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Spatio-Temporal Issues in Infrastructure Lifecycle 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 and maintenance activities, inspection data, environmental effects, etc. Conventional infrastructure management systems provide only limited support for representing and visualizing the spatio-temporal relationships within this information. This paper discusses the spatio-temporal issues in infrastructure lifecycle management systems. We start by discussing the requirements for building these systems, such as the integration of information from all stages of the lifecycle, including design, construction, inspection and maintenance; the needs to exchange and share this information across disciplines using standard representation; data models and visualization requirements of 3D and 4D models; and the interaction requirements when using these systems. Then we propose to use an object-relational data model to represent the spatio-temporal data and to base this model on Industrial Foundation Classes (IFC) allowing multiple views of the model. We also discuss a prototype system developed in Java language to demonstrate the proposed approach using the data of Jacques Cartier Bridge in Montreal. Different data types are integrated to build the spatio-temporal model including CAD data, digital maps, and digital elevation models. The 3D bridge model is linked with different scales of space and time to record events throughout the lifecycle with suitable levels of details. A friendly user interface is designed to retrieve and display scheduling and inspection information directly on the 3D bridge model.

1. INTRODUCTION

Infrastructure systems are usually large and have long life. During the lifecycle, many changes occur and it is important to get information about these changes and represent them with respect to the infrastructure model. The traditional way of representing the information is to build data-bases about the infrastructure, including drawings of the infrastructure, inspection database, images, and documentations related to the design, construction and maintenance. To find the location of the infrastructure, maps are necessary too. Various tools are available to create and record these data, such as CAD tools, which are used to create the 2D or 3D drawings of the infrastructure; Geographic Information Systems (GIS) software, which creates the map of the environment around the infrastructure; planning software, which creates the planning schedule of the construction; Database Management System (DBMS), which records the data of design, construction and inspection, and generate all kinds of reports; and Infrastructure Management Systems (IMS), which help in the decision making. However, these tools are not enough to create an obviously visual model to demonstrate the changes that take place during the lifecycle of the infrastructure. Therefore, the spatio-temporal data should be explicitly added to the existing databases and the model of the infrastructure. The spatio-temporal data include spatial data about present shape and 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.

Infrastructure includes many large-scale structures, such as bridges, tunnels, dams, etc. In this paper, we choose Bridge Management Systems (BMSs) as an example of infrastructure systems. Bridge lifecycle management aims to perform the management functionalities related to bridges from the conception stage to the end of their useful life, through the design, construction and operation and maintenance stages. BMSs include four basic components: data storage, cost and deterioration models, optimization and analysis models, and updating functions (Czepiel, 2004; Ryall, 2001).

The proposed approach presented in this paper makes the first attempt to integrate 4D bridge models with BMSs and to facilitate the spatio-temporal analysis for workspaces of complex shapes. Although 4D models have already been built to support construction planning and scheduling (Zhang et al., 2000), these models are not integrated with Facilities Management (FM) or infrastructure management systems.

This paper discusses the requirements for developing a prototype system that facilitates spatio-temporal data integration and analysis. This system should link all the information about the lifecycle stages of a bridge (e.g., construction, inspection and maintenance) to a 4D model of the bridge incorporating different scales of space and time in order to record events throughout the lifecycle. Special consideration is given to the spatial and temporal issues, such as the requirements to support navigation and interaction with the 4D model using different Levels of Details (LoDs), and to adopt available standards of interoperability. The basic computational issues for realizing the proposed approach are discussed. Then, a prototype system developed in Java language to demonstrate the feasibility of the proposed methodology is discussed in detail including the system architecture and the database and user interface designs. A case study about Jacques Cartier Bridge in Montreal is also demonstrated.

2. REQUIREMENTS OF SPATIO-TEMPORAL INFORMATION MANAGEMENT

(1) 4D visualization and interaction: 4D models will allow for spatio-temporal visualization and analysis that are not possible with present BMSs. 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). In many infrastructure projects, such as the case study discussed in a later section of this paper, a physical model of the project is built to check spatial interferences. 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.

