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An Enhanced Information Retrieval Method Based on Ontology for Bridge Inspection

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Abstract: Bridge management systems (BMSs) are widely used to assist an inspector in performing element-level bridge inspection. Retrieving and determining target elements to be inspected becomes an important factor in the efficiency of bridge inspection. This paper presents an enhanced information retrieval (IR) method based on ontology to predict the target elements. The novelty of this method is that an improved seven-step method based on automatic mapping technology is proposed to construct a new bridge inspection ontology (BIontology), which provides a knowledge base for the present IR method. A further novelty is that a new software architecture is designed for integrating ontology, and a promising prototype system based on the software architecture is developed to realize the present IR method using SPARQL query. In addition, a novel prediction algorithm based on the present IR method is proposed to automatically recommend the target elements. A case study of ontology construction is performed to demonstrate that the improved seven-step method can accelerate the construction of the BIontology compared with the manual method. A case study of bridge inspection is implemented to verify that the proposed algorithm outperforms an existing method, thereby validating the effectiveness of the present IR method.

Keywords: bridge inspection; information retrieval; ontology construction; automatic mapping; bridge management system

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1. Introduction

Bridge inspection is critical for bridge evaluation and maintenance decision-making and plays an important role in collecting bridge defect data. During a routine inspection, each element of each bridge component should be inspected. For bridges with many elements, the efficiency of routine inspection is the key problem that should be carefully considered. To improve the efficiency of bridge inspection, many Bridge Management Systems (BMSs) have been developed to assist with the implementation of bridge inspection, such as Pontis BMS [1] and the Chinese Bridge Management System [2]. These systems usually include mobile bridge inspection applications working on smartphones or tablet devices.

During a routine inspection, an inspector in the field chooses a particular element from bridge elements' taxonomic lists in a mobile bridge inspection application and records the condition of the element. The inspector will continue the process with the remaining elements. Due to the large number of bridge elements and the limited size of mobile devices, it is difficult for the taxonomic lists in the mobile application to show all the elements. The inspector needs to type a keyword to search for a target element every time he/she performs an element-level inspection. However, the search process can be quite time-consuming. An ontology-based IR method has the potential to overcome the shortcoming by automatically predicting the target element to be inspected. Consequently, the efficiency of bridge inspection can be improved.

Recently, the ontology-based IR method has gained extensive attention since this method usually seeks to enhance retrieval accuracy by trying to encode the inspector's searching intent and the contextual meaning of the keywords, rather than by exact keywords matching [3]. The ontology-based IR method has been applied in retrieving construction documents [4,5] and Building Information Model (BIM) resources [6–9]. Wu et al. [10] validated that the concrete bridge rehabilitation project management ontology (CBRPMO) can improve the search for project information compared with manual searching. Li et al. [11] demonstrated that the ontology-based IR method could make it more convenient for sensory data retrieval. However, in the field of bridge engineering, ontology applications are still at the conceptual phase stage [12]. Existing ontologies mainly focus on bridge maintenance [12] and rehabilitation [10]. These bridge ontologies do not fully cover bridge inspection information, and the construction of these ontologies requires a lot of manual work [10,13].

This study aims to propose an enhanced information retrieval method based on ontology to improve the efficiency of bridge inspection. To achieve this purpose, an improved seven-step method based on automatic mapping technology is proposed to accelerate the construction of a new ontology, bridge inspection ontology (BIontology). A new software architecture for integrating ontology is proposed and a prototype system based on the proposed architecture is developed. With these contributions, the ontology-based IR method is established. A prediction algorithm based on the proposed IR method can correctly predict the target element to be inspected, which can avoid the process of inputting a keyword to search for the target element.

The remaining contents of this study are organized as follows: The related works are thoroughly summarized in Section 2. Section 3 introduces an overall process of the proposed ontology-based IR method for bridge inspection. In Section 4, an improved seven-step method for quickly building the BIontology is introduced. In Section 5, a bridge inspection prototype system is developed to realize the proposed IR method by SPARQL query (an ontology-based data access [14]). A proposed algorithm for predicting the target element and a software architecture for integrating ontology are also described in this section. Section 6 provides two case studies to validate the effectiveness of the proposed method and the prototype system, and conclusions are finally drawn in Section 7.

2. Literature Review

2.1. Development of Bridge Inspection

In earlier years, bridge inspection mainly contained three major parts: deck, superstructure and substructure [15]. Inspectors needed to perform component-level inspections to obtain general condition ratings of the three parts. However, this level of detail is insufficient to help make maintenance decisions. To improve the precision and reasonability in maintenance decision making, ninety-eight Commonly Recognized elements and eight Smart Flags were recommended [16], based on which bridge inspection moved to element-level bridge inspection. Afterwards, bridge elements are further subdivided into three major classes: National Bridge Elements (NBEs, including 89 element types), Bridge Management Elements (BMEs, including 13 element types), and Agency Developed Elements (ADEs) in the AASHTO Guide Manual for Bridge Element Inspection [17]. ADEs may be sub-elements of NBEs or BMEs, or agency-defined elements without ties to the elements defined in this manual. In this context, more and more elements need to be inspected. The same development trend on bridge inspection can also be observed in China. Bridges are now classified into four primary categories, with each category broken into at least 16 components [18].

To improve the efficiency of bridge inspection, the method of inspection documentation has changed from record-keeping by pencil and paper to electronic data collection using a BMS [19,20]. The inspection time is significantly reduced, and the errors are avoided since the inspection data does not need to be re-entered into a database management system [21]. During a bridge inspection using a BMS, inspectors need to input a keyword to search for the target element and record the inspection results of the element. This procedure is quite time-consuming especially for bridges with many elements. Actually, this search process is not strictly necessary because the target element can be predicted according to spatial relationships among bridge elements. However, the widely used keyword-based IR method in BMSs cannot take account of semantic relationships (e.g., spatial relationships) among inspection-relevant objects [22]. Therefore, the IR method in the BMS should be improved to further enhance the efficiency of bridge inspection.

2.2. Ontology Application in the Construction Industry

Ontology can be regarded as an explicit specification of a representational vocabulary for a shared domain of discourse, which usually includes classes, relations among these classes, instances, and other objects [23]. With these merits, ontology can be used to improve IR performance. Early applications focused on searching some technical documents. Rezgui [4] enhanced the construction documents search service in the e-COGNOS system using ontology. Lin et al. [5] used a domain ontology to assist with the partitioning of documents and developed a concept-based search engine system for engineering domain-specific technical documents. In recent years, ontologies have been used in retrieving BIM resources [7–9]. Gao et al. [3] developed the domain ontology related to BIM-specific knowledge and provided an ontology-based query expansion approach to increase IR performance. Furthermore, Wu et al. [6] combined natural language processing technology with the ontology-based query expansion method and achieved higher performance than traditional keyword retrieval technology in a BIM object database.

