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Key Technological Advances and Deployment Challenges of Construction Robots in Intelligent Construction

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Abstract. The construction industry faces persistent productivity, safety, and coordination problems that cannot be solved by equipment upgrades alone. Under the broader agenda of intelligent construction, construction robots are becoming cyber-physical execution units that connect Building Information Modeling (BIM), sensing, artificial intelligence, and on-site operations. This paper analyzes the technological progress and deployment challenges of construction robots from two interrelated perspectives: autonomous navigation and human-robot collaboration. It argues that multi-sensor perception, BIM-assisted localization, Simultaneous Localization and Mapping (SLAM), improved path planning, and digital-twin-enabled safety monitoring have improved the feasibility of robotic systems in complex construction environments. However, wide deployment is still constrained by unstructured site conditions, model-to-reality discrepancies, fragmented data interfaces, low collaboration maturity, high implementation costs, and uncertain business incentives. The paper proposes four implementation strategies: open communication and data-interface standards, construction-specific safety guidelines for human-robot collaboration, financial and rental mechanisms for lowering the adoption threshold, and joint pilot projects involving industry, universities, research institutions, and end users. The study concludes that construction robots should not be framed as simple substitutes for human labor. Their more realistic role is to augment workers in hazardous, repetitive, precision-demanding, and data-intensive tasks while supporting a gradual transition from experience-based construction management to data-driven intelligent construction.

Keywords: intelligent construction, construction robots, autonomous navigation, BIM-SLAM, human-robot collaboration

1. Introduction

The construction industry remains one of the most difficult sectors to automate because production is temporary, spatially dispersed, and deeply dependent on changing site conditions. Unlike factory manufacturing, construction usually occurs in open or semi-open environments where workspaces are constantly reconfigured by newly installed components, temporary materials, workers, machines, and safety barriers. This project-based mode of production creates long-standing problems: low productivity growth, high occupational risk, inefficient information transfer, and weak continuity between design data and site execution. Construction automation has therefore attracted sustained

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attention, but its effects cannot be understood only as a matter of replacing manual labor with machines. Chen, García de Soto, and Adey noted that construction automation has shown productivity potential after years of development, while the precise benefits, challenges, and consequences require further clarification [1]. This observation is a useful starting point because it avoids both technological optimism and conservative rejection. In intelligent construction, a construction robot is better defined as a cyber-physical execution system than as a single mechanical device. It may include a mobile base, a manipulator, an end effector, sensors, control algorithms, task models, and interfaces to BIM or digital-twin platforms. Its value lies in translating digital information into physical site actions, such as layout projection, inspection, material transportation, grinding, spraying, bricklaying, welding, or quality measurement. Bock argued that conventional construction methods were reaching technical limits and that construction automation could move into larger-scale adoption when research and development efforts continued [2]. However, the transition from laboratory prototype to construction-site infrastructure remains difficult. The robot must know where it is, understand which objects are permanent or temporary, avoid workers and equipment, and interact with human supervisors in a way that is safe and intelligible. This paper focuses on two core technologies that determine whether construction robots can become operationally meaningful. The first is autonomous navigation and environmental perception, including multi-sensor fusion, BIM-SLAM alignment, and path planning. The second is human-robot collaboration, including collaboration modes, safety monitoring, and workflow integration. The paper then analyzes three deployment challenges: insufficient adaptability to unstructured environments, weak human-robot and robot-platform coordination, and high costs with uncertain adoption incentives. Finally, it proposes policy and implementation recommendations for standardization, safety governance, financial support, and joint pilot projects. The aim is not to present a comprehensive review of all construction robot types, but to build a coherent argument about why navigation and collaboration are the two technical bottlenecks most closely connected with real-world deployment.

2. Technological advances in construction robots

2.1. Autonomous navigation and environmental perception

Autonomous navigation is the precondition for construction robots to move from controlled demonstrations to real sites. A robot cannot execute a layout, inspection, or material-transfer task unless it can continuously estimate its pose relative to both the building and the task target. Construction sites challenge localization because Global Positioning System (GPS) is unavailable indoors, floors may be uneven, landmarks may be temporary, and obstacles may appear without prior notice.

2.1.1. Multi-sensor fusion

Single-sensor navigation is therefore fragile. Light Detection and Ranging (LiDAR) provides geometric range information, but dust, glass, and reflective surfaces may reduce reliability. Cameras provide rich visual cues, but lighting, texture, and occlusion can destabilize image-based localization. Ultra-Wideband (UWB) can support equipment or asset localization, but it requires beacon deployment and may be affected by site geometry. Inertial Measurement Unit (IMU) and wheel odometry provide high-rate motion information, yet they drift over time. The practical direction is multi-sensor fusion, not because it always produces centimeter-level accuracy in every

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scenario, but because redundant sensing can sustain localization when one sensing channel becomes unreliable.