(2) Lifecycle data integration: For any BMS to work effectively, it has to have as much pertinent input information about the bridge 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 the design information such as drawings, design calculations, soil investigation reports, etc., should be used to help the user understand the situation of the bridge at all stages.

(3) 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 LoDs. In the field of computer graphics, the basic idea of

LoDs is to use simpler versions of an object as it makes less and less contribution to the rendered image. When the viewer is far from an object, a simplified model can be used to speed up the rendering. Due to the distance, the simplified version looks approximately the same as the more detailed version (Shamir and Pascucci, 2001). As for the time LoDs, different types of schedules have different time units, such as month, week, day, and hour. Most previous research focused on workspaces where activities can be packaged in units that take several days or weeks to be done. For example, Akinci et al. (2002a) used three-week look-ahead schedule while Heesom et al. (2003) analyzed a weekly spatial layout. However, a more detailed temporal representation is needed for highly mobile resources, such as cranes utilized in highly dynamic environments with many concurrent activities.

(4) IFC 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. The Industrial Foundation Classes (IFC) is an open international standard managed by the International Alliance of Interoperability (IAI, 2004). Any object in IFC that has a geometric representation has two attributes: ObjectPlacement and Representation. The representation capabilities have two purposes: to add the explicit style information for the shape representation of products, and to add additional annotations to the product shape representations. There are two time-related resources in IFC: IfcDateTimeResource and IfcTimeSeriesResource. In IfcDateTimeResource, calendar date and local time are defined and functions about validity are also created. IfcTimeSeriesResource defines two types of time points and related values: regular time and irregular time. In regular time series, data are updated predictably at predefined intervals. In irregular time series some or all time stamps do not follow a repetitive pattern and unpredictable bursts of data may arrive at unspecified points in time. A typical usage of these entities is to handle data collected form sensors in a bridge health monitoring system.

(5) Virtual spaces representation: Besides the physical elements of the structure, there are virtual spaces, such as the workspaces needed for equipment, crew, etc. Workspace conflicts are one of the important problems that can delay construction activities, reduce productivity, or cause accidents that threaten the safety of workers (Guo, 2002). Workspace planning is particularly important in the case of large infrastructure projects, such as bridge construction and rehabilitation projects where heavy equipment is required. Previous researches simplified the shape of workspaces by assuming simple box shapes (rectangular prisms). However, this simplification is not always applicable in some cases for equipment workspaces. In order to represent more complex workspaces, it is proposed in this research to use shapes other than boxes, e.g., cylinders, cones, and spheres, or a combination of several shapes using Constructive Solid Geometry (Watt, 2000). Previous researches simplified the shape of workspaces by assuming simple box shapes (rectangular prisms). For example, Akinci et al. (2002a) suggested a generic representation of workspaces using a reference object, orientation, and volumetric parameters. However, this simplification is not applicable in the case of some equipment; for example, the workspace of a crane should be defined based on the range of the dimensions with the dynamic changes of its different components.

(6) Spatio-temporal analysis: Spatio-temporal analysis is the process of extracting or creating new information about a set of geometric or geographic features at a certain point of time. This type of analysis is useful for evaluating the suitability of a certain location, such as problems in site layout planning, or for predicting spatial conflicts, such as conflicts between workspaces (Akinci et al., 2002b). Workspace analysis aims to create different types of workspaces for crew, equipment, and other required spaces in the work site, detect conflicts between these workspaces, and then resolve these conflicts.

(7) Databases 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). The database should combine the information of the structure's model, the related activities during all the stages of the lifecycle, and the workspaces definitions based on related physical objects (elements of the structure and equipment) and activities.