As discussed above, in the construction industry, ontology technology has been applied to information retrieval. However, most papers investigated domain ontologies of building projects instead of non-building projects (e.g., bridges). The former ontologies cannot be directly applied to the latter because of the vast differences between them [24].

In the field of bridge engineering, some studies about ontology application [10–12,25] have been conducted. However, these studies mainly focused on knowledge management [26], and seldom focused on information retrieval [10]. Table 1 presents existing ontologies in bridge engineering. It can be seen that the existing ontologies do not fully cover bridge inspection knowledge areas and most ontologies are created manually. For instance, Li et al. [11] manually modeled a BSHM ontology to conveniently retrieve sensory data. Ren et al. [12] manually built a BrMontology and created a BrMontology-based knowledge base to assist engineers in making comprehensive decision. However, the BSHM ontology and BrMontology lack inspection-relevant information such as the spatial relationships among bridge elements, which would not be suitable for predicting the target element. Liu et al. [27] created a bridge ontology (BridgeOnto) and the BridgeOnto includes the composition (part to whole) relations between bridge elements and the bridge. This work improves the performance of extracting bridge elements from bridge documents. However, the main limitation of BridgeOnto is that it does not contain the spatial relationships among bridge elements, which is important for correctly predicting the target element. A semi-automatic method [13] was developed to generate a bridge ontology from an Industry Foundation Classes (IFC) model. However, compared with the widely used BMSs, the emerging IFC models are not established for most bridges, which limits the application scope of this method.

The above studies demonstrate the potential of ontology technology in improving the efficiency of information retrieval. However, there is still some work to be completed to improve the efficiency of bridge inspection. (1) The current ontology researches do not fully cover bridge inspection knowledge areas, and a new ontology model needs to be further constructed to support inspection-relevant information retrieval. Meanwhile, to alleviate the deficiency of hand-crafted ontology, a proposed improved seven-step method is to generate a bridge ontology by mapping relational data stored in the BMS rather than by parsing IFC models. This is the difference between our method and the method in the paper [13]. (2) The bridge ontology applications are still at the conceptual stage [12]. A new software architecture for integrating ontology and a bridge inspection system prototype need to be developed to realize the ontology-based IR method for bridge inspection. The proposed IR method can fully consider the spatial relationships among bridge elements. The spatial relationships also exist between the target element to be inspected and an inspected element. Consequently, the ontology-based IR method can provide assistance in searching for the target element to be inspected. Moreover, to recommend the target element more accurately, a prediction algorithm based on the proposed IR method is designed.

Table 1. Review of existing ontologies in bridge engineering.

Ontology	The Classes and Relations of the BIontology			Ontology Construction Method
	Classes	Relations		
	C1–C4 [1]	R1–R3 [2]	R4–R9 [3]	
BridgeOnto [27]	XX	XX	O	manual
CBRPMO [10]	O	O	O	manual
BSHM ontology [11]	XX	XXX	O	manual
BROT [13]	XX	XX	O	semi-automatic
BrMontology [12]	XX	O	O	manual
IPD-Onto [28]	O	O	O	manual
IC-PRO-Onto [29]	O	O	O	manual
Context Ontology [30]	X	O	O	not mentioned
IPD-Onto [31]	O	O	O	not mentioned
HiOnto [32]	X	X	O	not mentioned

[1] C1–C4 denote "Bridge", "BridgePortion", "BridgeComponent", "BridgeElement", respectively. [2] R1–R9 denote "isPortionOf", "isComponentOf", "isElementOf", "onTheEastOf", "onTheSouthOf", "isOn", "onTheWestOf", "onTheNorthOf", "isUnder", respectively. [3] O = not covered; X = rarely covered; XX = moderately covered; XXX = covered.

3. Methodology

Figure 1 presents an implemented process of the proposed ontology-based information retrieval method for bridge inspection, which comprises the following steps:

(1) Ontology construction: This step aims to construct a bridge inspection-relevant ontology. Firstly, existing ontologies and relational data related to bridge inspection are collected. Then, reusing these ontologies will be taken into consideration when the seven-step method [33] is adopted to build the BIontology. Meanwhile, the automatic mapping technology is applied to improve the seven-step method in order to accelerate the construction of the BIontology. After that, the BIontology can be established. Section 4 will describe the construction process of the BIontology in detail.

(2) Data conversion: This step aims to transform the BIontology from the Web Ontology Language (OWL) file to Resource Description Framework (RDF) data stored in the TDB database (an RDF triple stores). The BIontology derived from the first step is saved as an OWL file, and, in practice, the OWL file should be translated to RDF data to improve the readability. Apache Jena Fuseki (a SPARQL server) is deployed for the implementation of data conversion. After the OWL file is manually uploaded to the Fuseki server, the Fuseki server can automate the execution of the data conversion and then save the transformed data in the TDB database. This step is a simple manual process and thus will not be described again in the following sections.

(3) System development: This step aims to develop the bridge inspection prototype system to realize the semantic retrieval from the BIontology-based knowledge base. SPARQL query is used to retrieve bridge inspection information from the TDB database according to user input data. The prototype system should provide a nice man–machine interaction environment for executing the SPARQL queries and presenting the query results. The prototype system is not only a realization of the proposed IR method but can also be used to validate the effectiveness of the proposed IR method for bridge inspection. The development process of the prototype system will be discussed in Section 5.

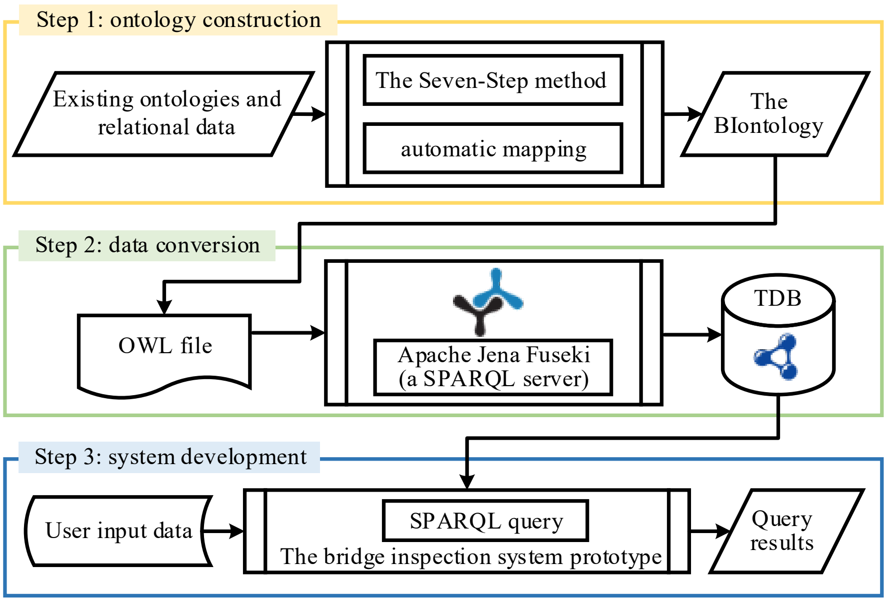

Figure 1. An implemented process of the ontology-based IR method.

