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Construction of Multi-granularity Spatio-temporal Object Model for Intelligent Highway Maintenance

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Abstract

With the continuous increase in the mileage of highway maintenance in our country, the tasks of highway maintenance are becoming increasingly heavy, posing new challenges for highway maintenance management. Current research on data models for highway maintenance mainly focuses on describing their spatiotemporal attributes, lacking a comprehensive expression of the characteristics and relationships of entities within highway maintenance scenarios. Moreover, traditional data management methods have many shortcomings in visualization and multidimensional information representation. Therefore, this paper constructs a multi-granularity spatio-temporal object data model framework aimed at intelligent highway maintenance by combining Multi-Granularity Spatio-Temporal Object Data Model (MGSTODM) with highway maintenance technical standards. An experiment was conducted using a highway maintenance scenario in a certain area of Beijing as an example. The results show that this model can efficiently express the multidimensional features of highway maintenance data, achieving a more comprehensive, realistic, and dynamic visualization of highway maintenance information, thus providing more effective support for maintenance data management and decision-making.

1. Introduction

At present, China's highway network has largely taken shape, with its total mileage ranking second in the world. However, under the dual influence of various natural environments and continuously increasing traffic volumes, the issue of pavement damage in China's highway network has become increasingly prominent. The number of pavement distresses, such as cracks, settlements, potholes, and alligator cracking, is gradually rising, leading to a significant decline in highway service capabilities and severely impacting the daily commutes of the public. With the continuous expansion of China's highway network, highway maintenance management faces new challenges. Contemporary highway maintenance data management technologies suffer from insufficient intelligence and suboptimal resource allocation, making it difficult to meet the refined and intelligent demands of modern highway maintenance management. In response to these issues, many scholars have conducted in-depth research on highway maintenance management and model construction.

(Qiao et al., 2019)designed a highway maintenance management system using XML based on SSH, enhancing the system's versatility. (Che et al., 2022) developed a highway maintenance management system, achieving informatization in highway management. (Lin et al., 2023) combined BIM technology with the C# programming language to develop a comprehensive management system for highway bridges, realizing standardization and informatization in highway bridge management. (Qin, 2021) constructed a highway maintenance management information system based on a 3DGIS platform, combining microscopic and macroscopic perspectives, which improved the efficiency of maintenance management. (Zheng et al., 2020) guided by the five-dimensional digital twin model, implemented a digital twin system for transportation infrastructure using GIS technology. (LIU et al., 2021)addressing the limitations of two-dimensional display for airport pavements and the large data storage requirements for large-scale BIM scenes, proposed a web-based visualization method for airport pavement quality differential expressions using Revit and Three.js technologies. (Li, 2021) adopted a SOA architecture and used BIM models as information carriers to construct an overall framework and system architecture for information resource management, developing a BIM-based highway information resource management system. While these studies effectively addressed issues related to the spatio-temporal integration and visualization of highway maintenance data, they still have several shortcomings. For instance, the display of data is relatively isolated and scattered, making it impossible to comprehensively and multi-dimensionally integrate and present highway maintenance data. Moreover, there is a lack of digital description and expression of attribute changes such as maintenance data, composition structure, and correlation relationships of entities and their affiliated objects, thus failing to fully convey multi-dimensional road maintenance information.

To comprehensively describe the multi-dimensional dynamic spatio-temporal changes throughout the entire lifecycle of spatio-temporal objects, (Hua, 2016) proposed an object-oriented modeling approach for a multi-granularity spatio-temporal object data model. This approach shifts away from the indirect spatial information modeling method based on maps as templates. Instead, it abstracts real-world entities and maps them into a virtual network environment through relevant technologies, resulting in the MGSTODM.

Based on highway maintenance technical standards, this paper identifies highway maintenance entities and utilizes the MGSTODM to construct models for highway maintenance scenarios. It primarily describes entity objects within highway maintenance scenarios at different scales from three aspects:

attribute characteristics, compositional structure, and associative relationships. This approach achieves multi-dimensional description and expression of highway maintenance data. Taking the highway maintenance scenario in a certain district of Beijing as an example, this paper constructs and implements a multi-granularity spatio-temporal object model for highway maintenance scenarios to validate the feasibility of the proposed model.

