AUTOMATED PLANNING AND VISUALIZATION OF MOBILE CRANE OPERATIONS BASED ON BUILDING AND SCHEDULE INFORMATION

Kevin Tantisevi[1] and Burcu Akinci[2]

ABSTRACT

Planning mobile crane operations and modeling workspace requirements of mobile cranes prior to their actual operations could minimize hazardous conditions and delays associated with spatial conflicts on construction sites. To model the workspace requirements and identify spatial conflicts related to crane operations, project engineers need to model and reason about spatio-temporal behaviors of cranes and coordinate them within a dynamic construction environment across time. Current tools for visualizing equipment motion in three dimensions (3D) and across time and for identifying spatial conflicts during operations have limitations associated with their reliance on users in identifying equipment locations and to model equipment motions experientially and manually. This paper presents a visualization tool that assists project engineers in planning operations of mobile cranes accurately and efficiently. This tool builds on discrete-event simulation by automatically creating a visualization of crane operations and generating workspace requirements that geometrically represent spaces occupied by mobile cranes during their operations. Based on the workspaces generated, it detects spatial conflicts between cranes and surrounding components expected to be in place during the time of operation and can help in determining appropriate locations for cranes to perform multiple operations with minimal relocation and without spatial conflicts.

KEY WORDS

4D CAD, mobile crane, workspace, visualization.

INTRODUCTION

Mobile crane operations are typically critical to timely and safe completion of a construction project as cranes are used in various activities across a construction site and a large number of building components are installed using cranes. Compared to other types of construction equipment, mobile cranes typically occupy relatively large spaces in three dimensions (3D) during an operation. When crane operations are not planned and workspaces of cranes are not taken into account prior to their operations, the potential for spatial conflicts between cranes and other components, such as building structures, other pieces of equipment, and temporary

[1] Graduate Research Assistant, Civil and Envir. Engrg. Department, 121 Porter Hall, Carnegie Mellon Univ., Pittsburgh, PA 15213, Phone +1 412/268-8769, FAX +1 412/268-7813, kevint@andrew.cmu.edu

[2] Assistant Professor, Civil and Envir. Engrg. Dept., 123F Porter Hall Carnegie Mellon Univ., Pittsburgh, PA, 15213, Phone +1 412/268-2959, FAX +1 412/268-7813, bakinci@andrew.cmu.edu

facilities located within close proximity, increases (Akinci et al. 2003, Schexnayder 2003). Existences of such spatial conflicts can potentially result in work interruptions, productivity reductions, hazardous work conditions, and damages to the existing structures (Akinci et al. 2003, Lin and Haas 1996, Schexnayder 2003). As reported by Occupational Safety and Health Administration (OSHA), in 1984-1994, 40% of the deaths involving cranes on construction sites were related to spatial conflicts (Suruda et al. 1997). These all suggest the need for modeling the workspaces of cranes and identifying possible spatial conflicts related to crane operations ahead of time so that project engineers and operators can be aware of the conflicts and therefore can proactively take necessary actions to prevent them.

Typically, planning crane operations involves selecting cranes and identifying and evaluating possible alternative locations, where cranes can be situated when performing related lifting tasks (Lin and Haas 1996). Unlike tower cranes that are situated at a fixed location and perform all operations within a given building zone, mobile cranes are assigned to specific lifting tasks (e.g., steel erection, roof installation, etc.) and move across a site to perform those tasks (Shapira and Glascock 1996). Thus, in principle, the locations of mobile cranes are determined based on where installation activities utilizing those cranes are executed. It is necessary that cranes be not encounter spatial conflicts when they are operating at the selected locations. In addition, it is preferred that cranes do not change locations more than necessary during construction as unnecessary relocation of cranes imposes additional mobilization works requiring coordination and preparation of workspaces for a crane prior to operations (Lin and Haas 1996). Moreover, time lost by relocation can cause delays in the start and completion of successive activities. Hence, it is necessary to determine the possible locations, where cranes can be situated to perform given lifting tasks without encountering spatial conflicts and with minimal relocation during operations.

A major challenge in identifying possible locations for cranes and modeling their workspace requirements stems from the fact that crane operations are dynamic. Although cranes are typically situated at a fixed location during an operation, their parts, such as a boom and a hook, move frequently. As a result, spatial conflicts between those parts and other nearby components can potentially occur in 3D and during a given period of operation. Hence, to identify possible spatial conflicts related to crane operations, engineers need to model and reason about spatio-temporal behaviors of cranes and coordinate and assess any impacts that they might have in relation to a construction environment changing across time.

