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Interlinking life-cycle data spaces to support decision making in highway asset management

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ABSTRACT

Technology advances have changed highway project delivery and asset management from relying on 2D paper documents to n-D digital data sets. However, the implementation of diverse software applications imposes big challenges for integrating life-cycle data to support decision making in highway asset management due to the potential inconsistencies of levels of detail, data syntax and semantics. This paper presents an ontology based exchange mechanism that enables unification and interconnection of life-cycle data spaces to support decision making in highway asset management. The mechanism consists of the following key components: (1) domain and merged ontologies, (2) data wrappers and (3) a data query and reasoning system. The mechanism was tested on a sample roadway project retrieved from Landxml.org, and the results indicated the success in integrating fragmented life-cycle data spaces and extracting information for asset management.

1. Introduction

There has been a progressive trend of adopting advanced technologies in the highway industry. Digital models (3D, 4D, and nD) have been widely implemented in various types of projects (bridges, roadways and other transportation projects) for a wide range of purposes (visualization, clash detection, constructability review, etc.) and have changed project delivery process and asset management from 2D paper-based documents to digital model based systems. This technology offers undeniable benefits to individual project stakeholders (engineers, contractors, owners, asset managers, etc.); however, due to the fragmented nature of the highway industry, a highway asset as a whole has not yet fully benefited from the potentials of digital models as a shared and reliable information source for life-cycle decision making. Since different project participants may use proprietary software platforms with different data structures, exchange of data becomes very challenging. Data exchange in a heterogeneous environment may lead to data loss, damage and requires time consuming processing in downstream phases. According to a research conducted by the National Institute of Standard and Technology (NIST), the un-interoperability issue was reported to cost the US capital facilities industry at least $15.8 billion per year, and two thirds of those costs were incurred during the operation and maintenance stages [1]. The major cost was time spent finding, verifying facility and project information, and transferring that information into a useful format. This finding indicates that the failure of collecting and transferring project data from upstream design and construction stages to asset management stage in proper format results in high operational costs. Therefore, a change from the traditional ad-hoc exchange mechanism to an interoperable exchange has become one of the top priorities in the vision of information and communication technology (ICT) implementation in the construction sector [2]. By seamlessly using electronic engineered files generated during planning, design and construction phases, a significant amount of efforts can be saved as assets are managed in order to provide superior results.

One of the earlier approaches to addressing the interoperability issue in the construction sector is the development of open data standards using object-oriented modeling (OOM) techniques or EXtensible Markup Language (XML). Examples of those standards include industry foundation classes (IFC) for the building sector and LandXML for the civil sector. Although these common standards consist of rich lists of concepts covering a wide range of phases and disciplines throughout the life cycle of a project, they are still insufficient to facilitate efficient data exchange [3,4]. One of the primary drawbacks of this approach is the lack of formal definitions of conceptualizations [5,6,7]. This limitation is likely to lead to ambiguity and semantic inconsistency between the data creator and the receiver. Moreover, the lack of explicit presentation of relationships in a complex set of concepts imposes big challenges on the end user since they must have a deep understanding about the data schema in order to correctly extract the desired data.

Recently, ontology has emerged as a solution to the issue of poor semantics in the existing open data standards. An ontology is an explicit formalization of a conceptualization which reflects several parts of the world [8]. Under the view of data modeling, ontology is regarded as

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an abstract model consisting of formal definitions of classes and relationships among them. The implementation of this approach in data modeling has been accelerated by the availability of semantics supported modeling languages such as ontology web language (OWL) [9] and resource description framework (RDF) [10] which are both developed by the World Wide Web Consortium (W3C). While OWL is meant to support modeling of classes, attributes and relationships, RDF offers a platform for describing individual metadata instances. Various authors have employed OWL and RDF to restructure IFC classes in the building sector, such as [11,12,13], whereas few research implementing these technologies have been carried out in the highway sector. Additionally, current ontology related research in the highway sector is mainly for knowledge management purposes. There is a lack of research that implements these technologies to formalize highway specific data elements for digital data exchange throughout the asset life cycle.

This paper presents an analysis of how an ontology based exchange mechanism can facilitate the interlinking of disparate and heterogeneous life-cycle data spaces so that digital data generated in upstream phases can be fully reused in asset management. Specifically, three domain ontologies and one merged ontology were developed using OWL to formulate the local conceptualizations and interrelationships involved in the design, construction and condition survey business processes. These ontologies are the crucial components of the mechanism as they provide sets of vocabularies for the translation of data instances from proprietary formats to the format of RDF triples. A prototype system was also built on the Jena API in Java environment to support data translating, querying and information reasoning. A use case was finally applied and analyzed to demonstrate the success of the proposed exchange mechanism in facilitating semantic interoperability between applications involved in a highway project.

