

Digital Scene Construction Method for Bridge Construction Based on Pan-Spatial Information System

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Abstract

Bridge construction scenes generate multi-source heterogeneous data that are difficult to organize and express in a unified way. This paper proposes a digital scene construction method for bridge construction based on the Pan-Spatial Information System. The method takes multi-granularity spatio-temporal objects as the core modeling units and follows the six-element framework of man, machine, material, method, environment and measurement, classifying the entities and information objects in bridge construction scenes into seven categories: bridge components, workers, machinery and equipment, bridge site environment, construction measures, monitoring and sensing, and quality inspection. The eight-dimensional description framework of the Pan-Spatial Information System is adaptively simplified into seven feature dimensions—spatio-temporal reference, spatio-temporal positioning, compositional structure, interrelationship, cognitive intelligence, behavioral actions and attributes—each with a symbolic expression. A linkage mechanism is established between the perceive–analyze–decide–act closed loop of cognitive intelligence and the seven-element operation model of behavioral actions. The resulting framework describes multi-granularity spatio-temporal objects in bridge construction scenes consistently and formally; it is machine-readable, computable and inferable, and it supports the unified organization of multi-source heterogeneous construction data, knowledge graph construction and dynamic deduction of construction processes. An illustrative application to a pier construction stage shows that the method works in real engineering scenarios.

Introduction

Bridge construction is a complex systems engineering process involving multiple elements, stages and participants [1]. A project extends over a wide area and a long period and draws on diverse resources—materials, equipment, labor and capital. The information structure is equally complex: monitoring and sensing data cover man, machine, material, method, environment and measurement, all of which must be exchanged and shared. Functional objectives are coupled as well. Quality control, such as maintaining the internal force state of the bridge structure, must be balanced against construction efficiency, safety risk and green economy. The process is also subject to numerous internal and external factors—technology, cost and environment among them—and therefore exhibits multiple parameters, dynamics and multiple disturbances. To cope with this complexity, the industry has developed various data integration platforms, including collaborative management platforms, intelligent construction systems and virtual construction software. These platforms aim to build multi-dimensional, multi-stage, real-time and high-fidelity digital scenes of bridge construction, thereby supporting project data integration, information sharing and decision-making and reducing the data gaps, information barriers and decision delays that hinder orderly project management.

Digital scene construction underpins intelligent bridge construction: it maps the physical construction process into the information space and characterizes it dynamically. The real world, however, is infinitely complex, and no information system can describe a real-time construction scene completely. Bridge construction scenes make this difficulty concrete. Macroscopic construction activities are intertwined

with microscopic material evolution; static components and facilities are coupled with moving personnel and equipment; low-frequency environmental changes coexist with high-frequency structural vibrations. Such multi-scale, multi-modal and multi-temporal complexity strains the expressive capacity and dynamic adaptability of traditional data models. How to construct a data model that describes bridge construction scenes directly, dynamically and with their correlations intact has therefore become a key scientific problem for the further development of intelligent bridge construction.

The Pan-Spatial Information System offers a theoretical path for resolving these contradictions. Hua and other scholars have studied its core issues and key technologies [2-4], showing that it features full scale, full type, full dynamics and full attributes and can describe the real world in a more direct, dynamic and correlated manner. It provides stronger capabilities for spatio-temporal data access, management, analysis and visualization, and it records the behavior and cognition of spatio-temporal entities, offering new means for intelligent spatio-temporal decision support and simulation analysis. Under this framework, a multi-granularity spatio-temporal object is defined as the concrete description of a multi-granularity spatio-temporal entity in a computer-built information space, expressed as data, models, rules, logic and knowledge. Bridge construction fits this framework well: its objects range in granularity from the bridge site down to materials, its entities range from static structures to dynamic equipment, and its data range from design parameters to real-time monitoring. What remains difficult is describing these multi-granularity, multi-type and multi-dynamic spatio-temporal objects consistently within a unified data model.

Research on digital scene construction for bridge construction has so far focused on digital twins and BIM. Zhu et al. [5] proposed a whole-process digital twin construction method and discussed key technologies such as the correlation and fusion of space-air-ground integrated monitoring data, intelligent construction and enhanced visualization of digital twin scenes, and process dynamic simulation and intelligent prediction. Zhang et al. [6] developed a knowledge-guided hierarchical digital twin scene modeling method for railway construction scenes, which addresses the hierarchical differences and insufficient semantic information in three-dimensional scene modeling and improves the flexibility and versatility of scene modeling, facilitating bridge design data expression, visual analysis and dynamic optimization of the construction process. Zhang et al. [7] built a "BIM+" refined management and control platform on systems engineering and cybernetics, realizing quantitative and dynamic management of project progress, cost and quality; the platform was verified on the Beijing–Xiong'an railway bridge. Shi [8] constructed a virtual geographical environment for bridges from multi-source terrain data, established a parametric bridge twin model with building information modeling (BIM) technology, and achieved high-fidelity virtual bridge construction scenes by integrating the two and optimizing the construction scene. Liang et al. [9] proposed a knowledge-driven intelligent construction method and system for bridge construction digital twin scenes, in which semantic modeling through knowledge graphs is coupled with environmental influencing factors, solving the problems of low operational efficiency and insufficient accuracy of existing modeling technologies. Taken together, these studies build digital twin platforms on digital twins, BIM technology and graphics engines, integrate monitoring data such as images, point clouds and sensing, and form digital twin models of bridge

construction. What they do not yet capture well are the behavioral dynamics, cognitive abilities and semantic correlations of construction objects, which makes it difficult to support deep applications oriented to dynamic deduction and intelligent decision-making of construction processes.

On the theoretical side, Hua et al. [3] constructed an eight-dimensional description framework for the multi-granularity spatio-temporal object data model, comprising spatio-temporal reference, spatial position, spatial form, compositional structure, interrelationship, cognitive ability, behavioral ability and attributes, and each dimension has since been studied in depth. For spatio-temporal reference, Du and Wu [10] summarized the common temporal and spatial systems and their interrelationships in the geographic information system (GIS) and established a spatial transformation framework for the Pan-Spatial Information System with good scalability and implementation efficiency, realizing whole-life-cycle management of objects. For compositional structure, Yang et al. [11] summarized the six basic characteristics of compositional structure, the types of object interactions based on composition relations and the formalized description methods; Li et al. [12] proposed a set of expression and operation methods for spatio-temporal object composition that improves the expression of compositional structure and reduces composition redundancy. For interrelationship, Zhang [13] studied data generation methods, data management technologies and association visualization algorithms; Wang et al. [14] divided interrelationships into spatial, temporal, attribute, causal and cognitive relations and analyzed their expression models; Cheng et al. [15] proposed a spatio-temporal data model expressing the dynamic changes of geographical entities and their interrelationships. For behavioral features, Cao et al. [16] elaborated the basic concepts, triggering modes, classification modes and description framework of spatio-temporal object behavior and proposed a general formalized description method; Zeng et al. [17] expressed the dynamic behavior of spatio-temporal objects as a binary tuple, established an individual dynamic behavior expression model and a linkage behavior expression model among objects, and discussed dynamic behavior expression from four aspects: dynamics, rules, data mining and agents. These studies have advanced the logical description and formalized expression of each feature dimension, but they remain largely within general theoretical construction in geographic information science. No multi-granularity spatio-temporal object data model has yet been established for the specific engineering scene of bridge construction, and systematic modeling methods for the dynamics of the construction process, the diversity of objects and the correlation of information are still lacking.

Research on the Pan-Spatial Information System and multi-granularity spatio-temporal objects has thus produced methods for the logical description and formalized expression of individual features, but work on digital space construction theory and on the construction methods of multi-granularity spatio-temporal objects for bridge construction scenes is still limited and far from systematic. This paper therefore introduces the Pan-Spatial Information System and multi-granularity spatio-temporal object theory into bridge construction. Combining the domain characteristics of bridge construction scenes, we construct a data description framework and modeling method for multi-granularity spatio-temporal objects oriented to bridge construction, so as to support the efficient circulation, dynamic expression and orderly management of bridge construction scene information and to provide a theoretical basis and

methodological support for intelligent bridge construction. Fig. 1 shows the overall technical framework of this research.

