Journal of Architectural Research and Development, 2026, Volume 10, Issue 1
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Design and Application of Intelligent Monitoring System for Bridge Construction Based on BIM + Internet of Things

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Abstract: To address issues such as data fragmentation, low visualization, and delayed early warning in traditional bridge construction monitoring, an intelligent monitoring system for bridge construction that integrates BIM (Building Information Modeling) and IoT (Internet of Things) technologies is proposed. Firstly, the core application requirements and technical challenges of BIM and IoT technologies in the field of bridge engineering are outlined. Secondly, a four-tier architecture system consisting of the "perception layer–transmission layer–data layer–application layer" was constructed, with a focus on explaining the functional modules, hardware selection, and software integration solutions at each level to achieve real-time collection, dynamic modeling, and intelligent analysis of key parameters such as structural stress, settlement, temperature, and equipment operational status during the construction process. Finally, based on an actual bridge engineering project, system application verification is conducted. By comparing the application effects of traditional monitoring methods with those of the intelligent monitoring system, the feasibility and superiority of the system in enhancing construction monitoring accuracy, efficiency, and safety management capabilities are validated.

Keywords: BIM technology; Internet of things; Bridge construction; Intelligent monitoring; System design; Engineering application

Online publication: Jan 30, 2026

1. Introduction

With the rapid development of China's transportation infrastructure construction towards large spans, complexity, and intelligence, the difficulty of bridge engineering construction has been increasing year by year, posing higher requirements for safety control and quality supervision during the construction process.

BIM technology, centered on three-dimensional digital models, enables information integration and visual management throughout the entire project lifecycle, providing an accurate information carrier for construction monitoring.

Meanwhile, IoT technology constructs a "connected everything" sensing system through various sensing devices, communication networks, and data processing terminals, enabling real-time collection and remote transmission of key parameters. The deep integration of these two technologies can break down the technological barriers of traditional monitoring models and achieve the goals of "real-time data, visualized models, intelligent analysis, and proactive control" during bridge construction [1]. Based on this, this paper designs an intelligent monitoring system for bridge construction based on BIM and IoT technologies. Through architectural optimization, software and hardware integration, and engineering application verification, it provides technical support for safety control in bridge construction and promotes the intelligent transformation of bridge engineering construction.

2. Integration mechanism and requirements of BIM and IoT technologies

2.1. Core logic of integration

The integration of BIM and IoT technologies aims to establish real-time mapping and closed-loop management between "physical construction" and "digital models". IoT is responsible for real-time collection of multidimensional physical data from the construction site, including structures, environment, and equipment, driving the evolution of BIM models from static design to dynamic construction twins. The BIM model serves as the hub for data integration and decision-making, enabling visual display, correlation analysis, and simulation forecasting of multi-source information. It then feeds back optimization instructions to the site, forming an intelligent closed loop of "perception-analysis-decision-control".

2.2. Key integration technologies

Deep integration relies on three categories of key technologies:

(1) Multi-source data integration technology

Based on standards such as IFC and XML, it unifies data formats and coding, and develops dedicated interfaces to achieve lossless interaction between IoT data and BIM platforms (such as Revit and Bentley) [2].

(2) Dynamic model updating technology

Based on real-time collected data, it employs algorithms to achieve automated and precise synchronization updates of the BIM model [3].

(3) Cloud-edge collaborative computing technology

It adopts an "edge computing + cloud computing" architecture. The edge side is responsible for real-time preprocessing and rapid warning, ensuring timely response; the cloud side is responsible for massive data storage, in-depth analysis, and global optimization, supporting scientific decision-making [4].

