drones

Review

An Overview of Drone Applications in the Construction Industry

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Abstract: The integration of drones in the construction industry has ushered in a new era of efficiency, accuracy, and safety throughout the various phases of construction projects. This paper presents a comprehensive overview of the applications of drones in the construction industry, focusing on their utilization in the design, construction, and maintenance phases. The differences between the three different types of drones are discussed at the beginning of the paper where the overview of the drone applications in construction industry is then described. Overall, the integration of drones in the construction industry has yielded transformative advancements across all phases of construction projects. As technology continues to advance, drones are expected to play an increasingly critical role in shaping the future of the construction industry.

Keywords: drone application; unmanned aerial vehicle; smart construction; aerial inspections; structure maintenance

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1. Introduction

In recent years, the construction industry has witnessed a remarkable transformation fueled by technological advancements. Among these innovations, drones have emerged as game-changers, redefining the way construction projects are planned, executed, and maintained. Equipped with sophisticated sensors, cameras, and GPS (global positioning system) technology, drones offer unparalleled capabilities to capture real-time data, generate accurate 3D models, and conduct remote inspections. This review paper aims to provide a comprehensive overview of the applications of drones in construction, shedding light on their impact across different project phases and highlighting the potential benefits they bring to the table.

Drones have rapidly evolved from being mere novelties to indispensable tools in the construction sector. By utilizing different types of drones, construction professionals can optimize their workflow, improve project coordination, and mitigate risks [1,2]. Surveying drones, equipped with high-resolution cameras and LiDAR (light detection and ranging) sensors facilitate precise mapping, topographical analysis, and site planning [3–5]. These drones capture detailed aerial imagery and generate comprehensive 3D models, enabling architects and engineers to make informed decisions about building placement, design optimization, and resource utilization [6,7].

Inspection drones, on the other hand, provide an unprecedented advantage in assessing hard-to-reach or hazardous areas of construction sites. Equipped with thermal cameras, high-resolution imaging systems, and even artificial intelligence, these drones enable efficient and accurate inspections of infrastructure, buildings, and equipment [8–10]. By swiftly identifying structural defects, monitoring construction quality, and ensuring compliance with safety regulations, inspection drones contribute to enhanced project transparency, reduced manual labor requirements, and improved overall project outcomes.

Beyond the core phases of design and construction, drones continue to revolutionize the maintenance stage. Regular inspections using drones enable proactive maintenance planning, identifying potential issues early on, and preventing costly repairs. By conducting detailed assessments of buildings, bridges, and infrastructure, drones contribute to the longevity and resilience of constructed assets. Additionally, the integration of drones in the maintenance phase allows for the swift identification and resolution of defects, leading to improved safety, and reduced downtime [8,11].

The utilization of drones in the construction industry represents a transformative leap towards achieving higher levels of efficiency, safety, and sustainability. By harnessing their data acquisition, monitoring, and inspection capabilities, construction professionals can make informed decisions, improve project outcomes, and optimize resource utilization. As drone technology continues to evolve, it is expected to play an increasingly pivotal role in reshaping the construction industry, fostering innovation, and driving the adoption of smart, resilient construction practices.

In this study, drone technology is reviewed by dividing the actual construction process into three different phases. The architecture of the paper is organized as follows. Section 2 describes the three different types of drones used in the construction industry with the advantages and disadvantages of using each of the drone types. Section 3 discusses the drones used at the designing phase, Section 4 reviews how drones are used at the construction phase and Section 5 overviews the maintenance phase, summarizing how drones are applied to ensure effective maintenance. Then, the study concludes with sections including challenges and opportunities and future directions.

2. Drone Types for Application in Construction Industry

There are various type of drones used in the construction industry for various purposes. In reference [6], the study conducted surveys from many construction companies to find out how drones were used for their construction projects and it showed that the most popular use of drones was in capturing progress photos, followed by taking promotional videos, conducting inspections, and enhancing site management (Figure 1).

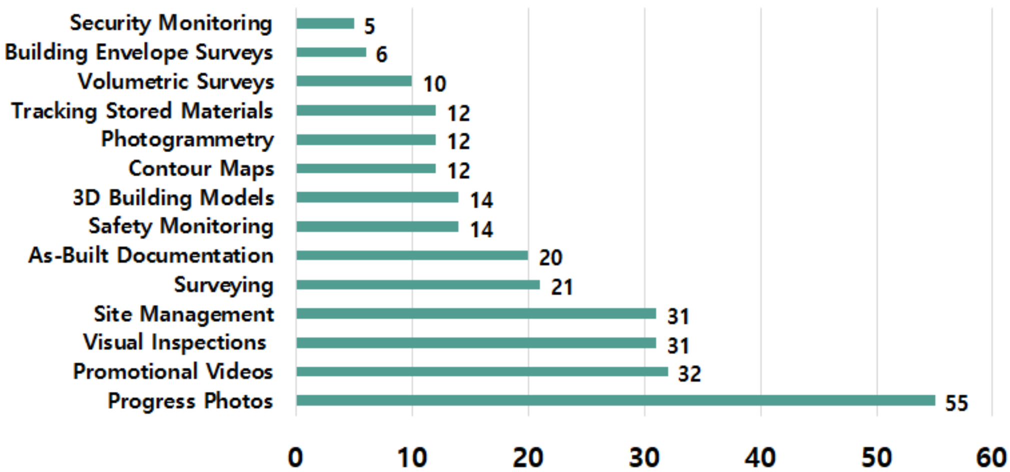

Figure 1. Drone applications result from survey companies [6].

As shown in Figure 2, fixed-wing drones, rotary-wing drones, and hybrid drones are three types of drones or unmanned aerial vehicles (UAVs) that are commonly used for various applications, including in the construction and maintenance industries. Each type of drone has its unique advantages and disadvantages, and choosing the right drone for a specific application depends on several factors, such as the size of the area to be covered, the required payload capacity, and the environmental conditions in which the drone will be operated (Table 1). Fixed-wing drones are ideal for covering large areas quickly [12], while rotary-wing drones are more suitable for close-range inspections and operations in confined spaces [13–15]. Hybrid drones offer a more versatile and adaptable solution, but may be more complex and expensive than fixed-wing or rotary-wing drones [16]. Ultimately, the right drone for a specific application should be chosen based on a careful analysis of the requirements of the task at hand.

