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Visualizing Crane Selection and Operation in Virtual Environment

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Abstract

Selecting suitable cranes in a construction project needs careful planning to meet several requirements from capacity, safety and spatial aspects. To provide construction managers with visual assistance, we present a method to design and implement advanced 3D animation methods to visualize crane selection and construction processes in 3D virtual environment. This paper discusses this approach including spatial conflict detection for equipment workspace using virtual crane animation based on forward and inverse kinematics. In addition, the virtual cranes can dynamically present their kinematics action while respecting the functional constraints for safety and effectiveness of operations. A prototype system developed in Java language is used to demonstrate the feasibility of the proposed method for realizing the proposed method.

Keywords

Visualization, construction operations, simulation, virtual reality, crane selection, kinematics animation, workspace.

1. INTRODUCTION

It is estimated that one crane upset occurs during every 10,000 hours of crane use. Approximately 3 percent of upsets result in death, 8 percent in lost time, and 20 percent in damage to property other than the crane. Nearly 80 percent of these upsets can be attributed to predictable human error when the operator inadvertently exceeds the crane's lifting capacity (Davis and Sutton 2003). With the advent of micro-processing electronics, load-measuring systems have been developed to sense the actual load and the boom angle and length and warn the operator as rated capacity is approached (Davis and Sutton 2003). Parallel to this development in equipment hardware, development in simulation software is making it possible to train crane operators using virtual reality (VR) (Simlog 2006) and to visualize the results of construction simulation (Kamat and Martinez 2001). Furthermore, much research has been done to study the selection of cranes and simulating the working processes using integer programming and optimization techniques (Lin and Haas 1996) and three-dimensional graphics (Hornaday et al. 1993; Dharwadkar et al. 1994). Other studies have been developed for crane selection and location optimization

utilizing knowledge-based expert systems (Zhang et al. 1999).

Another issue related to cranes is the selection of the suitable crane for a specific task. Selecting the wrong type of crane would result in large losses because of the high cost of renting or purchasing the equipment. The following criteria should be considered when selecting a crane (Mobile Crane Code of Practice 2006): (1) The weights, dimensions and lift radii of the heaviest and largest loads to be lifted; (2) The maximum lift height and radius, and the weight of the loads to be handled at these points; (3) The number and frequency of lifts to be made; (4) How long the crane will be required at the workplace; (5) The type of lifting to be done (e.g., precise placement of loads); (6) The type of carrier required—this depends on ground conditions and machine capacity in its various operating quadrants; (7) Whether loads are to be walked or carried; (8) Whether loads are to be suspended for lengthy periods of time; and (9) The workplace conditions, including the ground on which the crane is to be set up, access roads and ramps it must travel on, space for erection, and any obstacles that may impede access or operation.

Recently, Al-Hussein et al. (2001, 2005) developed a system that can assist in selecting and locating cranes on construction sites using the information of load charts and working range (Figure 1). This system uses a crane database, named D-Crane that has the load charts of different manufacturers and the key dimensions of each crane including its carrier, main boom, jibs/extensions, and accessories. The system ensures that the selected crane has the required lift capacity and can fit on site by satisfying a set of constraints described with detailed equations. In addition, the system can check the feasibility of the lifting path by creating a 3D graphical animation. However, the system supports a set of predefined configurations of the site layout focusing on buildings with simple shapes as the main type of obstacles. Therefore, for structures with more complex shapes, such as through truss bridges, the system may not be able to adequately represent the spatial constraints.

A more specific issue related to crane selection and operation is workspace planning, which is particularly important in the case of large projects where cranes are required. 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). Tantisevi and Akinci (2006) discussed the concept of workspaces of construction tasks that can be used to represent the spaces used by cranes during a specific task and to detect spatial conflicts. Another approach to check spatial conflicts is the simulation approach. Simulation can help in selecting the adequate equipment that satisfies both the requirements of construction tasks and the spatial constraints of the site (Law and Kelton 2000). Kamat (2001) presented a method for developing 3D animation of construction processes modelled at typical high level of abstraction. However, this method analyzes the kinematics motions of the cranes without considering the load capacity.