2. Construction method of highway maintenance object model

2.1 Basic information of highway maintenance and management objects

Highway maintenance entities are key objects within the highway maintenance scenario, possessing specific spatial locations and multi-dimensional attribute characteristics. Their attribute features change over time and are influenced by other entities. Under different spatio-temporal scales, multiple maintenance entities can be combined to form a larger whole or be divided into multiple sub-entities. Based on the varying needs of maintenance personnel, highway maintenance entities can be categorized at different granularity levels. The spatio-temporal objects can range from the entire road network or bridge structure to specific bridge components, traffic ancillary facilities, or damaged sections. The multi-granularity spatio-temporal entity information for highway maintenance is illustrated in Figure 1.

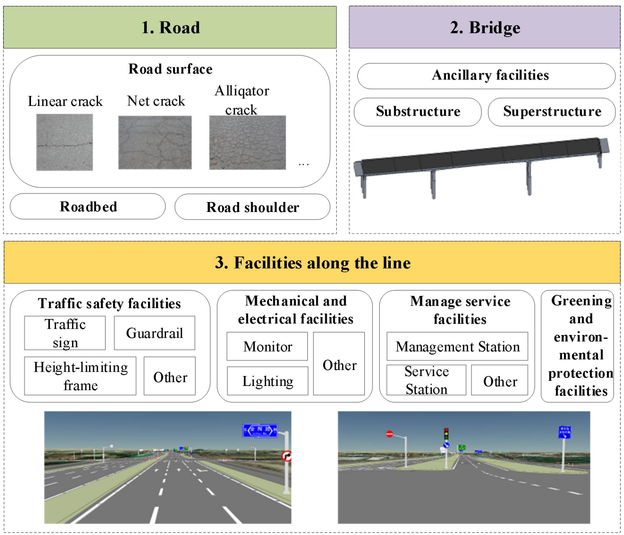

Figure 1. Highway maintenance entity.

2.2 Multi-granularity spatio-temporal object model for highway maintenance

Multi-granularity spatio-temporal objects are concrete descriptions of multi-granularity spatio-temporal entities from the real world within the information space constructed by computers. The modeling approach that simplifies and abstracts the real world into multi-granularity spatio-temporal objects is referred to as multi-granularity spatio-temporal object modeling, and the resulting model is known as the multi-granularity spatio-temporal object data model (Hua and Zhou, 2017). Compared to traditional GIS map models, the multi-granularity spatio-temporal object data model exhibits characteristics such as multi-granularity, multi-type, multi-form, and multi-reference frames.

In response to the complex environments and numerous spatio-temporal objects present in road maintenance scenarios, this paper proposes a multi-granularity spatio-temporal object model framework for highway maintenance scenarios. The model construction is illustrated in Figure 2. This framework follows the construction approach of the multi-granularity spatio-temporal object model to model highway maintenance objects from the real world within the computer information space, enabling a comprehensive, multi-dimensional, and multi-type expression of spatial information in highway maintenance scenarios. It can fully describe features such as the spatial location, spatial form, attribute information of entities, as well as their interrelationships with other entities. This approach better leverages various types of spatio-temporal information to provide a complete representation of highway maintenance scenarios, thereby supporting complex spatio-temporal data analysis and decision-making for highway maintenance.