The paper is organized as follows. This section provides the background of the topic and rationale for the research. Section 2 presents the state of the art regarding solutions to the interoperability problem. Section 3 discusses the overall architecture of the semantic exchange framework. Sections 4, 5, and 6 respectively explain the development of ontologies, data translator protocols and information extraction mechanism. Section 7 shows the results of the validation test. The final section summarizes the main findings of the research and discusses the limitations and potential future works.

2. Literature review

2.1. A brief introduction to data interoperability

Data interoperability is defined as the ability of heterogeneous sources to communicate with each other [14] so that data generated from one platform can be sharable and fully reused. Research efforts to address the interoperability problem can be classified into: syntax and semantic levels [15]. While the generation of syntactic interoperability aims to handle the mismatch between data formats, the semantic generation is to ensure the meanings and perspectives of data are precisely and unambiguously translated.

In attempts to address the syntactic interoperability issue, a variety of open data modeling languages have been developed. These languages offer common platforms for structuring abstract data models. Examples of these standards include STEP (also known as ISO 10303-11), unified modeling language (UML) and exentensible markup language (XML). Since these modeling standards are purely limited to syntax and structure, relations among data elements which provide context for the data are not explicitly represented. The lack of declarative semantics imposes big challenges on data exchange between disparate sources as they may use different sets of vocabularies. Exchanging of data relying on a common format would be straightforward if participants in each transaction have approval of mapping rules [16]. But establishing and managing such a standard for data integration of enormous numbers of distinct sources in the global level are challenging and time consuming.

Semantics is the next generation of interoperability research. Ontology based methods have been widely studied and demonstrated as an effective solution for achieving semantic interoperability. From the database point of view, ontology, as illustrated in Fig. 1, serves as an abstract schema for describing data instances in RDF format. An ontology consists of a set of nodes representing real-world concepts (classes or entities) and edges representing concept attributes (literal edges) or relations among concepts (object edges). RDF uses the triple structure which mimics the structure of a simple sentence to present resources (things, concepts) [17]. Each triple comprises three elements including: (1) subject, (2) predicate and (3) object. To allow for interaction in the global network, unification resource identifier (URI) is used to identify a concept, relation or resource.

2.2. Open standard based exchange mechanism

A variety of research efforts have been made for the last two decades to establish open data standards for the highway industry. Most of the existing standards were developed adopting XML technique. LandXML [18], a result of early international collaboration efforts in facilitating interoperability in the civil industry, covers the following main groups of data: survey data, ground model, parcel map, alignment, roadway and pipe network. As an effort to improve LandXML and propose a new standard specialized for the transportation industry, TransXML (NCHRP Project 20-64) project was chartered by the US National Cooperative Highway Research Program. TransXML focused on 4 business areas: survey/road design, construction/materials, bridge structures, and transportation safety [19]. Of these domains, survey and geometric roadway classes are mainly derived from Land XML and are included suggestions for improvement [20]. But, similar to LandXML, the domains of pavement design and asset management have not been exploited yet.

In addition to the XML based standards, several extensions of IFC for road have been developed for a variety of purposes. Shen et al. [21] developed an IFC model for highway projects; based on this structured data, a 3D model was also proposed for visualization purpose. Kim et al. [22] developed another roadway model which focuses on embankment and subgrade classes to support automatic extraction of fill and cut quantity. In an attempt to enhance data exchange between structural engineers and designers in road structures (e.g., bridges, tunnels), Lee and Kim [23] introduced a data model with the integration of structural components. In spite of these considerable research efforts, existing highway data standards still lack non-geometric information. As this

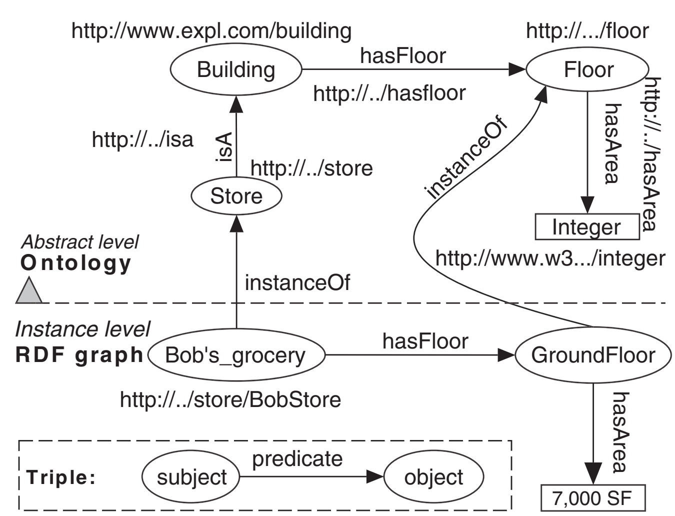

Fig. 1. An example of ontology and RDF structure.