3. FRAMEWORK FOR BMSs

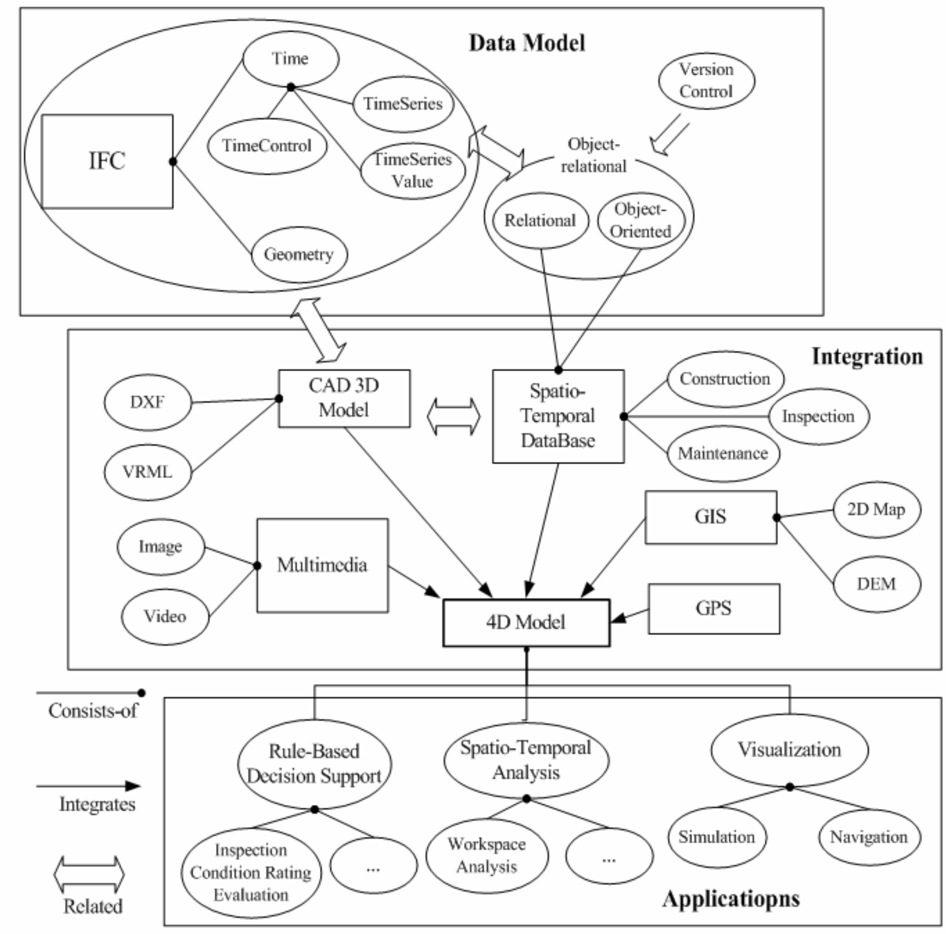


Figure 1. General structure of the framework

3.1 General Structure of the Framework

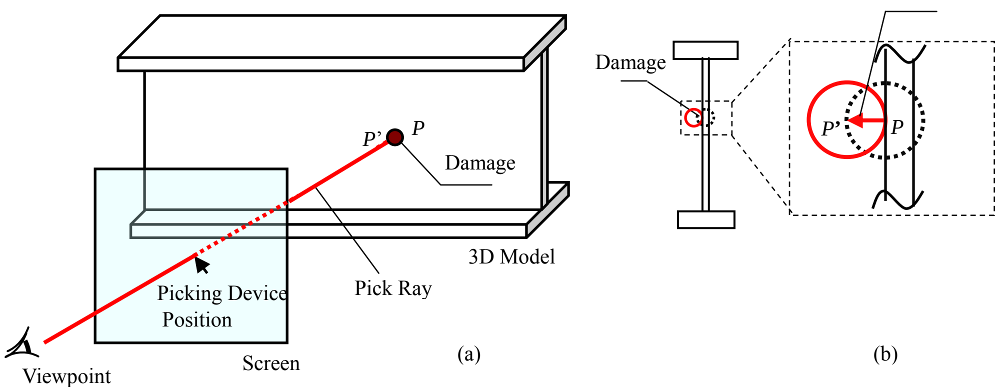
The general structure of the framework is shown in Figure 1. This structure is based on developing an object-relational data model, integrating a number of technologies and then using the data model and the integrated technologies to develop applications.