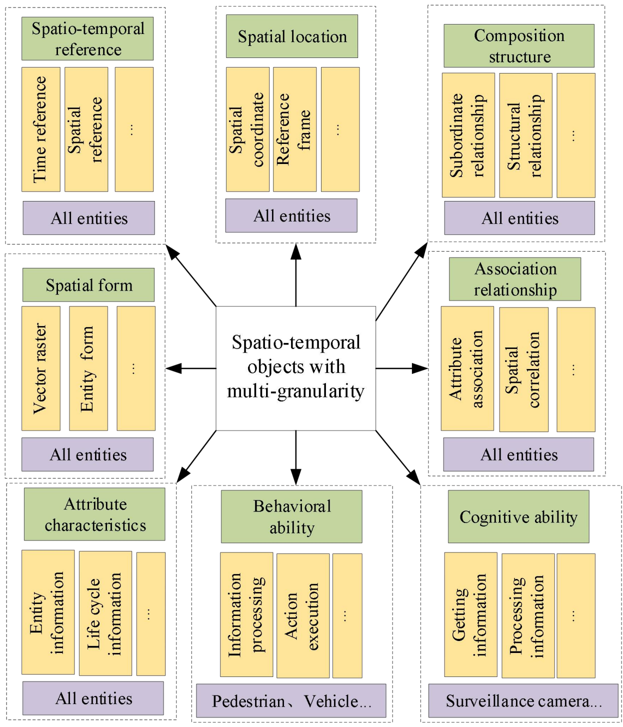

Figure 2. Multi-granularity spatio-temporal object model for highway maintenance.

2.3 Multi-dimensional feature description method for physical objects of highway maintenance

This paper primarily focuses on the visual display of road entities, road diseases, bridges, and ancillary facilities along the route within highway maintenance scenarios. It describes entity objects in highway maintenance scenarios at different scales mainly from three aspects: attribute characteristics, compositional structure, and interrelationships, thereby achieving multi-dimensional description and representation of highway maintenance data.

2.3.1 Description of Object Attribute Characteristics

The content expressed by a spatio-temporal object represents a comprehensive manifestation of all attributes of the corresponding spatio-temporal entity. Employing a multi-granularity spatio-temporal object data model to describe the attribute information of highway maintenance entities facilitates the mapping of these attributes into higher-dimensional spaces, thereby enabling a more detailed and precise depiction of the characteristics of spatio-temporal objects. Meanwhile, spatio-temporal entities encompass not only inherent static attributes but also dynamic attributes that change over time and due to production activities. Under different maintenance analysis requirements, the expression of attribute characteristics for multi-granularity spatio-temporal objects varies. At a macroscopic scale, when a highway serves as the object of maintenance analysis, the expression of its attribute characteristic set takes the form of Equation (1).

$$\begin{aligned} HighwayObject = \{&\text{“ID”}, \text{“HighwayName”}, \\ &\text{“HighwayPosition”}, \text{“HighwayLength”}, \\ &\text{“Time”}\ \text{“Describe”}, \text{“......”}\} \end{aligned} \tag{1}$$

Where:HighwayObject denotes a complete road, with HighwayName, HighwayPosition, and HighwayLength representing the highway's name, location, and length respectively, while Time signifies the temporal element, and Describe encapsulates multidimensional highway maintenance information.

At the microscale, when a road section unit serves as the object of maintenance analysis, its spatio-temporal object can be uniformly described based on the attribute characteristic fields in Table 1. Similarly, when a bridge unit is the focus of maintenance analysis, its spatio-temporal object can be described using the attribute characteristic fields in Table 2. Furthermore, when ancillary facilities along the route or road defects are the subjects of maintenance analysis, their spatio-temporal objects can be uniformly characterized according to the attribute feature fields in Table 3.

Attribute field	Data type	Field description
Road_Id	String	Unique identification of the road section
Road_Name	String	The name of the current section unit
Children	Object	The sub-objects contained in the current road section
Parents	Object	The parent object of the current road section
Total_length	Double	Total length of the road
Start_Station	String	The mileage marker number at the starting point of the road
End_Station	String	The mileage marker number at the end of the road
Time_Ref	String	Time reference
Con_Time	String	Road construction time
M_Time	String	Road maintenance time
Road_Index	Double	The relevant health index of the road
Bridge_Count	Int	The number of Bridges along the road

Table 1 .Highway Object Attribute table

Attribute field	Data type	Field description
Bridge_Id	String	The unique identification of the bridge
Bridge_Name	String	The name of the bridge
Road_Id	String	Road identification to which it belongs
Con_Time	String	Bridge construction time
Bridge_Type	String	Bridge type
Total_Length	Double	Total length of the bridge
Load_Grade	String	Bridge load grade
M_Time	String	Bridge maintenance time

Table 2. Bridge Object Attribute table

Attribute field	Data type	Field description
Object_Id	String	Object unique identifier
Object_Name	String	Object name
Object_Type	String	Facilities or diseases along the line
Object_Position	String	The location of the road section where the object is located
Object_Parent	String	The road section to which the object belongs
M_Time	String	Object curing time
M_Type	String	Object maintenance method
Length	String	Disease length
Width	String	Disease width
Area	String	Disease area

