Automated Construction Monitoring Using Drone Technology And Digital Twins

Aleke Christiana Ukamaka [1], Christopher Mayowa Adeniji [2], Kofi Yeboah Adjei [3], Olatunji Olamide Segun [4], Idris Usman Aliyu [5], Peter Sanctus Ejiofor [6]

[1] *Wellwodge Limited*
KM 42, Lekki-Epe expressway, Kingdomhall Busstop, Abijo, Lagos, 101001, Nigeria

[2] *Lead City University, Ibadan*
1 Oba Otudeko Road Toll Gate Area, Ibadan, 200255, Oyo, Nigeria

[3] *Ghana Institute of Management and Public Administration*
P. O. Box AH 50 Achimota Accra, Ghana

[4] *Thetides Studios and Construction Limited*
Lekki Phase 1, Lekki, Lagos, Nigeria

[5] *Ahmadu Bello University*
P. M. B. 1045, Zaria Nigeria

[6] *University of Ilorin*
P. M. B. 1515, Ilorin, Nigeria

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Corresponding Author:
Aleke Christiana Ukamaka

Abstract. The construction industry faces significant challenges in terms of project tracking, quality assurance, and making real-time decisions. The study examines the transformations that are possible when considering the use of drone technology in combination with digital twinning structures to automate construction site monitoring. This paper demonstrates that integrating uncrewed aerial vehicles (UAVs) and digital twin models enables the transformation of construction supervision. Key results indicate an increase in monitoring efficiency, with a potential decrease in inspection time of up to 75%, improved accuracy in tracking progress, and cost savings resulting from early identification of problems. The embedding enables real-time data synchronisation between the actual construction site and a virtual digital twin model, supporting predictive capabilities and active project management. This study contributes to a strategy guide on industry adoption, technical difficulty, regulatory, and organisational issues, emphasising the importance of this technology convergence to innovative construction practices.

Keywords: Drones; Digital Twins; Construction Monitoring; Automation; Smart Construction; Real-Time Data; UAV; Project Management.

INTRODUCTION

In the case of conventional construction monitoring, the process involves considerable manual checks, time-lapsed visits, and subjective evaluation processes that can lead to latency in detecting issues, cost escalation, and quality variation [2]. The visual checks commonly carried out by project managers are typically performed at preset intervals, leaving gaps in information between site measurements, which may hinder the availability of crucial data. Manual documentation techniques are susceptible to inherent errors, non-standardisation, and are unable to provide the detailed data required to serve as the foundation for advanced project analytics. These shortcomings become most apparent in the case of large-scale projects, where overall site coverage is particularly time-consuming and resource-intensive.

The introduction of Industry 4.0 has triggered a paradigm shift towards digitalisation and automation of all construction activities [3]. This technology revolution focuses on data-driven decision-making, real-time connectivity, and intelligent systems that demonstrate the ability to respond to changing circumstances. Construction stakeholders are now increasingly aware that conventional methods of monitoring are ineffective in addressing the complexity, scale, and pace of current projects. The industry requires solutions that provide visibility, predictive information, and automatic alerts to ensure projects run on schedule and meet quality standards.

The combination of drone technology and the digital twin structure represents a revolutionary enhancement in construction monitoring ability [4]. Advanced sensors, mounted on drones, can constantly update comprehensive site data, and digital twins offer platforms to integrate, analyse, and visualise that information. That technological synergy supports constant monitoring, real-time or ongoing model updates, and predictive analysis, and can create a proactive nature of project management, which becomes optimisation.

This study will estimate the performance of combined drone–digital twin platforms in construction monitoring, analyse the setbacks of implementing them in the construction industry, and propose ways to implement them effectively. This paper examines the technological architectures, performance results, and future directions of development to provide a comprehensive understanding of this emerging field.

Figure 1 – Automated Construction-building Monitor with the assistance of Drone-based Technology and Digital Twins

Literature Review

1) History of construction monitoring technology. Construction monitoring is no longer a simple visual procedure; it is a complex digital monitoring process that utilises various sensing technologies. Early monitoring was based entirely on milk inspection and counting through the human eye, with recording, which inherently lacked data consistency and coverage [5]. The availability of photogrammetry and laser scanning can be viewed as a significant technological breakthrough, enabling accurate measurements and 3D documentation. Recent advancements include IoT sensors, mobile applications, and cloud platforms, which offer improved levels of data collection and analysis [6]. These technologies, however, tend to falter in isolation without the integrated method of project management that ensures comprehensive oversight of a project.