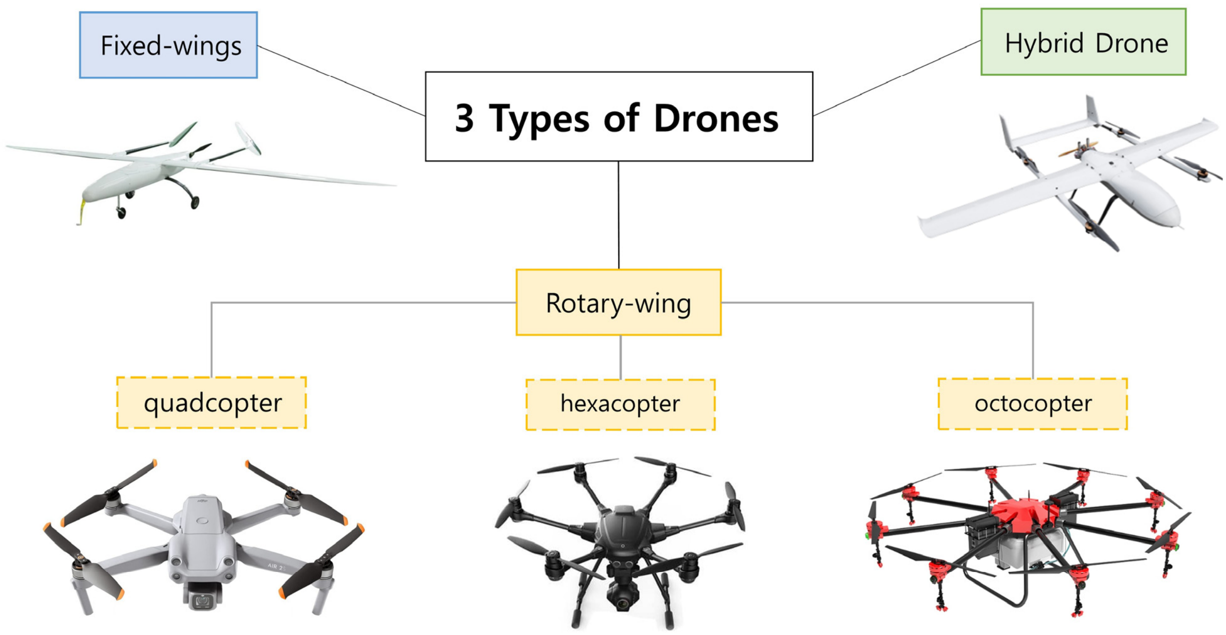

Figure 2. Three different types of drones used in construction industry.

Table 1. Three types of drones.

Types of Drones	References	Brief Summary
Rotary-wing Drones	Calantropio, A et al. [17] Villanueva, J.R.E et al. [18] Templin, T et al. [19] Anders, N et al. [20]	Large-scale topographic surveys
	Yi, W et al. [21] El Tin, F et al. [22]	Aerial inspections and monitoring of construction sites
	Sonkar, S et al. [23]	Capturing images in difficult weather
	Khan, S et al. [24]	UAV platform research
	Chae, M. H et al. [25] Sujit, P.B et al. [26]	Pilot's expertise needs
	Jin, J. W et al. [27]	High initial cost of fixed-wing drones
Fixed-wing Drones	Yang, H et al. [28]	Detailed inspections available
	Altınuç, K. O et al. [29]	Safe take-off and landing scenarios in case of failure
	Freimuth, H et al. [30] Kim, S.S. [31]	Accessible for small-scale civil engineering projects or businesses with limited resources
	Deng, C et al. [32]	Limited flight time
	Boon, M.A et al. [33] Thibbotuwawa, A et al. [34] Eck, C. [35] Li, X et al. [36]	Structural issues impact quality and stability
	Al-Rawabdeh et al. [37] Jacob-Loyola, N et al. [38] Motawa, I. et al. [39] Khaloo, A et al. [40] Lindner, G et al. [41]	High-resolution mapping, limiting advanced data collection

Table 1. *Cont.*

Types of Drones	References	Brief Summary
Hybrid Drones	Panigrahi, S et al. [42] Gunarathna, J.K et al. [43]	Benefits of long flights
	Saeed, A.S et al. [44] Yuksek, B et al. [45]	Increase detailed data collection
	Nguyen, K.D et al. [46]	Designed with numerical simulations

2.1. Fixed-Wing Drones

Fixed-wing drones offer several advantages for civil engineering applications but also come with a few disadvantages. They have longer flight times compared to rotary-wing drones. Their efficient forward flight allows them to cover larger areas and remain airborne for an extended period, which is beneficial for large-scale surveying and mapping projects. These drones can cover larger distances in a single flight due to their higher speed and endurance. This increased coverage area makes them ideal for large-scale topographic surveys [17–20], aerial inspections, and monitoring of construction sites [21,22]. Fixed-wing drones are generally more stable in windy conditions than multi-rotor drones. Their aerodynamic design and ability to withstand gusts allows them to maintain stability and capture high-quality imagery even in challenging weather [23]. They have a higher payload capacity, enabling them to carry heavier equipment such as high-resolution cameras and LiDAR sensors. This capability allows them to capture detailed aerial data for the precise mapping, 3D modeling, and volumetric analysis of construction sites. However, fixed-wing drones have some disadvantages to consider. They have limited maneuverability and cannot hover or fly in tight spaces like rotary-wing drones. This restricts their ability to inspect vertical structures or perform close-range inspections in congested areas. Furthermore, it requires a relatively longer runway or open area for take-off and landing compared to vertical take-off and landing (VTOL) drones. This can be a constraint in sites with limited space or challenging terrain [24].

Operating fixed-wing drones often requires skilled pilots due to their advanced flight characteristics and longer flight distances. Pilots need expertise in planning flight paths, conducting pre-flight checks, and coordinating with air traffic authorities, if necessary [25,26]. In general, fixed-wing drones are more expensive than rotary-wing drones due to their sophisticated design and advanced flight capabilities. The initial investment required for a fixed-wing drone system can be a barrier for small-scale civil engineering projects or businesses with limited budgets [27]. While fixed-wing drones offer significant advantages in terms of flight time, coverage area, and stability, their limited maneuverability, longer take-off/landing requirements, complex operation, and higher initial cost should be considered when selecting the appropriate drone for civil engineering applications.