Definition and classification of spatio-temporal objects in bridge construction scenes

Domain characteristics of spatio-temporal objects

Spatio-temporal objects in bridge construction scenes are the basic units of digital scene construction. What distinguishes them from general geospatial objects is their "constructiveness": the object set in a scene is not a statically existing geographical entity but a dynamic object system that is continuously generated, changed and eliminated as construction proceeds. This essential difference gives rise to the following characteristics.

- (1) Dense engineering semantics of objects. Each object in a bridge construction scene carries explicit engineering semantics: its existence state, spatial position and attribute parameters all correspond to specific engineering meanings. A bored cast-in-place pile, for example, has not only a geometric form and a spatial position but also engineering parameters such as design pile length, concrete strength grade and pouring time, which directly determine the safety behavior of the structure. The classification system must therefore fully consider the expression of engineering semantic information rather than focusing only on geometric and spatial attributes.
- (2) Stage dynamics of the object set. Bridge construction proceeds in well-defined stages, and the types and quantities of active objects differ significantly from one stage to another. Drilling rigs and casings dominate the foundation construction stage; formwork, climbing frames and tower cranes dominate the pier body construction stage; girder erection machines, cable cranes and deck cranes dominate the superstructure construction stage. The classification system must accordingly cover the object types of the whole construction period and support differentiated description of object sets in different stages.
- (3) Span of spatio-temporal scales of objects. Objects in bridge construction scenes span multiple orders of magnitude in space, from millimetre-scale bolts and welds, through metre-scale reinforcement cages and segmental girders, up to hectometre-scale pylons and kilometre-scale bridge site areas. Temporal scales differ just as widely: concrete pouring is measured in hours, construction stage transitions in months, and the whole construction period in years. This span of spatio-temporal scales is precisely why multi-granularity spatio-temporal object modeling theory applies to bridge construction scenes.
- (4) Strong coupling of inter-object associations. Objects in bridge construction scenes are densely associated. Some associations are spatial and topological, such as the connection between components and the positional relation between equipment and working faces; some are temporal dependencies, such as sequential constraints between construction procedures; some are causal, such

as the influence of environmental changes on construction parameters; and some are logical and compositional, such as the membership of components in the structural system. Modeling these interrelationships is therefore as important as classifying the objects themselves.

Classification of spatio-temporal objects

In engineering construction management, the six-element framework of "man, machine, material, method, environment and measurement" has been widely accepted in construction organization design, quality management and safety control. Starting from the basic elements of construction production, the framework decomposes construction activities into the interaction of six types of elements: personnel operation, machinery operation, material consumption, method execution, environmental influence and measurement inspection. We therefore take these six elements as the classification mainline and, in combination with the object characteristics of bridge construction scenes, divide the spatio-temporal objects in bridge construction scenes into seven categories: bridge components, workers, machinery and equipment, bridge site environment, construction measures, monitoring and sensing, and quality inspection. The mapping from the six elements to the seven categories is as follows: "man" corresponds to workers; "machine" corresponds to machinery and equipment; "material" is transformed into the bridge entity through the construction process and corresponds to bridge components, while the inspection information of raw materials falls under quality inspection; "method" corresponds to construction measures; "environment" corresponds to bridge site environment; and "measurement" corresponds to monitoring and sensing and quality inspection. Fig. 2 illustrates this mapping.

1. Bridge components. Bridge components are the basic units constituting the bridge structure entity. They are the core object type in bridge construction scenes and directly carry the geometric form, material composition and mechanical property information of the engineering entity. Their classification hierarchy follows the spatial composition logic of bridge structures. The Unified Standard for Application of Building Information Model in Highway Engineering (JTG/T 2420–2021) [21] organizes highway engineering information models into three levels—facility, sub-facility and component—and the classification of bridge components should be compatible with this hierarchy. On this basis, bridge components can be further subdivided into foundations, piers and abutments, pylons, main girders, cable systems and other subcategories, each subdivided again according to structural type and construction method: foundations, for instance, comprise spread foundations, pile foundations, open caisson foundations and diaphragm walls, and pile foundations can be further divided into bored cast-in-place piles, steel pipe piles and pre-stressed high-strength concrete (PHC) piles according to the pile-forming technology. The boundary of a bridge component object follows the principle of "independent organization of construction and inspection": a component should be the smallest structural unit that can be independently produced and independently inspected for quality during construction. This principle agrees with the division logic of divisional works in the Standard for Quality Inspection and Evaluation of Highway Engineering (JTG F80/1–2017) [22], so component objects can directly carry quality inspection data.

2. **Workers.** Workers are spatio-temporal objects with active behavioral and cognitive abilities, and they are the executive subjects of construction activities. What distinguishes workers from other object types is their possession of the two feature dimensions of cognitive intelligence and behavioral actions: personnel can perceive environmental information, make decisions and judgements, and execute corresponding construction operations. By functional role, workers include on-site workers such as formwork workers, steel bar workers and welders; project management personnel such as project managers, chief engineers and professional engineers; supervision personnel such as chief supervision engineers and professional supervision engineers; and representatives of the owner. They have behavioral abilities such as standing, walking, equipment operation and information transmission; cognitive abilities such as information reception, processing, analysis and decision execution; and attribute information such as name, gender, ethnicity and role. Workers are associated with structural components, equipment and construction measures, and their information can be extended beyond the basic attributes according to the functional and data transmission needs of different management systems.
3. **Machinery and equipment.** Machinery and equipment are the power devices and tool systems used to change the state or spatial position of objects during bridge construction; they are the material means by which the construction process advances. By construction environment, they fall into two categories: land construction equipment such as crawler cranes and concrete mixing plants, and marine construction equipment such as pile-driving barges, floating cranes and barges. By functional purpose, they divide into bridge-specific construction equipment such as highway girder erection machines, cable cranes and deck cranes, and general construction machinery such as excavators, loaders and transport vehicles. The Technical Specification for Construction of Highway Bridges and Culverts (JTG/T 3650—2020) [23] stipulates the requirements for equipment selection and configuration in each special construction chapter, and the classification of machinery and equipment objects should be compatible with the equipment classification system in that specification. What distinguishes machinery and equipment from bridge components is their high dynamics: equipment frequently changes its spatial position and operating state during construction, and behavioral action features such as lifting, travelling and slewing are important contents of the dynamic description of digital scenes.
4. **Bridge site environment.** The bridge site environment refers to the external natural conditions and applied loads that affect the bridge construction process; it is an important input for construction decision-making and safety control. By type, it covers hydrological conditions such as water depth, water level, flow velocity and tide; meteorological conditions such as wind speed, temperature, humidity and rainfall; geological conditions such as stratum structure, geotechnical parameters and groundwater; and seismic parameters such as peak ground acceleration and characteristic period. The Technical Specification for Structural Monitoring of Highway Bridges (JT/T 1037—2022) [24] divides monitoring contents into four categories—environment, action, structural response and structural change—among which the environmental monitoring parameters, including temperature and humidity, wind speed and direction, and rainfall, can serve as a direct reference for the digital description of bridge site environment objects. The essential difference from bridge components is

that the bridge site environment acts on the construction system from outside and its values are not directly controlled by construction activities, whereas the state changes of bridge components are directly driven by construction activities.

5. Construction measures. Construction measures are the temporary facilities, structures and process equipment set up to achieve the construction objectives of the bridge structure, and they are the material carriers of construction methods. They are usually dismantled or recycled after construction is completed and do not become part of the permanent bridge structure, yet they have a decisive influence on engineering quality and safety during construction. By function, they fall into three categories: temporary facilities such as steel bar processing plants, concrete mixing plants and prefabrication yards; temporary structures such as formwork systems, temporary supports and bracket systems; and construction tooling such as lifting appliances, positioning tooling and tensioning tooling. The criterion that distinguishes construction measures from bridge components is "permanence": bridge components form part of the permanent bridge structure, whereas construction measures only serve the construction process. Even so, construction measures and bridge components are closely associated spatially and mechanically during construction, and this association is a key content to be modeled in digital scenes.
6. Monitoring and sensing. Monitoring and sensing refers to the sensors and their data acquisition systems deployed at bridge construction sites for real-time monitoring and perception of structural states and environmental conditions; it is the key data entry for realizing the "virtual-physical mapping" of digital scenes. Sensor types commonly used in bridge construction include strain sensors, displacement sensors, acceleration sensors, temperature sensors, earth pressure cells, wind speed sensors and image sensors. Monitoring and sensing objects are dual in nature. A sensor is itself a physical entity existing in physical space, with attributes such as spatial position and model specifications; at the same time, its core function is to perceive the state parameters of other objects, and its behavioral features are embodied in data acquisition and transmission activities. A monitoring and sensing object is therefore not only an independent spatio-temporal object in the digital scene but also a carrier of feature data sources of other spatio-temporal objects.
7. Quality inspection. Quality inspection is the general term for activities that test, evaluate and record the quality of raw materials, procedures and finished products in the construction process, and it is the information carrier of quality management in digital scenes. By inspection stage, it divides into raw material inspection, such as the incoming inspection of cement, steel bars and aggregates; process inspection, such as the inspection of slurry indicators, drilling pressure and final hole conditions in bored pile construction; and finished product inspection, such as the acceptance of concrete strength, pile position deviation and integrity of pile foundations. Quality inspection differs from other spatio-temporal objects in that it is the "inspection activity" itself and the data records it generates, rather than a physical entity. An inspection activity has attributes such as an explicit timestamp, inspection method, inspection result and conformity judgement, which are associated with the inspected components, materials or procedure objects through interrelationships.