4. Construction of the BIontology

There are several approaches for constructing ontologies, such as METHONTOLOG [34], NeOn [35] and seven-step method. Among them, the seven-step method is the most popular one [24] and is widely used in the construction field [10]. However, this method is a manual process, and only reuses the existing ontologies. To fully utilize the relational data in a BMS, an improved seven-step method is proposed, and the automatic mapping technology is adopted to transform these relational data to an ontology model. Figure 2 shows the BIontology construction process using the improved seven-step method. The first three steps of the improved seven-step method are manual (described in Section 4.1), and the subsequent steps are the automatic mapping process (depicted in Section 4.2).

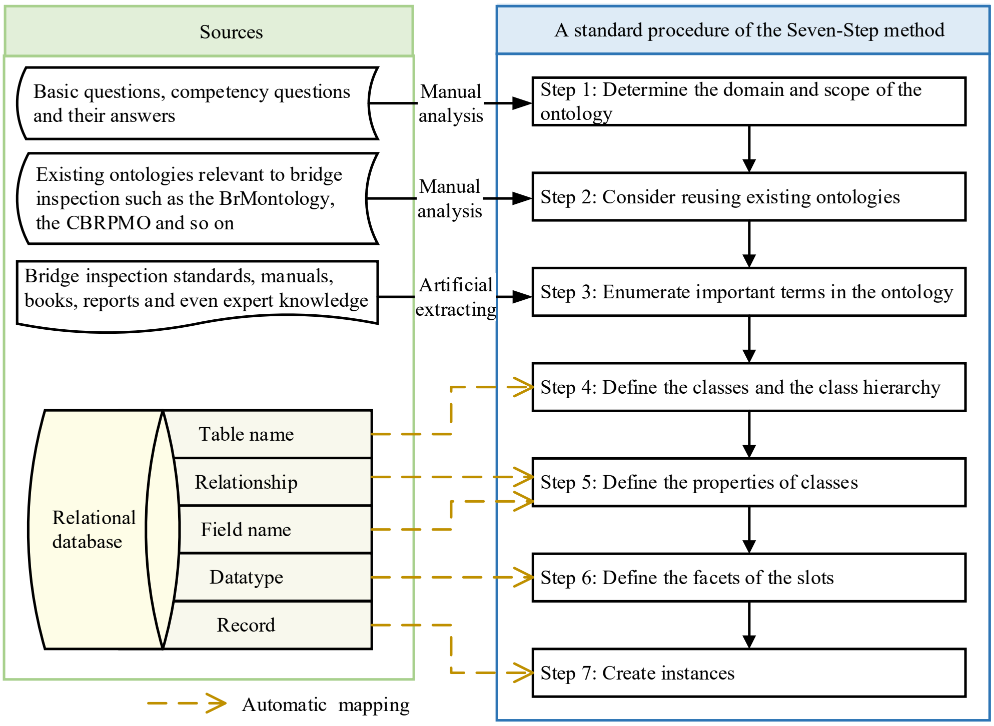

Figure 2. The improved seven-step method for the BIontology construction.

4.1. Manual Process of the BIontology Construction

In the improved seven-step method, the first step is to determine the domain and scope of the ontology. The answers to some basic questions help to determine the domain of ontology. To further limit the scope of ontology, several competency questions also need to be answered [36]. Typical questions and the corresponding answers are listed in Table 2. Judging from the designed questions and answers, the BIontology should focus on the bridge maintenance sector in the construction industry. Specifically, it should be restricted to the scope of bridge inspection. The BIontology should cover the information on bridge elements, bridge components, etc.

Table 2. Typical examples of basic questions and competency questions.

Problem Type	Question	Answer
Basic question	What is the purpose of using the BIontology?	The aim is to improve the capacity of inspection-relevant information retrieval in a BMS.
	What is the domain that the BIontology will cover?	The domain is bridge maintenance, especially bridge inspection.
	Who will use the BIontology?	The main users are bridge inspectors.
Competency question	Which element is on the east of the first wet joint?	The first slab.

The second step is to consider reusing existing ontologies. Some ontologies related to bridge engineering can provide valuable references to create the BIontology. The BrMontology covers structure in the class hierarchy, which are also the core concepts of the BIontology. The classes "Bridge" and "BridgeElement" of the BSHM ontology [11] can be reused in the BIontology. Meanwhile, to correctly predict the target element to be inspected, six relations, such as "onTheEastOf" and "onTheSouthOf", need to be added.

The third step is to enumerate important terms in the ontology. Important domain terms tend to be potential classes or slots in the ontology, which can be extracted from bridge inspection standards, manuals, books, reports and even expert knowledge. For example, the term "bridge component", which is taken from the *Standards for Technical Condition Evaluation of Highway Bridges* [18], can be extracted as a class in the BIontology. Other important terms associated with bridge inspection will include bridge, bridge element, etc. Specifically, in different application scenarios, the same term may be regarded as a class, a property or even an individual.

4.2. Automatic Mapping Process of the BIontology Construction

In general, a bridge inspection module is a basic part of a BMS, and bridge inspection information is usually stored in a relational database (RDB). Mapping technology provides an effective and feasible method to extract ontology from RDB [37–39]. For example, Figure 3 shows two typical RDB tables used for storing some information related to bridge components and elements. Some major components of the RDB tables in Figure 3 are highlighted with some different colored dotted boxes. The foreign key constraint "FK_BridgeElement_BridgeComponent" is used to establish the relationship between the two tables.

During an automatic mapping process, OWL is chosen as the ontology language. Mapping RDB to ontology means that the RDB components need to be transformed into corresponding OWL ontology components, which cannot be implemented without mapping rules. The typical mapping rules are listed in Table 3. These rules are independent of data stored in relational tables. In addition, any data (e.g., more spatial relationships or elements) stored in relational tables can be mapped to the BIontology based on these rules.