2.2. Rotary-Wing Drones

Rotary-wing drones, also known as quadcopters and multi-rotor drones, have their own set of advantages and disadvantages when used in the civil engineering field. Rotary-wing drones provide excellent maneuverability and the ability to hover, making them well-suited for close-range inspections of vertical structures and operating in tight spaces. Their agility allows for detailed inspections of construction sites and infrastructure [28], providing valuable data for engineers and project managers. These drones have shorter take-off and landing requirements compared to fixed-wing drones [29]. They can perform vertical take-offs and landings, eliminating the need for a runway or open area. This makes them more suitable for operating in confined construction sites or areas with limited space. Rotary-wing drones are relatively easier to operate compared to fixed-wing drones. They can be flown by pilots with less training and experience, making them accessible for small-scale civil engineering projects or businesses with limited resources [30,31].

The main disadvantage of rotary-wing drones is their limited flight time. They have shorter endurance due to the energy-intensive nature of hovering and maneuvering. This restricts their coverage area and makes them less suitable for large-scale surveys or monitoring projects that require long flight times [32]. Furthermore, it can be affected by wind and gusts more than fixed-wing drones. Their small size and lightweight construction make them more susceptible to wind disturbances, which can impact flight stability and the quality of captured data [33–36]. Compared to fixed-wing drones, rotary-wing drones have lower payload capacities. They can carry lighter equipment such as small cameras or sensors, which may limit their capabilities for high-resolution mapping or advanced data collection tasks [37–41]. In summary, rotary-wing drones offer advantages in terms of maneuverability, close-range inspections, and ease of operation. They are suitable for small-scale projects and operations in confined spaces. However, their limitations include shorter flight times, susceptibility to wind, and lower payload capacities.

2.3. Hybrid Drones

Hybrid drones combine the features and capabilities of both fixed-wing and rotary-wing drones. They can take off and land vertically like rotary-wing drones, allowing them to operate in tight spaces and perform close-range inspections. At the same time, they can transition to fixed-wing flight for efficient forward flight, enabling them to cover larger areas and achieve longer flight times. This flexibility makes them suitable for a wide range of civil engineering applications. Hybrid drones offer extended flight times compared to traditional rotary-wing drones. By transitioning to fixed-wing flight, they can conserve energy and cover larger distances in a single flight. This is advantageous for conducting large-scale surveys, mapping, and monitoring projects that require longer flight durations [42,43]. The combination of vertical take-off and landing capability and fixed-wing flight allows them to carry larger cameras, LiDAR sensors, or other equipment. This enhances their capacity for detailed data collection, such as in high-resolution mapping or 3D modeling of construction sites [44,45].

However, hybrid drones have some disadvantages to consider. They are generally more complex to operate compared to single-mode drones. Pilots require specific training and expertise to handle the transition between vertical and fixed-wing flight modes, as well as understanding the nuances of operating a hybrid system. Furthermore, hybrid drones may have higher initial costs compared to single-mode drones as the integration of both fixed-wing and rotary-wing capabilities requires additional engineering and design, leading to a potentially higher purchase price [46]. This cost factor may limit their accessibility for smaller civil engineering projects or businesses with limited budgets.

3. Drone Application during the Designing Phase of Construction

3.1. Suitable Site Selection

Choosing the right site for any construction project is one of the first steps before constructing a structure. It involves assessing various potential sites to determine the most suitable location for the project. Drones play a significant role in this process by providing valuable data and insights through aerial imagery and data collection. One of the primary advantages of using drones for site selection and evaluation is the ability to capture high-resolution aerial imagery [47,48]. Drones equipped with cameras can capture detailed photographs and videos of the prospective sites from different angles and altitudes. This imagery provides a comprehensive overview of the site, allowing project managers, architects, and engineers to assess its characteristics and potential. The aerial imagery obtained from drones enables the evaluation of factors such as accessibility, proximity to transportation networks, and neighboring infrastructure. By analyzing this information, stakeholders can determine if the site meets the project's logistical requirements. They can identify any limitations or challenges related to site access, which can impact construction activities and the transportation of materials and equipment [49].

3.2. Land Surveying and Mapping

Surveying and mapping construction sites using drones offers significant advantages over traditional methods, revolutionizing the field of land surveying and providing valuable data for design and construction processes. Surveying with drones involves capturing high-resolution aerial imagery that provides a comprehensive aerial perspective of the construction site. The data collected by drones, including images and measurements from sensors such as LiDAR [50–53] or thermal sensors [51], enables accurate assessments of the site's topography, existing structures, and boundaries. Precise measurements of distances, elevations, and contours can be obtained, contributing to the creation of detailed 3D models and accurate calculations. Additionally, drones assist in establishing survey control points for precise georeferencing, ensuring the accuracy and reliability of subsequent mapping activities.

Mapping with drones encompasses the generation of accurate maps and models of the construction site using aerial imagery and photogrammetry techniques [49,54]. High-resolution aerial imagery captured by drones covers large areas efficiently, providing a visual representation of the site's features. Photogrammetry algorithms process the overlapping images to create 2D and 3D maps, including topographic maps that depict elevations, contours, slopes, and other topographic features [50,55–57]. Orthomosaic maps, created by stitching together multiple images, offer geometrically accurate and orthorectified representations of the site, facilitating precise measurements, distance calculations, and visual analysis. Moreover, drones assist in asset inventory by mapping existing structures, utilities, and vegetation, allowing designers and planners to incorporate them into their design processes [58,59].

The general process for using drones in surveying and mapping a construction site involves several key steps. It begins with pre-flight planning, where the survey area is defined, flight paths are determined, and necessary permits and safety measures are ensured [25,60,61]. During the flight, the drone captures aerial imagery and data using onboard sensors. Once the data are collected, it is processed using specialized software to generate accurate maps, models, and orthomosaics [48,59,62,63], where Figure 3 shows a general process of creating a digital terrain model regarding UAV photogrammetric process and field survey parameters [64].