Hierarchical structure and interrelationships of spatio-temporal objects

Spatio-temporal objects in bridge construction scenes exhibit a natural hierarchical structure in granularity. Take bridge components as an example. At the macro-granularity, the whole bridge can be regarded as one integral object; at the meso-granularity, it can be decomposed into divisional work objects such as foundations, substructures and superstructures; and at the micro-granularity, each division can be further subdivided into specific components, such as a pile or a pier body segment, which can in turn be decomposed into parts such as reinforcement cages and embedded parts. Workers can likewise be described at the granularities of project, department, crew and individual, and machinery and equipment at the granularities of equipment group, equipment and part.

Granularity selection should serve specific application scenarios: macro-granularity suits global progress control and resource allocation, meso-granularity the technical management of divisional works, and micro-granularity component-level quality traceability and refined construction control. The multi-granularity hierarchical structure allows the same physical scene to be described and analyzed at different levels of abstraction, which is an important guarantee for the flexibility of digital scenes.

In data modeling, the granularity hierarchy is expressed through compositional structure: the compositional structure of a high-level object describes its containment of low-level child objects, and low-level objects record their membership in high-level parent objects through interrelationships. This bidirectional hierarchical expression mechanism ensures the consistency and traceability of the multi-granularity object system.

The interrelationships among the seven categories of objects in bridge construction scenes can be summarized into four basic types.

(1) Compositional relations. These describe the whole-part containment relations between objects, such as that between bridge components and parts and that between construction crews and workers. Compositional relations are the basis of the multi-granularity hierarchical structure and are modeled through the compositional structure feature.

(2) Spatial relations. These describe the spatial topological and metric relations between objects, such as the positional relation between machinery and working faces, the attachment relation between sensors and measured components, and the contact relation between temporary supports and supported structures. Spatial relations are jointly expressed through the spatio-temporal positioning feature and the interrelationship feature.

(3) Temporal relations. These describe the temporal sequence and duration relations between objects or object states, such as the sequential constraints between construction procedures, the time intervals of equipment entry and exit, and the temporal connection between concrete pouring and curing. Temporal relations are the basis of construction progress modeling and process traceability.

(4) Causal relations. These describe the driving and influencing relations between objects, such as the influence of bridge site environmental changes on the adjustment of construction measures, the influence of the state of construction measures on component quality, and the triggering of construction decisions by abnormal monitoring data. Causal relations provide the semantic basis for risk warning and intelligent decision-making in digital scenes.

Construction of the multi-granularity spatio-temporal object data model for bridges

In digital scenes of bridge construction, different types of spatio-temporal objects call for different emphases in data description. Bridge components, as the core entity objects, are described mainly in terms of compositional structure and attributes. Workers and machinery and equipment, as dynamic objects, are particularly prominent in behavioral actions and cognitive intelligence features. Bridge site environment and monitoring and sensing objects center on spatio-temporal positioning and attributes, whereas construction measures and quality inspection objects rely more on interrelationships and spatio-temporal references to establish semantic links with other objects. On this classification basis, we construct a data description framework for spatio-temporal objects that expresses the various bridge objects in a consistent, formalized manner.

Data description framework for spatio-temporal objects

For multi-granularity spatio-temporal objects, the Pan-Spatial Information System theory has established a description framework with eight dimensions [3]: spatio-temporal reference, spatial position, spatial form, compositional structure, interrelationship, cognitive ability, behavioral ability and attributes. Universal as this framework is in geographic information science, it suffers from dimensional redundancy when applied directly to bridge construction scenes.

Considering the domain characteristics, construction process, described objects and data information of bridge construction, we specialize the eight-dimensional feature framework for this domain in three aspects. First, "spatial position" is merged with the temporal attribute into "spatio-temporal positioning". Objects in bridge construction scenes always exist in spatio-temporal unity: whether it is the installation and positioning of components, the movement trajectory of equipment, or the temporal variation of the bridge site environment, every spatial position carries an explicit timestamp, and the two cannot be separated in expression. Second, "spatial form" is incorporated into "attributes". In bridge construction, spatial form mainly concerns the transformation of material states, such as the transition of concrete from liquid to solid and the melting and solidification of metal in welding; the objects and phenomena involved are limited, so spatial form is no longer listed as an independent feature but expressed uniformly within attributes. Third, "cognitive ability" and "behavioral ability" are renamed "cognitive intelligence" and "behavioral actions", respectively, to highlight the autonomous decision-making and active response characteristics of objects in intelligent bridge construction scenes and to stay

consistent with the discourse of the current intelligent construction field. After this simplification, the multi-granularity spatio-temporal object data model for bridge construction scenes is described in seven dimensions: spatio-temporal reference (SR), spatio-temporal positioning (SP), compositional structure (CS), interrelationship (IR), cognitive intelligence (CI), behavioral actions (BA) and attributes (AT). Fig. 3 shows the overall architecture and linkage relationship of the seven feature dimensions.

Data feature description of spatio-temporal objects

Spatio-temporal reference (SR)

The spatio-temporal reference defines the spatio-temporal expression datum of spatio-temporal objects; it ensures that multi-source data are measured, transformed and fused within a unified framework. This feature consists of a temporal reference system and a spatial reference system. The temporal reference system includes a master reference system represented by coordinated universal time (UTC) or Beijing Time, and a self-reference system with the project commencement time as the origin. The spatial reference system includes a global master reference system represented by the China Geodetic Coordinate System 2000 (CGCS2000) or the World Geodetic System 1984 (WGS84), a parent reference system describing the relative position of an object in its parent container, and a self-reference system defining the local coordinate direction of the object itself.

Eq. (1) gives the symbolic representation of the spatio-temporal reference.

$$SR = (T_Ref, S_Ref_Global, S_Ref_Parent, S_Ref_Local) \quad (1)$$

The four components are defined as follows.

(1) T_Ref is the temporal reference system, defining the datum of time measurement. Absolute time is expressed as (Type: Absolute, Standard: UTC, Epoch: null), and relative time as (Type: Relative, Standard: Project-Calendar, Epoch: 2024-05-01T00:00:00Z).

(2) S_Ref_Global is the global spatial reference system, defining the datum frame of global or absolute spatial coordinates; a geodetic coordinate system, for example, is expressed as (Type: Geodetic, Datum: CGCS2000), and a projected coordinate system as (Type: Projected, CRS_ID: EPSG:4547).

(3) S_Ref_Parent is the parent spatial reference system, defining the relative spatial frame of an object in its parent container; it is optional, e.g., (Type: Local, Parent_ID: Bridge-Model-001, Origin: (0, 0, 0)).

(4) S_Ref_Local is the local spatial reference system, defining the inherent local coordinate system of the object itself; it is also optional, e.g., (Type: Cartesian, Origin: (0,0,0), Orientation: (Forward: (1,0,0), Up: (0,0,1))).

For a pier component, the spatio-temporal reference can be written as $SR_{Pier} = (T_Ref = (Type: "Absolute", Standard: "UTC+8", Epoch: None), S_Ref_Global = (Type: "Geodetic", Datum: "CGCS2000"), S_Ref_Parent = (Type: "Local", Parent_ID: "Bridge-Project-2024", Origin: "CP-N1"), S_Ref_Local = (Type: "Cartesian", Origin: (0, 0, 0), Orientation: (Forward: (1, 0, 0), Up: (0, 0, 1))))$). Here the pier component adopts Beijing Time as the temporal datum, CGCS2000 as the global spatial coordinate system, the overall coordinate system of the bridge project as the parent coordinate system with the project control point N1 as the origin, and a local coordinate system whose origin sits at the centre of the bottom surface of the component with the Z-axis vertically upward.