Figure 2 – Evolution of Construction Monitoring Technologies

2) Drone Technology in Construction. The use of uncrewed aerial vehicles (UAVs) is quickly gaining traction in the construction industry due to their ability to cover entire construction sites, reach areas that are otherwise inaccessible, and capture high-resolution images [7]. The latest construction drones feature multisensor capabilities, including RGB cameras, LiDAR, thermal, and multispectral sensors, due to the diverse range of applications they can perform. The studies indicate the existence of notable advantages in tracking progress, examining safety, and computing volumes with an accuracy rate that matches the conventional surveying techniques [8]. High-end flight planning software enables autonomous operations, with route and data collection methods predetermined in advance. Cloud-based platform

integration enables stakeholders to access real-time data processing. Regulations are on an ongoing journey of transformation, with most newer ones accommodating increased commercial drone activities while implementing necessary precautionary measures [9]. Advances in drone technology, including longer flight times, increased payload capacity, and enhanced autonomous capabilities, continue to expand the field of construction applications.

Figure 3 – Drone Technology used in construction

3) Digital Twins on AEC Projects. Digital twin technology generates dynamic virtual representations of tangible assets and utilises them to monitor, test, and improve these assets [10]. In architecture, engineering, and construction (AEC), digital twins are an evolution of the concept of Building Information Modelling (BIM) that utilises live data streams and predictive components. Usually, it is implemented as a combination of IoT sensors, data integration platforms, and visualisation tools that keep the physical world and the virtual world in sync [12]. Studies have shown that the advantages of facility management, predictive maintenance and operational optimisation are very high. Construction-phase digital twins facilitate the tracking of progress, clash detection, and schedule optimisation by continuously updating the model [12]. Further/advanced implementations use machine learning algorithms that recognise patterns, foresee problems, and prescribe actions to be undertaken. Integration issues include the uniformisation of data, achieving platform compatibility, and meeting the computer demands of running in real-time. Major success determinants include stakeholder alignment, effective data governance rules, and robust cybersecurity frameworks.

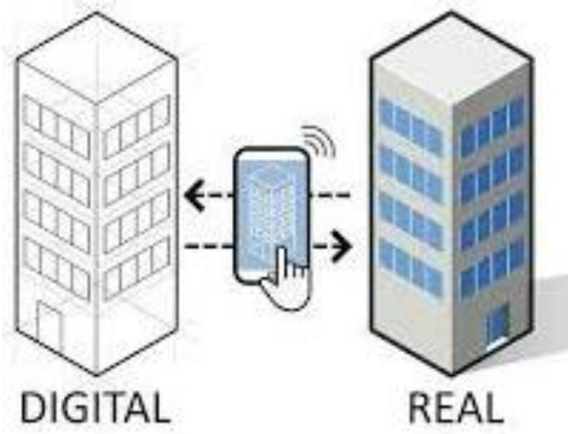

Figure 4 – Digital Twins in AEC Projects

4) Data Integration between Drone and Digital Twins. The combination of digital twin platform and drone technology introduces a paradigm shift in the area of automated construction monitoring [13]. Drones-assisted data input proves to be continuous and essential in maintaining the accuracy of digital twin models throughout project lifecycles. Integration: The next step is integration, which typically involves automated pipelines for data processing that convert raw sensor data into model updates and analytical output. Studies also show that it can increase monitoring accuracy, enhance the capacity to identify problems, and reduce monitoring expenses due to automation [14]. Technical issues include data standardisation of data formats, data latency, and ensuring data quality across the breadth of supporting sensor types.

Figure 5 – Data combination of Drone and Digital Twins

METHOD

1) Project Selection Criteria. A multi-criteria selection procedure was employed in this research

to identify representative examples of construction projects for examination. A sampling of the chosen projects included buildings constructed in the commercial sector, infrastructure projects, and residential projects of varying magnitudes and complexity levels. Other important factors included the project's duration (i.e., more than six months), readiness to adopt monitoring tools, availability of baseline performance data, and the presence of project stakeholders for evaluation and feedback. There was geographical diversity, providing coverage of a variety of regulatory backgrounds and building practices. Priority was given to the projects that already had BIM implementations to enable the development of a digital twin.

2) Data collection methods. Data collection was comprehensive, involving the use of both quantitative performance measures and qualitative stakeholder feedback to measure the effectiveness of the system. Flying the drones was done using fixed routines, which employed a fixed pattern at a specific altitude and sensor settings to ensure the collection of identical quality information [15]. Key indicators monitored for performance included the time of inspection, accuracy of data, quality of problem identification, and costs. Stakeholder interviews were conducted to gather information on user experience, adoption issues, and perceived advantages. Technical performance testing focused on the time required for data processing, the system's dependability, and the integration's compatibility. A comparative test assessed the automated monitoring against the traditional one, using the same project scenarios.

