(UR-16) Integrated Framework for Lifecycle Infrastructure Management Systems

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ABSTRACT: There is much information needed to manage the activities and events that occur throughout the lifecycle of an infrastructure system, such as a bridge, including construction, inspection, and maintenance activities, environmental effects, etc. Conventional infrastructure management systems provide only limited support for representing and visualizing this information. Using a 4D product model to visualize information related to different stages of the lifecycle of structures is a powerful method to understand the spatial and non-spatial relationships between the components of the structure and the changes over time of the attributes of these components. This paper discusses an integrated framework for lifecycle infrastructure management systems. This framework integrates information from different sources and links it to the 4D model of the product. A prototype system is developed in Java language to demonstrate the proposed approach using the data of Jacques Cartier Bridge in Montreal.

1. INTRODUCTION

Infrastructure systems are usually large and have long life. During the lifecycle, many changes occur and it is important to collect and manage information about these changes and represent it with respect to the infrastructure model. The traditional way of representing the information is to build databases about the infrastructure, including drawings, inspection database, images, and documentations related to the design, construction and maintenance. To specify the location of the infrastructure, maps are necessary too. Various tools are available to create and record these data, such as CAD tools, Geographic Information Systems (GIS), planning software, Database Management Systems (DBMS), and Infrastructure Management Systems (IMS). However, these tools are not enough to create an integrated visual model and to demonstrate the changes that take place during the lifecycle of the infrastructure.

The main objective of this paper is to investigate an integrated framework for future infrastructure management systems. These systems will benefit from the rapid progress in information technologies including 3D and 4D modeling, tracking methods, spatial analysis, wireless communications, and mobile and distributed computing (Hu and Hammad, 2005; Mozaffari et al., 2005). The framework should accommodate all these technologies and be general enough so that it can be customized to the special requirements of each type of infrastructure systems. For this purpose, the specific domain knowledge that is necessary for each type of these systems should be kept separate from the system as a metadata description file. The framework should be equipped with a flexible mechanism to reconfigure itself by importing this knowledge and customizing the databases and the user interface of the system. Although the ontology of the lifecycle information of infrastructure systems that would be necessary for realizing this mechanism does not exist at the time being, standardization in the AEC industry has been active in recent years and several standards for products and processes related to buildings, bridges, etc. have been developed (IAI, 2005; aecXML, 2005). These standards would provide the basic metadata for building the ontology discussed above. Sunkpho and Garrett (2003) suggested a similar approach using eXtensible Markup Language (XML) to describe the metadata necessary for realizing a Java-based inspection framework that can be applied for bridge or car inspection. The present research aims to extend this approach and integrate it with a framework for mobile data infrastructure management system.

In this research, we choose Bridge Management Systems (BMS) and Facility Management Information Systems (FMIS) as examples of infrastructure systems. However, because of space limitation, the discussion in the rest of the paper will focus on BMS. This paper discusses the requirements for developing the framework described above for facilitating lifecycle data integration and analysis. This framework should link all the information about the lifecycle stages of an infrastructure (e.g., construction, inspection and maintenance) to a 4D model incorporating different scales of space and time in order to record events throughout the lifecycle. A prototype system developed in Java language to demonstrate the feasibility of the proposed framework is discussed. A case study about Jacques Cartier Bridge in Montreal is also demonstrated.

2. REQUIREMENTS OF THE INTEGRATED FRAMEWORK

(1) 4D visualization and interaction: 4D models will allow for spatio-temporal visualization and analysis that are not possible with present BMS. This integration of space and time will result in the following advantages: (1) Visualizing different types of data, e.g., displaying the changes in a bridge 3D model at a specific time or during a specific period of its lifecycle; (2) Providing a user-friendly interface which can reduce data input errors; (3) Facilitating data sharing; and (4) Improving the efficiency of database management. 4D visualization can be understood more quickly and completely than the traditional management tools (Fischer, 2001).

(2) Lifecycle data integration: For any BMS to work effectively, it has to have as much pertinent information about the bridges as possible. The amount of information will depend upon the size and complexity of the system but basically all systems will have modules dealing with inventory, inspection, maintenance and finance. If available, all types of design information such as drawings, design calculations, soil investigation reports, etc., should be used to help the user understand the situation of a bridge at all stages.