This tuple-based representation encapsulates all spatio-temporal datum elements into structured data that computers can parse, store and verify directly, covering multi-level reference requirements from global to local and from absolute to relative. Tuple components can be extended with additional attributes, such as coordinate units and projection parameters, without changing the overall structure. The standardized structure and naming ensure the uniqueness and accuracy of spatio-temporal datum expression, laying a foundation for the transformation and fusion of multi-source spatio-temporal data.

Spatio-temporal positioning (SP)

On the basis of the spatio-temporal reference, spatio-temporal positioning further describes the spatial position, orientation and dynamic changes of an object at a specific moment. A timestamp determines the instant or interval of the object on the time axis; spatial coordinates determine its position; and parameters such as orientation, velocity and angular velocity describe its instantaneous state or motion trajectory in a given reference system.

Eq. (2) expresses spatio-temporal positioning symbolically.

$$SP = (T, P, O, V, \omega)$$

Its five components are defined as follows.

(1) T (Time): a timestamp or time interval indicating the moment or period when the state takes effect. An instant is expressed as t (e.g., 2023-10-27T10:30:15.000Z), and an interval as $[t_start, t_end]$ (e.g., [2023-10-27T10:30:00Z, 2023-10-27T10:35:00Z]).

(2) P (Position): a spatial coordinate triple (x, y, z) whose reference system is defined by the spatial reference system in SR. Global absolute coordinates take the form (longitude, latitude, elevation), and local relative coordinates the form $(local_x, local_y, local_z)$.

(3) O (Orientation): the rotational state of the object in space, expressed by Euler angles (roll, pitch, yaw) or quaternions (q_x, q_y, q_z, q_w) .

(4) V (Linear velocity): the triple (v_x, v_y, v_z) of the position change rate, whose coordinate axis directions are consistent with the reference system of P .

(5) ω (Angular velocity): the triple $(\omega_x, \omega_y, \omega_z)$ of the orientation change rate, representing the angular velocities of rotation about each coordinate axis.

For the instantaneous positioning of a precast girder segment, $SP_Girder = (T: "2023-10-27T10:30:15.000Z", P: (114.318, 30.517, 85.2), O: (0.0, 0.0, 90.0), V: (0.0, 0.0, 0.0), \omega: (0.0, 0.0, 0.0))$. That is, at 10:30:15 on 27 October 2023, the precast girder was located at CGCS2000 geodetic coordinates $(114.318^\circ E, 30.517^\circ N, \text{elevation } 85.2 \text{ m})$, placed horizontally with its axis at 90° to due north, and stationary.

This representation integrates the spatio-temporal reference system, instantaneous state and dynamic change into a complete description of the spatio-temporal state of an object. Together with the spatio-temporal reference feature, it flexibly supports absolute and relative as well as global and local reference situations. The introduction of velocity V and angular velocity ω provides key inputs for dynamic behavior analysis and intelligent decision-making.

Compositional structure (CS)

Spatio-temporal objects do not exist in isolation; they are organized into multi-granularity hierarchical structures through "whole-part" relations. The compositional structure feature describes such constituent relations between objects, including logical compositional membership relations and spatial topological relations. A bridge, for example, consists of substructures such as foundations, piers and main girders, and a pier consists of components such as the cushion cap, pier body and bent cap. This recursive decomposition defines the internal construction and functional division of objects.

The compositional structure is expressed symbolically in Eq. (3).

$$CS = (Whole, \{Part_1, Part_2, \dots, Part_n\}, Relation) \quad (3)$$

It has three components.

(1) Whole: the unique identifier of the whole object, e.g., "Bridge-B1".

(2) $\{Part_1, Part_2, \dots, Part_n\}$: the set containing the unique identifiers of all direct constituent parts.

(3) Relation: a tuple or rule describing the spatial topological or logical relations among the parts and between the parts and the whole.

The compositional structure supports recursive definition. For a simply supported girder bridge, the three-level recursive expression is as follows:

CS_Bridge = (Whole: "Bridge-B1", Parts: {"Pier-Abutment-1", "Pier-Abutment-2", "Girder-01"}, Relation: "SupportedBy")

CS_Pier = (Whole: "Pier-Abutment-1", Parts: {"Cap-Beam-1", "Column-1", "Column-2", "Foundation-1"}, Relation: ("ComposedOf", "SupportedBy"))

CS_Foundation = (Whole: "Foundation-1", Parts: {"Rebar-Cage-1", "C40-Concrete-Batch-88"}, Relation: "EmbeddedIn")

Recursive definition allows the compositional structure to describe any granularity level from macro to micro and supports dynamic switching of multi-granularity views. Each (Whole, Relation, Part) triple maps directly onto a semantic statement in a knowledge graph, which provides a basis for associative reasoning. In construction progress simulation, once the states of all underlying parts change to "completed", the system can automatically update the state of the parent part to "completed", realizing automatic aggregation of progress.

Interrelationship (IR)

Interrelationship describes the mutual influence, action and constraint relations among spatio-temporal objects. These include mechanical associations, such as shear transfer between adjacent girder segments; spatial associations, such as the redistribution of adjacent bridge deck elevations caused by pier settlement; logical associations, such as the requirement that concrete pouring follow the completion of formwork installation; and attribute associations, such as the influence of ambient temperature on the hydration rate of concrete. Interrelationship is the core carrier of the dynamic semantic network among objects.

Eq. (4) gives the symbolic representation of interrelationship.

$$IR = (ID, Subject, Predicate, Object, Attributes, T_Valid, Spatial_Scope) \quad (4)$$

Its six components are defined as follows.

- (1) ID: the unique identifier of an interrelationship instance.
- (2) Subject and Object: the subject and object of the relation, i.e., the unique identifiers of the two spatio-temporal objects participating in the relation; the relation points from the subject to the object.
- (3) Predicate: the type of the relation, which explicitly defines the nature of the interaction. Mechanical associations include "transmitStressTo" and "supportedBy"; spatial associations include "adjacentTo" and "connectedTo"; logical associations include "precedes" and "requiredBy"; and attribute associations include "influences" and "controls".

(4) Attributes: a set of key-value pairs describing the specific parameters, strength or nature of the relation, e.g., {"force_magnitude": "500 kN", "force_direction": "vertical"}.

(5) T_Valid: the valid time interval of the relation, capturing the fact that a relation may exist only in a specific construction stage, e.g., [2024-05-20T00:00:00Z, 2024-06-15T00:00:00Z].

(6) Spatial_Scope: the spatial scope constraint within which the relation takes effect; optional.

Consider the temporal constraint that concrete pouring must follow the completion of formwork installation and steel bar binding: IR_Precedence = (ID: "REL-PREC-556", Subject: "Activity-Template-Install-Girder-20", Predicate: "precedes", Object: "Activity-Concrete-Pouring-Girder-20", Attributes: {"logical_type": "FS", "lag_time": "PT0H0M0S"}, T_Valid: "[2024-05-01T00:00:00Z, 2024-05-15T00:00:00Z]", Spatial_Scope: "Girder-20_Location").

Through explicit predicate definitions and attribute parameters, IR expresses relations quantitatively; through the constraints of temporal validity and spatial scope, it captures the spatio-temporal dynamics of relations. Aggregated in large numbers, IR instances form an influence propagation network among objects, providing a computable data basis for risk transmission analysis and construction scheme optimization.

Cognitive intelligence (CI)

Cognitive intelligence describes the intelligent ability of spatio-temporal objects to perceive, analyze and make decisions based on knowledge; it covers perceptual, analytical, decision-making and control abilities. Typical engineering scenarios include intelligent monitoring systems that perceive ambient wind speed in real time and warn of lifting safety risks, BIM models that fuse multi-source data to predict concrete strength development, girder erection machines that autonomously plan lifting paths and avoid obstacles, and temperature sensors that cooperate with sprinkler systems to adjust curing humidity automatically.

Cognitive intelligence is essentially an abstraction of the decision-making loop of an agent; its symbolic representation is given in Eq. (5).

$$CI = (\text{Perceive, Analyze, Decide, Act, KnowledgeBase, Goal}) \quad (5)$$

All six components are functions or data sets:

(1) Perceive (perception function): acquires information from the external environment and other objects; takes environmental signals and states of other objects as inputs; outputs structured perception data Perception_Data.