The data model in the framework is an object-relational data model. Data are stored in a hierarchy from most detailed element, such as a deck panel, 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. In addition, definitions from IFC geometric model resources are used to create multi-representation of the bridge model with different LoDs. The data stored in the database about the structure of the bridge can be read automatically and a logical 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 life cycle, and CAD 3D models of the bridges. Further integration is necessary with GIS, tracking technologies and multimedia information. 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 bridge. Using this map, the models of bridges can be located on geographic global coordinates. In order to create a 3D map, 2D layers can be draped on the Digital Elevation Model (DEM) of the same area.

With the integrated 4D model, the framework can be used to develop many applications, such as visualization, analysis, and decision-making 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. Other important applications are spatio-temporal analysis applications, such as workspace analysis. The different workspaces for each activity can be generated and conflicts between these workspaces can be detected and resolved using a rule-based expert system approach.

3.2 Computational Aspects of the Framework



(a) (b)

Figure 2. Example of picking the 3D model for marking damage: (a) 3D sketch and (b) side view

3.2.1 Picking Behavior

Interaction with the 3D model is mainly facilitated by picking the elements of the model. Picking is the process of selecting shapes in the 3D virtual world using the 2D coordinates of the picking device. In order to interactively retrieve or update information related to the picked element, it is important to know the location and the orientation of that element in the 3D environment of the virtual reality. A pick shape is selected as the picking tool. Pick shape could be a ray, segment, cone, or cylinder. The pick shape extends from the viewer's eye location, through the picking device location and into the virtual world. When a pick is requested, pickable shapes that intersect with the pick shape (e.g., pick ray) are computed. The pick returns a list of objects, from which the nearest object has to be found. After the closest object (*O*) is found, the surface (*F*) that faces the user should be identified to display a suitable feedback. Through the calculation of the distance between the picking device position and the intersection points, the nearest intersection point (*P*) can be found as well as the geometry of the face (*F*) that contains (*P*). The normal vector (*N*) on surface (*F*) can be calculated based on the current coordinates. The normal vector is used to represent the orientation of that face. Based on *P* and *N*, the shape representing the feedback can be created and inserted in the scene graph at point *P'* with an offset distance from the surface *F* proportional to the size of the shape. The vector representing point *P'* can be found using the following equation:

$$[1] \qquad \vec{P}' = \vec{P} + \text{offset} \times \vec{N}$$

The following example of the visual feedback based on picking is given to illustrate the method of calculation (Figure 2.). In the case of inspection, the system allows the user to directly add a damage, which is represented by a 3D shape, on the surface of the inspected element. The location of the damage is represented by the point (*P*) of the picking. However, to show this damage on the surface, the center point of the 3D shape of that damage should be moved in the direction of the normal vector on that surface (*N*) with a small offset distance based on to the size of the 3D shape as shown in Figure 2(b). Otherwise, the damage on a thin element, e.g. the web of a steel beam, may appear on both surfaces of the web due to the small thickness of the web. The center point of the damage representation can be calculated using Eq. (1).