Table 3. Attribute table of damage objects of facilities or roads along the line

2.3.2 Description of Object Composition Structure

In the multi-granularity spatio-temporal object model, the compositional structure of entities reflects the relationship between the whole and its parts. The whole is the result of the organic integration of various elements, while each part serves as a fundamental building block of the whole. An entity object within a highway maintenance scenario can be decomposed into multiple sub-spatio-temporal objects or recombined with multiple peer-level spatio-temporal objects to form a larger spatio-temporal object. The parent objects of entities in a highway maintenance scenario primarily include two categories: road networks and ancillary facilities along the route. Among them, the sub-objects of road networks encompass roads of different grades, such as expressways, arterial roads, secondary arterial roads, and branch roads. These roads of varying grades can also be composed of ordinary road sections and bridges. The sub-objects of environmental and traffic ancillary facilities include traffic signs, gantry frames, streetlights, cameras, management stations, service stations, and so on. The compositional structure of entities in the road maintenance scenario is described in Table 4.

Scene	Entity type	Parent object	Sub-object	Quantity
Highway maintenance	Road network	$\sum_{1}^{N}$ ROAD	ROAD1,..., n	N
	Ancillary facilities along the line	$\sum_{1}^{N}$ OTHER	OTHER1,.., n	N

Table 4. List of entity components for highway maintenance scenarios

2.3.3 Description of Object Association Relationship

Association relationships describe the interactions, constraints, and influences that arise among similar or dissimilar entities in highway maintenance scenarios due to factors such as location, characteristics, and morphology. These relationships primarily include subordination relationships, symbiotic relationships, positional relationships, causal relationships, control relationships, and others, as illustrated in Figure 3. Over the lifecycle of a highway maintenance scenario, the strength, types, and attributes of these association relationships between entities can vary to different degrees with the passage of time. Within a spatial scope corresponding to a specific moment, the association relationships between spatio-temporal objects can be regarded as a set, which can be expressed as Equation (2).

$$TSv = \{(t, Sv)\} \tag{2}$$

Where: TSv represents the set of visualized spatial scope; t denotes a specific moment in time; Sv indicates the spatial scope and the associated relationships corresponding to moment t.

There are also various forms of relationships among highway maintenance entities, such as one-to-many, many-to-one, and one-to-one types. These association relationships can be further elaborated using Equation (3).

$$\begin{aligned} &Object\_Relation = \{Rela\_Object, Rela\_Type, Rela\_Name, \\ &Rela\_Desc, From\_Object, To\_Object\}, \\ &From\_Object = \{Object\,1, \ldots\ldots, ObjectN\}, \\ &To\_Object = \{Object\,1, \ldots\ldots, ObjectN\} \end{aligned} \tag{3}$$

Where, Object_Relation represents the association relationship between entities in the highway maintenance scenario; Rela_Object denotes the unique code for the current association relationship; Rela_Type indicates the type of the current relationship; Rela_Name stands for the name of the current relationship; Rela_Object provides a detailed description of the association relationship information between entities; From_Object represents the entity from which the association relationship originates; and To_Object represents the entity to which the association relationship is directed.

