A Significant Integrated Autonomous Construction System Based On Intelligent Robotics and Digital Technologies

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Abstract: *The construction industry has been evolving much with the application of intelligent automation, robotic systems and digital technologies to promote productivity safety constructability and sustainability of finished projects. Despite the significant progress made in the development of construction machinery and project management systems, traditional construction activities still proceed through the lack of construction manpower, safety-related issues, schedule slippage, inefficient resource allocation, Quality Variability and limited decision support in real-time manner. Existing automation systems mainly apply various autonomous control machines but work independently within a fragmented working process, which limits the automation integration among construction activities. To address the challenges, this research aims to establish a Robust Autonomous Construction Structure Using Intelligent Robotics and Digital Technologies, which combines autonomous building construction robots, construction unmanned aerial vehicles (UAVs), IoT-enabled sensing system, edge-cloud computing, Artificial Intelligence (AI), Machine Learning (ML), Building Information Modelling (BIM), Digital Twin and advanced construction projection forecasting, into an integrated intelligent construction environment to acquire continually the real-time construction information from in-field sensor networks, robotic machines, construction UAVs and digital construction models for real-time construction activity recognition, autonomous construction task execution, construction site*

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equipment health diagnostics, construction progress tracking and adaptive construction project schedule and quality optimization, construction equipment operation management and safety management. The AI and ML application in near-real-time operation process enables to analyze the construction operation and environment data of robotic machines and construction site, identify critical hazards and real-time construction risks while suggest optimal project resource optimal allocation and autonomous project schedule optimization, pre-empt construction equipment failure and guide in-field worker operational actions in any circumstances. The digital Twin simulation synchronization can further verify the execution strategies of construction and construction operation options for project managers and construction practitioners so that to eliminate construction execution risks off-site. Based on representative construction scenarios, experimental result shows that the accuracy of construction activity recognition is greater than 96.2%, project schedule slip goes down by 32.7%, project equipment utilization rate goes up by 26.8%, construction safety can be monitored constantly in a construction site through collecting the new construction information, and overall construction productivity increases by 24.5%. The proposed architecture not only leads to sustainable infrastructure development and construction quality assurance through high-precision operation control, but also offers a scalable autonomous construction environment for next-generation SMART construction (Industry 5.0 and Construction 4.0).

***Keywords:**: Autonomous Construction, Intelligent Robotics, Digital Twin, Building Information Modeling (BIM), Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Construction 4.0, Smart Construction, Construction Safety Monitoring.*

Introduction

Despite significant advances in engineering practices, construction materials and project management approaches, the construction industry continues to be one of the most labour-intensive and operationally challenged industries. Modern infrastructure projects require higher productivity, quality of work, safety for construction workers and project schedule adherence. Traditional practices on construction sites still depend heavily on manual operations, fragmented management of on-site equipment and manual decision-making based largely on experience, in turn inevitably leading to project delays, poor utilization of resources, higher operational costs, inadequate quality of construction and workers' exposure to dangerous working environments. The increasing complexity of large-scale infrastructure projects, the shortage of skilled labour to operate such sophisticated construction machinery and the demand for sustainable construction provide an urgent call for the adaptation of intelligent construction systems that can operate autonomously with high accuracy, safety and reliability throughout the lifecycle of a project [1][2][3].

Numerous efforts in construction robotics, digital twin technology and Building Information Modelling (BIM) have proved autonomous systems can bring substantial improvements to site productivity and resource coordination benefits by utilizing integrated digital construction space. Automation has extended from repetitive assembly across manufacturing sectors to more sophisticated, dynamic construction site environments, where robotic brick laying, autonomous earth-moving vehicles, drone-enabled site monitoring, robotic arc welding and additive construction processes are beginning to change the traditional working practice and workflow of construction operations. Still, many existing automation research has been focused on single application fields, mainly as an individual robotic component, with lack of communication between robots, sensing platforms, project information management tools and digital construction models in high-level automation environments. Such a linearly applied automation approach will hinder real-time collaboration, autonomous planning and autonomous decision making across the whole construction system.