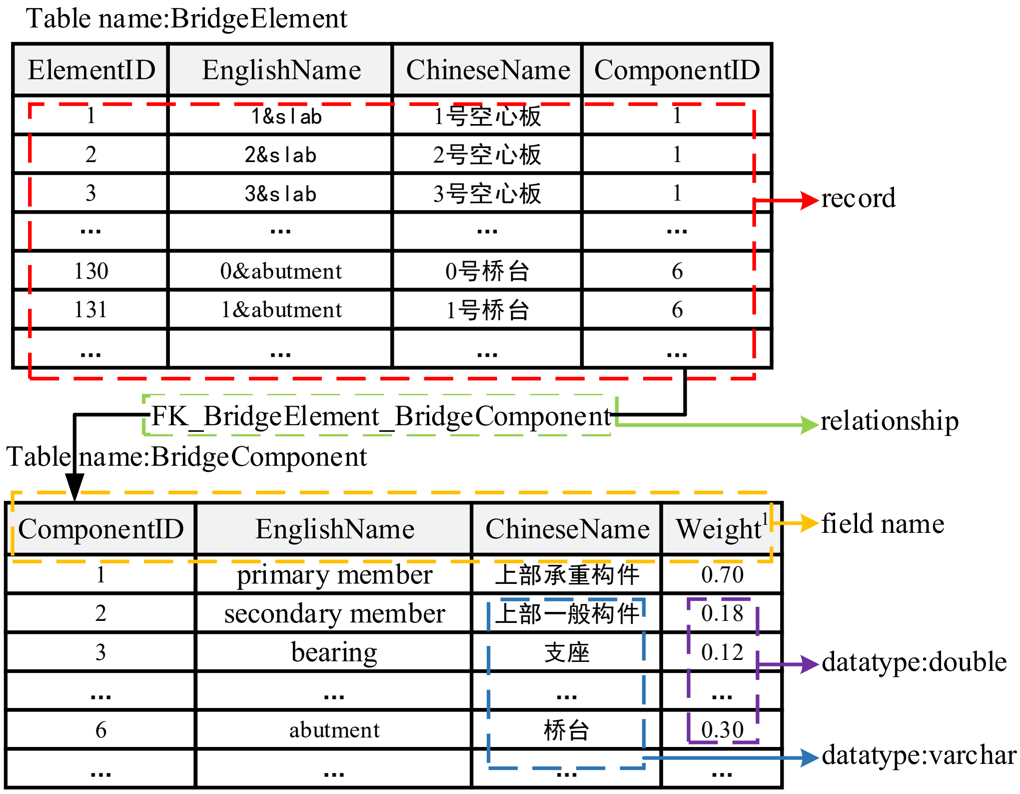

Figure 3. The relational database tables related to bridge inspection (partial view). [1] "Weight" denotes the weightiness of a bridge component in the process of evaluation of bridge condition, according to the standards for Technical Condition Evaluation of Highway Bridges in China.

Table 3. Typical mapping rules for mapping RDB to ontology.

Rule	RDB Component	Ontology Component	Example
Rule 1	Table name	Class name	Table name "BridgeElement" will be mapped into the class "BridgeElement".
Rule 2	Relationship	Object property of the class	Relationship "FK_BridgeElement_BridgeComponent" will be transformed into object property "isElementOf", whose domain and range are the class "BridgeElement" and "BridgeComponent", respectively.
Rule 3	Field name	Datatype property of the class	Field name "ChineseName" and "Weight" will be converted into datatype property "ChineseName" and "Weight" of the class "BridgeComponent".
Rule 4	Datatype	Facet of the slot	Datatype "varchar" and "double" will be expressed in "xsd:string" and "xsd:double".
Rule 5	Record	Instance (i.e., individual)	Bridge element name "1&slab" (i.e., the first slab) will be translated to an instance of the class "BridgeElement".

In practice, the subsequent steps, the mapping process, were implemented by a Python program. Figure 4 presents the mapping process from RDB to OWL ontology. PyMySQL was used to retrieve data from the bridge inspection database (e.g., MySQL). Then, RDFLib was used to transform the bridge inspection data into OWL ontology based on the mapping rules in the Python program.

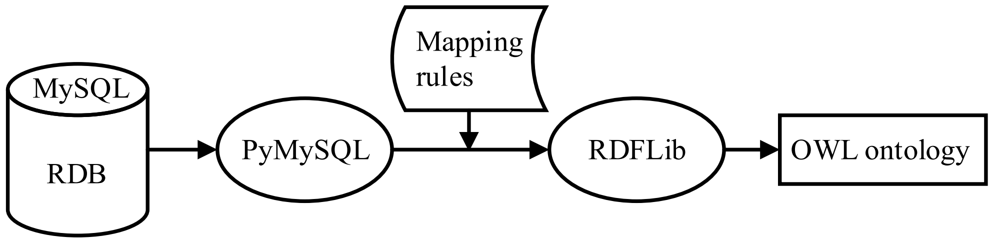

Figure 4. The mapping process from RDB to OWL ontology.

After implementing the mapping process, some ontology components relevant to bridge element had been added to the BIontology. Due to the lack of the spatial relationships among bridge elements in the relational database, the spatial relationships were also manually added to the BIontology in Protégé after finishing the automatic mapping process. As a result, the BIontology includes 4 concepts, 9 relations and 18 restrictions. Figure 5 presents a partial view of classes, individuals, and properties in the BIontology owing to space restrictions. "isIndividualOf" is an object property linking the individual "abutment" to the class "BridgeComponent". The "abutment" is an individual of the "bridge component". "isComponentOf" is an object property linking the individual "abutment" to the individual "substructure". "weight" is a datatype property linking the individual "abutment" to the data literal "0.30", which is a type of an xsd: double. The object property "onTheNorthOf" linking the individual "1&wetJoint" to the individual "1&slab" means that the first wet joint is on the north side of the first slab. The property "onTheNorthOf" has the inverse property of "onTheSouthOf". There are other spatial relationships in the BIontology, such as "onTheEastOf", "onTheWestOf", "isOn" and "isUnder".

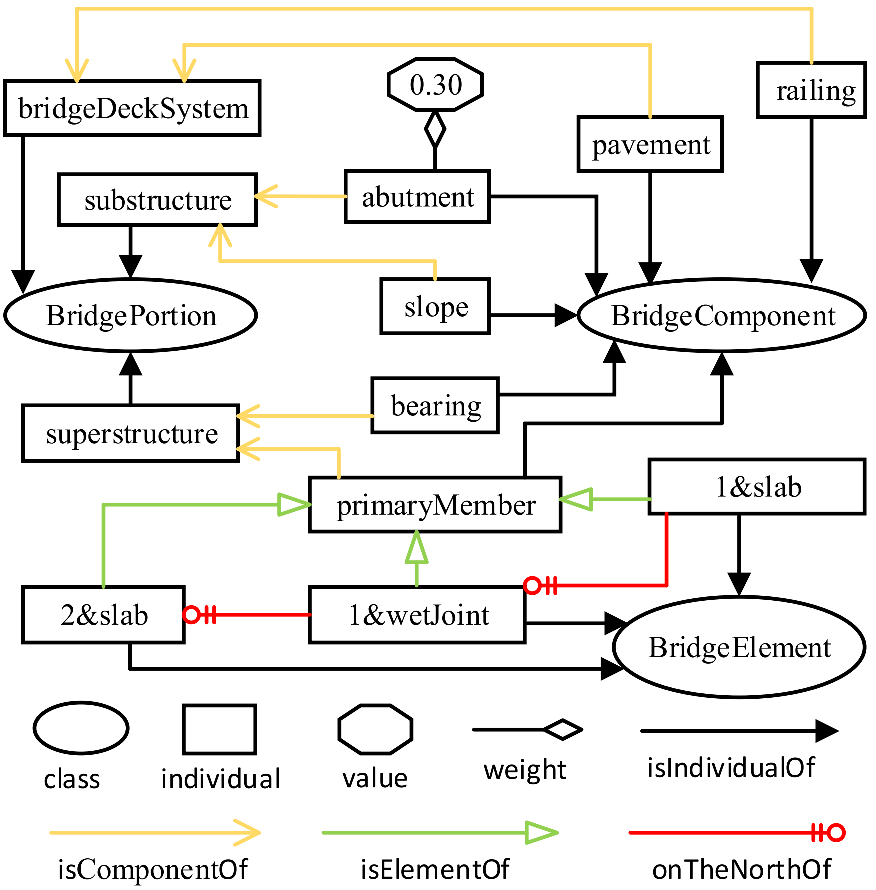

Figure 5. Partial view of the BIontology.