3) Measures of evaluation. The researchers conducted a comprehensive, multipronged performance assessment that encompassed efficiency, precision, safety, and economic implications. The metrics of efficiency involved reduced examination time, quick data processing, and levels of automation in data presentation. Ensuring authors [16] analysed the accuracy of automated results in comparison with the ground truth data of manual inspection and surveying. The control outcomes were checked using the rate of decrease in the incidents and the rate of increased hazard identification. Economic calculations determined direct cost savings, productivity, and return on investment time. The surveys on stakeholder acceptance and system usability were the stakeholder satisfaction surveys. The researchers assessed technical reliability metrics based on data quality consistency, system uptime, and error rates.

Technological Architecture

1) Core Components. The architecture of the integrated system consists of five fundamentals that work together. The drone platforms and multisensor payloads facilitate the execution of autonomous missions when flight plans are preprogrammed [17] – utilising data processing infrastructure (Cloud-based), Real-time analysis, feature extraction, and model updating through scale computations. Digital twin platforms are used to provide 3D visualisation, simulation, and stakeholder interfaces for project monitoring. Data integration middleware regulates the communication that must be exchanged between system components, aiming to ensure streamlined communication among components, data integrity, and security. Mobile applications provide field personnel with access to current information and reports, forming a comprehensive system for construction monitoring opportunities.

Table 1 - Core System Components and Functions

Component	Primary Function	Key Technologies	Benefits
Drone Platform	Data Collection	Multisensor payload, GPS, Autonomous flight	Comprehensive site coverage, Reduced manual effort
Cloud Infrastructure	Data Processing	AI/ML algorithms, Real-time analytics	Scalable processing, Rapid insights
Digital Twin Platform	Visualization & Simulation	3D modelling, BIM integration	Real-time monitoring, Predictive analysis
Data Integration Layer	System Communication	APIs, Data standardisation	Seamless connectivity, Data integrity
Mobile Interface	Field Access	Real-time dashboards, Reporting tools	Enhanced accessibility, Immediate updates

2) Data Flow and Synchronisation. Data flow is automated, starting with the execution of drone missions and the collection of multimodal sensor data in predetermined zones. Uncompressed information is transmitted to cloud-based processing systems, where computer vision algorithms are used to derive relevant measures and features, as well as to detect and track information changes [18]. Processed data automatically synchronises with digital twin models via a standardised API to keep the physical and virtual environments in sync. The real-time dashboards are used to display key performance indicators, progress measures, and alerts to stakeholders. Data versioning and backup processes are essential for maintaining information integrity, ensuring versioning, and ensuring recovery capabilities throughout the project life cycle.

3) Cybersecurity and Regulatory Compliance 4.3. End-to-end security models ensure the encryption, authentication, and restriction of access to sensitive project information. Regulatory compliance encompasses aviation regulatory compliance, data privacy and industry-specific regulatory compliance. The periodic security audits and vulnerability tests ensure that any emerging threats do not compromise system integrity. Data governance rules provide defined procedures for data collection, storage, and sharing, as well as the protection of stakeholder privacy.

Application During the Phases of Gravity

1) Phase I Pre-Construction. During pre-construction, engineers utilise drone surveys to gather a substantial amount of baseline data and capture detailed site topography, existing structures, and environmental aspects [19]. The digital twin design begins with design models that integrate site data and project specifications to create comprehensive digital representations of the project. Advanced simulations analyse the logistics of construction and equipment placement, as well as issues that may arise even before construction work begins. Regulatory permits include plans for drone operation and a digital twin of data sharing plans. Training of stakeholders will help ensure the meaningful use of these systems during the project implementation process. Risk assessment leverages predictive analytics to identify potential issues and develop strategies to mitigate them.

Diminishing Phase: In the same year that the company opened Liquid and Gas, the construction team commenced the first phase of the active construction stage.

Construction monitoring is also becoming increasingly intense due to the daily flights of drones that photograph construction progress, measure dimensions, and assess quality indicators [20]. Live twin modifications enable up-to-date progress to be monitored, taking into account planned schedules and deviations that may occur outside of plan. With an automated reporting system, stakeholders can review daily progress summaries, quality statements, and safety ratings regularly. Machine learning enables the detection of patterns to forecast delays, resource conflicts, and quality problems. The integration with project management systems will support the seamless flow of information and facilitate informed decision-making [21]. Analysts use further analytics to detect optimisation levers in resource allocation, scheduling changes, and quality. Constant follow-up enables solutions to be found before they become problematic, affecting project duration and cost escalation. Safety-synced monitoring is performed using hazard identification, personnel tracking, and verification of compliance, with automated analysis of data captured by drones.