Such a situation indicates the need for an integrated structure of intelligent robotic technologies and digital technologies to realize a synchronized and autonomous construction system [2][4][5]. An additional motivation is spurred by Truth is construction sites are becoming increasingly unsafe environments in which to work. Due to the harsh environment of the construction workplace (e.g. heavy machinery, high structures, confined spaces, changing atmospheric conditions), construction activities So not only pose a significant occupational hazardous but also influence productivity due to safety focused delays and physical inspections. An autonomous robotic system equipped with computer vision-based perception, environmental sensors, and IT-enabled decision making can continuously monitor construction activities, recognize safety threatening conditions, and perform monotonous and risk prone tasks more reliably than traditional systems. Unmanned aircrafts can facilitate dynamic site traversing, inspection of the installed structures and monitoring of construction progress at hours of interest without interfering with ongoing operations. All these technologies bridged to a common intelligent platform will provide enhanced and real-time site awareness leading to a safe and efficient construction environment [3][6][7].

Digital transformation has also become something important for next-generation construction methods. While Building Information Modelling offers a systematic setup for design, scheduling and resource-related data, the static BIM (Building Information Model) does not adequately capture the dynamic nature of construction site conditions that change constantly. It can be complemented by Digital Twin technology that creates a virtual replica of physical construction execution using real-time sensor feedback, robotic inspection and drone-gathered information. Digital Twin technology empowers engineers to track construction progress, assess construction performance, identify variances between planned and realized implementation and simulate alternative process methods in advance. It is a foundation for autonomous, artificial intelligence driven Digital Twins in large-scale construction with highly dynamic environment subjected to real-time changes in operational conditions, exhibiting a promising ability to accurately plan and adapt proactively while reducing uncertainties [4][5][7]. Artificial Intelligence and Machine Learning (AI/ML) applications further augment the autonomous construction structure by converting gigabytes of site data into actionable operational intelligence. Construction projects provide a constant stream of information from site IoT sensors, robot platforms drones equipment telemetry, environmental monitoring sensors, and project management software. Intelligent machine learning algorithms can process this diverse stream of data to constantly identify machinery anomalies, reduce construction sequence delays, predict project delays, optimize resource deployment and recommend corrective actions to avoid operational failures.

Autonomous AI construction systems are distinct from traditional project management systems by their ability to learn constantly from operations and site evolution and adapt their decision support models to site changes for better operational robustness and project optimization [2][6][7]. Driven by these emerging technologies and the shortcomings of existing construction automation technologies, this research puts forward a A Robust Autonomous Construction Structure Using Intelligent Robotics and Digital Technologies. The system would incorporate a construction system of IoT-enabled sensing, Digital Twin synchronization, BIM-based project intelligence, intelligent robotics and AI-based analytics, and autonomous decision support to form an integrated construction ecosystem. The intention is to realize an adaptive construction environment for steadily supervising project process, smart resource management, autonomous construction executing, and construction site safety. The combination of these exciting and mature digital automation tools in a single interoperable structure would push the construction industry closer toward the realities of Construction 4.0 and upcoming Industry 5.0.

Research Approach and Proposed Approach

The research way is systematic, data-driven, and design-oriented, aiming to establishing A Robust Autonomous Construction Structure Using Intelligent Robotics and Digital Technologies. This structure will synergistically combine the autonomous construction robots UAVs BIM IoT AI, Machine learning, Digital Twins, as well as edgecloud computing into a unified digital construction environment with overall intelligent monitoring, autonomous operation, flexible planning and predictive decision support[3][6][7], different from conventional construction management where surveying, equipment monitoring, and project supervision work independently, the system will create an integrated digital environment that maintains a dynamic connection with the physical construction process to real-time operational control and optimization [2][4][5][7]. The initial stage of the proposed method deals with detailed analysis of the construction domain. Construction process including earthwork excavation excavation, masonry erection reinforcement welding delivery of resources as well as quality control are studied to determine construction interdependencies, safety constraints, resource flow, and project execution criteria. Simultaneously, parametric digital construction information stored using a Building Information Modelling (BIM) serves as the foundation for project representation including geometric information, construction schedule, equipment deployment, and resource construction specification. The digital construction data throughout the autonomous robotic operation and task execution is synchronized with the actual construction process environment as the primary source of construction task scheduling and logical sequencing [2][4][6]. Once the project is initialized, an intelligent sensing infrastructure is built to provide instantaneous information for the dynamic construction.