(2) Analyze (analysis function): processes perception data and performs evaluation, prediction or diagnosis in combination with the knowledge base; takes Perception_Data and KnowledgeBase as

inputs; outputs the understanding of the current situation or the predicted state Situation.

(3) Decide (decision function): selects actions according to the analysis results and goals; takes Situation, Goal and KnowledgeBase as inputs; outputs a specific decision or action plan Decision.

(4) Act (execution function): converts the decision into specific physical actions or information release behaviors; takes Decision as input; outputs the behavioral action Action.

(5) KnowledgeBase: the set of knowledge owned by the object, including rules (IF-THEN), models, cases and interrelationships.

(6) Goal: the core task that the object needs to optimize or complete, which drives the decision-making process.

A wind speed monitoring and early warning system can be written as $CI_WindAlert = (Perceive: \lambda p: \{ "wind_speed": query_sensor("anemometer_01") \}, Analyze: \lambda p, kb: \{ "risk": "High" \text{ if } p["wind_speed"] > kb["max_wind"] \text{ else } "Low" \}, Decide: \lambda s, g, kb: \{ "Issue_Alert" \text{ if } s["risk"] == "High" \text{ else } "Continue" \}, Act: \lambda d: send_alert(d), KnowledgeBase: \{ "max_wind": 15.0 \}, Goal: "Ensure_Lifting_Safety")$.

This representation turns cognitive intelligence from an abstract concept into a computable closed loop of "perceive–analyze–decide–act": Perceive relies on the attributes feature AT to acquire real-time data, KnowledgeBase stores and draws on the interrelationship feature IR for contextual reasoning, and Act outputs specific behavioral actions BA. CI thus connects the three features AT, IR and BA into a complete intelligent decision-making chain.

Behavioral actions (BA)

Behavioral actions describe the specific operations and responses that spatio-temporal objects can execute. They include information behaviors and physical behaviors: personnel standing, walking and transmitting information; workers binding steel bars and supporting formwork; pump trucks pouring concrete; girder erection machines starting, stopping and lifting; tower crane booms slewing and lifting; sensors sensing data and issuing early warnings; and incremental launching equipment driving girder segments to slide forward. Behavioral actions are triggered by preset programs, external instructions or changes in environmental states, carry explicit control parameters, and interact dynamically with associated objects.

A behavioral action is a standardized encapsulation of an "event" or "operation", expressed symbolically in Eq. (6).

$$\text{Action} = (\text{Actor, Verb, Target, Parameters, Trigger, Precondition, Effect}) \quad (6)$$

Its seven components are defined as follows.

- (1) Actor: the unique identifier of the spatio-temporal object that executes the action.
- (2) Verb: the core type or name of the action. Physical behaviors include "Move", "Lift", "Rotate" and "Pour", and information behaviors include "Sense", "Transmit", "Alert" and "Update".
- (3) Target: the identifier of the object on which the action acts; optional.
- (4) Parameters: a set of key-value pairs describing the control parameters of the action, e.g., {"velocity": 0.5, "destination": (x, y, z)}.
- (5) Trigger: the event or condition that initiates the action, e.g., "On_Command(Command_ID: CMD-123)" or "When(Perception.humidity < 90%)".
- (6) Precondition: the system state or safety conditions that must be satisfied before the action is executed; optional, e.g., {"self.status": "idle", "wind_speed": "< 15 m/s"}.
- (7) Effect: the expected changes to the states of the actor itself, the target or the environment after the action is successfully executed, e.g., {"Target.position": "destination", "Project.progress": "updated"}.

For the lifting of a precast girder by a girder erection machine, the action reads Action_Lift = (Actor: "GirderErectionMachine-01", Verb: "Lift", Target: "PrecastGirder-25", Parameters: {"lift_height": 30.0, "speed": 0.1}, Trigger: "On_Command(Command_ID: CMD-LIFT-20241027-001)", Precondition: {"self.status": "anchored_and_ready", "wind_speed": "< 15 m/s"}, Effect: {"Target.position": "at_installation_position", "Project.progress": "girder_25_installed"}).

This representation brings three practical benefits. With Precondition defined explicitly, the system can verify safety before executing an action and thus prevent misoperation. With Effect defined explicitly, the digital scene can simulate the consequences of behaviors in advance, supporting virtual verification of construction schemes. And because Trigger can be driven directly by the Decide function of the cognitive intelligence module, the representation closes the intelligent loop of "perceive–decide–execute".

Attributes (AT)

The attributes feature describes the essential characteristics and real-time states of spatio-temporal objects and serves as the data basis of the other six features. It consists of static attributes, dynamic attributes and metadata. Static attributes are inherent parameters that do not change over time, such as geometric dimensions, material strength grades and design parameters. Dynamic attributes are real-time states that change with time, environment or behavior, such as structural stress and strain, equipment operating temperature and environmental monitoring values, recorded as timestamped data streams. Metadata describes the units, data types, sources and accuracy of the attributes themselves, ensuring that the data are parsed correctly and remain traceable.

The attributes feature is expressed symbolically in Eq. (7).

$$\text{Attributes} = (\text{Static_Attributes}, \text{Dynamic_Attributes}, \text{Metadata}) \quad (7)$$

All three components are sets of key-value pairs:

- (1) Static_Attributes: static attribute key-value pairs {Key: Value}, such as geometric dimensions {"length": 30.0, "width": 2.5} and material properties {"concrete_grade": "C50", "steel_elastic_modulus": 2.0e5}.
- (2) Dynamic_Attributes: dynamic attribute key-value pairs {Key: (Value, Timestamp)}, such as structural states {"stress": (25.6, "2024-05-27T10:30:00Z")} and equipment states {"operating_speed": (0.5, "2024-05-27T10:30:00Z")}.
- (3) Metadata: metadata key-value pairs {Key: {Metadata_Key: Metadata_Value}}, such as units {"stress": {"unit": "MPa"}, "length": {"unit": "m"}} and data types {"concrete_grade": {"data_type": "string"}, "stress": {"data_type": "float"}}.

For a girder erection machine, the attributes feature reads AT_Erector = (Static_Attributes: {"model": "JQ900", "max_lifting_capacity": 900.0, "max_span": 40.0}, Dynamic_Attributes: {"current_load": (650.5, "2024-05-28T10:30:15Z"), "hydraulic_pressure": (28.5, "2024-05-28T10:30:15Z")}, Metadata: {"max_lifting_capacity": {"unit": "t", "data_type": "float"}, "hydraulic_pressure": {"unit": "MPa", "data_type": "float"}}).

Separating static from dynamic attributes avoids conceptual confusion; metadata allows computers to parse units, verify data types and trace data sources automatically; and the timestamps in dynamic attributes establish the semantic association between the attributes feature and the spatio-temporal positioning feature. Together, the three constitute the raw data basis for the analysis and decision-making of the cognitive intelligence module.

Illustrative application

To test the applicability of the proposed method, we construct an illustrative scenario of the pier body construction stage of a medium-scale cable-stayed bridge (denoted as Bridge-Project-2024). The main construction activities in this stage include steel bar binding, formwork installation, concrete pouring and curing of the pier body segments; a tower crane and a concrete pump truck serve as the main equipment, and anemometers and strain gauges are deployed on the pier for real-time monitoring. The digital scene of this stage was organized following the seven-category classification system, and the key objects were instantiated as shown in Table 1.

Table 1. Instantiation of spatio-temporal objects in the pier construction stage.

Object category	Instantiated object	Key features populated	Data source
Bridge components	Pier-Abutment-1 (pier body segment)	SR, SP, CS, AT	Design drawings, BIM model
Workers	Steel bar workers, formwork workers, site engineer	CI, BA, AT	Personnel management system
Machinery and equipment	Tower crane TC-01, concrete pump truck	SP, BA, AT	Equipment IoT platform
Bridge site environment	Wind speed, temperature, humidity at site	SR, AT	Meteorological monitoring station
Construction measures	Formwork system, climbing frame	CS, IR, AT	Construction scheme documents
Monitoring and sensing	Anemometer-01, strain gauges on pier	SP, BA, AT	Sensor data acquisition system
Quality inspection	Concrete strength test of pier segment	IR, AT	Quality inspection records

Taking the pier component Pier-Abutment-1 as the core entity, we defined its spatio-temporal reference with CGCS2000 as the global datum and the project control network as the parent reference (see Eq. (1)). Its position and orientation were updated through the spatio-temporal positioning feature as construction proceeded. Its compositional structure recursively decomposed the pier into cushion cap, pier body and bent cap, and further into reinforcement cages and concrete batches. Its attributes recorded both static parameters (design elevation and concrete grade C40) and dynamic states (pouring progress and measured strain) with timestamps.