2.3. Core requirements for bridge construction monitoring

Bridge construction monitoring must meet the following core performance indicators: structural stress monitoring error $\leq \pm 5\%$, settlement monitoring accuracy $\leq \pm 0.1$ mm; data acquisition cycle ≤ 10 s, transmission delay ≤ 5 s, warning response time ≤ 3 s; achieve real-time linkage and multi-dimensional interactive display of monitoring data with the BIM model; the system must adapt to high-temperature, high-humidity, and strongly interfering environments, with a hardware monthly failure rate $< 0.5\%$ and software failure-free operation time ≥ 720 h/month [5,6].

3. Design of an intelligent monitoring system for bridge construction based on BIM + internet of things

3.1. System design principles and core objectives

3.1.1. Design principles

(1) Practicality

Align with actual engineering needs, select easily deployable and operable hardware and software, and avoid technological redundancy;

(2) Scalability

Adopt a modular design, reserve standard interfaces, and support flexible expansion of functions and scenarios;

(3) Security

Implement full-process data encryption, strict access control, and network protection to ensure system and data security;

(4) Collaborative

Ensure compatibility and interoperability with existing management platforms and BIM design models to achieve business collaboration.

3.1.2. Core objectives

The system aims to achieve five major objectives: integrating multi-dimensional real-time data to build a unified monitoring data center and eliminate information silos; enabling visualization and dynamic correlation analysis of monitoring data based on BIM; establishing an intelligent hierarchical early warning system for early identification, early warning, and rapid response to risks; providing decision support for construction optimization through data mining and simulation to enhance safety and efficiency; and creating a comprehensive digital construction file to provide a data foundation for the entire lifecycle operation and maintenance of the bridge [7].

3.2. Overall system architecture design

Based on the four-tier architecture concept of "perception-transmission-data-application", the overall architecture of the intelligent monitoring system for bridge construction based on BIM + Internet of Things is designed. Each tier operates collaboratively from top to bottom, forming a complete monitoring loop, as shown in **Figure 1**.

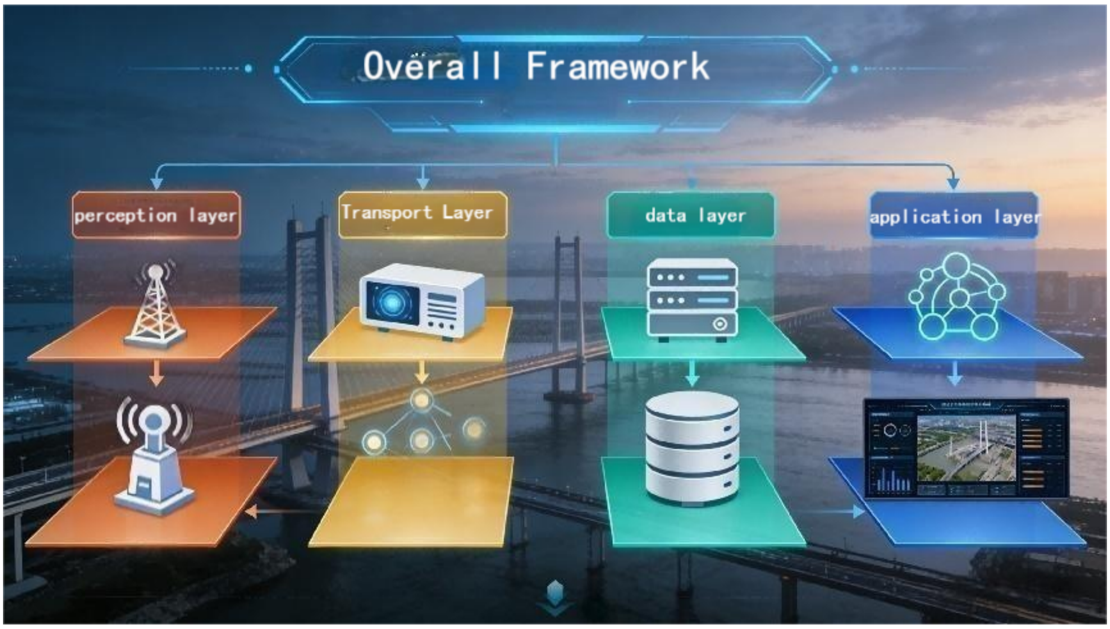

Figure 1. Overall system architecture design.