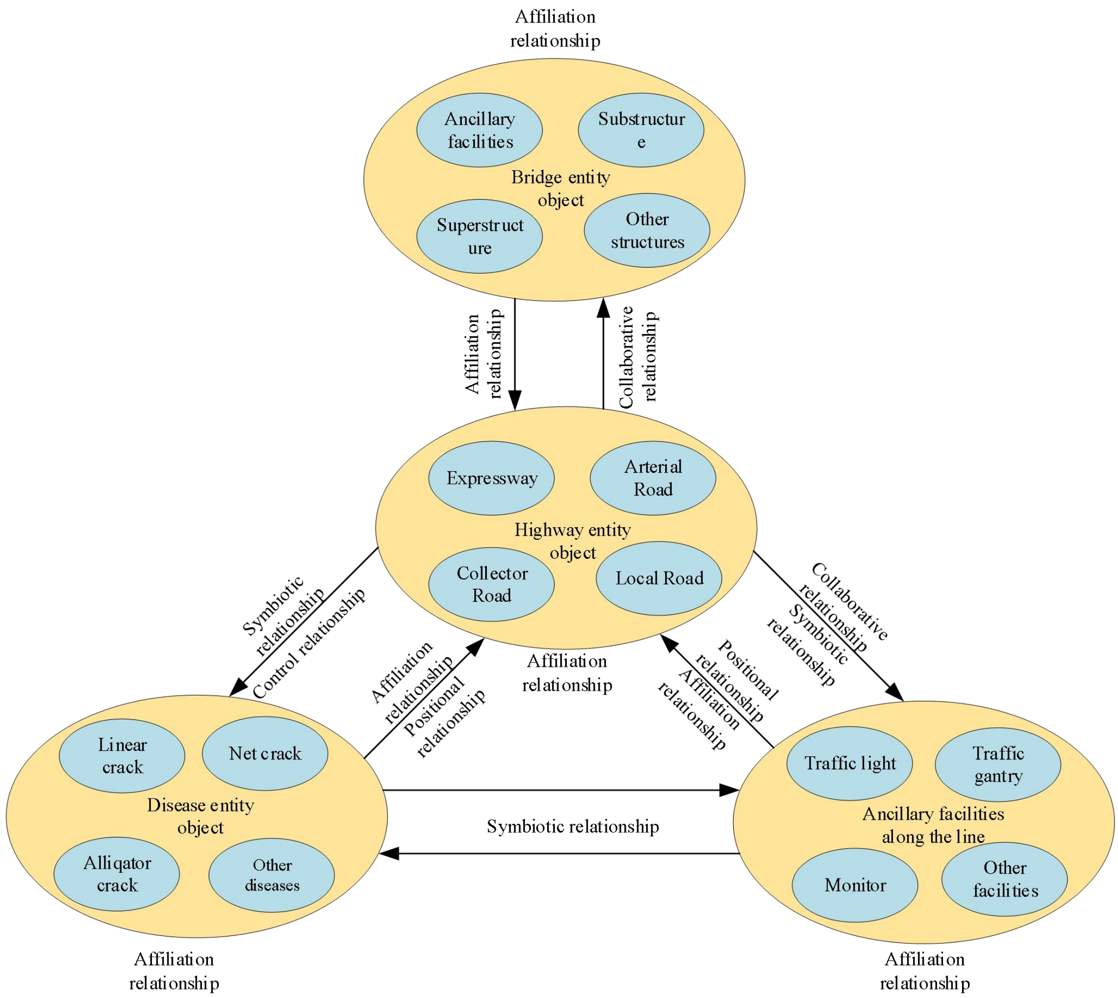

Figure 3. The spatio-temporal object correlation relationship diagram of highway maintenance scenarios.

3. Experimental verification and analysis

This paper takes the highway maintenance scenario in a certain area of Beijing as the experimental subject to validate the proposed method. The basic data required for the experiment includes: fundamental information on highways and bridges, attributes and spatial coordinates of highway maintenance entities, highway inspection and maintenance records, patrol and maintenance information of ancillary facilities along the route, as well as association relationships among maintenance entities and their change data. Using the aforementioned data, a multi-granularity spatio-temporal object model for the highway maintenance scenario was constructed, and the results were visually displayed.

3.1 Modeling of Spatio-temporal Objects in Maintenance Scenarios

In order to more scientifically and comprehensively describe the entity objects within highway maintenance scenarios, it is essential to first cognize and abstract the real-world highway maintenance scenarios. Building upon this foundation, by integrating Revit modeling software with relevant foundational road data, the abstracted results are modeled to construct spatio-temporal object models for highway maintenance entities. These models encompass various representational forms, including point, linear, planar, and three-dimensional shapes. Subsequently, based on the similarities among entity objects, they are classified into different categories, forming various types of spatio-temporal object classes for highway maintenance scenarios, primarily including categories such as highways, road defects, bridges, and ancillary facilities along the route. Finally, each type of spatio-temporal object is encoded according to classification standards, assigning a unique index identifier to every object, thereby establishing a structured and semantically clear spatio-temporal object model system.