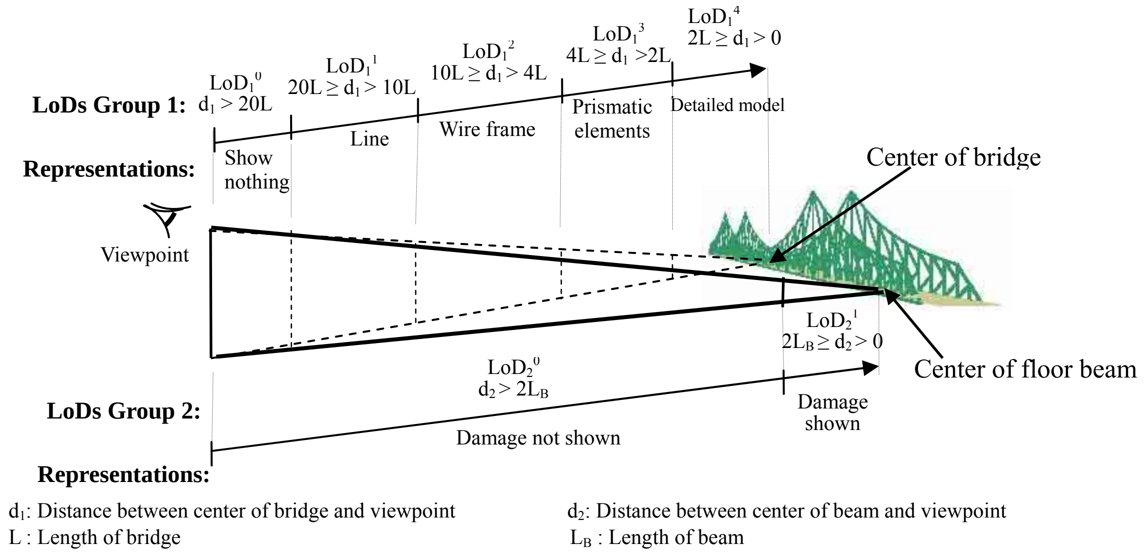


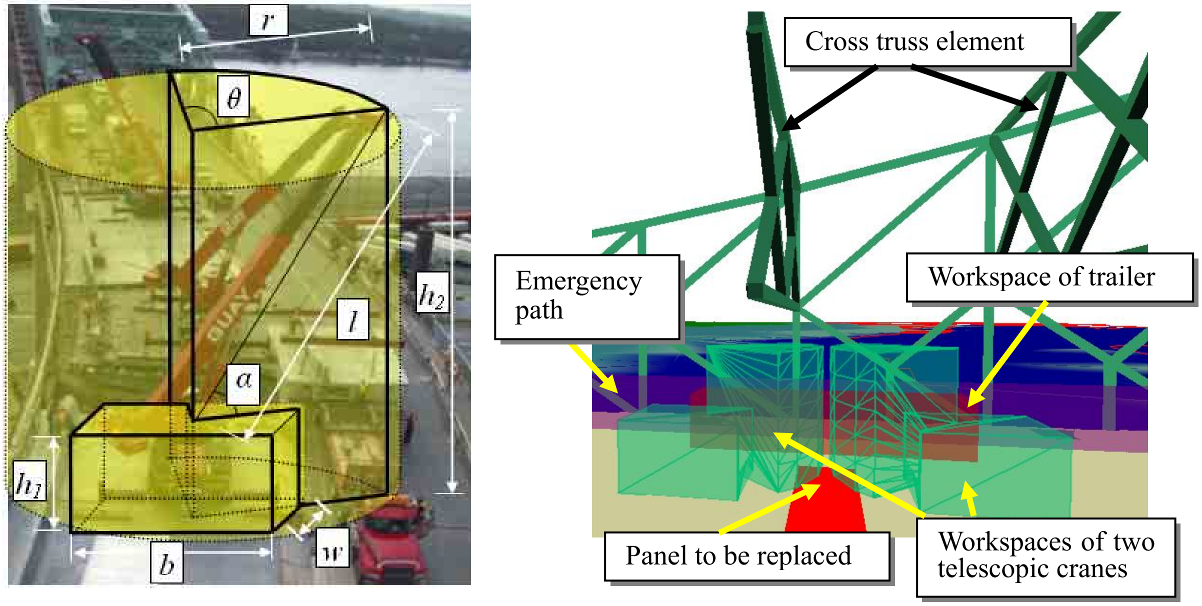
Figure 3. Relationship between distance and LoDs for the bridge and the damages on a floor beam

3.2.2 LoDs

The basic idea of LoDs is to use simpler versions of an object to meet different precision needs and improve the image rendering performance. When the viewer is far from the object, a simplified model can be used to speed up the rendering. Due to the distance, the simplified version looks approximately the same as the more detailed version. LoDs algorithms consist of three major parts: *generation*, *selection*, and *switching*. *Generation* is generating different representations of a model with different detail. *Selection* is choosing a LoDs model based on certain ranges for the distance. *Switching* is changing from one representation to another. When the user moves, this event is detected and the distance between the user and the object is calculated. Based on this distance, the corresponding switch will be selected and the model that should be displayed in this range is rendered. Also, LoDs can be used in parallel with respect to different objects in the same system, such as the bridge element and the damages on the element. Each LoDs group uses different referential center point and distance range and operates only on objects related to that group. As shown in Figure 3, two LoDs groups can be used in parallel. LoDs Group-1 is for the whole bridge model, which includes five different cases: nothing shown, line, wire frame, prismatic elements, and detailed VRML objects. The distance d_1 is measured between the viewpoint and the center of the bridge. The distance range is defined in general depending on the bridge length. In this example, the visible range is from 0 to 20 times of the bridge length. LoDs Group-2 is for the damages on a floor beam, which includes two cases: show or not show the damages. The distance d_2 is measured between the viewpoint and the center of the beam.