5. Development of the Prototype System

A BMS usually consists of some modules, and assisting bridge inspection is a function of a BMS [40]. This study aims to explore the improvement effect of the proposed IR method on bridge inspection using a BMS. Therefore, a simple system for bridge inspection is developed. Here, SPARQL query will be used for retrieving inspection-relevant information from the BIontology-based knowledge base in the prototype system.

The prototype system was implemented as a web application. The architecture of the prototype system comprises a user interface layer, a business logic layer and a data storage layer, as shown in Figure 6. To implement the proposed IR method, the TDB database and a semantic retrieval middleware were applied to a conventional software architecture. The TDB database was introduced into the data storage layer to store the BIontology-based knowledge because OWL ontologies are principally exchanged as RDF documents [41] and TDB has high performance on RDF store [42]. SPARQL query in the middleware was correspondingly used to fetch inspection-relevant knowledge from the TDB database in the business logic layer.

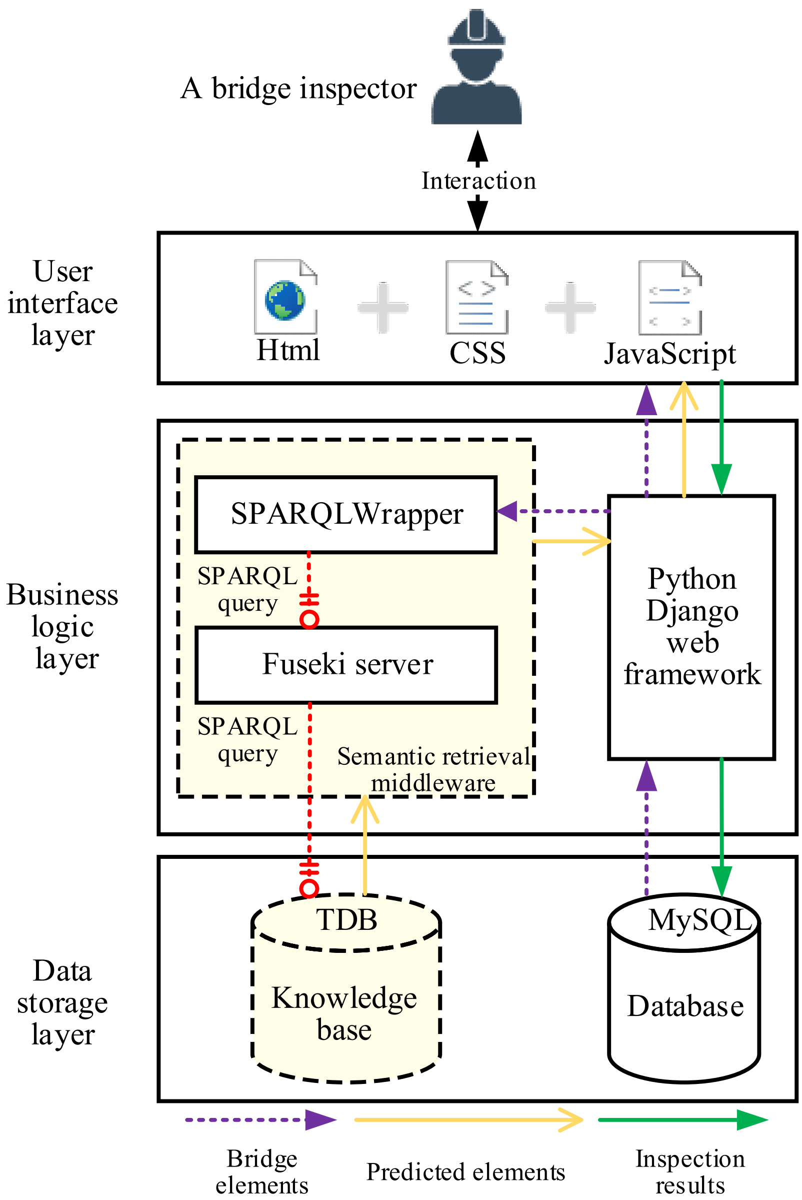

Figure 6. Architectural diagram of the prototype system.

As shown in Figure 6, the user interface layer is a web browser-based graphical user interface (GUI), which is developed in three web development languages: HTML, CSS and JavaScript. A bridge inspector can expediently interact with the system via this layer. Specifically, the inspector can input a bridge element name as a keyword to search for the required result. He/she can also choose an element from predicted elements by the system, which is the expected effect. Subsequently, the inspector can input the exact location, type, extent, condition state, maintenance actions, etc.

The business logic layer (BLL) in Figure 6 is served as a mediator between the user interface layer and the data storage layer. This layer consists of the TDB database and the MySQL database, which stored the BIontology-based knowledge and relational data related to bridge inspection, respectively. In the BLL, the Jena Fuseki in the semantic retrieval middleware can read inspection-relevant knowledge from the TDB database using SPARQL queries. The SPARQLWrapper can transmit the query results to the Python-based framework. The Python Django web framework in the BLL can be used to not only receive the user input and send the query results back to the user interface layer, but also write data (e.g., the inspection results) to and read (e.g., bridge elements) from the MySQL database.

In addition, the introduction of the semantic retrieval middleware and the knowledge base make it possible to predict the target element to be inspected by using spatial relationships among elements. Figure 7 shows the prediction algorithm. The algorithm is based on the experiential knowledge that an inspector usually inspects elements one by one along a certain direction in a contiguous space. In other words, the target element has a close spatial relationship with the present element being inspected in most cases. This spatial relationship can be determined according to the last inspected element and the present element, and the direction of this relationship is from the last element to the present element. The element that has this spatial relationship with the present element is regarded as the top priority of candidate elements to be inspected. Moreover, elements that have other spatial relationships with the present element are also identified as candidate elements to avoid omitting a potential target element. The presented prediction algorithm does not require a predefined inspection sequence. Compared with the predefined sequence, this prediction algorithm is of great applicability because the actual inspection could be different from the predefined sequence due to traffic and lane-closure restrictions. In the proposed algorithm, bridge knowledge is modelled by the ontology rather than by a relational database or a graph database for the following two reasons: (1) the ontology can support domain knowledge sharing and reuse [12,33] and (2) the ontology can make it easier for a domain expert in bridge engineering to model bridge knowledge compared with a relational database or a graph database.