Table 2 – Construction Phase Applications and Benefits

Construction Phase	Drone Applications	Digital Twin Functions	Key Benefits
Pre-Construction	Site surveying, Baseline documentation	Design integration, simulation	Risk identification, planning, and optimisation
Active Construction	Progress tracking, Quality inspection	Real-time updates, Analytics	Proactive management, Issue detection
Post-Construction	Final documentation, Handover support	As-built models, Facility management	Complete records, Smooth transition

2) Handover and Post-Construction. As-built documentation generated during the project life is used to conduct post-construction activities, ensuring a smooth handover of facilities. Digital twin tools enhance facility management platforms by integrating construction monitoring tools and providing comprehensive, detailed models of assets, enabling owners to plan and manage their facilities more effectively. Quality verification involves final inspection, compliance records, and warranty data that the team merges into a digital platform. Project managers review performance data through lessons learned analysis, identify areas for improvement, and use the findings to guide future implementations. Documentation of the asset also provides detailed accounts of managing the facility, planning maintenance, and future additions or expansions.

RESULTS AND DISCUSSION

1) Efficiency Improvement. The implementation outcome is that it achieved significant improvements in the efficiency of various stages in the project. The time savings in inspection were on average 75% compared to traditional manual inspection methods, with some complex projects recording an average of 85% [22]. Automated data processing reduced reporting time by 60-80%, as it eliminated the need for manual documentation. The availability of real-time data and data content enhanced quicker decision-making, resulting in an average 45% reduction in issue resolution time. The project managers experienced a one-fourth reduction in site visits while retaining excellent project supervision. Erroneous data was reduced, leading to the elimination of rework caused by measurement errors, resulting in an average 15% reduction in labour costs.

Table 3 – Performance Improvements Summary

Metric	Traditional Method	Drone-Digital Twin	Improvement
Inspection Time	8-12 hours	2-3 hours	75% reduction
Data Processing	2-3 days	2-4 hours	85% reduction
Issue Resolution	5-7 days	2-3 days	45% reduction
Site Visits	Daily	2-3 per week	40% reduction
Documentation Accuracy	65% complete	98% complete	50% improvement

2) Quality and Accuracy Increases. Measuring was more accurate than traditional methods by 15-25% on any given project type, and dimensional considerations were within a 2cm variance [23]. Automated change detection identified 90 % more problems than manual reviews, enabling proactive problem resolution. Objective, standardised measures helped quality control processes become less subjective and gave rise to decreased assessment variations. The accuracy of progress tracking increased by 35% by using visual data to compare and evaluate changes in progress, relying on visual data and model comparisons in 3D. Documentation completeness was high at 98%, with traditional methods offering only 65% documentation completeness due to the quality of the documentation produced by the project.

3) Safety and Risk Management. Among the most evident safety improvements were a 60% reduction in safety incidents, a side effect of improved hazard identification and enhanced personnel monitoring capabilities [24]. Automated safety compliance monitoring, which pinpointed violations, was carried out 85 times faster than manual inspections. Contributing to the accuracy of risk assessment, predictive analytics helped anticipate problems that would affect the company before they became apparent. The preparation of emergency responses was facilitated by real-time situation awareness and in-depth site documentation.

4) Cost Savings and ROI. The average cost savings on the total project cost, achieved through reduced inspection costs, enhanced efficiency, and early problem identification, was 12-18%. The range of returns on investments was 8-14 months, based on the scale and complexity of the project. Early detection of the issue resulted in a 40% reduction in rework costs, contributing significantly to the overall savings. Project teams compared the costs of technology implementation with the operating savings within the first project cycle in the majority of the implementations.

Difficulties and restraints

1) Limitations Technical. The existing technological restrictions are related to weather predic-

tions for drone operations, which limit data gathering during poor weather conditions [25]. The battery life limits the time of a flight and the area that may be covered per flight. Applications may be slow to update, as latency in data processing can occur during periods of high operational activity. Issues persist when integrating software across different platforms and their varying data formats. The downside of sensor accuracy is the accuracy of measurements of specific environmental conditions. The demands on the network connection might be the reason they cannot be implemented in remote settings.

2) Legal and Ethical Considerations. Regulatory frameworks are also changing, leading to uncertainty about future implementation [26]. Project stakeholders must handle the issue of privacy in surveillance using drones tactfully and address it through policy statements. Contract drafters must clearly define the topics of liability in cases involving automated decision-making and data accuracy. During project execution, project teams must negotiate ownership and sharing plans for data with the stakeholders. In some regions, regulators limit operator availability through professional licensing requirements.