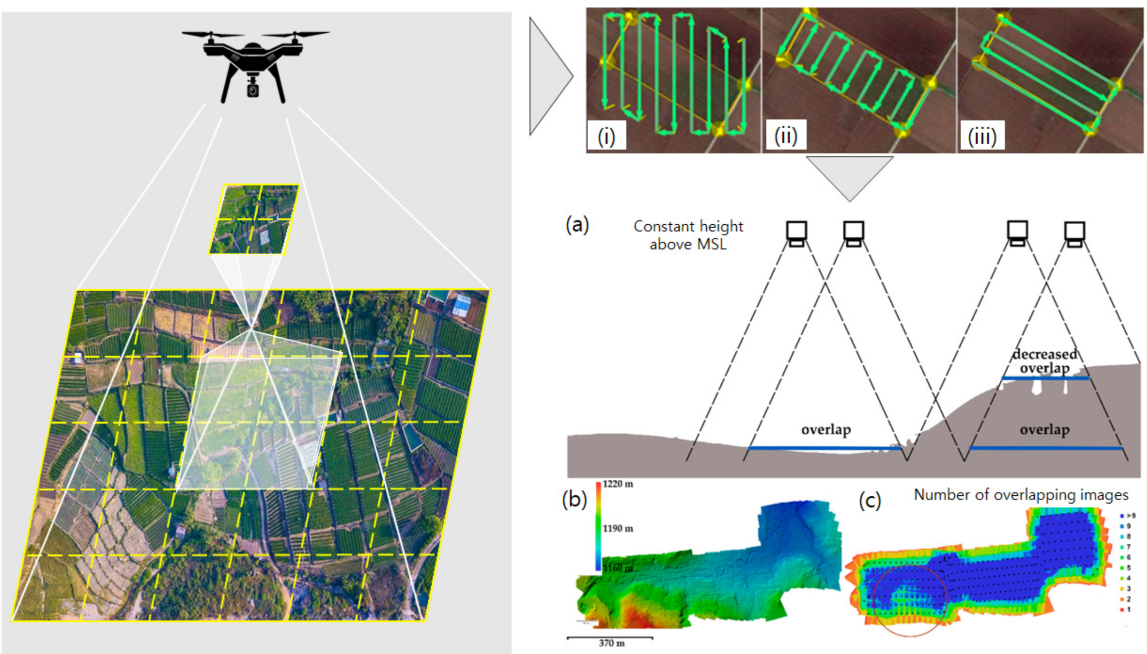

Figure 3. A general process for generating a digital terrain model with a drone (cf. [64]).

Overall, the utilization of drones in surveying and mapping offers significant benefits, including efficient data collection, high accuracy, comprehensive visual information, and enhanced decision-making capabilities. The combination of surveying and mapping with drones provides valuable insights for design, engineering, and asset management processes, ultimately improving the efficiency and quality of construction projects.

4. Drone Application during the Construction Phase

The use of drones in the construction industry has been growing rapidly in recent years. Drones offer numerous benefits during the construction phase, such as improving safety, enhancing efficiency, and reducing costs. Figure 4 shows the percentage of content for the references used in this section at construction phase where we can see that "support for rescue operations", at 31.6%, is most commonly used drone application.

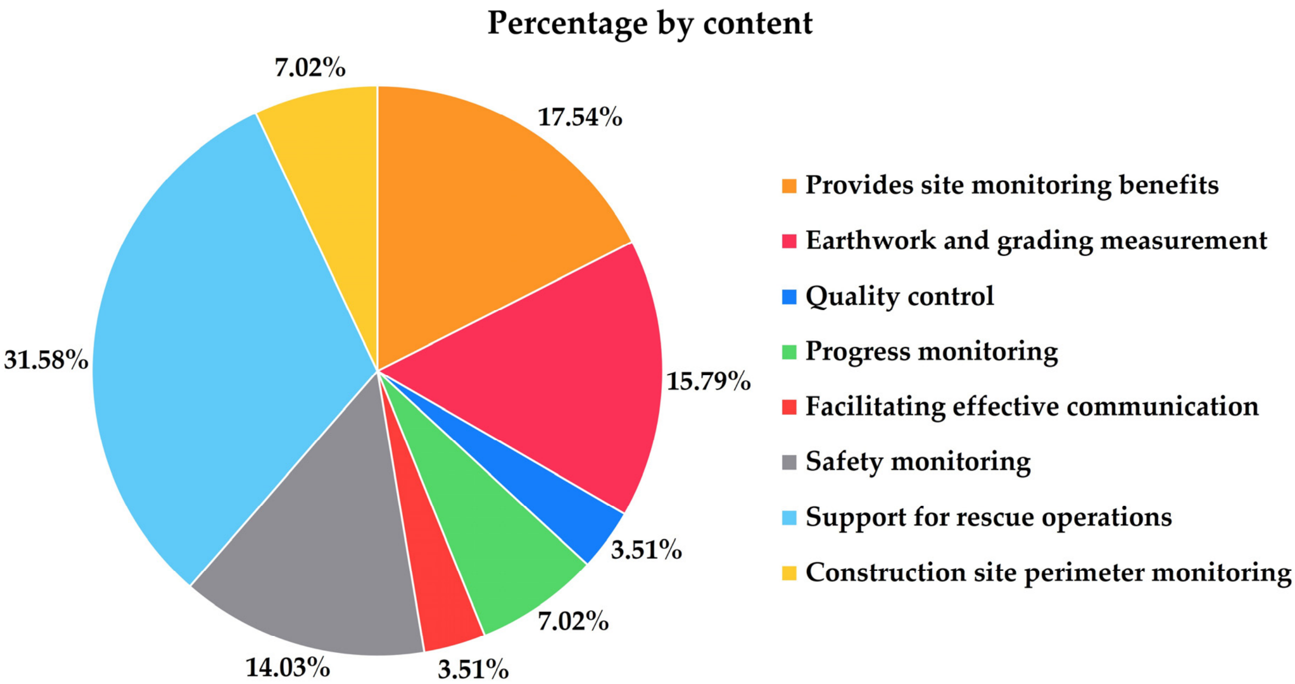

Figure 4. Percentage of content for drone applications at construction phase.

4.1. Earthwork and Grading Monitoring

Earthwork and grading monitoring using drones in the construction phase has revolutionized the way construction projects are executed and managed. Drones equipped with high-resolution cameras and advanced sensors offer a range of benefits, including increased efficiency [65–67], improved accuracy [68–71], and enhanced safety [72–74]. Figure 5 shows a case study of a construction project of an apartment building complex in Seoul, Republic of Korea for a 771 household capacity where a drone was used to 3D model the area [70]. Using the UAV platform in this study, four primary analysis and visualization types were performed. These were automatic volume calculation with cut-and-fill volume data, height difference review by comparing two terrain models from different time stamps, site monitoring through 2D/3D visualization, and documentation of the project from start to completion. Traditional methods of earthwork and grading monitoring often rely on manual measurements, which are prone to human error. Drones, on the other hand, offer exceptional accuracy and precision. They capture precise measurements and detailed images of the site, allowing for accurate volume calculations [75–78], cut and fill analysis [77,79,80], and slope monitoring [81–83]. This level of accuracy helps minimize rework, optimizes resource allocation, and ensures compliance with design specifications.