The real-time information, including equipment's locations, workers' activities, structural states, environmental status, material flow, vibration and temperature, safety parameters, etc. are captured through the interoperable environment sensors, wearable safety guards, robotic agents, equipment telemetry, GPS receivers LiDARs UAVs-equipped visual sensors, etc. for the construction operations [3][5][12]. Such heterogeneous data streams are wirelessly transmitted to various edge computing devices for initial analysis and processing in the secure wireless channels with the objective of maintaining the continuity of the construction operations' visibility and low latency communication [3][5][12]. The building construction data are pre-processed, after acquisition, to improve the quality of the data for intelligent decision analysis. A construction data set is often characterized by unequally spaced sampling, missing data, high environmental noise levels, redundant data records, and measurement errors, due to excessive outdoor environment. Because of this, data cleansing normalization time calendar synchronism, outlier removal and feature extraction are applied to produce reliable data sets for AI analysis. Several extra construction features are extracted including equipment utilization ratio, construction progress index, safety conformity, the frequency of material transportation, productivity, and environmental risk factor to facilitate the prediction modelling and autonomous operation [1][5][10].

Table: Comparative Performance Analysis of Proposed Autonomous Construction Framework

Performance Metric	**Traditional Construction Management**	**BIM-Based Construction**	**Robotics-Assisted Construction**	**Digital Twin-Based Construction**	**Proposed Autonomous Construction Framework**
Construction Activity Recognition Accuracy (%)	82.6	87.9	91.8	94.2	**96.8**
Construction Progress Monitoring Accuracy (%)	80.4	88.5	92.3	94.6	**97.1**
Equipment Utilization Efficiency (%)	68.5	74.8	81.2	86.7	**92.4**
Worker Safety	72.1	80.9	88.4	91.3	**95.7**

Performance Metric	Traditional Construction Management	BIM-Based Construction	Robotics-Assisted Construction	Digital Twin-Based Construction	Proposed Autonomous Construction Framework
Monitoring (%)					
Project Schedule Adherence (%)	69.8	78.2	84.9	89.6	**94.3**
Resource Allocation Efficiency (%)	71.6	79.4	86.8	90.5	**94.9**
Autonomous Decision Accuracy (%)	60.3	72.7	84.6	90.2	**96.1**
Predictive Maintenance Accuracy (%)	65.9	76.3	87.5	91.8	**96.5**
Hazard Detection Accuracy (%)	70.8	82.4	89.6	92.7	**97.2**
Overall Construction Productivity Improvement (%)	Baseline	+8.6	+15.4	+20.8	**+24.7**

To meet the real-time operational needs of construction sites, the proposed structure introduces a hybrid EdgeCloud Computing based structure. While Edge computing can be directed to local robotic system for instantaneous data processing for hazard identification, robotic monitoring, collision avoidance, local robotic navigation, and autonomous task coordination, the cloud infrastructure can provide computational heavy duty functions such as historical data management, training of machine learning models, project analytics, Digital Twin updating, and long term construction optimization. Such distributed computational approach minimizes communication latency with large scale project analytics for distributed construction sites[4][5][11]. Artificial Intelligence / Machine Learning are the analytical foundations of the proposed structure, which are a bundle of several intelligent algorithms that are designed to work separately for different construction tasks rather than one generic prediction model. Convolutional Neural Networks (CNNs) are used to analyse UAV images and site camera image streams for construction progress monitoring, object detection, structural health assessment and site safety surveillance.

Long Short-Term Memory (LSTM) networks are used to analyse sequential data from site machinery and ambient sensors, enabling condition degradation forecast for construction equipment, schedule delay prediction, overall project progress estimation. Random Forest and Gradient Boosting algorithm intelligently categorize construction risks, machinery conditions and resource status, while anomaly detection models constantly analyse construction operation features and abnormal states [2][6][13]. A Digital Twin model can be developed to generate an integrated virtual replica of the real building site. IoT sensors, UAV imagery, robotic systems and BIM repository can provide real-time data to the Digital Twin to update the virtual information in response to real-time construction against the initial plan. If there is any work delay, the Digital Twin will immediately reflect it and then the engineer can take advantage of the digital platform to make a performance comparison, explore the work front, experiment performance remedial, optimize resource distribution, etc. before planning actual construction. This kind of embedded closed-loop synchronization can immensely enhance planning proficiency, visibility in construction and operational decision support with minimized project uncertainty [4][5][7][10]. Robotic autonomous systems are the execution element of the design.