The wind speed warning scenario illustrates the closed-loop linkage of cognitive intelligence and behavioral actions. The anemometer Anemometer-01, a monitoring and sensing object, continuously wrote wind speed measurements into its dynamic attributes. When the measured wind speed exceeded the threshold of 15 m/s defined in the KnowledgeBase, the cognitive intelligence of the monitoring system completed the perceive-analyze-decide-act loop and issued a warning decision. This decision served directly as the Trigger of the lifting suspension action of the tower crane: the Precondition {wind_speed < 15 m/s} of the scheduled lifting action was no longer satisfied, so the lifting action was suspended, and the Effect updated the states of the target girder segment and the project progress. Meanwhile, interrelationship instances—such as the attachment relation between Anemometer-01 and the pier and the precedence relation between formwork installation and concrete pouring—were registered with temporal validity, supporting causal tracing of subsequent quality inspection records.

In this application, the pier construction stage was described consistently in a unified data model. The compositional structure enabled automatic aggregation of construction progress from concrete batches to the whole pier; the interrelationship network supported the tracing of quality problems to specific procedures, materials and environmental conditions; and the CI-BA closed loop realized automatic

response from environmental perception to construction action control. The proposed framework is thus operable in real engineering scenarios and can accommodate multi-source heterogeneous data from design documents, monitoring systems and management platforms.

Discussion

Innovation and advantages of the method

Compared with current BIM and digital twin methods, the proposed method differs essentially in three dimensions.

(1) A dimensional leap from "geometric attributes" to "spatio-temporal behavioral cognition". Traditional BIM, centered on the "geometry + attributes" of the industry foundation classes (IFC) standard [18], focuses on three-dimensional geometry and static attributes. Digital twin methods incorporate sensor data access but remain largely at the level of "data superposition". By introducing cognitive intelligence and behavioral actions, our method systematically describes the dynamic behaviors, interrelationships and autonomous decision-making abilities of construction objects, moving from "geometric form" to "behavioral cognition". Spatio-temporal objects are upgraded from "passive data containers" to "active intelligent entities", and digital scenes can evolve from visualization tools into intelligent decision-making engines.

(2) A relationship upgrade from "static association" to "dynamic semantic network". Traditional BIM expresses relations mainly as static connections through IfcRelConnects [18], and the information lacks deep semantic links. Our formalized definition of interrelationships endows each relation with an independent identifier, attribute parameters, temporal validity and spatial scope, constructing a dynamic knowledge network of mutual influence among objects. This moves from "information integration" to "semantic association" and closes the loop from state perception and causal-tracing diagnostic analysis to decision assistance, laying a foundation for knowledge graph construction and semantic reasoning.

(3) A structural deepening from "single granularity" to "multi-granularity hierarchy". The hierarchical decomposition of traditional BIM is static. With the recursive definition of the compositional structure, our method supports dynamic multi-granularity switching of spatio-temporal objects from macro to micro, achieving efficient data processing through "on-demand loading and on-demand updating".

To evaluate these advantages systematically, we compared the BIM method represented by the IFC standard [18], the digital twin method characterized by sensor data fusion [19-20] and the proposed method in nine dimensions: core data unit, spatio-temporal expression, structural organization, relation expression, intelligent ability, behavior modeling, attribute management, granularity flexibility and knowledge expression (Table 2).

Table 2. Comparison of feature differences between the proposed method and existing methods.

Feature dimension	Traditional BIM	Digital twin	Proposed method
Core data unit	Components	Components + sensor data	Multi-granularity spatio-temporal objects
Spatio-temporal expression	Static coordinates	Static coordinates + timestamps	Spatio-temporal reference + spatio-temporal positioning (incl. velocity/orientation)
Structural organization	Static hierarchical decomposition	Static hierarchy + data binding	Recursive compositional structure (supporting dynamic reorganization)
Relation expression	Spatial/logical relations	Spatial/logical + data association	Multiple associations (mechanical/spatial/logical + temporal validity)
Intelligent ability	None	None (driven by external data)	Cognitive intelligence (perceive–analyze–decide–act closed loop)
Behavior modeling	None	Simple animation	Behavioral actions (trigger/precondition/parameters/effect)
Attribute management	Static attributes	Static attributes + dynamic data	Attributes (static/dynamic/metadata)
Granularity flexibility	Fixed hierarchy	Fixed hierarchy	Multi-granularity dynamic switching
Knowledge expression	None	Limited	Knowledge base + rules + cases

The seven-feature formalized description framework is machine-readable, computable, inferable and knowledge-graph-constructible. Structured tuples can be parsed and verified directly by computer programs; the coordinates and velocities in SP, the attribute parameters in IR and the function definitions in CI feed directly into computational analysis; the interrelationship network and the knowledge base allow the system to perform semantic reasoning, such as automatically deriving scheduling constraints; and each triple maps directly onto a knowledge graph description, providing a standardized data source for advanced semantic reasoning and knowledge discovery.

Limitations and challenges

The seven-feature formalized description framework is theoretically complete, but transforming it from a theoretical model into engineering practice still faces several challenges, and these are the key bottlenecks restricting the application of the method.

(1) Engineering implementation of the formalized description framework is difficult. Although the seven-feature symbolic expression is theoretically complete, acquiring complete data in engineering practice is

far from easy. The construction of the KnowledgeBase of cognitive intelligence and the definition of trigger conditions and preconditions of behavioral actions, in particular, require domain experts to invest substantial effort in knowledge extraction and rule writing. A medium-scale cable-stayed bridge project, for example, involves dozens of construction procedures and hundreds of working conditions, and the CI and BA feature description of each procedure requires deep collaboration between domain experts and knowledge engineers. Reducing the cost of knowledge acquisition and establishing a semi-automatic knowledge extraction toolchain is the key bottleneck of engineering implementation.

(2) The boundary of multi-granularity spatio-temporal objects is hard to define. In practical engineering, "multi-granularity" presents a dilemma: overly fine granularity causes an explosion in object quantity and makes computation infeasible, whereas overly coarse granularity loses descriptive accuracy. The steel box girder of a long-span bridge, for instance, can be decomposed into dozens of components such as top plates, bottom plates, webs, U-ribs and diaphragms. Modeling all of them at the finest granularity would yield objects on the order of millions, and the interrelationship network would grow exponentially, making it difficult for existing graph databases and reasoning engines to complete global queries and reasoning within a reasonable time. At present, systematic granularity selection criteria are lacking, and the optimal granularity level cannot be determined automatically according to engineering task requirements.

(3) Compatibility with the existing engineering software ecosystem is limited. The data formats of current BIM/IFC standards, finite element analysis software and project management systems differ considerably from the seven-feature description framework. The IFC standard [18], centered on "geometry + attributes", lacks native support for behavioral actions and cognitive intelligence; finite element software takes nodes and elements as basic data units, which do not fully correspond to the multi-granularity hierarchical structure of spatio-temporal objects; and project management systems organize data with a work breakdown structure, leaving a semantic mapping gap with the recursive compositional structure of CS. Establishing standardized mapping and conversion mechanisms for bidirectional interoperability between the seven-feature description framework and the existing software ecosystem is a prerequisite for promoting the engineering application of the method.

(4) Real-time requirements conflict with computational complexity. The perceive–analyze–decide–act closed loop of CI has high real-time requirements. In time-sensitive scenarios such as safety warning, the process from sensor data access to warning instruction issuance is usually required to complete within seconds or even sub-seconds. In large-scale object networks, however, the reasoning query and knowledge computation of interrelationships IR face significant time complexity challenges. When an object network contains tens of thousands of nodes and hundreds of thousands of association edges, graph-traversal-based associative reasoning can take several seconds or even tens of seconds, too slow for real-time requirements. A balance must therefore be sought between the response speed and reasoning depth of CI, and optimization strategies such as incremental reasoning, local subgraph computation and edge-cloud collaboration need to be explored.