Recent studies show how multi-source perception can be integrated with construction information. Braga and colleagues proposed a modular platform for construction site navigation and asset localization that incorporated BIM-based semantic navigation, UWB beacon tracking, a cascade navigation stack, and a graphical user interface for non-expert operators [3]. The important implication is that perception should not be separated from user interaction. A navigation system that is technically accurate but unusable by site workers will not be adopted. By linking global BIM layouts with real-time local sensing, such a platform reduces the gap between robotic autonomy and practical field control. In this sense, localization is not merely a geometric problem, but an interface problem between the robot, the information model, and the human operator.

2.1.2. BIM-SLAM alignment

BIM-SLAM integration is another major advance. Traditional SLAM builds and updates maps from sensor data, but long trajectories, repetitive corridors, and incomplete structures can cause drift or ambiguous associations. BIM provides structural priors, semantic labels, and spatial boundaries before the robot enters the site. However, BIM is normally an as-designed representation, whereas construction sites contain missing elements, modified layouts, temporary materials, and dynamic obstacles. The central problem is therefore not whether BIM should replace SLAM, but how the two can be coupled so that the robot aligns the planned building with the observed site. Stührenberg and Smarsly proposed LiDAR Inertial Odometry-Building Information Modeling (LIO-BIM), a framework that couples LiDAR-inertial odometry with BIM for real-time localization and mapping under scan-BIM deviations [4]. This approach indicates that BIM can constrain drift while SLAM can account for deviations from design information.

Quadruped robots provide a useful example of the BIM-SLAM direction because they can climb stairs and access areas that are inconvenient for wheeled platforms. Tuomisto and colleagues developed an automated inspection framework in which a quadruped robot used BIM-initialized 3D LiDAR SLAM, adaptive BIM-driven navigation, and next-best-view planning for object inspection [5]. Their reported results are important because construction robots rarely operate in perfect model-to-reality correspondence. A useful robot must continue operating when BIM contains discrepancies, when obstacles are dynamic, or when access routes are partially blocked. The value of BIM-SLAM is therefore adaptive alignment: the robot treats BIM as a structured prior, but not as an unquestionable truth.

2.1.3. Path planning

Path planning converts localization into executable motion. Global planning usually relies on A*, Dijkstra, topological graphs, or BIM-derived occupancy maps to generate a route from the robot position to the target. Local planning must then react to workers, carts, temporary materials, and changing safety zones. Wang, Liu, Jiang, and Liu proposed a path planning method for construction robots based on improved A* and BIM, emphasizing that the original A* algorithm may create excessive turning nodes, unsmooth paths, and insufficient consideration of dimensional constraints [6]. This is directly relevant to construction robots because a path that is mathematically short may be physically unsuitable for a robot carrying tools or materials. Smoothness, turning radius, clearance, and task-specific constraints are not secondary details. They determine whether a planned route can be executed without repeated human intervention.

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The Dynamic Window Approach (DWA) is widely used as a local planner because it evaluates admissible velocities within a short time horizon and selects trajectories based on goal direction, velocity, and obstacle distance. Ögren and Leonard discussed DWA as a form of model predictive control and proposed a convergent version to address goal-reaching limitations [7]. In construction robotics, a combined architecture is often more realistic than a single optimal planner. BIM-derived global planning can define a feasible route through rooms, doors, corridors, and work zones, while local planning can adjust robot velocities when the site changes. The practical objective is not only to minimize travel time but also to generate smooth, predictable, and safe motion.

2.2. Human-robot collaboration

Human-robot collaboration is the second core technology area. Construction robots are often discussed as autonomous systems, but most real applications still require human supervision, intervention, or cooperative task execution.

2.2.1. Collaboration modes

Liang, Wang, Kamat, and Menassa proposed a taxonomy of collaborative construction work that includes preprogramming, adaptive manipulation, imitation learning, improvisatory control, and full autonomy [8]. This taxonomy is useful because it connects the level of robot autonomy with the level of human effort. A layout robot following a preplanned route, a manipulator adapting to material tolerances, and a robot learning from worker demonstration occupy different positions in this spectrum. The more unstructured the task, the more valuable human perception, judgment, and improvisation remain.

2.2.2. Safety monitoring

Safety technologies determine whether collaboration can be accepted on site. Small mobile robots and quadruped robots can reduce worker exposure to unsafe areas, but they also introduce new risks. A robot may collide with a worker, distract attention, create psychological discomfort, or obscure the responsibility boundary in an emergency. Sun, Jeelani, and Gheisari categorized safety challenges for mobile robots in construction into physical risks, attentional costs, and psychological impacts [9]. This categorization suggests that safety cannot be reduced to collision avoidance. A technically collision-free robot may still be unsafe if it distracts workers, moves unpredictably, or forces workers to continuously monitor it. Therefore, safety must be designed at the levels of perception, motion control, communication, training, and construction management.