Figure 5. Drone data processing results of 3D point cloud (**left**) and orthomosaic (**right**) [70].

4.2. Quality Control and Progress Monitoring

Drones play a crucial role in quality control by capturing high-resolution imagery and data that allow for thorough inspections and defect detection. The detailed imagery enables inspectors to identify even minor defects, such as cracks, corrosion, or surface imperfections, that might be missed during ground inspections [84,85]. By comparing the captured data with the construction plans or 3D models, inspectors can quickly identify any deviations or errors in the construction process. This early detection of defects enables timely rectification, ensuring that the project meets the required quality standards. Drones also facilitate the systematic documentation and tracking of identified defects, providing a clear record of issues that need to be addressed.

Drones provide an efficient and accurate method for monitoring construction progress throughout the project's lifecycle. By regularly capturing aerial imagery or conducting photogrammetry surveys, drones enable project managers to assess the status of different construction activities [86–89]. The captured data can be compared against the project timeline, enabling progress tracking and the identification of any delays or bottlenecks. Real-time progress monitoring allows for proactive decision-making and resource allocation adjustments to keep the project on schedule. Additionally, drones facilitate effective communication among the construction team, enabling stakeholders to visualize and understand the progress of the project [90,91]. This visual documentation of the construction site's evolution aids in coordination, reducing the likelihood of misunderstandings, and fosters a shared understanding of the project's status among all stakeholders.

By leveraging drones for quality control and progress monitoring, construction projects can significantly improve efficiency, minimize rework, and ensure that the project is delivered on time and within the specified quality standards. The use of drones enhances the accuracy and thoroughness of inspections, enabling the identification of defects and deviations from design plans. Real-time progress monitoring enables project managers to proactively address any issues or delays, optimizing resource allocation and ensuring the project stays on track. Ultimately, drones contribute to better construction outcomes, improved project coordination, and enhanced communication among all project stakeholders.

4.3. Safety Monitoring

Safety monitoring using drones during the construction phase has emerged as a valuable tool for enhancing safety practices and mitigating potential hazards. Drones equipped with advanced cameras, sensors, and data processing capabilities offer several benefits for safety monitoring in construction. By capturing high-resolution imagery and videos, drones can identify unsafe conditions such as unstable structures, debris, equipment malfunctions, or improper use of personal protective equipment [92–96]. The aerial perspective allows inspectors to assess the overall safety of the site, identify potential risks, and take necessary preventive measures [97–99]. Figure 6 shows a case study for using a drone for safety monitoring in a high-rise building construction project in Santiago, Chile. From the study, it was possible to identify safety issues using drone images as shown in the figure, such as a lack of guardrails and worker without safety rope, to ensure a safer environment for the workers.

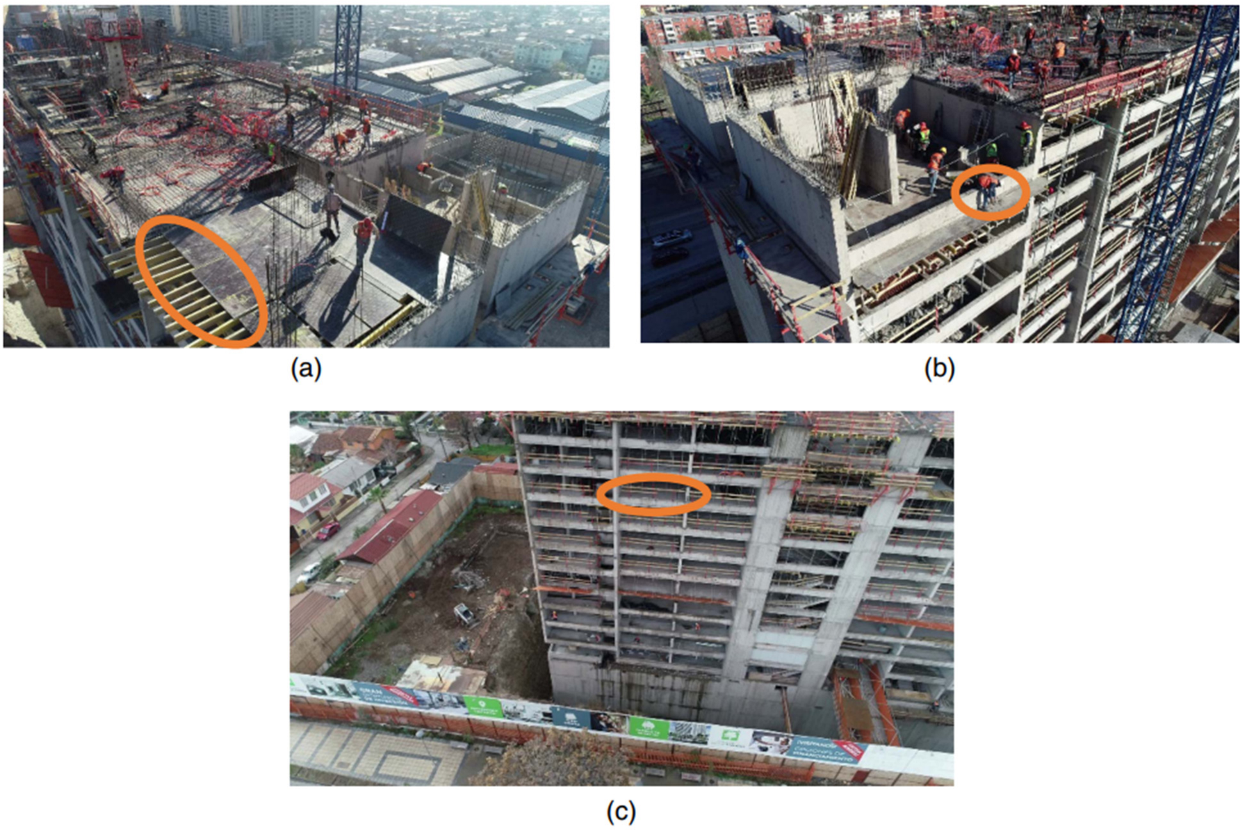

Figure 6. UAV images for safety monitoring at a construction site in Chile: (**a**) lack of guardrails; (**b**) worker without safety rope; and (**c**) lack of guardrails (Images by Jhonattan G. Martinez) [92].