This paper focuses on this need for reasoning about dynamic behaviors of mobile cranes in identifying their possible locations and modeling their workspace requirements. The next section describes current approaches for determining the locations and modeling the workspaces of mobile cranes and discusses problems associated with those approaches. Based on the problems discussed, it highlights the needs for representations and formalisms for automating the generation of workspaces of mobile cranes. The following sections describe research studies related to planning crane operations, an approach developed in this research to address these needs, and implementation of the approach in identifying possible locations for mobile cranes and modeling their conflict-free workspaces.

CURRENT PRACTICES FOR PLANNING CRANE OPERATIONS

Currently, planning mobile crane operations is mostly done intuitively and informally (Shapira and Glascock 1996). Engineers identify possible locations for mobile cranes, based on the specifications and lift-capacities of the cranes provided by crane manufacturers (Al-Hussein et al. 2005, Hornaday 1993, Lin and Haas 1996). Such specifications generally provide information related to the maximum lifting radius and lifting height of cranes and the maximum weight of materials that can be lifted by each type of cranes under various operating conditions (e.g., the amount of counterweight and the extent of an outrigger). By considering the locations, where building components installed by a mobile crane are and the lift-capacities of the crane, engineers identify a set of possible locations for a crane and then select a specific location experientially.

In certain cases, particularly where job sites are tightly congested, engineers create an additional plan for mobile cranes to perform specific tasks, using a series of two-dimensional (2D) drawings. These drawings show where cranes are expected to be located at different periods of time during construction (Akinci et al. 2003). By examining such 2D drawings based on their experiential knowledge, they try to identify possible locations for cranes that minimize spatial interference problems during construction. This 2D drawing-based approach has major limitations in identifying possible spatial conflicts and assessing the validity of possible locations of cranes since it does not convey the fact that available spaces on a construction site change in 3D and that the crane operations involve dynamic movement of a crane. Hence, possible spatial conflicts identified using these 2D drawings are not always accurate, resulting in engineers selecting unfeasible locations for mobile cranes.

Commercially available 4D CAD tools exist for modeling and visualizing dynamic construction environment and identifying possible spatial conflicts in three dimensions and over time. A basic 4D CAD simulation model, which comprises integration of building components and construction activities, allows users to visualize the expected evolution of building structures during a period of construction, based on scheduled activities. Some 4D CAD tools, such as Bentley Dynamic Animator, also provide a modeling environment for users to create and view animations of operations of pieces of equipment during the execution of activities (Bentley 2001). To create animations of equipment operations, the users integrate a basic 4D CAD model with additional object models, which contain geometric information of pieces of equipment and motion characteristics of each part of the equipment, and manually define a sequence of geometric transformations of pieces of equipment during operations. When such animations are created, it is possible to identify possible spatial conflicts related to pieces of equipment and other components expected to be in-place during a given operation by visually evaluating the animations or using an automated clash detection tool. In automated systems, spatial conflicts are checked at each discrete time step of the visualization.

Although the visualization tools provide capabilities for modeling motion of equipment and identifying related spatial conflicts, some difficulties exist when they are used for planning crane operations. Creating an animation that demonstrates a possible scenario of mobile crane operations performed at selected locations manually is error-prone and time-consuming. Engineers need to identify crane operations required by installation activities in a given schedule and then model the dynamic movements of cranes during those operations, based on their own experiences. In addition, current visualization tools allows spatial conflicts to be identified by only checking collisions between pieces of equipment and building structures at each time step of the discrete-event simulation of activities. The accuracy of spatial conflicts detected depends on a proper user-identified time increment of the simulation. To identify possible spatial conflicts related to crane operations accurately, users might need to select a very fine time increment (e.g., as small as one second), which could however result in an excessively long simulation of construction activities. Akinci et al. (2003) estimated that it could take days of works in creating, reviewing, and modifying animations to show dynamic motions of cranes for all crane operations involved in a construction project.

The limitations of the current practice and commercially available visualization tools suggest that engineers need a planning tool that identifies possible locations for mobile cranes and their corresponding workspaces based on given building and schedule information more accurately and efficiently. The research described in this paper focuses on this need and developed an approach for automatically identifying possible locations for mobile cranes and modeling their workspace requirements. It builds on discrete-event simulation of crane operations, which accounts for dynamic motions of cranes, to identify spatial conflicts related to crane operations. The next section discusses previous research studies in planning and modeling crane operations and highlights areas, where our developed approach extends those research studies.