(3) GIS integration and tracking technologies: In large-scale infrastructure projects, GIS are inevitably needed for generating information that relates to locations. Spatial conflicts would not be understood fully if they were not linked to geographical locations as perceived in the real world (Zlatanova et al., 2002). Therefore, the 4D model of the bridges should be located on a 3D map. In addition, in field tasks, the location of the user needs to be recognized. Finding the location of the user can be achieved using Differential GPS (DGPS), Real-Time Kinematic GPS (RTK-GPS), or video tracking.

(4) Requirements of space and time scales: All the information about the lifecycle of a bridge should be linked to a 4D model of the bridge incorporating different scales of space and time in order to record events throughout the lifecycle with suitable Levels of Details (LoDs) (Hammad et al., 2004b).

(5) Standardization: Standardization is important for facilitating data sharing and exchange between all the groups involved in bridge management at all the stages of the lifecycle. There are different standardization widely used in the Architecture, Engineering, and Construction (AEC) industry. International standards, such as IFC and STEP, consider both the product and process models to export/import data between applications. XML is an emerging standard for modeling the information that is widely used in Internet-based Business-to-Business (B2B) applications. These standards can be used to retrieve metadata of the framework of the IMS for different types of infrastructures, e.g., BMS and FMIS (Sunkpho and Garrett, 2003).

(6) Simulation and spatio-temporal analysis: Spatio-temporal data include spatial data about present conditions, past changes, and the time of these changes. It should be linked to the 3D model to create a 4D space (including time) to show the changes as they happen over time. 4D CAD tools include both the temporal and the 3D geometric information to display when and where the changes occurred. Physical (e.g., structural) and virtual (e.g., work-related) spaces should be visually represented in the 4D model to extend the spatial concept. Furthermore, spatio-temporal analysis is necessary to help the user generate new data and support the decision-making for future work.

(7) Database requirements: Although relational database management systems are still the norm in BMS practice, object-oriented modeling and programming tools are widely used in software engineering and can greatly enhance the quality of the software. A good combination of the two approaches is the object-relational approach to database development which can relate the information in the relational database with the data structure of bridge components as described in object-oriented programs (Object-Relational Mapping, 2004).

(8) Mobile and location-based computing: BMSs should support mobile and location-based computing by providing user interfaces that could be used on thin clients, such as PDAs and tablet PCs (Fujitsu, 2004), equipped with wireless communications and tracking devices, such as a GPS receiver. For example, in the case of a bridge inspector equipped with a mobile or wearable computer that has a tracking device, based on the location and orientation of the inspector and the task to be achieved, the system may display information about the parts of interest within the focus of the inspector, or navigation arrows to the locations where cracks are most likely to be found.

(9) Decision-support requirements: Bridge management tasks are in general knowledge-intensive tasks demanding specialized study and practical training. Therefore, the knowledge necessary for each task should be knowledge-engineered in a way that it is readily accessible and applicable in a certain situation based on the task. Rule-based expert systems can be used to organize the knowledge pertaining to each group of tasks, e.g., inspection or maintenance, and these rules can be automatically activated in certain situations based on the context of the task that is executed using agents technology (Mizuno et al., 2002; Russell and Norvig, 2003).