The present paper aims to extend the previous research on crane selection and simulation while taking advantage of the interaction between the user and the system in a VR model. The paper discusses the method of establishing an interactive system for visualizing crane selection and operation considering the load capacity and the spatial constraints.

2. PROPOSED APPROACH

The advantage of visualization is that the user can simulate and check the functional constraints and interferences that may happen in reality between the 3D physical elements and virtual workspaces or among virtual workspaces. In many infrastructure projects, such as the case study discussed in Section 5, a physical model of the project is built to check the usability of different types of cranes and to check workspace interferences. The following subsections discuss the modelling of a crane and its workspace and the general interactive procedure of equipment selection and workspace analysis. The proposed approach for visualizing crane selection and operation in virtual environment (VE) is part of a more comprehensive research project undertaken by the authors and aiming to study the spatio-temporal conflicts related to construction equipment (Zhang and Hamad 2005). This paper focuses on visualizing the interactive crane selection and operation while checking workspace conflicts and functional constraints within a VE of the construction site.

2.1 Crane modelling and animation

In order to build a general model for a crane that can be used in interactive VR simulation, an abstract crane model should be created to represent the different components of the crane and their topological relationships. Furthermore, kinematics animation is essential for producing the interaction needed to operate a crane in the VE. Figure 2 (Davis and Sutton 2003) shows an example of a hydraulic crane that has four degrees of freedom (DoF) for the movements of the boom and hook.

Figure 1. Example of load chart and working range (Groove Crane 2006)

Figure 2. The DoF of a crane

Figure 3 shows a partial abstract model of the crane including its carrier, boom, jib, hook, counterweight, etc. Each of these components has a graphical representation that can be created in a separate file. In order to realize crane's kinematics animation, the Cyclic Coordinate Descent (CCD) method is used (Wang and Chen 1991). For example, the initial and final positions of the lift can be used to calculate the inverse kinematics transformations to be applied on the crane model using the CCD method. The proposed system has the following functionalities:

- (1) Based on the information of the abstract model in the database, the system can generate instances of different kinds of cranes combining the graphical representations of their components. A transformation matrix is used to specify the relative location of each component with respect to its parent. For example, the first part of the boom is located relative to the carrier of the crane. After generating the crane model, the prototype system applies the suitable transformation (scaling, rotation, and translation) on the crane so that it is correctly located at the initial position in the VR model. The parent-child relationships between the components guarantee the consistency of the relative positions of the components when the user simulates the operation of the crane. For example, when the user starts extending the length of the boom from its initial compact length, a translation is applied on the second part of the boom with a step of unit length up to the total length of the second part. Then, the same transformation is applied on the third part of the boom, and so on, until the boom reaches its full length.

Figure 3. Partial abstract model of a crane

- (2) In addition to following the kinematics relationships, the simulated operation of a crane should respect the constraints imposed by the working ranges and load charts. Several rules are developed to represent these constraints which are stored in the database. The working range shows the minimum and maximum boom angle according to the length of the boom and the counterweight. Load charts give the lifting capacity based on the boom length, boom angle and the counterweight.
- (3) Furthermore, geometric attributes (e.g., transformations, normal vectors) of the physical objects (e.g., structural elements) are computed based on information extracted directly from the scene graph. This information is used to locate the crane relative to a physical object. The normal vectors of the surfaces of the objects are used to represent the orientation of the crane, and offset distances along those vectors are used to define its relative location (Figure 4).
- (4) After interactively selecting a crane from the database and positioning it in the VE at a suitable location, the user of the system can specify the lift weight before operating the crane to simulate the lifting task. The system can dynamically detect the changes of the boom length and angle and check whether the manoeuvring operation is allowed by querying the database.
- (5) The system continuously checks and prevents any collision of crane with other objects in VE.