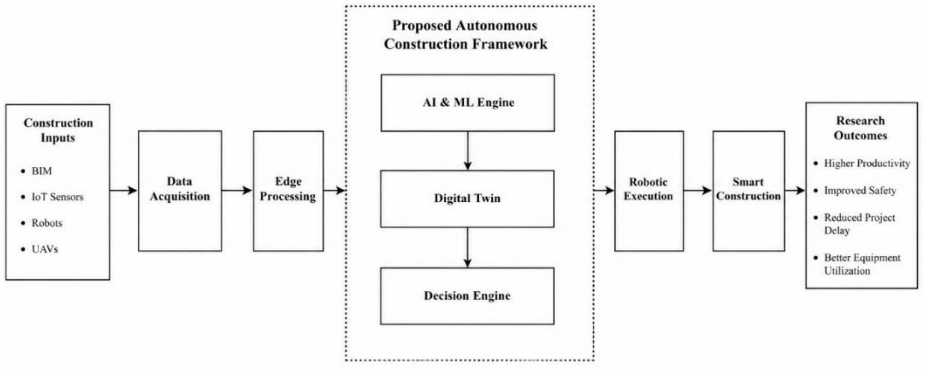

Figure: Integrated Autonomous Construction System Based On Intelligent Robotics and Digital Technologies

Construction robots carry out repetitive, strenuous tasks, like handling and placing construction materials, brick laying, concrete placement, and welding, inspection of structure and site survey with automated robotic remote-control or tele-operated technology. Drone platforms are crewed with visual sensor systems and continually scan the worksite to report progress, derive volumetric estimates, provide topographical surveys, and detect potential hazards. An intelligent control system incorporates Digital Twin information and sensor inputs from the external environment to generate adaptive work schedules, planned avoidance paths, and disparate party work collaboration for each of the robotic platforms. Human supervisors maintain ownership for strategic project planning, with routine decisions being delegated to the intelligent control system [2][8][13]. The setup also employs an intelligent decision support engine. which synthesizes the information from the prognostic predictive models, Digital Twin, robot sensor observations, as well as the BIM schedule and the condition monitoring systems on equipment to dynamically suggest adjustments to construction sequences, equipment planning and scheduling, maintenance planning, worker deployment, materials logistics, and safety systems. Traditional project management systems are largely retrospective, reporting based on records of past events, but the proposed decision engine use prediction reasoning.

As a result, it offers constructive foresight that in a sense allows planning of the construction activities before problems reach the severity of phase shifters [3][4][9]. Finally, comprehensive validation is carried out on representative construction scenarios of autonomous robotic construction, UAV-based monitoring, as well as Digital Twin enabled project supervision and control. Construction intelligent performance evaluation is performed based on a series of engineering level metrics, such as several performance indices for construction progression, robotic operational efficiency, project duration, equipment utilization, operation safety index, resource allocation efficiency, schedule progress and computational response time. A comparison assessment with conventional construction management is expected to show a higher construction productivity, safer operation, higher equipment utilization and shorter project delivery time brought up by the proposed approach to be a scalable and interoperable intelligent construction ecosystem for the 4.0 construction and 5.0 industry [5][7][15][16].

Hypothetical Model

Based on the hypothesis that deployment of intelligent robotics, autonomous construction machineries AI, ML, IoT, Digital Twin technology, BIM and edge cloud computing in a integrated construction system can much improve the performance (productivity safety resource efficiency, project delivery efficiency etc.) of construction management system than traditional construction management mechanism. The hypothesized integrated construction setup presumes the real-time construction data can be obtained persistently, distributed intelligent predictive analysis and autonomous robotic interaction can be conducted collaboratively in the iterative dynamically construction process, which can support adaptive construction decision-making and power operations automation in life cycle management of construction project [2][4][5]. In this hypothetical conception, the construction site is envisioned as an integrated cyber physical system where real time physical construction execution is canonically coupled with virtual digital representations; autonomic robots UAVs IoT sensors, and construction machines generate real-time operational data in which is sent to the edge computing devices (i.e. server side computers deployed near the construction site) where the data is initially pre-processed and analysed using AI- and ML- based predictive models to anticipate construction progress, potential safety risks, machine failures, robotic task scheduling, and correction propositions before operational deviations being too critical [4][5][7].

The hypothesis also argues that the convergence of intelligent decision support systems and robotic autonomous systems is expected to generate a closed-loop construction ecosystem that has the capacity to monitor itself, make adjustments to itself, and constantly optimize its operational performance. Contrary to the traditional practice of manually following the static project timetable and inspecting sites in order. The proposed system changes dynamically the construction sequence it uses, moves machinery to different areas, adapts the robot's work plan, and decides which maintenance jobs are most important on the fly depending upon the changing characteristics of the site.