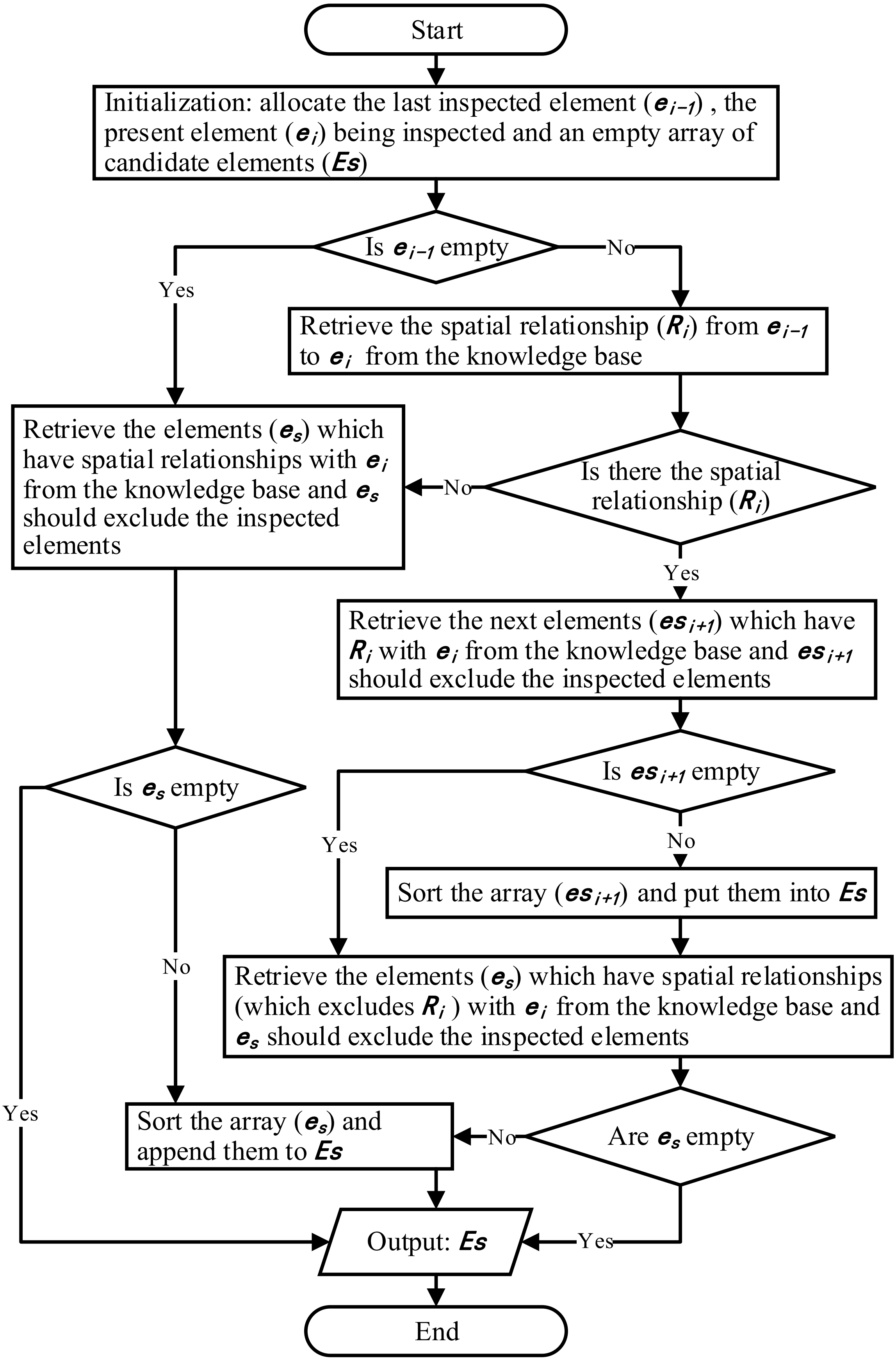

Figure 7. The proposed algorithm for predicting the target element.

6. Case Studies

6.1. A Case Study of the BIontology Construction

This case study is provided to quantitatively test the efficiency of the proposed BIontology construction method. The Qingzhou Channel Bridge (QZCB) in the Hong Kong–Zhuhai–Macao Bridge is selected as a case study bridge. Figure 8 gives the overview of the QZCB, which is a two-pylon, five-span, cable-stayed bridge with a main span of 458 m. The superstructure of the QZCB is divided into 695 elements according to the *Standards for Technical Condition Evaluation of Highway Bridges* in China. Each bearing is regarded as an element. Each segment of main beam or pylon is divided into an element. Each stay-cable system is divided into four elements: a tensile element, an anchor element, a cable encapsulation and a damping device.

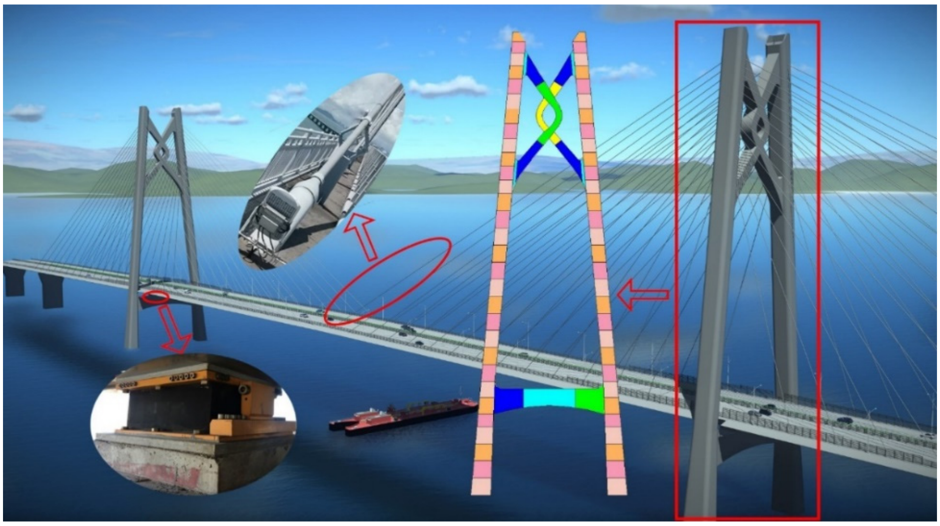

Figure 8. The overview of the QZCB from the bridge decomposition perspective.

Table 4 presents the comparison of average time spent on creating an individual "bridge element" using the proposed automatic mapping method and the manual method. It can be seen that the average time using the proposed automatic mapping is no more than 0.0033 s, which is much less than the minimum average time (37.5674 s) using the manual method. This is because the manual method needs to first check elements information and then enter data into the Protégé. In the data entry process, data-entry errors are almost inevitable, and a small amount of time is also wasted on fixing mistakes. In contrast, the automatic mapping method is not affected by artificial factors since this method can transform the relational data to OWL ontology without human operation. Hence, the automatic mapping method can dramatically increase the efficiency of the BIontology construction.