2.2 Workspace modelling

Simulation of crane operation needs considerable effort. In some cases, it may be enough to generate a simplified model of the crane workspace without the details of the kinematics of the crane components. For specific activity of construction, the workspace of a crane can be defined to check the possible conflicts between equipment workspaces and ensure the safety on site. To represent workspaces in the 3D 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. Figures 5 (a) and (b) show the workspace of a crane, which can be generated based on the parameters obtained from the database and input from the user. Workspaces are located in the VE following the same method explained in step (3) in section 2.1. After all the workspaces are created based on the above information, conflict detection is applied on pairs of workspaces (or a workspace and a physical object), which 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 (Zhang et al. 2005).

2.3 Procedure of visualizing crane selection and operation and workspace analysis

This section identifies the main steps needed in a computerized system for visualizing crane selection, operation and the workspace generation and analysis. The system will integrate information from, and add information to, the following databases and models (Figure 6):

- (1) Activity database: This database includes information about all the activities in the construction project, such as the start and finish times of each activity, the target physical components and their attributes, and the types of equipment required in that activity. For example, in the project of the replacement of a bridge deck that is discussed in the case study, a typical activity is the replacement of an old section of the deck with a pre-fabricated panel. In this example, each activity will include the start and finish times, the ID number of the target section, and the required equipment such as cranes, trucks, etc.
- (2) Equipment databases: Equipment manufacturers and large construction companies usually have databases of different equipment used in their work. These databases include the specifications about the different models of a certain type of equipment. D-Crane is a good example of such databases (Al-Hussein 2001).

- (3) Workspace and conflict database: This database has the schemata representing the attributes of workspaces and spatio-temporal conflicts. Workspaces are represented by composite shapes, and each basic shape is described by a number of parameters. Conflict information is calculated using a conflict detection algorithm (Watt 2003). This information includes reference to the conflicting workspaces and the duration for which the conflict exists in addition to the attributes of the intersection shape of the workspaces, such as its volume. This database is specific for each project and can be used by the construction project manager for resolving the conflicts.
- (4) 3D model of the site: This model integrates the digital terrain model of the construction site and the 3D CAD models of the surrounding structures. In addition, 3D shapes representing the workspaces will be generated and added to this 3D model as explained below. These shapes will be used to visualize and detect conflicts between the 3D elements representing the structures and the workspaces, or among the workspaces themselves, using the conflict detection algorithm. The 3D model of the equipment based on CAD drawings is also added to the 3D VE.

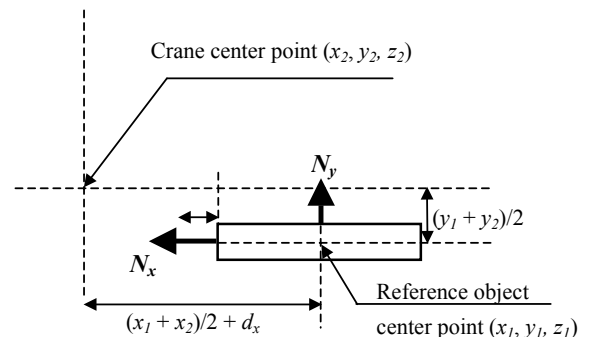
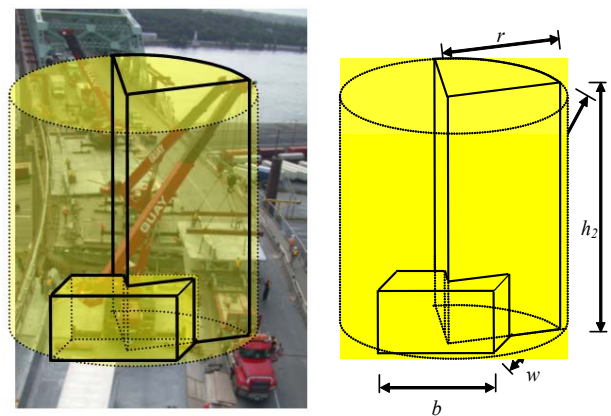