In terms of data storage and management, various attribute information of highway maintenance entities is organized and managed according to the eight aspects outlined in the multi-granularity spatio-temporal object data model: spatio-temporal reference, spatial location, spatial form, compositional structure, association relationships, attribute characteristics, behavioral capabilities, and cognitive capabilities. These aspects are applied to each spatio-temporal object model respectively. Additionally, this paper adopts a hybrid database structure for the storage and management of road maintenance data. Based on the characteristics of different data types, suitable database systems are selected: Neo4j is used to store relationship data among spatio-temporal objects, MongoDB stores three-dimensional model data, HBase manages positional change information, and MySQL preserves attribute data related to road defects. Ultimately, a well-structured, efficient, and reliable multi-granularity entity spatio-temporal object dataset for road maintenance is constructed, providing solid support for subsequent data analysis and scenario modeling.

In terms of front-end visualization, a Browser/Server (B/S) architecture is adopted, with the system built using the JavaScript language and the Vue progressive framework. The models are visualized in three dimensions on the Cesium digital globe, while multi-dimensional and comprehensive visualization of maintenance data is achieved with the aid of components such as Element UI and ECharts, as illustrated in the figure4.

The multi-modal characteristics of some entity objects in a highway maintenance scenario in a certain district of Beijing are described as follows through the aforementioned data model framework:

(1) Description of attribute characteristics of entity objects. At the macro scale, the focus is primarily on the 3D visualization of spatio-temporal object models for roads, road segments, and bridges. When a highway is selected as the object for maintenance analysis, its attribute set is described as follows:

HighwayObject={"ID： 20"， "HighwayName： A certain road in Beijing"，"HighwayPosition：Northeast of a certain district in Beijing"， "HighwayLength： 30km"， "Time： June 29, 2023"， "Describe： The auxiliary traffic facilities along this road are functioning normally, and the overall technical condition is in good state. The Pavement Condition Index (PCI) stands at 90.2, with a rating of Grade A; the Riding Quality Index (RQI) is 4.1, also rated Grade A; the Pavement Performance Index (PQI) reaches 82.5, earning a Grade A rating. Consequently, the overall condition of the road is classified as good."， "..."}.

The visualization of attribute characteristics from a microscopic perspective in road maintenance scenarios primarily involves 3D visualization of spatio-temporal object models for road ancillary facilities and road defects. From this viewpoint, road maintenance personnel can gain a detailed understanding of the health conditions of specific road ancillary facilities and defects, as shown in the figure5.

Figure 4. Road maintenance scene.

Figure 5. Multi-dimensional attribute characteristics of disease objects in road maintenance scenarios.

(2) Description of the compositional structure of entity objects. The highway maintenance scenario in a certain district of Beijing is described using the aforementioned compositional structure description method. Based on maintenance analysis requirements, the highway maintenance scenario is divided into different granularities for description, primarily by detailing the road network, the composition of ancillary facilities along the route, and their corresponding sub-objects at various levels of granularity,as shown in Figure 6.

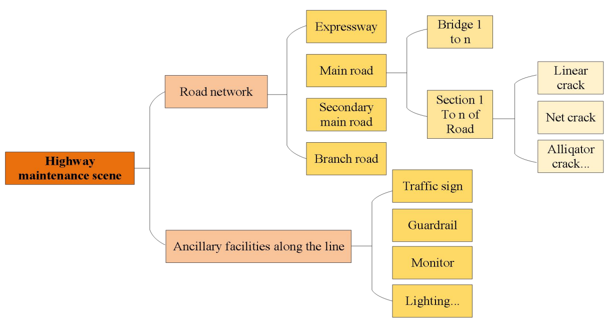

Figure 6. Composition structure diagram of physical objects in highway maintenance scenarios.

(3) Description of the associative relationships among entity objects. Analyzing the associative relationships between spatio-temporal objects in highway maintenance scenarios helps maintenance personnel better understand the mutual influences among these objects caused by road maintenance activities or temporal changes. The associative relationships between spatio-temporal objects in the highway maintenance scenario of a certain district in Beijing can be categorized into two types. The first type includes control, constraint, and subordination relationships between parent and child objects. The second type encompasses collaborative, constraint, and symbiotic relationships among parallel objects. Network data visualization methods are employed to represent the associative relationships between spatio-temporal objects in the road maintenance scenario, as illustrated in the figure. The multi-granularity spatio-temporal object model enables efficient expression of changes in the associative relationships among entity objects in the highway maintenance scenario. By clicking on the relationship lines between spatio-temporal objects, the associative relationships between them can be displayed.