The perception layer, serving as the data acquisition terminal of the system, is responsible for real-time capture of various key parameters and forms the foundation for system operation. The transport layer undertakes the task of data transmission, enabling interconnection and interoperability between the perception layer and the data layer. The data layer is responsible for data storage, processing, and standardization, providing data support for the application layer. The application layer, based on the BIM model, implements core functions such as data visualization, intelligent analysis, and early warning control, directly serving construction management decision-making. Each layer operates independently while collaborating synergistically to ensure the stability and efficiency of the system.

3.3. Detailed design of each layer

3.3.1. Design of the perception layer

The perception layer is responsible for multi-dimensional data acquisition of construction status. It is divided into three major modules: structural perception, environmental perception, and equipment perception, based on the monitoring objects.

Equipment selection adheres to the principles of accuracy, durability, and environmental adaptability, with deployment focusing on key load-bearing areas and risk zones [8]. The specific design is shown in **Table 1** below:

Table 1. Design of the perception layer

Perception module	Monitoring parameter	Selected equipment	Technical specifications	Deployment location
Structural perception module	Main Girder Stress	FBG Strain Sensor	Range: -200 to 1500 με; Accuracy: ± 1 με; Temp. Range: -40 to 85 °C	Mid-span, supports, and concentrated load areas of main girder
	Pier/Pylon strain	Resistance strain gauge	Sensitivity: 2.0 ± 1%; Measurement Range: -3000 to 3000 με; Protection: IP67	Lower-middle and top connection areas of piers/pylons
	Structural settlement	Hydrostatic leveling system	Accuracy: ± 0.1 mm; Range: 0–500 mm; Output: RS485	Pier/pylon foundations, key sections of main girder
	Horizontal displacement	Laser displacement sensor	Range: 0–50 m; Accuracy: ± 0.05% FS; Response Time: ≤ 1 ms	Top of piers/pylons on both sides of the bridge
Environmental perception module	Temperature	Digital temperature sensor	Range: -40 to 125 °C; Accuracy: ± 0.5 °C; Supply: 3.3–5V	Main girder, piers/pylons, and construction site periphery
	Humidity	Integrated temp./humidity sensor	Humidity Range: 0–100% RH; Accuracy: ± 3% RH; Output: Analog	Temporary site facilities, component storage areas
	Wind speed	Ultrasonic anemometer	Range: 0–60 m/s; Accuracy: ± 0.1 m/s; Strong anti-interference	Top of main girder, top of bridge erection machine
	Rainfall	Tipping bucket rain gauge	Range: 0–4 mm/min; Resolution: 0.1 mm; Output: pulse	Open area of the construction site
Equipment perception module	Equipment load	Pressure sensor	Range: 0–500 t; Accuracy: ± 0.2% FS; Protection: IP68	Crane hook, load-bearing parts of erection machine
	Operating speed	Hall effect RPM sensor	Range: 0–10,000 rpm; Accuracy: ± 1 rpm; Fast response	Output shaft of equipment motor
	Positioning precision	GPS positioning module	Positioning accuracy: ± 2 cm; Update rate: 10 Hz; BeiDou/GPS dual-mode	Mobile equipment (e.g., bridge erection machine, tower crane)

The deployment strategy for the perception layer combines focused coverage with redundant configuration. Sensors are densely placed at critical sections of bridges, vulnerable areas, and core components of large equipment to ensure the continuity and reliability of data acquisition.

3.3.2. Design of the transport layer

The transport layer is responsible for ensuring the stable and real-time uploading of data. Given the expansive scope and complex environment of construction sites, a hybrid transmission architecture combining "wired backbone network + wireless coverage network" was adopted.