(5) Domain knowledge is difficult to formalize. Much empirical knowledge in bridge construction is tacit and unstructured, and formalizing it into rules and models in the KnowledgeBase is hard. The empirical judgements of senior technical workers and the contextualized decisions of on-site engineers often exist as fuzzy rules in experts' minds, lacking explicit parameter boundaries and quantitative indicators. Making such tacit knowledge explicit, structured and computable is the core difficulty in improving the decision accuracy of CI and also a frontier research direction of domain knowledge engineering.

Conclusions

Main conclusions

Focusing on the construction theory and method of digital scenes for bridge construction, this paper takes the Pan-Spatial Information System as the theoretical basis and multi-granularity spatio-temporal objects as the core modeling units, and systematically studies the classification of spatio-temporal objects in bridge construction scenes, data model construction and formalized description framework. The main conclusions are as follows:

(1) We established a classification system of seven categories of spatio-temporal objects for bridge construction scenes. Around the six elements of "man, machine, material, method, environment and measurement", all entities and information objects in bridge construction scenes are divided into seven categories: bridge components, workers, machinery and equipment, bridge site environment, construction measures, monitoring and sensing, and quality inspection. This provides a classification framework for standardized object management of digital scenes in bridge construction.

(2) We constructed a seven-feature formalized description framework comprising spatio-temporal reference, spatio-temporal positioning, compositional structure, interrelationship, cognitive intelligence, behavioral actions and attributes, and established a symbolic expression formula for each feature dimension. The framework realizes the dimensional leap of spatio-temporal objects from "geometric attribute description" to "spatio-temporal behavioral cognitive description"; it is machine-readable, computable and inferable, and provides a standardized data basis for knowledge graph construction and intelligent decision support.

(3) We constructed a formalized description and linkage expression mechanism of cognitive intelligence and behavioral actions. Cognitive intelligence is deconstructed into a four-element function chain of "perceive–analyze–decide–act", and behavioral actions are abstracted into a seven-element operation model of "actor–verb–target–parameters–trigger–precondition–effect". The two form a closed loop through a trigger–response relationship: the decision output of cognitive intelligence directly drives the trigger conditions of behavioral actions, and the execution effects of behavioral actions feed back to the perception input of cognitive intelligence through the dynamic update of the attributes feature. This mechanism enables spatio-temporal objects to respond autonomously to environmental changes and execute construction tasks actively within a unified spatio-temporal framework, providing a core driving

mechanism for the evolution of digital scenes of bridge construction from static visualization to dynamic intelligence.

Outlook

(1) Construction of a domain knowledge graph for bridge construction and knowledge reasoning. Based on the seven-feature data description framework, we will systematically construct a domain knowledge graph for bridge construction covering the three-domain association of "objects–events–data", and introduce graph neural networks and knowledge reasoning algorithms to promote the upgrading of digital scenes from "visual management" to "knowledge-driven decision-making".

(2) Deepening of cognitive intelligence. A hybrid intelligence architecture of "rule guidance + data drive" will be constructed, and deep learning and reinforcement learning methods will be introduced to learn optimal control strategies and risk patterns automatically from historical construction data, realizing the continuous evolution of cognitive intelligence.

(3) Deep integration with physical engines. The mapping relationship between spatio-temporal objects and finite element models will be established, and physical simulation results will be fed back to the digital scene in real time, realizing the integration of "mechanical simulation of the construction process + safety assessment + early warning and decision-making".

(4) Transformation path from theoretical model to engineering practice. Aiming at the engineering implementation requirements of the seven-feature formalized description framework, future research will focus on semi-automatic domain knowledge extraction tools, granularity selection criteria for multi-granularity objects, bidirectional mapping mechanisms with BIM/IFC standards, and efficient storage and query architectures for large-scale object networks, so as to establish a complete transformation path from theoretical framework to deployable software systems and realize large-scale application in bridge engineering.

Declarations

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References

- [1] Zhang Hong, Wang Min, Zheng Hehui, et al. Research on theory and practice of whole-process multi-element intelligent bridge construction[J]. Journal of Southeast University (Natural Science Edition), 2025, 55(4): 1061-1069.
- [2] Hua Yixin. Core issues and key technologies of pan-spatial information system[J]. Journal of Geomatics Science and Technology, 2016, 33(4): 331-335.
- [3] Hua Yixin, Zhou Chenghu. Data model description framework of multi-granularity spatio-temporal objects for pan-spatial information system[J]. Journal of Geo-information Science, 2017, 19(9): 1142-1149.
- [4] Jiang Nan, Fang Cheng, Chen Minjie. Preliminary study on cognition and expression of pan-spatial information system[J]. Journal of Geo-information Science, 2017, 19(9): 1150-1157.
- [5] Zhu Jun, Zhu Qing, Zhu Bing, et al. Digital twin-driven intelligent bridge construction method[J]. National Remote Sensing Bulletin, 2024, 28(5): 1340-1349.
- [6] Zhang H, Zhao W, Han Z, et al. Knowledge-guided digital twin modeling method of generating hierarchical scenes for a high-speed railway[J]. Transactions in GIS, 2023, 27(7): 2017-2041.
- [7] Zhang J, Li J, Liu B, et al. The design and application of BIM+ refined management and control platform for the Jingxiong railway bridge[J]. High-speed Railway, 2023, 1(3): 211-218.
- [8] Shi Yiqun. Virtual simulation research on construction process of suspension bridge in hazardous mountainous area based on digital twin[D]. Chengdu: Southwest Jiaotong University, 2022.
- [9] Liang Ce, Zhu Jun, Zhu Qing, et al. Knowledge-driven intelligent construction method and system for bridge construction digital twin scenes: CN115544264B[P]. 2022-12-30.

- [10] Du Ying, Wu Yuguo. Construction and implementation of spatio-temporal reference in pan-spatial information system[J]. Engineering of Surveying and Mapping, 2024, 33(5): 21-28.
- [11] Yang Zhenkai, Zhang Jiangshui, Li Xiang, et al. Preliminary study on basic issues of composition structure of spatio-temporal objects[J]. Journal of Geomatics Science and Technology, 2021, 38(6): 639-645.
- [12] Li Rui, Shi Jiahao, Dong Guangsheng, et al. Research on composition structure expression of multi-granularity spatio-temporal objects[J]. Journal of Geo-information Science, 2021, 23(1): 113-123.
- [13] Zhang Zheng. Research on key technologies of generation, management and visualization of spatio-temporal object association relations[D]. Zhengzhou: PLA Strategic Support Force Information Engineering University, 2022.
- [14] Wang Jianjian, Wang Yannan, Zhou Liangchen, et al. Classification system and expression model of association relations of multi-granularity spatio-temporal objects[J]. Journal of Geo-information Science, 2017, 19(9): 1164-1170.
- [15] Cheng Bo, Guan Xuefeng, Xiang Longgang, et al. A conceptual data model for dynamic changes expression of spatio-temporal objects and their association relations[J]. Journal of Geo-information Science, 2017, 19(11): 1415-1421.
- [16] Cao Yibing, Hua Yixin, Guo Shaomeng. Research on description method of behavior characteristics of multi-granularity spatio-temporal objects[J]. Geomatics World, 2018, 25(2): 23-29.
- [17] Zeng Mengxiong, Hua Yixin, Zhang Jiangshui, et al. Research on dynamic behavior expression model and method of multi-granularity spatio-temporal objects[J]. Journal of Geo-information Science, 2021, 23(1): 104-112.
- [18] ISO 16739-1: 2024. Industry foundation classes (IFC) for data sharing in the construction and facility management industries—Part 1: Data schema[S]. Geneva: International Organization for Standardization, 2024.
- [19] Mungaray-Carrillo A, Xia Y, Lozano-Galant F, et al. Sensor-driven digital twins for bridge infrastructure: A critical review of BIM-enabled integration, monitoring architectures, and operational maturity[J]. Applied Sciences, 2026, 16(12): 5873. DOI: 10.3390/app16125873.
- [20] Hoskere V, Hassanlou D, Rahman A U, et al. Unified framework for digital twins of bridges[J]. Automation in Construction, 2025, 175: 106214. DOI: 10.1016/j.autcon.2025.106214.
- [21] Ministry of Transport of the People's Republic of China. Unified standard for application of building information model in highway engineering: JTG/T 2420—2021[S]. Beijing: China Communications Press, 2021.

[22] Ministry of Transport of the People's Republic of China. Standard for quality inspection and evaluation of highway engineering—Section 1 Civil engineering: JTG F80/1—2017[S]. Beijing: China Communications Press, 2017.