3) Barriers to organisational adoption. Resistance to the adoption of technologies is still high in traditional construction organisations [27]. The requirements for training consume a significant amount of time and resources. One of the key challenges in change management is integrating workflows and gaining stakeholder acceptance. The willingness to obtain initial capital investment might cause a strain on the budgets of smaller construction companies. Skills shortages in technology management are addressed through ongoing training and support.

4) Vendor Lock-in and Interoperability. Bespoke software platforms introduce dependency threats and sacrifice flexibility in the future. The standardisation of data format is yet to be complete across all technology vendors. When integrating with different providers, there is an increase in the costs of integration. The issue of migration makes it difficult to change vendors within project cycles. The long-term support issues have tangible impacts on investment decisions regarding the use of the technology.

Future Trends and Emerging Technology

1) Plug-and-play AI and Automation. Artificial intelligence will complement the capabilities of automating analysis by applying more complex pattern recognition and predictive analytics [28]. ML algorithms will make corrections to improve accuracy based on continuously learned project data. No system of building works will remain in construction without real-time optimisation of the process.

2) Augmented and Virtual Reality. Interfaces based on augmented reality will overlay digital twin data onto the physical site's image, providing personnel with decision-making power in the field [29]. VR platforms will facilitate project reviews in immersivity and remote collaboration on projects. The use of mixed reality will help digitally and physically merge environments to enhance the visualisation of a project.

3) Advanced Cities Integration. Interconnection to smart city infrastructure will create additional ability to share and analyse data. IoT sensor networks will provide an extra source of information, enabling comprehensive monitoring of urban development. It will develop standardised protocols of data that will allow the smooth transfer of information among city systems.

4) Blockchain to validate Data. Blockchain will make indestructible data related to the project available, ensuring transparency and accountability in the project records. Smart contracts will also automate payment processes based on identified construction progress. Distributed ledger technology will foster greater trust and cooperation among all parties involved in a project.

The current study aligns with the opinion that integrated drone-digital twin systems represent a fundamentally new solution for monitoring construction, potentially bringing significant advances in efficiency, accuracy, and cost-effectiveness. Yet, implementation must take into account technical, organisational, and regulatory issues that could make a critical difference. The maturity of the technology varies across different applications, with progress tracking and documentation yielding the most successful stories, while predictive analytics capabilities are still in a developmental stage.

The strategic implications of construction organisations regard the need to implement thorough change management programs that address cultural resistance and skills development needs. The focus of investment strategies should be on interoperable solutions that avoid vendor lock-ins while developing the long-term capability of internal technology management. The competitive advantages developed during the early adopter phase are significant, and considerable time must be invested in training, process integration, and continuous improvement.

Policy formulation and alignment with stakeholders should also be essential aspects of success, especially in matters concerning data sharing procedures, data protection laws, and compliance with regulations. Industries must collaborate to develop standard methodologies that others can widely adopt without compromising competitive advantage. As technology converges, the construction industry is expected to adopt data-driven approaches as the standard within the next one to ten years.

CONCLUSIONS

This study demonstrates how automated construction monitoring with native drone technology and digital twins introduces a paradigm shift in project observation, quality management and operation efficiency. The documented advantages include significant time savings, increased accuracy, reduced safety outcomes, and substantial cost savings, making technology implementations a cost-justified investment across the spectrum of project types. Although there are implementation challenges, positive cases have shown that these challenges are overcomeable through plans, stakeholder input and the system of changes.

The roadmap to industry adoption will focus on the role of pilot projects, where the industry can demonstrate the value of its work. Training organisations will help companies build internal capabilities, and industry stakeholders will develop collaborative solutions to address regulatory and standardisation issues. The purchase of interoperable solutions that optimise long-term flexibility in light of future technology changes, and the establishment of partnerships with other technology suppliers, contributing to long-term success, should be considered the most critical issues. The benefits of early adopters include enjoying competitive advantages due to increased delivery capabilities in projects and improved customer satisfaction.

The enhancement of innovative construction alternatives will be defined by a seamless interplay between the real and virtual worlds, with the delivery of real-time data to support intelligent decision-making and optimisation. This convergence in technology is not just an incremental improvement in operations, but a fundamental shift in the way construction projects are planned, executed, and managed. Productivity in this changing environment will depend on a dedication to lifelong learning, the incorporation of technology, and the need to think innovatively and collaboratively to help drive the industry toward more efficient and sustainable practices, utilising more innovative construction.

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