(1) Wireless transmission

It utilizes the synergy of 4G/5G and LoRa technologies. 4G/5G is employed for transmitting large-bandwidth, low-latency services such as video and high-frequency sampled data, while LoRa is used to connect widely distributed, low-power sensors for temperature and humidity, with its long-range and high-penetration capabilities compensating for network blind spots.

(2) Wired transmission

Optical fiber and industrial Ethernet are used between the control center and fixed equipment to form a highly reliable, high-bandwidth data backbone. Additionally, by deploying relay nodes in areas with weak signals, encrypting data transmission with SSL/TLS protocols, and implementing data retransmission mechanisms, the coverage, security, and integrity of the transmission links are comprehensively ensured [9].

3.3.3. Data layer design

The data layer serves as the data hub of the system, adopting a "cloud-edge" collaborative storage and computing architecture to achieve full lifecycle management of data.

(1) Data storage

An industrial real-time database is deployed on the edge side to cache and process high-frequency real-time data, meeting local rapid response requirements. The cloud employs distributed databases and object storage to archive massive historical data, BIM models, and documentation, supporting elastic expansion and long-term preservation. An automated off-site backup mechanism was established to ensure data security.

(2) Data processing

A two-tier pipeline of "edge preprocessing + cloud-based in-depth analysis" is implemented. Edge nodes perform data cleaning, filtering, and compression, while the cloud conducts data fusion, calibration, and utilizes big data algorithms to mine data correlations and trends [10].

(3) Data standardization

Establish unified data coding, formatting, and exchange standards (e.g., adopting the IFC standard to unify BIM data) to break down information silos. Meanwhile, establish a data quality assessment and feedback mechanism to ensure the accuracy and usability of data flowing into the application layer.

3.3.4. Application layer design

The application layer serves as the interface for human-computer interaction. Based on a unified data foundation and BIM models, the following five core functional modules are developed:

(1) BIM visual monitoring

Dynamically associate real-time monitoring data with BIM models to enable visual representation of working conditions, data querying, and risk visualization. Support 3D navigation, component querying, and historical data retrieval, with automatic model alerts when data exceeds limits.

(2) Intelligent analysis and prediction

Integrate monitoring data with BIM simulation models to assess structural safety status, simulate and optimize construction plans, and predict equipment failures, achieving a shift from "post-event awareness" to "pre-event prediction".

(3) Hierarchical early warning and control

Establish a “blue, yellow, red” three-tier early warning system that automatically triggers multi-channel (audible and visual, SMS, platform) alarms based on thresholds and generates closed-loop handling work orders to track risk resolution.

(4) Construction progress management

Dynamically compare actual progress with BIM planned progress to visually present progress deviations, assisting in resource scheduling and plan adjustments.

(5) Digital archive management

Automatically archive data, reports, and documents throughout the entire construction process to form traceable and searchable digital twin archives, laying the foundation for delivery and operation and maintenance handover.

3.4. System hardware and software integration plan

3.4.1. Hardware integration

Hardware integration is carried out around the “sensing-transmission-processing” chain. The sensing layer aggregates data from various sensors through multifunctional data acquisition terminals; the transmission layer constructs a “wired + wireless” hybrid network using wireless gateways, optical fibers, and other equipment; the processing layer relies on edge and cloud servers for data storage and computation; users access the system through various terminals. During integration, emphasis is placed on equipment standardization and interface compatibility, and through reasonable physical deployment and protective design, stable operation of the hardware in complex construction environments is ensured.

3.4.2. Software integration

The software integration adopts an architecture of “BIM platform + IoT platform + application modules”. The BIM platform is responsible for model construction and visualization, the IoT platform handles device connectivity and data scheduling, and the application modules, developed based on Python/Java, implement core business functions. By developing standardized data interfaces, efficient data interoperability among various platforms and modules is achieved. Additionally, the human-computer interaction interface has been optimized to enhance the system’s usability.

