uses like fitness, beacons, and healthcare. Additionally, like conventional Bluetooth, BLE has a range of roughly 50 meters and a transmission throughput of 1 Mbps. Numerous topologies, including broadcast, p2p, mesh, and star, are supported by the protocol. Though it uses the same frequency as conventional Bluetooth, 2.4 GHz to 2.48 GHz, BLE is incompatible with its predecessor. BLE is a promising technology for usage in UAVs due to its fast data rate and low power consumption [88].

2.9.3 Wi-Fi

Digital televisions, laptops, tablets, smartphones, and other gadgets all employ Wi-Fi, a popular short-range communication protocol [87]. Based on the IEEE 802.11 protocol stack, Wi-Fi is available in multiple versions with different power consumption, bandwidth, and data rate levels. 2.4 GHz and 5 GHz are the unlicensed spectrum band in which Wi-Fi works [88]. Wi-Fi's fast data throughput and immunity to interference problems are caused by the orthogonal frequency division multiplexing (OFDM) modulation. Wi-Fi is a great option for UAVs because of these characteristics. Additionally, it may be implemented in both infrastructure and ad hoc modes due to its modular design.

2.9.4 Long -Term Evolution for machine-type communication (LTE-M)

LTE-M is a low-power wide-area communication standard developed by the 3GPP to support machine-to-machine communications and IoT applications [89]. The protocol provides a high data rate as well as increased bandwidth. It operates within 3GPP specified licensed spectrum band. The increased adoption of LTE-M protocol in UAV applications can be attributed to its design architecture which allows seamless integration with existing cellular infrastructure. Furthermore, its long range, low latency, resistance to interference, and weather conditions have all contributed to its growing popularity [87].

2.10 Challenges Encountered When Using UAVs In Construction

Despite the potential benefits of using UAVs in the construction industry, there are several challenges and limitations that must be considered and addressed when implementing this technology. These consist of technical constraints, data processing difficulties, legal and regulatory hurdles, training and expertise issues, and safety concerns.

2.10.1 Regulatory and Legal Issues

Aviation authorities like the Federal Aviation Administration have enforced stringent regulations on the use of drones in construction [90], [91], [92], and [93]. The inability to fly drones outside of the operator's field of vision is one of its main drawbacks, which makes it difficult to do autonomous, extensive site inspections.

2.10.2 Technical Limitations

One of the main technical challenges faced by UAV's is their restricted flight duration [94], [95]. Most commercial UAV's can only operate for approximately 20 to 30 minutes on a single charge, which restricts the volume of data that can be gathered in one flight session. These limitations become particularly problematic for large scale construction projects that demand thorough action and monitoring all extended periods. Another significant constraint is the limited operational range of UAV [95]. These devices often struggle to travel long distances or maintain a stable connection with their controllers or base stations. This issue can hinder their ability to cover expensive construction sites or operate effectively in areas with weak signal reception. Additionally, the quality of data collected using UAV's inspection can be affected by technical shortcomings including limitations in area resolution, sensor precision and data processing capabilities. Subpar Data 10 may result in inaccurate or incomplete evaluations of construction sites' condition, ultimately affecting decision making processes and project outcomes. Given these technical limitations, it is crucial for construction companies and inspection firms to carefully evaluate the capabilities of UAV's before deploying them for inspections [96]. Factors such as weather conditions; environmental changes and the specific requirements of the site should be considered [82]. Moreover, ensuring that UAVs are equipped with high quality cameras, sensors and robust data processing systems is essential for effective data analysis and interpretation [97], [98]. In addition, UAVs are limited in their ability to access certain areas of construction sites. For example, UAVs may not be able to access tight spaces, such as tunnels or narrow corridors, or to fly indoors in areas with limited visibility or signal interference [99].

2.10.3 Data Processing And Quality Challenges

The calibre of the data gathered has a significant impact on how well drones work in building. For precise site monitoring and analysis, high-resolution photography, exact geographic data, and trustworthy sensor readings are essential. Technical issues with picture quality, sensor accuracy, and data processing power, however, can lead to imprecise or insufficient assessments of building site conditions, which can eventually influence decision-making procedures and project results [27].

Drones also produce vast amounts of data, which present processing and storage issues [100]. To automate data analysis and expedite real-time decision-making, cloud computing and artificial intelligence (AI) algorithms are being created. One major obstacle still stands, nevertheless, in guaranteeing a smooth interface with the current construction management software.

2.10.4 Training and Expertise

Drone deployment requires skilled workers with knowledge of data processing, UAV operation, and regulatory compliance [101]. Due to the requirement for businesses to spend in the development of specialized skills among their employees, professional training raises expenses and temporarily lowers production. Automation developments and simplified, user-friendly drone control interfaces can lower the barrier to competence and boost uptake [102]- [103].

2.10.5 Safety concerns and Public Perception

Although drones increase construction safety by removing the need for workers to visit hazardous areas, they also raise new issues. Injuries or property damage could arise from potential accidents caused by drone malfunctions, crashes, or operator error. Strict safety protocols, fail-safe systems, and collision-avoidance technology must be implemented in order to lessen these risks [104], [105]. For UAV inspections, weather conditions might also pose safety risks. Rain, strong winds, and other weather conditions might affect UAV control and stability, which could result in mishaps or damage to equipment [53]. When employing UAVs for building inspection, security is a crucial factor to take into account in addition to safety issues. As [106] and [107] have pointed out,there are potential risks of cybersecurity breaches and malicious use that can compromise communication between the UAV and the control station. this can end up leading to unauthorized access, data leakage or even hijacking of the UAV.

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