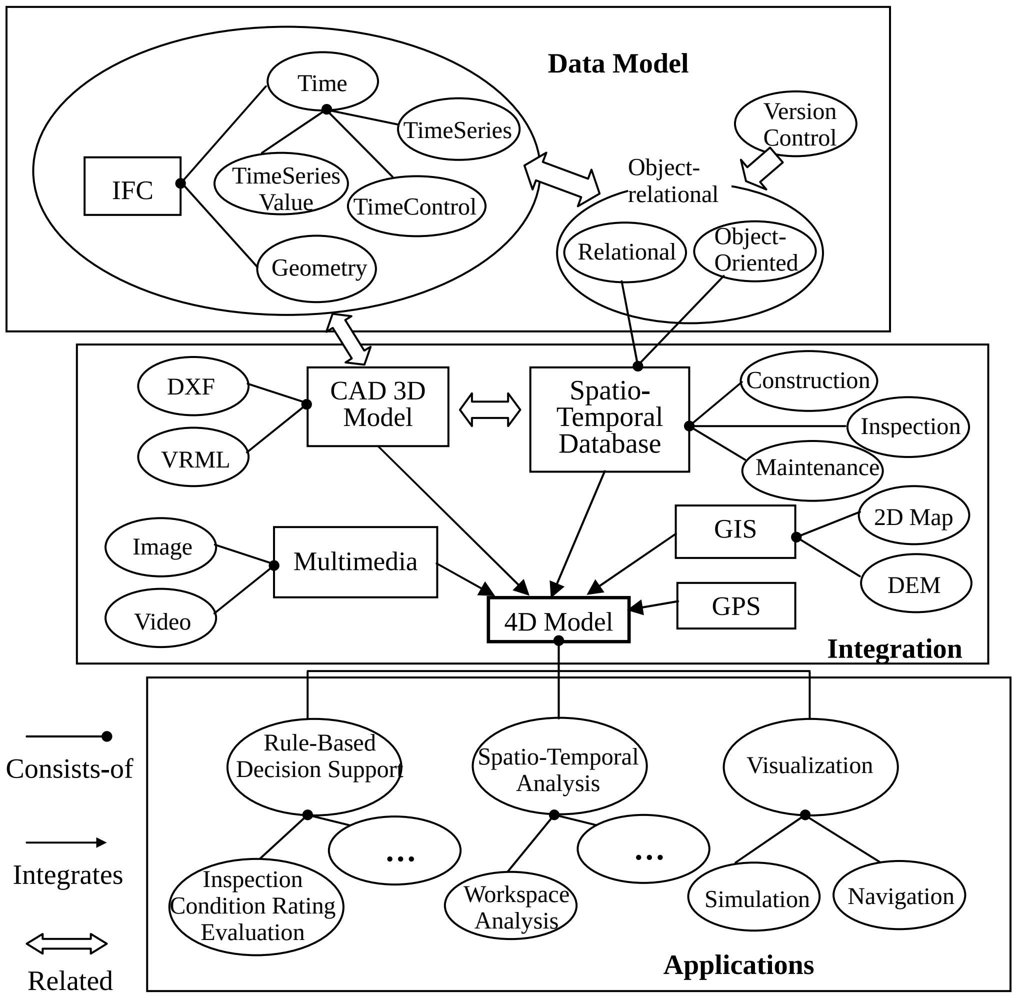

Figure 1. General structure of the framework

3. FRAMEWORK FOR LIFECYCLE BMS

The general structure of the framework is shown in Figure 1. This structure is based on developing an object-relational data model, integrating a number of technologies and then using the data model and the integrated technologies to develop applications. The data model in the framework is an object-relational data model. Data are stored in a hierarchy from most detailed element to the main bridge structure. Each object table is related to the sub- or super-tables. Activities occurring during the lifecycle are linked with related objects' tables to add details about time, type of the activity, etc. The time entities in the database are defined based on the time resources definitions of IFC (IAI, 2005). The data stored in the database about the structure of the bridge can be read automatically and a hierarchical tree is created based on the structure.

The core of the framework is a 4D Model that integrates a spatio-temporal database covering the different stages of the lifecycle and CAD 3D models of the bridges. A 3D map of the area covered by the BMS is needed in the framework to permit the computations based on the location of the bridges. Using this map, the models of bridges can be located using geographic global coordinates.

With the integrated 4D model, the framework can be used to develop many applications, such as visualization, analysis, and decision-support applications. Visualization has powerful functions for interacting with the system in a virtual reality or augmented reality modes (Hammad et al., 2004a). Users can query the database through the GUI or by picking a specific element, and get the results as visual feedback in the 4D model, e.g., information about the painting or rehabilitation history. Users can easily navigate in the 3D space using navigation tools.

4. PROTOTYPE SYSTEM AND CASE STUDY

To demonstrate the feasibility and usefulness of the proposed methodology, a prototype system is developed and discussed in detail in Hammad et al. (2004b).

4.1 Case Study

Jacques Cartier Bridge is chosen as the subject of the case study. Jacques Cartier Bridge is a five-lane bridge with about 2.7 km in length, spanning the St. Lawrence River between the cities of Montreal and Longueuil (PJCCI, 2004). Over the last 70 years, the old reinforced concrete bridge deck had suffered seriously from the increase of the number and load of trucks and the de-icing salts used extensively since the 1960s. During two construction seasons in 2001 and 2002, the bridge underwent complete re-decking of the five lanes. The new deck is constructed of precast, prestressed and post-tensioned panels made of high performance concrete. The bridge data were acquired from the bridge management authority (Jacques Cartier and Champlain Bridges Incorporated) (PJCCI, 2004; Zaki and Mailhot, 2003). The data include AutoCAD drawings, deck rehabilitation schedules and inspection and maintenance records. Several 3D models with different LoDs were created by converting the DWG file of the bridge into DXF (Data eXchange Format) and VRML (Virtual Reality Modeling Language) and extracting the information about the geometry and topology of the bridge elements into the database. In addition, we acquired the digital map and the DEM data of Montreal to generate 2D and 3D maps (Clément, 2004).