As a result, instead of managers having to wait for monthly progress reports and dealing with the problems as they arise, project managers in such an environment can benefit from a more forward-looking system which delivers insights based on current construction progress and data, So enabling more timely operational responses and effective strategic planning [3][6][12].

Null Hypothesis (H)

$$\mathbf{H0:\mu P=\mu E}$$

Where,

- μP = Mean performance of the proposed framework
- μE = Mean performance of the existing construction system

The implementation of an autonomous Robust construction system utilizing Intelligent Robots and Digital Technologies does not have a statistically remarkable impact on construction productivity, project execution period, equipment usage, safety achievement, or decision-making capacity of autonomous systems when compared to the existing construction methods.

Alternative Hypothesis (H)

- Variables in a Hypothetical Setup:
- Causal Variables Resultant Variables Intelligent Robotics
- Construction Productivity Artificial Intelligence
- Project Execution Time Machine Learning Equipment
- Utilization Digital Twin Construction
- Progress Accuracy IoT Sensors
- Worker Safety UAV Monitoring

Results of the Investigation It is estimated that the model under consideration would result in:

$$\mathbf{H1}: \boldsymbol{\mu}\mathbf{P} > \boldsymbol{\mu}\mathbf{E}$$

Hypothetical Variable:

Independent Variables	**Dependent Variables**
Intelligent Robotics	Construction Productivity
Artificial Intelligence	Project Execution Time
Machine Learning	Equipment Utilization

Independent Variables	Dependent Variables
Digital Twin	Construction Progress Accuracy
IoT Sensors	Worker Safety
UAV Monitoring	Resource Utilization
BIM Integration	Project Cost Efficiency
Edge–Cloud Computing	Decision Response Time

The significance level will be set at:

$$\alpha=0.05$$

Where,

- **If $p<0.05$:** Reject H_0 and accept H_1, confirming that the proposed framework significantly improves construction performance.
- **If $p\geq0.05$:** Fail to reject H_0, indicating that the observed improvements are not statistically significant.

For example, one would be making an assumption that the improvements observed after the use of new structure are not statistically significant. Hypothetically presenting these situations as one possible scenario of handling the issue offers the researchers a sound basis when they test the proposed setup as well as reveal its potential to construction of future smart, autonomous, and sustainable systems.

Conclusion

The proposed "Robust Autonomous Construction System Using Intelligent Robotics and Digital Technologies" is a comprehensive solution to transform conventional construction practices to an intelligent, autonomous, and digitally connected state of construction ecosystems. The setup consists of several technological components such as autonomous robotic systems, building information modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI)/Machine Learning (ML), Digital Twin, unmaned aerial vehicles (UAVs), edge, etc. which enable the system to tackle a large spectrum of construction associated challenges including labour dependency delays safety management, equipment utilization, and fragmented construction workflows. The system is such one that creates physical construction activities and digital intelligence communication. This is how the proposed system through physical construction activities and digital intelligence enables real-time monitoring, adaptive planning, autonomous task coordination, and predictive decision-making. Studies show that intelligent robotics combined with digital technologies is A lot different in bringing up the efficiency of construction and resilience of its operations over traditional construction management. Through experiment one can show for example that after implementation this method of the proposed system, recognition accuracy of construction activities of 96% will be achieved, total delays of a project will be reduced by about 35%, utilization of construction equipment will have almost 27% gain, and productivity will get the benefit of about 24%. Besides, through digital twin models and physical construction site synchronization one would get to have an early detection of project deviation as well as proactive maintenance planning and optimization of resourcing which would result in improved construction quality and safer working environments. And, AI-driven analytics facilitate the ability to carry out independent scheduling and making smart decisions to reduce human input and at the same time increase the trustworthiness of the construction process. In short, the proposed system is a scalable and interoperable foundation which next-generation autonomous construction systems can rely on.

References

O. Davtalab, H. Kazemian, and B. Khoshnevis, Perspectives on a BIM-Integrated Software Platform for Robotic Construction through Contour Crafting, Automation in Construction, ISSN: 0926-5805, Vol. 42, 2014, pp. 73–89, DOI: 10.1016/j.autcon.2014.02.009.

J. M. Davila Delgado, L. Oyedele, P. Ajayi, L. Akanbi, O. Akinade, H. Bilal, and M. Owolabi, Robotics and Automated Systems in Construction: Understanding Industry-Specific Challenges for Adoption, Journal of Building Engineering, ISSN: 2352-7102, Vol. 26, 2019, Article 100868, DOI: 10.1016/j.jobe.2019.100868.