Table 4. Comparison of the BIontology construction times.

Bridge Component	Number of Elements	Automatic Mapping		Manual Method
		Total Time (s)	Average Time [1] (s)	Average Time [1] (s)
Bearing	16	0.0529	0.0033	39.6024
Main beam	85	0.1147	0.0013	45.2090
Bridge pylon	146	0.1775	0.0012	41.5220
Stay-cable system	448	0.4608	0.0010	37.5674
Superstructure	695	0.80589	0.0012	40.9752

[1] Average time is equal to total time divided by the number of elements.

6.2. A Case Study of Bridge Inspection

To validate the effectiveness of the proposed ontology-based IR method, a single-span prestressed concrete hollow slab bridge with a length of 20 m and width of 7.5 m in Guangdong, China, was selected as a case study bridge. Figure 9 shows a schematic diagram of the main elements numbering of the bridge. There are 44 main elements to be inspected in this case, including each bearing, slab and wet joint, etc. Accessory elements such as lighting and marker sign are not included.

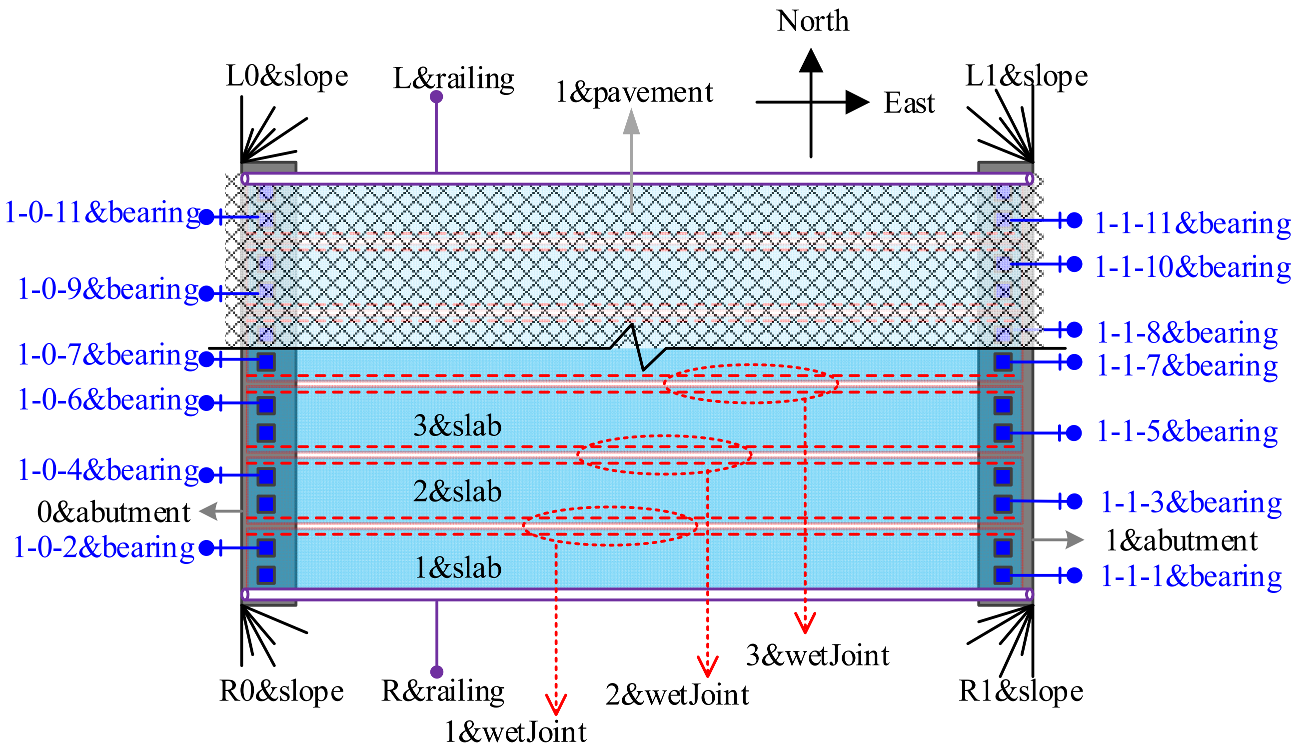

Figure 9. Schematic diagram of elements numbering scheme of the selected bridge.

According to the implemented process of the proposed IR method, the BIontology of this bridge was created and visualized in the Protégé environment. Figure 10 shows partial elements and their spatial relationships. In this case, when two elements (e.g., “1&wetJoint” and “2&slab”) can touch each other or they (e.g., “1-1-3&bearing” and “1-1-4&bearing”) are adjacent, the spatial relationships among them can be established in the BIontology. This is because the inspector usually tends to inspect the target element that is close to the inspected element. Afterwards, the BIontology was manually uploaded to the Fuseki server for data conversion, and the transformed data were stored in the Jena TDB database. Bridge inspection could be implemented using the developed prototype system when the BIontology construction and data conversion were completed.

Figure 11 shows the screenshot of the bridge inspection prototype system. An inspector was inspecting the bridge element called “1&slab” and typing in a defect “crack”. Meanwhile, some elements (“1&wetJoint” and “1-0-1&bearing”, for instance) are recommended as candidate elements to be inspected using the proposed prediction algorithm. After recording the rest of the defect-relevant information of the element, the inspector can choose an element from the candidate elements and go on inspecting this element without using the keyword-based IR method.

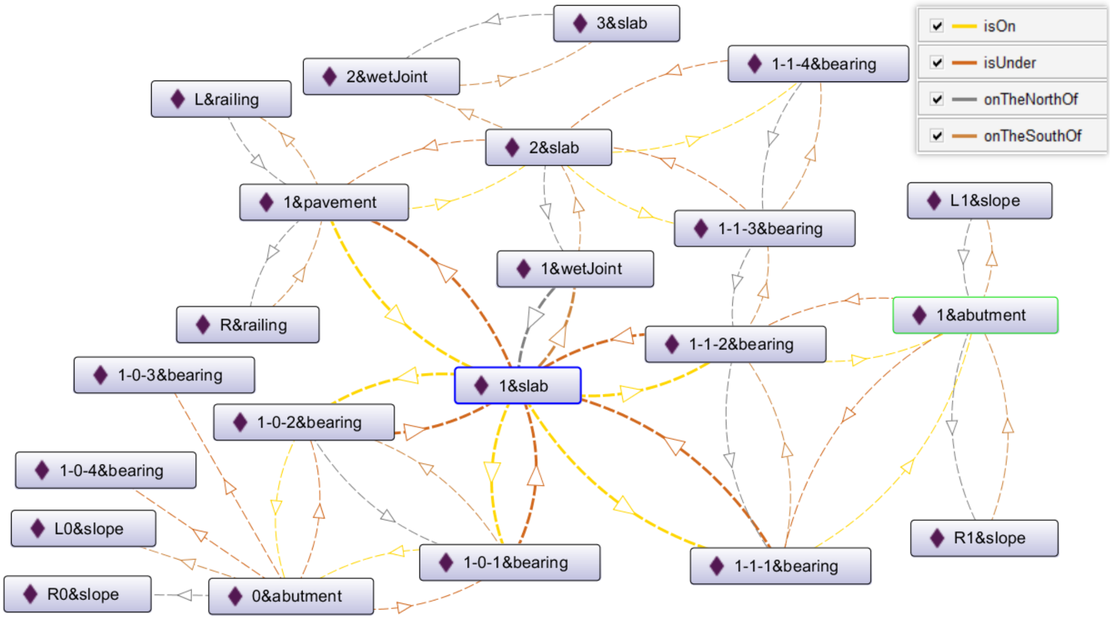

Figure 10. The BIontology visualization in Protégé (partial view).