In the event of an emergency or incident on a construction site, drones can quickly provide real-time situational awareness. By capturing live video feeds and aerial imagery, drones assist emergency response teams in assessing the situation, identifying access points, and planning rescue operations [100–108]. Drones equipped with thermal cameras can aid in locating missing persons or hotspots in fire incidents [109–117]. This real-time information helps expedite emergency response efforts, ensuring the safety of personnel on-site. Beyond safety monitoring, drones can enhance site security by providing surveillance capabilities. Drones equipped with cameras and sensors can monitor the construction site perimeter and detect unauthorized access [47,49,118,119]. The live video feeds and recorded footage can be used for investigations, enhancing site security and protecting valuable construction assets.

4.4. Material Tracking and Delivery

Drones are also being used in various industries for delivering materials including the construction industry. [120–128]. They can deliver materials quickly and efficiently, reducing the time and cost associated with traditional delivery methods. This is particularly useful in areas with limited access or where heavy machinery cannot be used.

5. Drone Application during the Maintenance Phase

The use of drones in the maintenance of structures has been increasing in recent years. Drones offer numerous benefits in structure maintenance, such as improving safety, enhancing efficiency, and reducing costs. It can provide real-time data on the condition of structures, allowing maintenance teams to make informed decisions and adjust maintenance schedules accordingly. Drones equipped with high-resolution cameras, LiDAR technology, and thermal cameras can detect defects and damage in structures that might not be visible to the naked eye (Figure 7). This can help maintenance teams detect problems early, before they become major issues. Furthermore, it is possible for drones to be used for repair and restoration of structures. They can be used to apply coatings, sealants, and other materials to structures in a fraction of the time it would take using traditional methods. The following subsections discuss the research of the aforementioned areas.

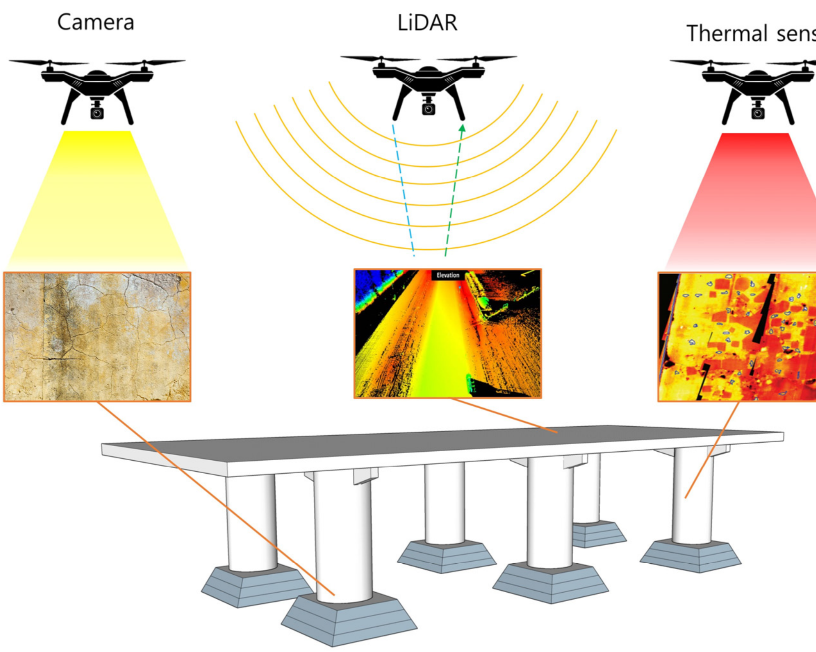

Figure 7. Difference of drone equipped with camera, LiDAR, and thermal sensor [129,130].

5.1. High Resolution Camera-Based Inspection with Drone

Drones have revolutionized the field of bridge maintenance. The ability to inspect bridges from the air provides engineers and maintenance crews with valuable data that can be used to ensure the safety and structural integrity of bridges. Drones equipped with cameras are particularly useful for bridge inspections as they can capture high-resolution images of the structure, allowing for a more detailed analysis of damage. One of the main advantages of using drones for bridge inspections is the increased safety they provide [130–137]. Drones can access areas that are difficult or dangerous for humans to reach, such as the underside of bridges or high above the ground. This reduces the need for maintenance workers to use scaffolding or other equipment, which can be expensive and time-consuming to set up. Additionally, drones can be operated remotely, reducing the risk of injury to maintenance workers who would otherwise have to climb the bridge structure to perform inspections. Another benefit of using drones for bridge inspections is the speed at which they can complete inspections. Drones can quickly fly over the bridge, capturing images and videos that can be analyzed in real-time. This allows for a faster turnaround time for inspection reports, reducing downtime for the bridge and minimizing disruption to traffic.

The high-resolution images and videos captured by drones can reveal details that may be missed during a visual inspection by human inspectors. This can include cracks or other signs of wear that are not immediately visible to the naked eye [138–140]. By providing a more detailed analysis of the bridge, maintenance crews can identify potential problems before they become serious issues, reducing the need for costly repairs and extending the lifespan of the bridge. In addition to inspections, drones can also be used for ongoing monitoring of bridge conditions. They can be programmed to fly over the bridge at regular intervals and capture data on changes in the structure over time. This can help maintenance workers identify potential problems before they become a serious issue. For example, drones can be used to monitor changes in the condition of the bridge after extreme weather events such as floods, typhoons, and earthquakes [141–143].

One of the challenges of using drones for bridge maintenance is the need for skilled operators. Drones require a trained operator who can maneuver the drone safely and capture high-quality images and videos. Additionally, the analysis of the data captured by the drone requires specialized knowledge and expertise. Therefore, it is essential to have a team of skilled professionals to operate the drones and analyze the data.