RELATED RESEARCH STUDIES IN PLANNING CRANE OPERATIONS

Many approaches have been developed to assist engineers in planning crane operations at construction sites. Several developed approaches are used for selecting the type of mobile cranes and determining the locations of the selected mobile cranes (Al-Hussein et al. 2005, Lin and Haas 1996), while some are used specifically for optimizing the locations of tower cranes (Tam et al. 2001, Zhang et al. 1999). In those approaches, a set of objectives and constraints, such as the reach capacity, safety, relocation, and costs associated with crane operations, is taken into account for evaluating alternative locations and determining the optimal one.

To determine possible locations for cranes to operate with minimal relocation and without spatial conflicts, several approaches incorporate creating a two-dimensional (2D) work envelope to represent an area reachable by a crane. The size of the work envelopes changes depending on the expected spatial configuration (e.g., the length and angle of a boom of a crane) of a mobile crane during an operation. Although 2D work envelopes are useful for determining possible crane locations that minimize the relocation, they can create accuracy problems in identifying possible spatial conflicts. Since spatial conflicts between cranes and existing building structures can occur in three dimensions, and not all every component existing within the circular work envelope during an operation has spatial conflicts with the crane, there can be cases, where spatial conflicts are identified in a 2D envelope, while in fact the spatial conflicts do not occur. Such false-negative cases could result in missing some feasible locations for cranes.

In addition to optimizing the crane locations, several researchers developed approaches for automatically generating motions of a crane while the crane is operating at a fixed location (Kamat 2003, Kang and Miranda 2004, Ajmal Deen Ali et al. 2005). Since in those approaches, spatial conflicts between a crane and building structures are tested in three dimensions and throughout the course of motion, the spatial conflicts detected are expected to be accurate. However, those approaches are not effectively used to identify possible locations for mobile cranes, since they rely on a user to select the locations where a crane operation takes place so that motion of cranes can be modeled and possible spatial conflicts are checked accordingly. As a result, the crane locations identified may not minimize the relocation of cranes.

Realizing the limitations of the previous research approaches in determining the locations for mobile cranes, we developed an approach to facilitate engineers in selecting locations of mobile cranes by providing them with a set of good locations and allowing them to visualize dynamic motions of cranes during operations. These good crane locations are locations, where cranes can be situated to perform multiple operations with minimal relocation and without experiencing spatial conflicts. This developed approach builds on discrete-event simulation of crane operations as it provides an accurate way of identifying possible spatial conflicts related to crane operations. A detailed discussion of our approach is provided in the next section.

APPROACH

In this research, we developed an approach for automating the identification of possible locations for mobile cranes and the generation of their workspaces. It takes the followings as input: (1) a building design, (2) a schedule, (3) material information, (4) crane specifications, and (5) construction methods. Similar to 4D CAD simulations, this approach centers around an integrated model containing geometric information of building components, construction activities, and their relationships of a specific project. An activity is described by the start and finish times, its resource requirements (e.g., the quantities and types of materials and equipment utilized), and a construction method. Material information contains the type, weight, and geometric information of materials. Crane specifications involve geometric information and lift-capacities of cranes and information about joints connecting different parts of cranes. Construction methods are construction planning knowledge describing how activities are executed (Aalami 1998). In this research, construction methods are defined by a user using a template and linked to activities. The goal is to identify possible locations for mobile cranes and to generate their corresponding workspaces during the execution of activities based on the knowledge captured in construction methods.

Figure 1 shows an IDEF0 model describing an overview of the approach developed in this research. The developed approach consists of three parts: (1) transformation of process information to enable the generation of dynamic motions of mobile cranes; (2) generation of equipment workspaces; and (3) identification of possible locations of the cranes. Subsections below provide descriptions of these three parts in detail.