[23] Ministry of Transport of the People's Republic of China. Technical specification for construction of highway bridges and culverts: JTG/T 3650—2020[S]. Beijing: China Communications Press, 2020.

[24] Ministry of Transport of the People's Republic of China. Technical specification for structural monitoring of highway bridges: JT/T 1037—2022[S]. Beijing: China Communications Press, 2022.

Figures

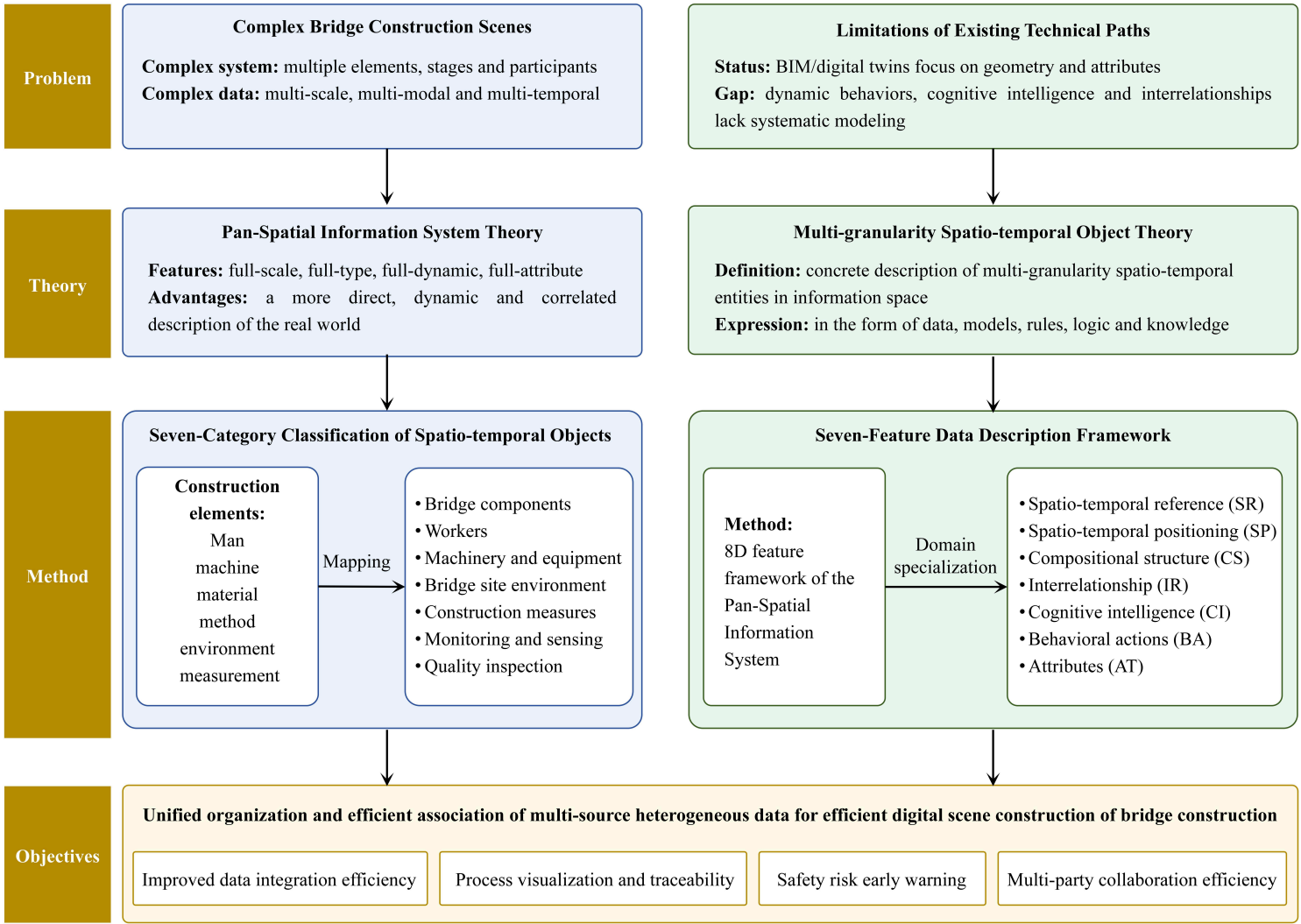


Figure 1

Overall research framework of digital scene construction for bridge construction.

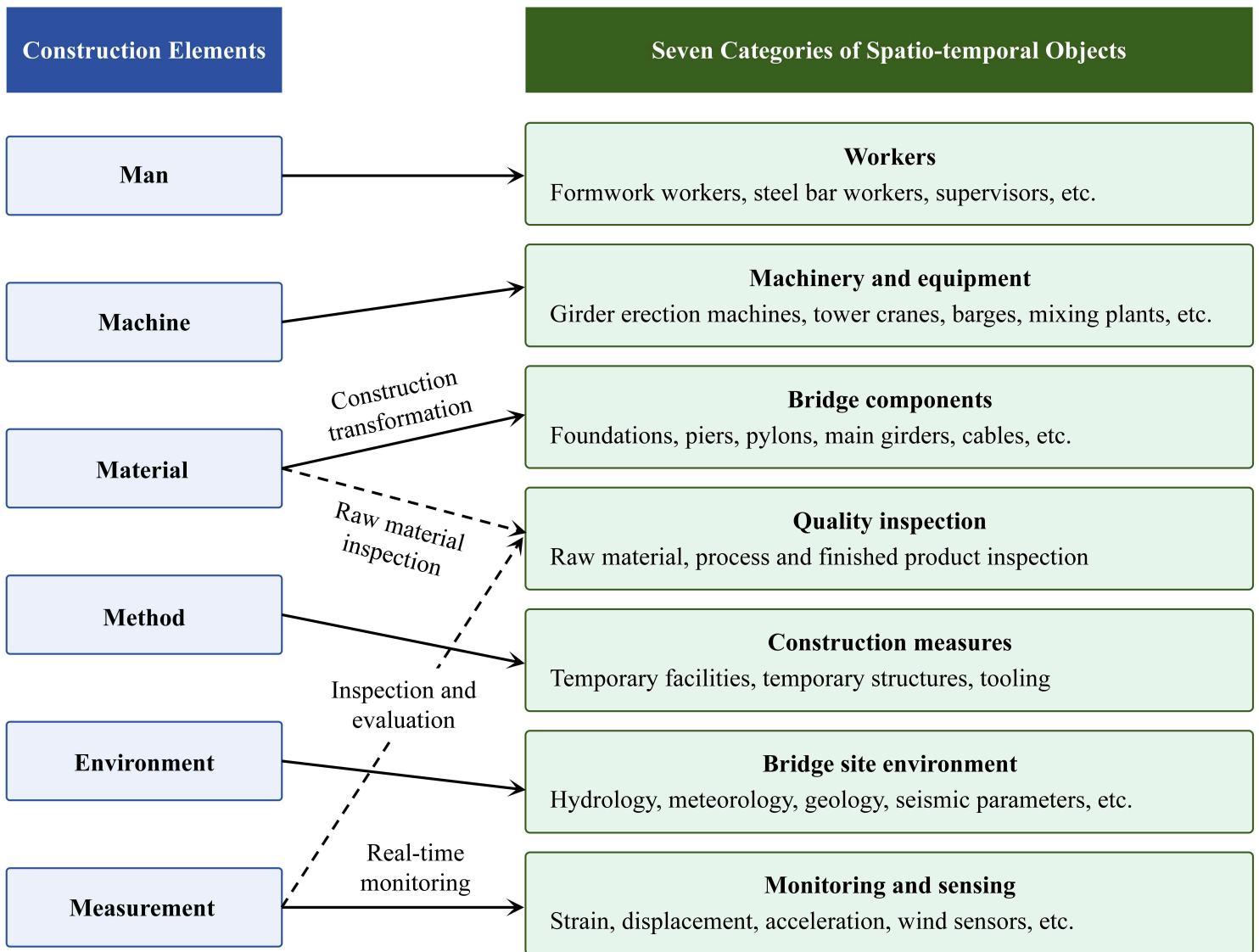


Figure 2

Mapping relationship between construction elements and the seven categories of spatio-temporal objects.



Figure 3

Overall architecture of the seven-feature data model for multi-granularity spatio-temporal objects in bridge construction scenes.

Supplementary Files

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