3.2.3 Virtual Spaces

To represent virtual spaces, such as workspaces, on the 4D model, information about the workspaces should be retrieved from the database based on a specific period of time. All the corresponding activities are retrieved, and the information about the related physical objects (structural elements, equipment, etc.) are found and used to initialize the attributes of the workspaces, such as the start time and the duration of a workspace. Furthermore, geometric attributes about the physical objects (e.g., transformations, normal vectors, etc.) are computed based on information extracted directly from the scene graph. This information is used to find the location of a workspace relative to a physical object. The normal vectors of the surfaces of the objects are used to represent the orientation of the workspace, and offset distances along those vectors are used to define its relative location. After all the workspaces {WS} are created based on the above information, conflict detection is applied on pairs of workspaces (or a workspace and a physical object) that have temporal overlap. If a conflict exists, a conflict shape is created, its attributes are calculated, and the conflict information is added to the database for future analysis of the conflict.



(a) Workspace of a crane superimposed on a picture of construction site;

(b) Workspaces of an activity on the bridge model

Figure 4. Example of workspaces of telescopic cranes

In order to represent complex workspaces, it is proposed in this research to use shapes other than boxes, e.g., cylinders, cones, and spheres, or a combination of several shapes using CSG (Watt, 2000). CSG is a solid modeling method that combines simple solid shapes called primitives to build more complex models using Boolean operators, such as union, difference, and intersection. Using CSG, complex shapes can be created to represent more realistic workspaces, such as the workspace of a telescopic crane shown in Figure 4(a). In this example, the composite shape of the crane workspace is created by computing the union of a box representing the workspace for the crane body (including the outriggers) and the workspace of the boom with partial lifting zone. The workspace necessary for the boom is computed by taking the intersection of the complete lifting zone (cylinder) and an intermediate shape representing the angle of the boom's rotation around a vertical axis.

4. PROTOTYPE SYSTEM DEVELOPMENT AND CASE STUDY

To demonstrate the feasibility and usefulness of the proposed methodology, a prototype system is developed (Hammad, 2004b). This prototype system is designed to fulfill the requirements discussed in Section 2 and the computational methods discussed in Section 3 to realize the following major functions: (1) Representing the 4D model of bridges with different LoDs; (2) Designing a user-friendly interface with access control that can be used in mobile situations; (3) Developing comprehensive bridge databases including construction, inspection, and maintenance records. (4) Representing virtual spaces and facilitating spatio-temporal analysis for conflicts occurring between physical elements and workspaces, or among workspaces.

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). The bridge has a steel truss frame combined with prestressed concrete (PC) decking structure system. The super structure is seated on RC piers. Inaugurated in 1930, this bridge carries about 43 million vehicles per year with an annual increase rate of 2.4%, making it one of the busiest bridges in North America when considering traffic volumes per lane. 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. Consequently, the deck has been replaced in 2001-2002. This replacement project is the most significant restoration project ever undertaken on a Canadian bridge. 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 which were prefabricated in a temporary plant installed near the south end of the bridge. 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 General Implementation Details

The structure of the prototype system closely follows the framework architecture explained in Section 3.1. The system integrates a 3D model of a bridge with object-relational database, GIS and 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 a bridge. In order to allow for information sharing on the Internet, Java programming 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 Java developers writing programs that access information stored in databases. The commands to be executed by the DBMS on the database are based on SQL (Structured Query Language). The database of the 4D model is designed with Microsoft Access XP to present 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. Also, for each activity, different types of workspaces are defined 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 Projection (MTM) is used because it is the standard projection used by the local government. The GIS has the main functions for zooming and retrieving information about the attributes of different layers. In addition, to locate the bridge model on the map, the same map of Montreal and the DEM were added to the 3D browser.