Digital-twin-enabled monitoring offers a promising route for safety assurance. Lin, Guo, Jin, and Guo proposed a safety monitoring system for seamless worker-robot collaboration that perceived workers, robots, and materials, calculated dynamic protective separation distances, and validated collision mitigation in static and dynamic conflict scenarios [10]. The significance of this work is that it treats safety as a real-time spatial relationship rather than a fixed boundary. Traditional fences may be unsuitable on construction sites because they fragment workspaces and do not adapt to changing tasks. A dynamic digital twin can represent the approximate occupied space of workers, robots, and materials, then support context-sensitive slowing, stopping, or replanning. In practice, such systems must still address sensor reliability, latency, privacy, and integration with existing site management processes.

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2.2.3. Workflow integration

Task-level implementation is equally important because construction robots create value only when their capabilities match the production logic of a specific work package. Digital fabrication research shows that robotics may be especially valuable for geometrically complex components, where manual methods require repeated measurement, formwork adjustment, and error correction. Garcia de Soto and colleagues found higher productivity in the robotic construction method for complex walls [11]. This finding should be interpreted carefully. It does not mean that every robotic process is automatically cheaper, faster, or safer. It means that robots are more likely to be economically convincing when complexity, repetition, precision demand, and digital continuity are present at the same time. A robotically fabricated wall, an automated layout mission, or a quadruped inspection route can all be justified differently: one emphasizes fabrication precision, one reduces manual layout effort, and one improves access to difficult or unsafe spaces.

Therefore, the technological progress of construction robots should be evaluated by workflow integration rather than by isolated autonomy. Melenbrink, Werfel, and Menges framed on-site autonomous construction robots as a step toward unsupervised building [12]. In practical construction, however, "unsupervised" should not be read as immediate removal of people from the process. A more realistic interpretation is that robots will gradually take over bounded sequences of sensing, moving, positioning, and executing while humans remain responsible for task definition, exception handling, quality acceptance, and ethical or safety judgment. This layered autonomy is more suitable for the near future than a binary distinction between manual construction and fully robotic construction.

3. Main deployment challenges

The first challenge is insufficient technical adaptability. Construction environments are unstructured not only because they contain obstacles, but because the status and significance of those obstacles change over time. A pallet of materials may be an obstacle in the morning, a task target at noon, and disappear by the evening. A wall shown in BIM may not yet exist, and a temporary support may be absent from the model. SLAM can update geometry, but it may not understand task semantics. BIM can provide semantics, but it may be outdated or incomplete. This mismatch produces a fundamental autonomy problem: the robot must reason across inconsistent layers of information. For this reason, future navigation systems need continuous model updating, uncertainty-aware planning, and mechanisms for asking human operators for clarification when the scene violates assumptions.

The second challenge is the low maturity of human-robot coordination. Many construction robots still perform isolated tasks under operator control or close supervision. They are productive only when the site is prepared for them, the task boundary is narrow, and the operator can resolve exceptions quickly. However, construction productivity problems are rarely isolated. They arise from interactions among design changes, material delivery, subcontractor sequencing, safety constraints, and inspection requirements. If robots cannot exchange data with BIM, scheduling, safety, and quality systems, they become another isolated technology layer. BIM-based robot task planning research shows that robots can retrieve building information for task planning and execution, but manually encoding complete lifecycle information for robots is impractical [13]. This reinforces the need for standardized semantic interfaces and task-level communication protocols.

The third challenge is cost and adoption uncertainty. Robots require capital expenditure, software adaptation, maintenance, sensor calibration, safety validation, worker training, and workflow redesign. The economic case is highly task-dependent. García de Soto and colleagues found that

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robotic digital fabrication was more productive for complex walls, suggesting that the value of robotic construction increased when geometric complexity penalized conventional methods [11]. This does not imply that every robot is economical in every project. For simple repetitive tasks with cheap labor and low precision requirements, conventional methods may remain more cost-effective. For hazardous, complex, or precision-intensive tasks, robots may create value by reducing rework, improving consistency, and capturing data. Adoption decisions therefore require task-level cost-benefit models rather than general claims about automation.

Organizational incentives also matter. Yi and Fukuda argued that robotic and automated construction technologies can improve productivity and sustainability, but high research and development costs and insufficient investment discourage innovation among construction firms [14]. In addition, Law, Chang, and Siu investigated construction robotics adoption from a multistakeholder perspective in Hong Kong, indicating that adoption depends on the interests and concerns of different actors rather than on technical feasibility alone [15]. Owners may care about project risk and return on investment. Contractors may care about schedule reliability and labor coordination. Workers may care about safety and job security. Regulators may care about liability and compliance. A robot can fail commercially even when it works technically if these stakeholder incentives are not aligned.