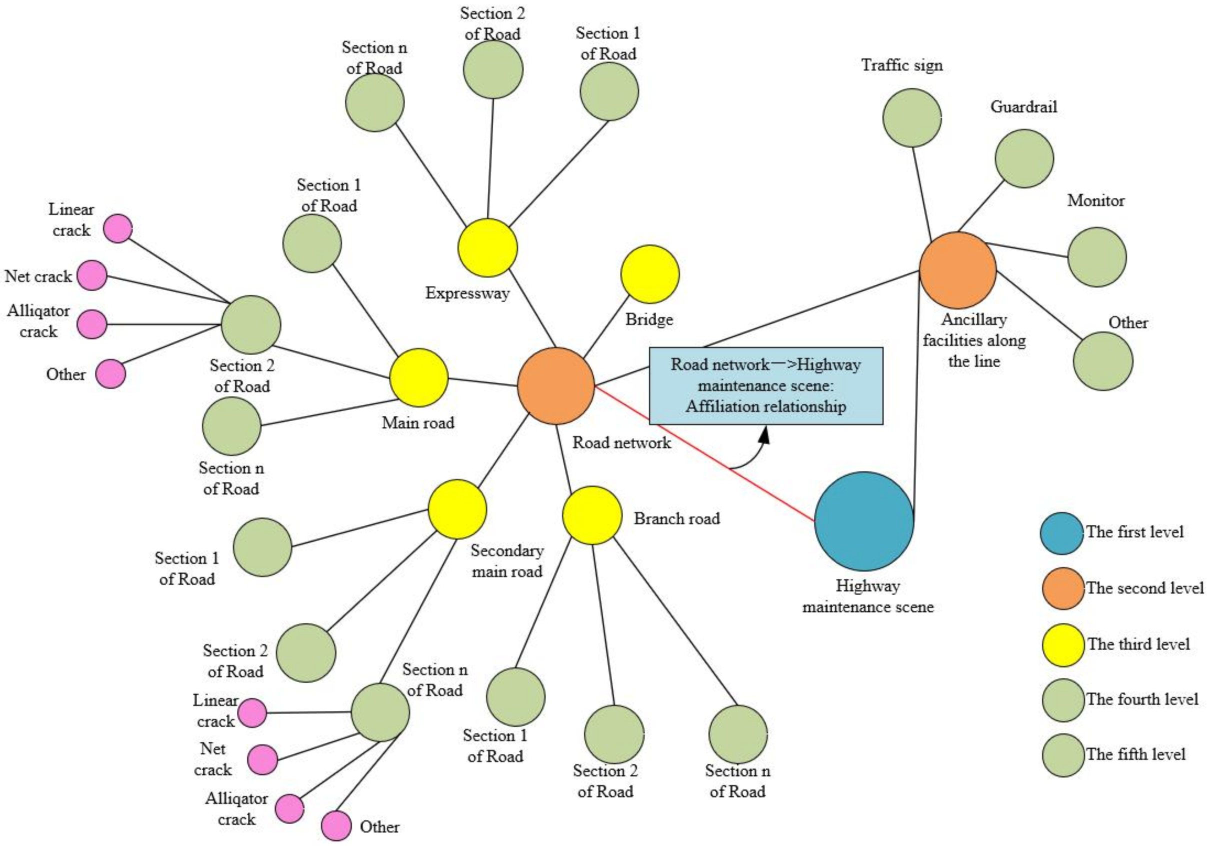

Figure 7. The association relationship diagram of entity objects in road maintenance scenarios.