3.5. System security and reliability design

3.5.1. Security design

System security covers three aspects: data, equipment, and permissions. This includes full-chain encryption and authentication for real-time data collection, transmission, and storage; physical protection and status monitoring of critical hardware equipment; and role-based hierarchical permission management for users, combined with dual authentication to ensure secure access.

3.5.2. Reliability design

Through hardware redundancy (hot standby for critical equipment, redundant sensor deployment), software fault tolerance (exceptional data handling, algorithm optimization, and regular maintenance), and rigorous industrial-grade environmental adaptability selection, the system ensures continuous and stable operation under complex working conditions.

4. System application validation and effect analysis

4.1. Project overview

To validate the system's effectiveness, a continuous beam bridge project with a main span of 180 meters across a river was selected as the application scenario. This project is characterized by its large span, complex environment (high humidity and strong winds near the river), and numerous large-scale equipment, posing significant challenges for traditional monitoring methods and providing a typical scenario for validating the system.

4.2. System deployment and commissioning

The deployment adhered to the design architecture, completing the installation of sensing equipment, network construction, central and terminal deployment, and software integration. During the commissioning phase, continuous testing and parameter tuning were conducted for 72 hours to evaluate hardware accuracy, network performance, software functionality, and system interoperability, ensuring that all indicators met standards and the system achieved a stable operating state.

4.3. Application process and data collection

The system operates continuously throughout the entire construction cycle. Taking the cantilever casting stage as an example, the system monitors the stress and deformation of the main beam, as well as the status of the bridge-erecting machine in real time. When the monitored data approaches the threshold, the system promptly issues warnings, guiding construction adjustments and successfully controlling risks at their inception. Throughout the project, over ten million data points have been collected, and the system has operated stably and reliably.

4.4. Analysis of application effects

Compared with traditional methods, the system has achieved significant improvements in core indicators, as shown in **Table 2**.

Table 2. Analysis of application effects

Evaluation dimension	Traditional method	Intelligent monitoring system	Improvement
Monitoring accuracy	Stress: ± 3.5%; Settlement: ± 0.3 mm	Stress: ± 1.8%; Settlement: ± 0.08 mm	Accuracy improved by 48–73%
Data acquisition efficiency	Manual, intermittent sampling	Automatic, continuous sampling (every 10 s)	Efficiency increased by orders of magnitude; manual labor reduced by 75%
Early warning timeliness	> 30 minutes (requires manual intervention)	≤ 3 seconds (automatic response)	Real-time response capability achieved
Hazard detection rate	65% (mainly overt hazards)	98% (including latent hazards)	Detection capability enhanced by 50%
Schedule control	Deviation rate: ± 5%	Deviation rate: ± 1.2%	Control precision significantly improved

The analysis indicates that the system has achieved precise monitoring, digital management, and intelligent decision-making, effectively ensuring construction safety, quality, and progress.

5. Conclusion

The intelligent monitoring system architecture integrating BIM and IoT proposed in this paper effectively addresses the fragmentation and lag issues of traditional monitoring, providing a comprehensive solution for real-time visualization and intelligent control of bridge construction. Through the collaborative design and engineering integration of the four layers of "sensing, transmission, storage, and application", the system achieves unified management and application of multi-source data, with its security, reliability, and scalability verified. Engineering practice demonstrates that the system can significantly enhance monitoring efficiency and safety management levels, holding significant value for widespread application. Future research can further optimize system functionalities: Firstly, by introducing AI deep learning algorithms to enhance the system's predictive capabilities for complex risk scenarios; Secondly, by expanding the system's application scenarios to enable full lifecycle monitoring throughout the bridge construction and operational maintenance phases; Thirdly, by optimizing the system's hardware integration solutions to develop compact, low-power, high-precision dedicated sensing devices, thereby reducing deployment costs.

Disclosure statement

The authors declare no conflict of interest.

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