A further challenge is the lack of construction-specific safety certification and responsibility allocation. Industrial collaborative robot standards are often designed for relatively stable factory cells, where task geometry and access control can be defined in advance. Construction sites are open, temporary, and multi-employer environments. When a robot injures a worker or damages a component, responsibility may involve the robot supplier, the software developer, the contractor, the operator, the safety manager, and the project owner. Without clear process guidelines, firms may avoid deployment because the liability risk is ambiguous. Safety governance must therefore be integrated with procurement, training, commissioning, daily operation, emergency response, and incident documentation.

Interoperability is another underappreciated deployment barrier. A construction robot needs far more than geometric coordinates. It needs to know which spaces are accessible today, which components are installed, which tasks have priority, which zones are restricted, and who can authorize a change in robot behavior. These data are usually distributed across BIM files, schedules, safety plans, quality checklists, and informal site communication. If each robot vendor builds a closed data pipeline, every project must repeat integration work, and contractors will hesitate to scale from one pilot to multiple sites. Interoperability should therefore be understood as a productivity condition, not merely as an information-technology preference.

4. Policy and implementation recommendations

First, the industry should establish open communication and data-interface standards for construction robots. The standardization target should include BIM object identifiers, task instructions, robot pose, safety-zone status, obstacle categories, and execution feedback. Open interfaces do not eliminate competition among vendors. Rather, they reduce project-level integration cost and prevent data vendor lock-in. Industry Foundation Classes (IFC) and semantic maps can provide the base vocabulary, but robot operation also requires time-dependent information such as construction progress, temporary access rules, and task priority. A minimum viable data standard would allow robots, BIM platforms, digital twins, and project management systems to share enough information for task execution without forcing all firms into one proprietary ecosystem.

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Second, construction-specific safety guidelines for human-robot collaboration should be developed. Such guidelines should cover robot admission checks, site induction, permitted task areas, dynamic separation distances, manual takeover procedures, emergency stop requirements, data logging, worker notification, and accident responsibility. Safety rules should distinguish between distant interaction, such as autonomous inspection, and proximal collaboration, such as material handover or shared assembly. They should also define when a robot may continue operating, slow down, stop, or request human confirmation. This procedural layer is essential because technical safety functions become meaningful only when workers and managers know how to use them.

Third, governments and industry associations should lower the adoption threshold through subsidies, tax incentives, demonstration projects, and shared rental platforms. Small and medium-sized contractors are unlikely to purchase expensive robots for uncertain future tasks. Rental or robot-as-a-service models can convert capital expenditure into operating expenditure and allow firms to test use cases before long-term adoption. Public support should not simply subsidize hardware purchase. It should prioritize verified use cases, training programs, safety certification, and data collection. This would create a more reliable evidence base for deciding which robotic applications deserve scale-up.

Fourth, joint pilot projects involving universities, robot vendors, contractors, owners, and regulators should be encouraged. Construction robots cannot mature through laboratory testing alone, because the key difficulties arise from real site variability. Pilot projects should focus on tasks with high risk, high repetition, high precision, or high data value. Examples include layout, scanning, progress monitoring, spraying, grinding, rebar tying, and material delivery. Each pilot should define measurable indicators: task time, labor reduction, positional error, rework rate, safety incidents, worker acceptance, setup time, and total cost. The results should feed back into technical design, safety standards, and procurement specifications.

Finally, construction robot deployment should be treated as an organizational transformation rather than equipment substitution. A robot changes the work package, information flow, training requirement, and quality-control procedure. If it is inserted into a traditional workflow without redesign, it may add coordination burden instead of reducing it. Intelligent construction requires a shift from device-centered pilots to process-centered integration. The main question should not be "Can the robot perform this action?" but "Can the robot, the worker, the information model, and the project organization complete this task more safely, consistently, and economically together?"

5. Conclusion and outlook

5.1. Conclusion

This paper analyzed the key technological advances and deployment challenges of construction robots in intelligent construction. Autonomous navigation, BIM-SLAM integration, path planning, human-robot collaboration, and safety monitoring constitute the technical foundation for construction robot deployment. The main value of robots is not simple labor replacement. Their more realistic role is to augment human workers in hazardous, repetitive, precision-demanding, and data-intensive tasks, while connecting digital construction information with physical execution. Current bottlenecks include weak adaptability to unstructured site conditions, inconsistent data interfaces, low collaboration maturity, uncertain cost recovery, and incomplete safety governance.

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5.2. Outlook

Future research should focus on robust multimodal perception, continuous BIM-to-site alignment, semantic task planning, multi-robot coordination, human-centered interfaces, dynamic safety evaluation, and economic assessment models. Construction robots will become stable infrastructure for intelligent construction only when technology, standards, management processes, and business models mature together.

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