3.2 Result Analysis

The multi-granularity spatio-temporal object data model for highway maintenance scenarios proposed in this paper offers several advantages over traditional highway maintenance scenario models:

(1) More Comprehensive Information Representation. Traditional highway maintenance research primarily focuses on two-dimensional or three-dimensional modeling of entity objects and simple integrated management of various highway maintenance data. However, this approach has significant limitations in describing the multi-dimensional dynamic characteristics and complex associative relationships of entity objects in highway maintenance scenarios. In contrast, the highway maintenance scenario model constructed based on multi-granularity spatio-temporal objects enables the unified integration and associative representation of multi-source heterogeneous data, including text, images, charts, videos, and more. This model not only depicts the spatial form of highway maintenance entities but also comprehensively reflects their compositional structure, attribute characteristics, and complex associative relationships with other objects. By doing so, the representation of highway maintenance information becomes more complete and systematic, facilitating efficient organization and management of multi-dimensional maintenance data and providing a solid data foundation and model basis for subsequent analysis, decision-making, and intelligent applications.

(2) More Multidimensional Visualization Approaches. Traditional highway maintenance scenario research often employs pictures, charts, text, and videos for one-way display in visualization, lacking in-depth interaction with users and struggling to meet the demands for dynamic data analysis and multi-dimensional presentation in actual maintenance work. In contrast, the highway maintenance scenario model constructed based on multi-granularity spatio-temporal objects possesses stronger visualization capabilities. This model can flexibly display the attribute information, compositional structure, associative relationships, and evolutionary processes of spatio-temporal objects at specific time points or periods according to the specific analysis needs of maintenance personnel. Additionally, it supports the presentation of morphological

changes in objects from different spatial scales and observation perspectives.

4. Conclusion

In response to the issues of information isolation and scattered distribution in the management and visualization of current highway maintenance data, which make it difficult to meet the demands for expressing and comprehensively displaying the spatio-temporal correlations of multi-dimensional maintenance data, this paper proposes a method for constructing a multi-granularity spatio-temporal object model tailored to highway maintenance scenarios. Taking the highway maintenance scenario in a certain district of Beijing as a case study, experiments and validations were conducted. The research results indicate that this model can more comprehensively and multidimensionally describe the spatial form and attribute characteristics of road entities. Compared to traditional models, it offers significant advantages in terms of granularity levels, dimensional breadth, and information completeness. This model not only enhances the efficiency of organizing and managing highway maintenance data but also provides robust support for dynamic querying, in-depth analysis, and scientific decision-making of maintenance data, demonstrating promising application prospects. However, the model has certain limitations in describing real-world highway maintenance scenarios. Subsequent research will delve deeper into aspects such as model storage and management, visualization analysis, and expression to better meet the refined maintenance management application needs of transportation management departments.

References

Che, D. F., Qiu, K. H., Shi, P. F.,Guo,P. Y., 2022. Design and implementation of highway maintenance management information system based on GIS. *Highway*, 67(12), 362 – 367.

Hua, Y. X., 2016. Core issues and key technologies of full-space information systems. *Journal of Geomatics Science and Technology*, 33(4), 331 – 335.

Hua, Y. X., Zhou, C. H., 2017. Description Framework for Multi-granularity Spatio-temporal Object Data Model Oriented to Pan-spatial Information Systems [J]. *Journal of Geo-information Science*, 19(09): 1142-1149.

Lin, R. Y., Lei, J. Y., Zhang, S. J., Gao, J., 2023. Integrated management system for highway bridges based on BIM technology. *Highway*, 68(10), 219 – 225.

LIU, Z.,GU, X. Y., DONG, Q.,Tu, S. S.,2021.3D visualization of airport pavement quality based on BIM and WebGL integration[J].*Journal of Transportation Engineering*, Part B:Pavements,2021,1 47(3).

Li, X., 2021. Research on BIM Information Resource Management of Transportation Infrastructure Based on Multi-source Data Fusion [D]. Southeast University.

Qiao, X., Gou, Y., Lu, S., 2019. General design technology of highway maintenance management system based on XML. *Modern Electronic Technology*, 42(12), 144 – 147.

Qin, Y., 2021. Research on highway maintenance management information system based on 3DGIS. Master’s thesis, China University of Mining and Technology.

Zheng, W. H., Zhou, X. Y., Wu, H. P., Li, H. M.,Zhu, X. T., 2020. Digital Twin System for Highway Transportation Based on 3D GIS Technology [J]. *Computer Integrated Manufacturing Systems*, 26(01): 28-39.