Figure 4. Translation distance for locating crane



(a) Workspace representation (b) Workspace Parameters

Figure 5. Workspace representation

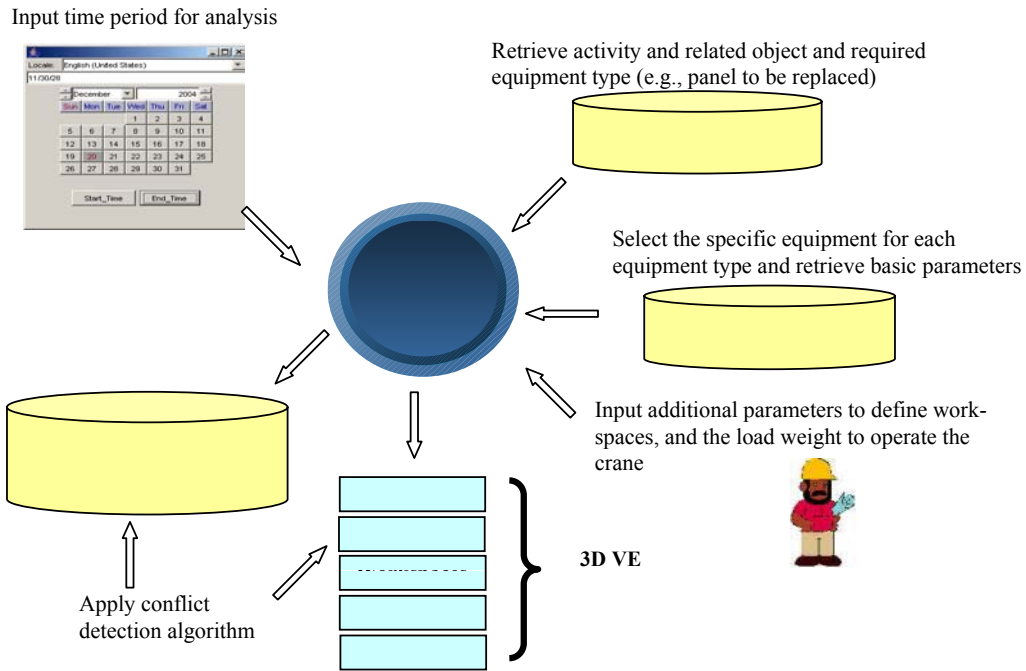


Figure 6. General procedure of workspace analysis and crane operation

Using the above databases and the 3D VE, the following procedure can be applied:

- (1) The user starts by selecting the main activity to be considered in the crane selection, operation and the workspace analysis.
- (2) The system retrieves the information about this activity and all other overlapping activities from the activity database. The information includes the related objects and the required equipment types.
- (3) Then, feasible equipment are selected for each required type from the corresponding equipment database. It should be noted that selecting the optimal equipment is beyond the scope of this research.
- (4) The next step is to retrieve the basic equipment parameters necessary to define their workspaces.
- (5) Other parameters that are necessary for creating workspaces and that are related to the specific site layout are input manually using the user interface of the system. In addition, the relative location of equipment on site can be defined with respect to the reference object that was retrieved from the activity database in step 2, such as the section of the bridge deck to be replaced. The parameters include the orientations and the offset distances between the workspace and the object. Furthermore, the user can input the load weight to simulate the crane operation in the 3D environment.
- (6) In this step, workspaces are generated using the parameters introduced in steps 4 and 5. To locate a workspace in the 3D model, the absolute location of the reference object is retrieved and combined

with the relative location of the workspace to generate the absolute location of the workspace. Meanwhile, the 3D model of the crane is also generated on the same location inside the workspace. The user can use the keyboard or joystick to control the operation of the crane.