Figure 11. The screenshot of the bridge inspection prototype system.

To test the accuracy of the presented algorithm for predicting the target elements to be inspected, 4 inspectors are required to inspect all the 44 elements of this bridge according to their own route independently. Every time an element is inspected, the system provides the predicted elements. The prediction results can be accepted as true when the predicted elements include the target element to be inspected. The accuracy Acc_0 is by:

$$Acc_0 = \frac{CT_0}{TT} \times 100\% \tag{1}$$

where CT_0 is the times of cases with a correct prediction, TT is the total times of predictions. In particular, if the first candidate element of the predicted elements is the target element, the accuracy Acc_1 is computed by:

$$Acc_1 = \frac{CT_1}{TT} \times 100\% \quad (2)$$

where CT_1 is the times of cases in which the first candidate element is the target element.

The context-aware computing framework (CACF) [21] is selected as the method for comparison because (1) the CACF shares the same goal that the proposed algorithm does, i.e., predicting the target element to be inspected, and (2) the CACF is used to accomplish the goal based on the logic that the elements beside an inspector are identified as the target elements, which is also the same as the logic of the proposed algorithm. The CACF firstly tracks the pose of the inspector and constructs a geometric model of the spatial region in the inspector's vision. Then, the CACF coordinates the geometry of the bridge elements with the constructed viewing region to compute the list of components within the inspector's spatial context. Lastly, the contextual elements are prioritized to determine the target elements.

Figure 12 shows a comparison of the prediction results between our proposed algorithm and the CACF based on a global positioning system (GPS) and magnetic compass. The prediction performance of the CACF depends on the GPS device class. In Figure 12, WASS-GPS and RTK-GPS denote Wide Area Augmentation System-capable GPS and Real Time Kinematic GPS, respectively. The highest precision rate of the CACF is 56%. The candidate elements of our algorithm include the next target element averagely in 80% of cases, which is much higher than the precision rate of the CACF. In addition, on average, the first candidate element of our algorithm can be right 69% of the time, which is still 13 points higher than the highest precision rate of the CACF. It means that the inspector can directly choose the target element, and the prototype system can even treat the first candidate element as the next target element by default in most cases. From the above observations, it can be concluded that our algorithm is a more effective method in improving prediction performance for the target element. Moreover, the proposed algorithm does not rely on the specialist equipment. Therefore, compared with CACF, the proposed methodology is convenient and economical.

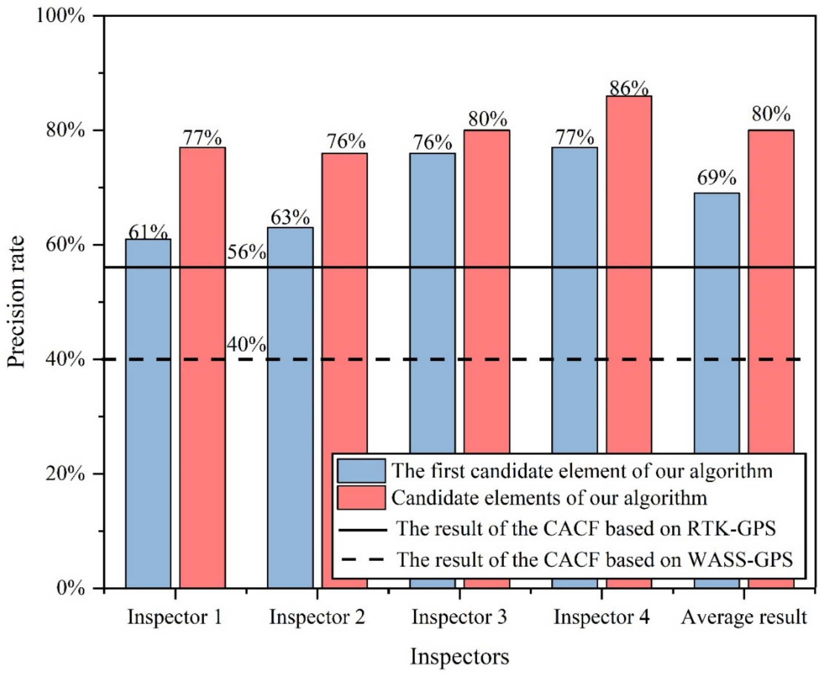

Figure 12. Comparison of prediction results between our algorithm and the CACF.

7. Conclusions

This study proposed an enhanced information retrieval method based on ontology to enhance the efficiency of bridge inspection. The automatic mapping technology was introduced into the seven-step method to quickly build the BIontology. A bridge inspection prototype system was developed to realize the proposed IR method. The effectiveness of the proposed method was validated by two case studies. The conclusions can be summarized as follows:

(1) Compared with the keyword-based IR method, the proposed ontology-based IR method can be used to correctly predict the target element to be inspected. The bridge inspection case demonstrated that the performance of our prediction algorithm based on the proposed IR method is better than that of the context-aware computing method [21].
(2) The improved seven-step method based on automatic mapping technology can make full use of the relational data in a BMS and can promote the construction of the BIontology from manual to semi-automatic. The construction efficiency of the BIontology can be greatly improved compared with the traditional manual method. The proposed method has a wider application scope than the existing semi-automatic method [13].
(3) The proposed software architecture can be used to integrate ontology, and the developed prototype system based on this architecture can be utilized to realize the ontology-based IR method. The software architecture and the prototype system deepen ontology application in bridge engineering and promote the relevant research from a conceptual stage to a practical stage.

It is noteworthy that due to the lack of the spatial relationships in the relational database of our BMS, the spatial relationships were manually added to the BIontology, which is time-consuming. This problem is expected to be solved by ontology generation methods [13,43] from IFC models. Automatic extraction of spatial relationships from an IFC model will be left as part of our future work. Recently, the ontology building method based on the knowledge-type-aware framework has attracted wide attention. We will try to adopt the method to improve the build process of bridge ontology in the future.

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