The concept of using a drone equipped with a camera for damage detection of structures can be seen in Figure 8. Once the images are captured from the camera, it is transferred to a computer for image processing to enhance the quality of the images, improve contrast, and reduce noise or distortion. Then, various image analysis algorithms can be employed to automatically detect and locate cracks in the processed images. These algorithms typically involve edge detection, texture analysis, or pattern recognition techniques to identify regions that indicate crack presence. Here, detected cracks can be classified based on their characteristics, such as length, width, orientation, or severity. It is worth noting that the effectiveness of high-resolution cameras for crack detection depends on various factors, such as the image quality, lighting conditions, surface texture, and the expertise of the image analysts. It is important to establish appropriate standards and guidelines for image capture, processing, and analysis to ensure accurate and reliable crack detection results. Additionally, the integration of advanced technologies such as artificial intelligence (AI) and machine learning can enhance crack detection capabilities by training algorithms to recognize and classify cracks more accurately, thereby improving the efficiency and effectiveness of the process.

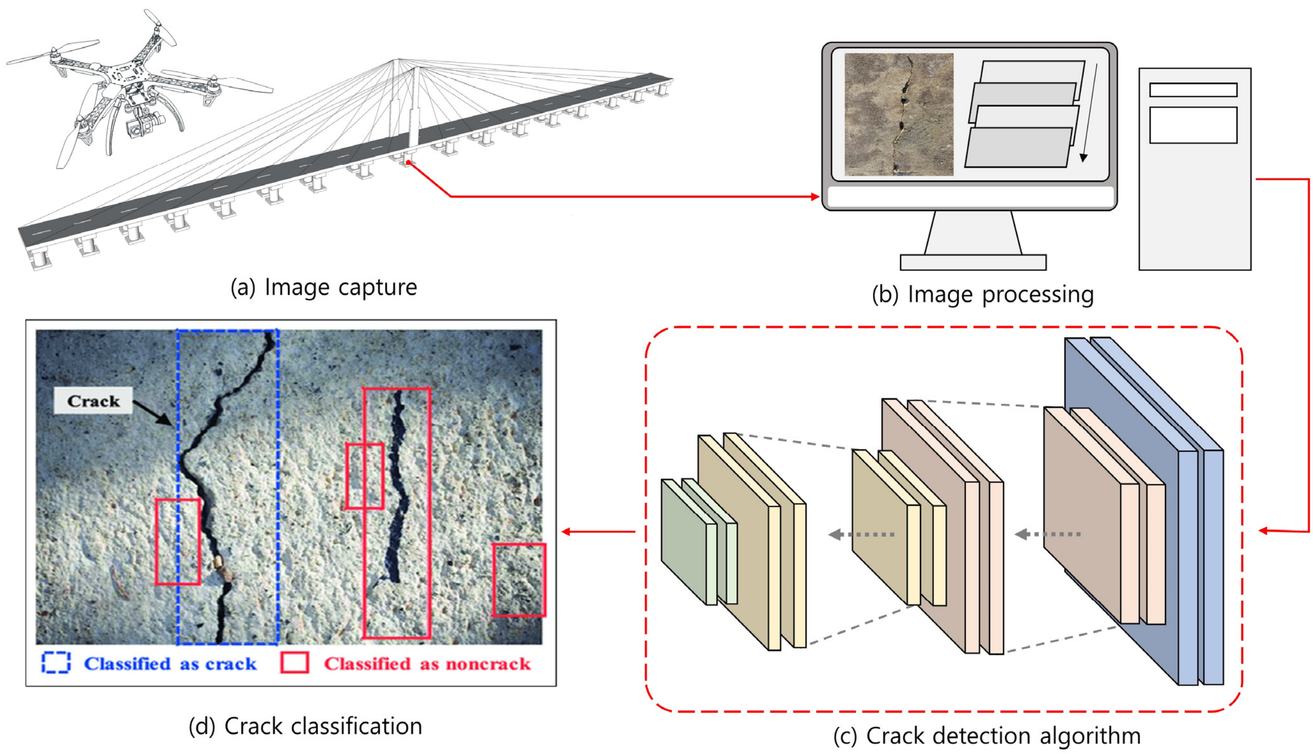

Figure 8. General concept of crack damage detection using a drone [144].

5.2. Drone Equipped with LiDAR for Structure Maintenance

LiDAR is a remote sensing technology that uses laser light to measure distances and create detailed 3D maps of the surroundings. It is often referred to as the optical equivalent of radar, as it uses light instead of radio waves. In a typical LiDAR system, a laser emitter emits short pulses of laser light, usually in the infrared range. These pulses of light are directed towards the target object. When the laser light hits an object, a fraction of the light is reflected back towards the LiDAR system where the time taken for the laser light to return is calculated to measure the distance between the system and the object. By combining these distance measurements with the known position and orientation of the LiDAR device, a point cloud of the surrounding environment can be generated, which represents the location and shape of objects.

Drones equipped with LiDAR technology can be a powerful tool for structure maintenance to ensure safety as they offer a wide range of advantages and opportunities for efficient and effective inspection and monitoring of various structures, including buildings, bridges, and industrial facilities. The ability to generate accurate 3D point cloud data of structures can be utilized for the precise mapping, modeling, and visualization of the structure, providing valuable insights for maintenance and assessment purposes [145–148]. These data can be processed and analyzed to detect and identify various structural issues, including cracks, deformations, and corrosion [131,149]. By comparing the captured data with reference models or previous scans, changes in the structure's condition can be identified, allowing for timely maintenance interventions and the prevention of further deterioration or failure.

While the utilization of LiDAR-equipped drones for structure maintenance holds immense potential, it is important to consider the challenges associated with this technology. Data processing complexity is one such challenge, as the captured LiDAR data require specialized software and expertise to convert it into useful information for analysis [150,151]. Skilled operators are required to operate the drones and process the collected data effectively. Another challenge lies in adverse weather conditions. Rain, fog, or other inclement weather can affect the performance of LiDAR systems, potentially reducing data quality or hindering data collection altogether. This limitation necessitates careful planning and scheduling of drone operations to ensure optimal weather conditions for data collection. Sensor accuracy is another aspect that requires attention. While LiDAR sensors offer high precision, variations in sensor quality or calibration can impact the accuracy of the captured data. The regular calibration and maintenance of the LiDAR system are crucial to ensure reliable and accurate measurements. Signal interference is also a consideration when using LiDAR-equipped drones. Obstacles such as trees, power lines, or other structures in the vicinity can obstruct the LiDAR signals, leading to incomplete or distorted data. Proper flight planning and obstacle avoidance algorithms are essential to mitigate these interference issues and ensure data integrity.