3. IMPLEMENTATION

To demonstrate the feasibility and usefulness of the proposed method, a prototype system has been developed and discussed in detail in this section. The prototype system is built using Java language integrating 3D models of cranes and structures, object-relational database, and some constraints of crane load charts and work ranges. The 3D models are created using Java3D, which is an API for developing portable applications and applets that can run on multiple platforms (Walesh and Gehringer 2001). The database is designed with Microsoft Access XP and is accessed using Java Database Connectivity (JDBC). The temporal information associated with each activity and related objects are also stored in the database. The names, types, dimensions, locations, properties, and the start and end dates of the construction or maintenance activities of each member are defined in the corresponding tables. The data can be retrieved and updated using Structured Query Language (SQL). 3DS loader and Java Advanced Imaging (JAI) are used to implement the 3D models and texture mapping.

Information about the available component of the selected crane is instantly retrieved from the database and listed. Once a component is selected, the related information is automatically retrieved from the database and

added to the 3D model of the crane in the VE. Figure 7 shows an example of dynamically changing the hook of a crane.

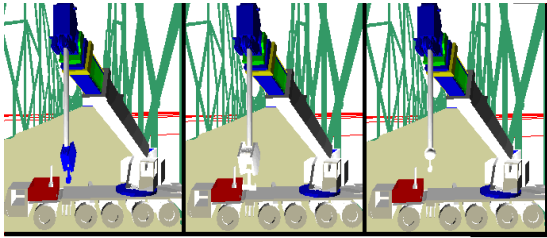


Figure 7. Dynamically changing the hook of a crane

The user can operate the virtual crane to gain a real-time experience and test the loading capacity of the crane under functional constraints and the limits of the workspace. Based on the functional constraints, the system dynamically calculates and displays the current angle and length of boom, and whether the current action is safe or not as shown in Figure 8. In Figure 8(a), the system checks the current status and shows a warning message when the current angle and length of the boom do not meet the capacity requirement. The user can interactively operate the crane to find the work range for the defined capacity as shown in Figure 8(b).

5. CASE STUDY

The re-decking project of Jacques Cartier Bridge in Montreal is used to evaluate the prototype system. The deck of this bridge was replaced in 2001-2002. The new deck is constructed of precast, prestressed and post-tensioned panels made of high performance concrete. The case study focuses on the two activities of removing existing deck sections and installing new panels on the main span of the bridge. The existing deck was removed by saw-cutting the deck into sections similar in dimensions to the new panels. Each existing deck section was removed by two telescopic cranes and a new panel was installed using the same cranes. Figure 9 shows a schematic representation of the worksite layout during the deck replacement.

Figure 10 shows the 3D crane models and their workspaces on the bridge using our prototype system. The user can operate the cranes to evaluate and test the spatial conflicts of workspaces. Because of the low clearance below the cross-frames of the through trusses, the operation of the crane is difficult. Both conflicts among workspaces and between workspaces and physical elements are detected.

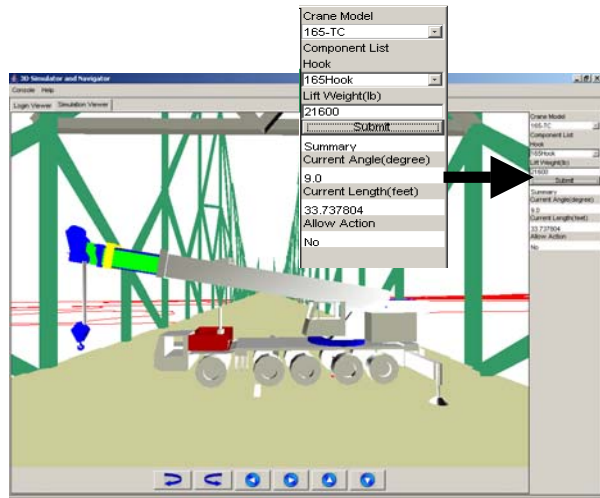
6. CONCLUSIONS AND FUTURE WORK

The paper presented a new method to select and operate cranes in virtual reality environment. The method enables engineers to visualize crane selection and operation, simulate construction processes, and generate