4.2 Implementation Details

The system integrates a 3D model of a bridge with an object-relational database, tracking components, and multimedia equipment to develop a 4D model for BMS. Using the 4D model, the user can directly interact with the system to get information on a certain stage of the lifecycle of the bridge. In order to allow for information sharing on the Internet, Java language is used to build the system. The 4D model is built using Java 3D based on the CAD drawings of the main span of Jacques Cartier Bridge and other data about the original construction and re-decking schedules. At this stage, only the bridge truss and the deck panels are considered. Virtual universes in Java-3D can be created from *scene graphs*. Scene graphs are assembled from objects to define geometry, location, orientation, and appearance of objects. Java 3D scene graphs are constructed from node objects using BranchGroups to form a tree structure based on parent-child relationships. TransformGroup objects can be constructed by applying Transform3D objects, which represent transformations of 3D geometry such as translations and rotations (Walesh and Gehinger, 2001).

Java Database Connectivity (JDBC) is a programming framework for accessing information stored in databases. The commands to be executed by the DBMS are based on SQL (Structured Query Language). The database of the 4D model is created with Microsoft Access XP to represent the information of the structural components. Objects can be grouped and linked with the activities. The temporal information associated with each activity and related objects are also stored in the database. The name, type, dimensions, location, properties, and the starting and ending dates of the construction or maintenance activities of each member are defined in the corresponding tables. A GIS sub-system is created using MapObjects Java Edition (ESRI, 2004). The map includes several layers related to Montreal City, such as a boundary layer and layers for the roads, rivers, and administrative areas. The Modified Transverse Mercator (MTM) projection is used because it is the standard projection used by the local government. In addition, to locate the bridge model on the map, the same map of Montreal and the DEM were added to the 3D browser.