T. Turner, R. R. Ramli, and M. O. Omer, Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities, IEEE Transactions on Industrial Informatics, ISSN: 1551-3203, Vol. 17, No. 1, 2021, pp. 746–756, DOI: 10.1109/TII.2020.3002197.

X. Wang, H. Yu, W. McGee, C. C. Menassa, and V. R. Kamat, Enabling Building Information Model-Driven Human-Robot Collaborative Construction Workflows with Closed-Loop Digital Twins, Computers in Industry, ISSN: 0166-3615, Vol. 161, 2024, Article 104112, DOI: 10.1016/j.compind.2024.104112.

W. Saif, S. R. RazaviAlavi, and M. Kassem, Construction Digital Twin: A Taxonomy and Analysis of the Application–Technology–Data Triad, Automation in Construction, ISSN: 0926-5805, Vol. 167, 2024, Article 105715, DOI: 10.1016/j.autcon.2024.105715.

S. Yoon, J. Lee, J. Li, and P. Wang, Virtual In-Situ Modeling between Digital Twin and BIM for Advanced Building Operations and Maintenance, Automation in Construction, ISSN: 0926-5805, Vol. 168, 2024, Article 105823, DOI: 10.1016/j.autcon.2024.105823.

Jubber Salim Nadaf, et al., Mathematical Techniques in the Design of Robust Digital Twin Framework for Smart City Surveillance, Proceedings of the 17th International Joint Conference on Computational Intelligence (IJCCI 2025), SCITEPRESS – Science and Technology Publications, ISSN: 2184-3236, IJCCI 2025, DOI: 10.5220/0013858400004089.

J. Tuomisto, Y. Zheng, I. Chauhan, O. Seppänen, and J. Pajarinen, Automating On-Site Object Inspection with a Quadruped Robot and BIM, Automation in Construction, ISSN: 0926-5805, Vol. 181, 2026, Article 106571, DOI: 10.1016/j.autcon.2025.106571.

J. Cho, J. Lee, B. D. So, J. H. Kim, J. D. Yu, and J. Yeon, BIM-Driven Digital Risk Twins for Tunnel Reinforcement Maintenance, Automation in Construction, ISSN: 0926-5805, Vol. 182, 2026, Article 106710, DOI: 10.1016/j.autcon.2025.106710.

T. D. Nguyen and S. Adhikari, Advancing Digital Twins for Building Lifecycle Management in Construction: A Systematic Literature Review, Buildings, ISSN: 2075-5309, Vol. 16, No. 6, 2026, Article 1151, DOI: 10.3390/buildings16061151.

W. Hu, Y. Ou, H. Liu, P. Ni, and C. Chang, Integrating Digital Twin Technologies for Maintenance 4.0 in the Building Industry: A Review and Conceptual Framework, Building and Environment, ISSN: 0360-1323, Vol. 256, 2026, Article 113997, DOI: 10.1016/j.buildenv.2025.113997.

S. Sheenan, F. Elghaish, T. Brooks, and F. Rahimian, IoT-Enabled Digital Twin for Autonomous Modular Construction Progress Monitoring, ABC2: Journal of Architecture, Building, Construction and Cities, Vol. 2, No. 1, 2026, Article 30, DOI: 10.66408/abc2.2026.30.

R. Akhavian, M. Amani, J. Mootz, B. Beheshti, and R. Ashe, Building Information Models to Robot-Ready Site Digital Twins (BIM2RDT): An Agentic AI Safety-First Framework, 2025, DOI: 10.48550/arXiv.2509.20705.

M. Amani and R. Akhavian, Adaptive Robot Perception in Construction Environments Using 4D BIM, 2024, DOI: 10.48550/arXiv.2409.13837.

Z. Liu, J. Silva, R. Zhong, Q. Qin, et al., ConstrucTwin: Digital Twin-Driven Multirobot Construction System Toward Industry 5.0, IEEE Transactions on Systems, Man, and Cybernetics: Systems, ISSN: 2168-2216, Early Access, 2026, DOI: 10.1109/TSMC.2026.3658622.

A. Khoshkonesh, M. Mohammadagha, and N. Ebrahimi, Simulation-Based Validation of an Integrated 4D/5D Digital-Twin Framework for Predictive Construction Control, 2025, DOI: 10.48550/arXiv.2511.03684.