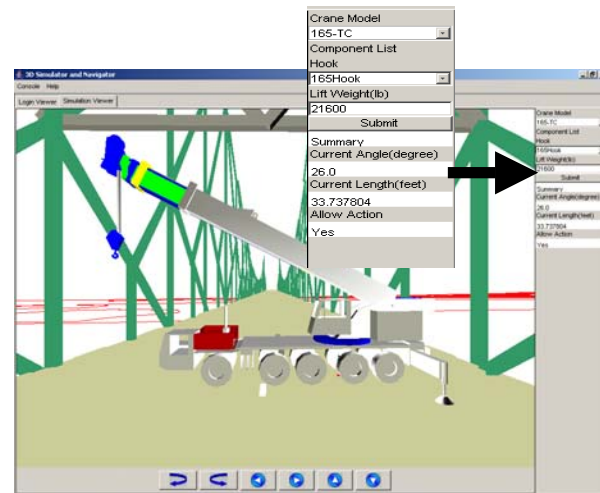
workspaces based on functional and spatial constraints on site. The proposed method enhances the safety of crane operation by evaluating possible collisions and capacity constraints in a virtual environment. Future development will include the following aspects: (1) Modelling the deflection responses of a crane under the lift load; and (2) Extending the method used in this research for crane selection and operation to other construction equipment.

7. ACKNOWLEDGEMENTS

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(a) Boom configuration violates the constraints



(b) The user adjusted the crane to the safe work range

Figure 8. Checking functional constraints under defined lift weight

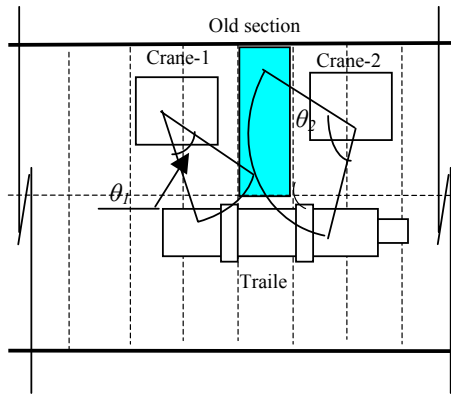
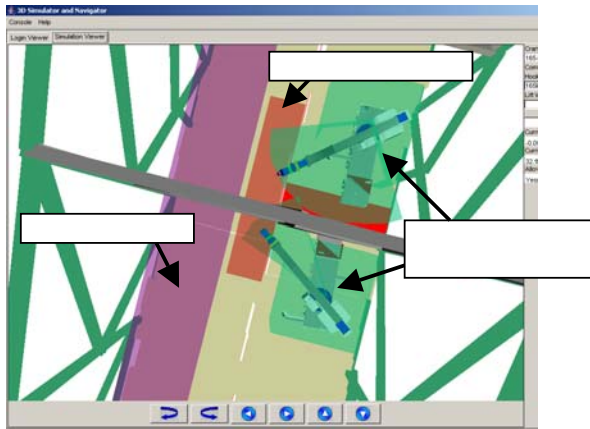
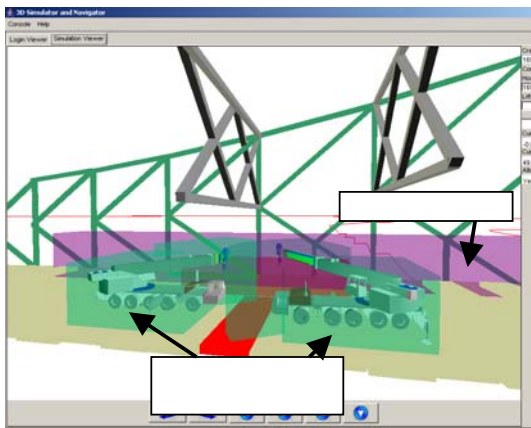


Figure 9. Worksite layout on the bridge



(a) Top view



(b) Side view

Figure 10. Cranes and workspace layout on the bridge

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