4.3 Visualization and simulation

The main user interface of the system is shown in Figure 5. 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 logic 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.

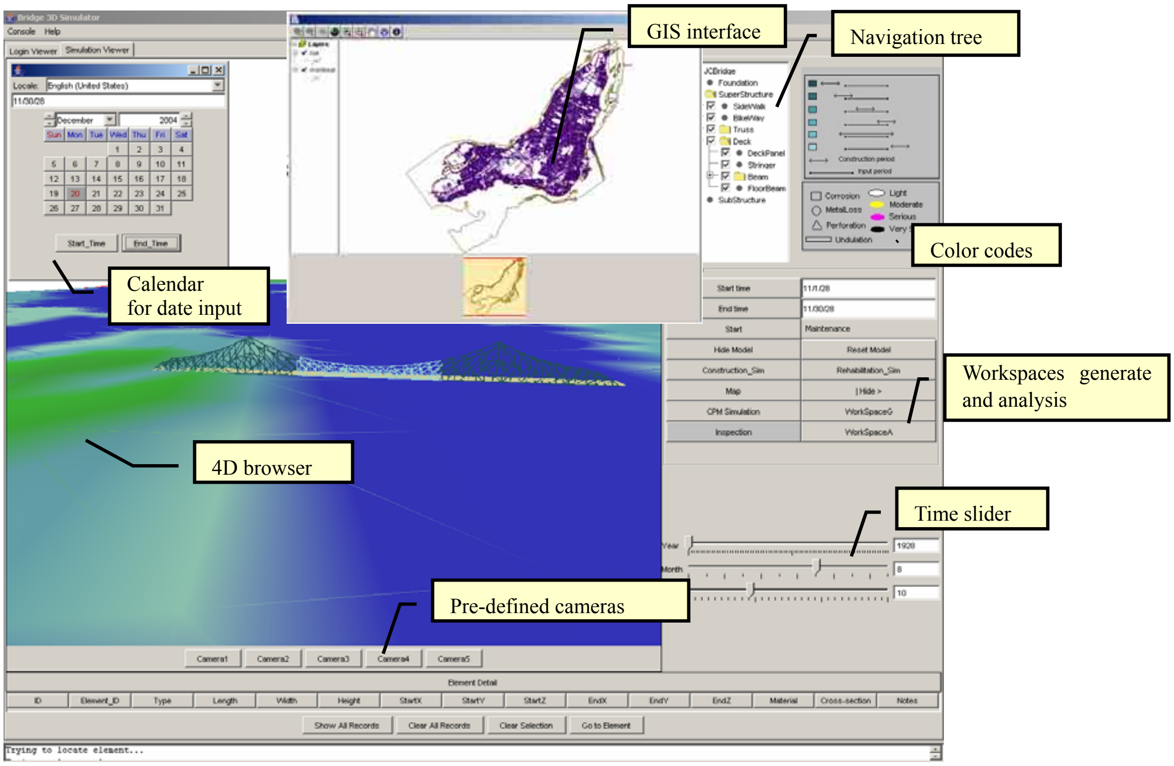


Figure 5. Screen shot of the user interface of the prototype system

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 damages.

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 5). 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.

4.4 Workspaces representation and conflict detection

Figure 4 (b) shows the workspaces of cranes, truck, and an emergency path related to replacing a deck panel. To be differentiated from the physical elements, the workspaces are represented in transparent objects with different colors. User can use the calendar to define the time period and the related activities can be found through querying the database. Then the workspaces are generated according to the information of related activities, objects, and their attributes predefined in the database. The conflict between workspaces and physical elements and among workspaces can be detected and visualized directly on the model, and the interference ratios of volume and time can be calculated for further analysis of conflict resolution.

5. CONCLUSIONS

This paper emphasized the importance of spatio-temporal information in model-based lifecycle infrastructure management systems. A framework for object-relational data model, technology integration and applications development was discussed based on the requirements of managing of spatio-temporal information. Several computational issues for realizing the framework were discussed, such as picking, LODs, and virtual spaces representation and conflict detection. 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 BMSs. 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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