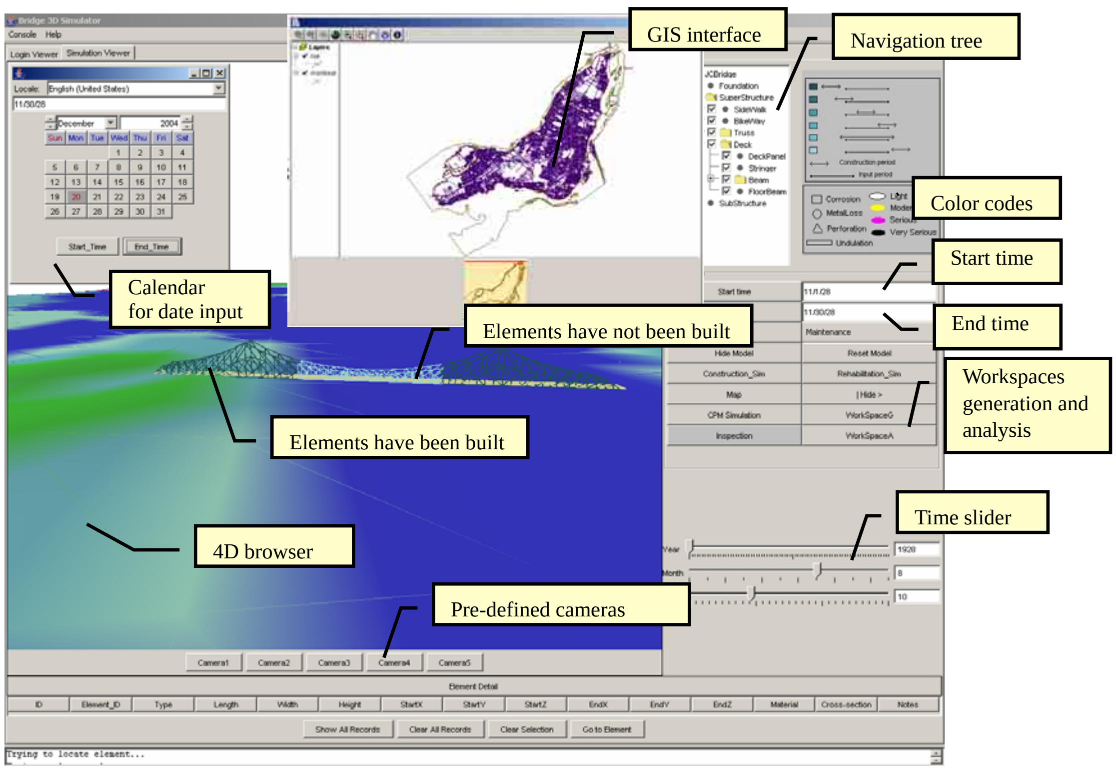

Figure 2. Screen shot of the user interface of the prototype system

4.3 Visualization and Simulation

The main user interface of the system is shown in Figure 2. On the right side, there is a time input interface that allows the user to query the database about events that happened during a specific period (e.g., which parts of the bridge were constructed by the end of 1928? What is the sequence of replacing the deck panels in 2001?). The start and end dates of a period can be input using a calendar interface or sliding bars, and the 3D model will reflect the corresponding elements with different colors representing the progress ratio. A hierarchical tree of the bridge structure is shown on the right side. Each tree node has a check box, which facilitates showing or not showing that element in the 3D model. In addition, the user can navigate the 3D bridge model and select an element of the bridge by picking that element. Upon selection, the element will be highlighted and the related information about the element will be displayed. Alternatively, the user can select an element from the database interface and the element will be highlighted in the model. Furthermore, a number of simulations were developed to demonstrate the usefulness of the 4D approach, such as displaying elements sequentially with different colors according to construction, painting, or rehabilitation periods. When the user inputs a specific time period, the color of each element will change to reflect the status of the construction according to predefined color codes to indicate if the element has been built, under construction, or has not been built.

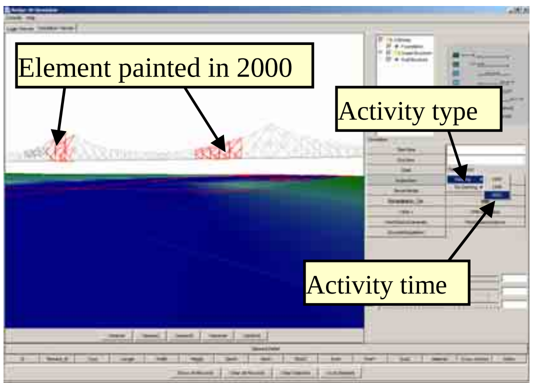

Figure 3. Painting history simulation

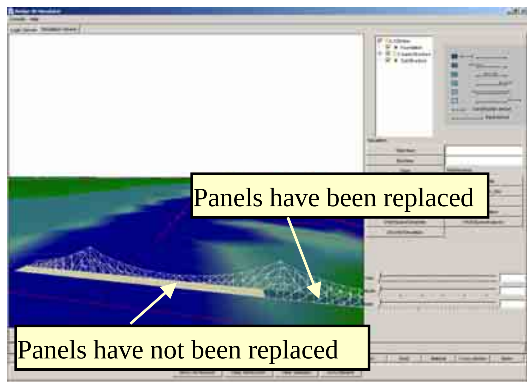

Figure 4. Deck replacement simulation

In Figure 3, the painting activity in 2000 is selected to show which part of the truss was painted during that year. In Figure 4, for the re-decking project of the bridge, a simulation of the deck replacement sequence can be shown on the model.

Four different LoDs for the shape can be used in this system. Line, wire frame, prismatic elements, and detailed VRML objects are used according to the distance between the viewpoint and the model to optimize the performance of the system. When the viewpoint is far from the bridge, the user can see only one line representing the axis of the bridge. When the viewpoint comes nearer, the user can see the wire frame, prismatic elements and the detailed objects, sequentially. The concept of LoDs is also used to control the display of defects (Hammad et al., 2004b).

A calendar and sliding bar interfaces are used to specify a date or a period of time and the time step, representing the temporal LoDs, to be used in a simulation (Figure 2). Different temporal LoDs are needed during construction and maintenance periods. The year or the specific date of the maintenance action can represent the time of maintenance. For example, the painting of the main span was done in several years. The inspection time is usually represented by the date of inspection.

5. CONCLUSIONS

This paper emphasized the importance of the integration of information in lifecycle model-based infrastructure management systems. A framework for object-relational data model, technology integration and applications development was discussed based on the identified requirements. Several computational issues for realizing the framework were also discussed. The developed prototype system integrates 3D graphics and a database to realize the 4D model of Jacques Cartier Bridge. The preliminary testing of the system and its user interface showed that it has good potential for realizing future lifecycle IMS. Further development and testing of the system in practical situations are necessary to improve the functionalities and usability of the system.

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