To address these challenges, researchers are exploring advanced data processing techniques to streamline the analysis of LiDAR data and extract meaningful information more efficiently. Improved sensor technologies and calibration methods are being developed to enhance the accuracy and reliability of LiDAR measurements [152–155]. Moreover, advancements in drone navigation and obstacle avoidance systems are being pursued to ensure safer and more precise operations, even in complex environments [156–160]. Integration with other sensing technologies, such as thermal imaging or multispectral cameras, is also being explored to enhance the inspection capabilities of LiDAR-equipped drones and enable a more comprehensive assessment of structural conditions.

5.3. Drones Equipped with Thermal Camera for Structure Maintenance

Thermal cameras mounted on drones enable the capture of thermal images, providing valuable insights into temperature variations and potential issues within the structures being inspected [118,161–163]. Thermal cameras capture infrared radiation emitted by objects, allowing the visualization of temperature variations. By detecting these temperature differences, thermal camera drones can identify various structural issues, including insulation problems, moisture infiltration, electrical faults, and thermal bridges. The ability to identify these anomalies at an early stage enables proactive maintenance and prevents further damage or deterioration.

Once thermal images are acquired, image processing and analysis techniques are employed to extract valuable information and identify potential anomalies. Image enhancement, noise reduction, and temperature calibration are crucial steps in preparing the thermal data for analysis. Advanced algorithms and machine learning approaches can be applied to automate the anomaly detection process, improving efficiency and reducing the burden on inspectors.

Several case studies and real-world applications have demonstrated the effectiveness of thermal camera drones in structure maintenance. These applications include monitoring the energy efficiency of buildings, assessing the integrity of infrastructure, inspecting solar panels, and identifying insulation or HVAC (heating, ventilation and air conditioning) system failures. The use of thermal camera drones for structure maintenance offers significant advantages in terms of accessibility, early anomaly detection, and cost-effectiveness. With continued advancements in drone technology, thermal imaging capabilities, and data analysis techniques, the integration of thermal camera drones into standard maintenance practices holds immense potential for enhancing the safety and longevity of structures.

6. Challenges and Opportunities

With the opportunities provided by the wide application of drones using in civil engineering projects, there are still challenges that need to be addressed to fully leverage the potential of drone technology in this field. For all three phases of design, construction, and maintenance, one of the crucial challenges is its limited flight time and range as battery life remains a significant constraint for drones. Most commercial drones have relatively short flight durations, limiting their ability to cover large construction sites or inspect extensive infrastructure. This limitation hampers their overall operational efficiency, requiring frequent battery replacements and recharging. Currently, research and development efforts are continuously improving battery energy density and recharge rates, allowing drones to operate for longer periods and cover greater distances. The adoption of alternative power sources, such as fuel cells, solar panels, or wireless charging, could potentially eliminate the need for frequent battery replacements, enhancing operational efficiency. Environmental conditions such as strong winds, rain or fog can impede drone operations affecting project time which is another challenge for drones. Drones are susceptible to turbulence caused by high winds, and precipitation can damage sensitive electronic components, leading to potential downtime and increased maintenance costs. Designing drones with robust structures, waterproofing, and advanced navigation systems can enable them to withstand harsh weather elements and continue operations in challenging environments safely. With the opportunities that lie ahead with drone technologies to improve safety at construction sites, monitoring processes, surveys, 3D modeling and more, civil engineers can harness the capabilities of drones to drive innovation, optimize project management, and promote safer and more sustainable infrastructure development.

7. Future Directions

Over the years, drone technology has evolved and become more sophisticated, offering a wide range of applications in areas such as those shown in this study. From this, we can predict that future drones will be equipped with advanced automation and AI capabilities to conduct missions with minimal human intervention such as autonomous flight planning and obstacle avoidance. AI-powered drones can autonomously navigate complex terrains, identify and assess potential hazards, and conduct advanced data analysis. This automation streamlines data collection, data processing, and reporting, enabling civil engineers to make informed decisions faster and more accurately. Furthermore, improvements in battery technology and drone design will lead to extended flight times to allow drones to cover large areas in a single flight, making them more effective for tasks where an extensive reviewer works on energy storage systems, as can be found in reference [164].

An extremely encouraging prospect for the future of drone applications in the civil industry involves incorporating 5G connectivity. The advanced capabilities of 5G networks, including substantially higher data transfer rates, remarkably low latency, and expanded capacity, enable seamless real-time communication between drones and ground stations. Through the implementation of 5G-enabled drones, civil engineers gain the ability to remotely oversee construction sites and infrastructure with enhanced accuracy and efficiency. This seamless exchange of high-resolution data and live video feeds empowers them to make agile decisions, enabling swift responses to dynamic project conditions. Collaborative swarm technology is another area which needs to be further researched in the future for drones as their ability to operate in swarms will revolutionize various civil industries. Drones working together will enhance efficiency and data collection capabilities which can be applied at construction sites. Such technology could possibly increase the demand for drones and with the increase in numbers, one cannot ignore that there will be a strong emphasis on making drones more environmentally friendly and sustainable. This could involve using bio-inspired designs, energy-efficient propulsion systems, Micro Air Vehicles [165], and materials with reduced environmental impact.

8. Conclusions

In conclusion, the review of drone applications in the construction industry underscores their significant contributions across various phases of the construction process, including design, construction, and maintenance. The utilization of different types of drones has proven to be immensely beneficial in enhancing efficiency, accuracy, and safety within the industry.

During the design phase, drones equipped with high-resolution cameras and advanced mapping capabilities have revolutionized site surveys and aerial mapping. These drones enable construction professionals to gather precise data, generate accurate 3D models, and assess topography. This, in turn, facilitates informed decision-making and enhances the overall design process. In the construction phase, drones have played a vital role in monitoring construction progress, conducting inspections, and ensuring safety. Equipped with real-time video transmission and thermal imaging cameras, drones provide a comprehensive and timely overview of the construction site, identifying potential issues for increasing productivity. Furthermore, drones have also demonstrated their utility in the maintenance phase of construction projects. By conducting routine inspections of structures, buildings, and infrastructure, drones efficiently detect and identify any damages, enabling proactive maintenance, cost reduction, and the prolongation of asset lifespan.

Overall, the integration of drones in the construction industry has brought about transformative advancements in efficiency, accuracy, and safety across all phases of the construction process. As technology continues to advance, it is expected that drones will increasingly play a critical role in shaping the future of the construction industry, empowering professionals to achieve higher productivity, minimize risks, and deliver projects of exceptional quality.

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