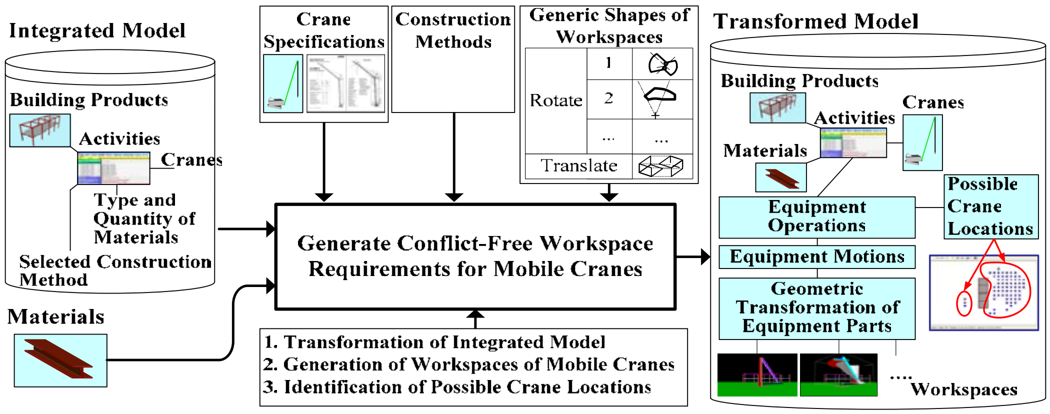

Figure 1: Overview of Approach

TRANSFORMATION OF PROCESS INFORMATION

The developed approach transforms an integrated model containing construction activities, which are defined in relation to building components, into a model containing construction processes at multiple levels of detail including construction activities, equipment operations, motions, and geometric transformations of pieces of equipment. Descriptions of different levels of detail of construction processes for visualization purposes are provided by Kamat (2003). The transformation mechanism is subdivided into two parts: extraction of crane operations from installation activities and generation of motion of cranes during those operations. This mechanism identifies what construction activities utilize cranes and then generates a sequence of crane operations during the execution of those activities. A crane operation comprises a set of movements of a crane for accomplishing a lifting task by moving a piece of material from one location to another. A crane operation is repetitive throughout construction as installation of building components involves moving pieces of material to their corresponding target locations, where building components are expected to be installed. A crane operation can be decomposed into a set of geometric transformations of parts of a crane (Kamat 2003). These geometric transformations are used for visualizing crane operations and generating workspaces, which will be described in the next section.

The transformation mechanism developed decomposes construction activities into crane operations and motions, based on construction methods utilized by those activities. In our research, we built on a construction method model template (CMMT) developed by Aalami (1998) to capture planning knowledge necessary for generating construction activities at levels of detail other than the ones specified in a design or a schedule. A CMMT represents the planning knowledge as a skeletal net linking an activity to its sub-activities. Activities represented in a CMMT are defined generically in the form of the types of building components to be constructed, resources utilized, and operations in relation to the resources. In our research, we extended this construction method description to contain a set of generically-defined equipment operations that capture how pieces of equipment move during the execution of each construction method. For example, during each beam installation activity, a mobile crane moves its boom so that its hook is over a beam, lowers the hook down, and has its hook attached to the mid point located on a side shown as the top of the beam in a design. After the beam is attached to the hook, the crane moves the hook toward the final location, where the beam is specified to be based on the design information, and then places the beam. The above information is generic as it does not refer to any specific mobile cranes, but qualitatively describes crane operations performed during the execution of any beam installation activities utilizing mobile cranes. We developed a template and a set of vocabulary for a user to define such generic information in the form of the positions of a hook of a crane relative to materials to be lifted and building components to be installed by the crane at different states of operation.

By mapping construction methods to project-specific activities, the developed approach automatically generates crane operations during the execution of those activities. Then, it utilizes an inverse-kinematic approach to determine a sequence of geometric transformations of cranes during the generated operations, based on the positional information of a hook specified in the construction methods. More discussions on the representation of construction methods and the transformations of process information based on the construction methods can be found at Tantisevi (2006). The geometric transformations of parts of cranes are used in creating workspaces of cranes that will be discussed in the next section.

GENERATION OF WORKSPACES

In this research, equipment workspaces were primarily used for identifying possible spatial conflicts related to crane operations without a need for selecting a fine time increment for simulation. Workspaces enable identification of spatial conflicts between a piece of equipment and existing building components by checking for such conflicts only once during a given operation. This is different from current spatial conflict detection approaches in which the course of motion is subdivided into time steps and spatial conflicts between actual pieces of equipment and building components are identified at each time step. Equipment workspaces are geometrically represented by a set of polyhedrons, each of which encloses a space occupied by an equipment part or an attached material moving during an operation. To detect spatial conflicts, pairwise geometric intersections between polyhedrons constituting workspaces and building components are tested. It is possible to accelerate the spatial conflict detection by organizing geometric objects (e.g., workspaces and building components) in a scene in hierarchical spatial data structures, such as a bounding volume hierarchy (Kamat 2003).

Generation of the workspace involves creating polyhedrons enclosing spaces occupied during each geometric transformation of a part of a piece of equipment and materials attached to the equipment and aggregating those polyhedrons according to equipment operations. Since a crane consists of multiple parts, which translate or rotate with respect to each other during an operation, the polyhedrons generated in this research have different shapes, depending on the type of a geometric transformation of a part of a crane. Figures 2(A) and (B) illustrate examples of the polyhedrons generated to encapsulate spaces occupied by an object when moving along a certain direction and rotating about a certain axis. Figure 2(C) shows a collection of the polyhedrons generated to represent a workspace of a crane during an operation. These polyhedrons are represented by a set of triangles, which can be directly used in geometric intersection tests against building components that are expected to be in place during operations.

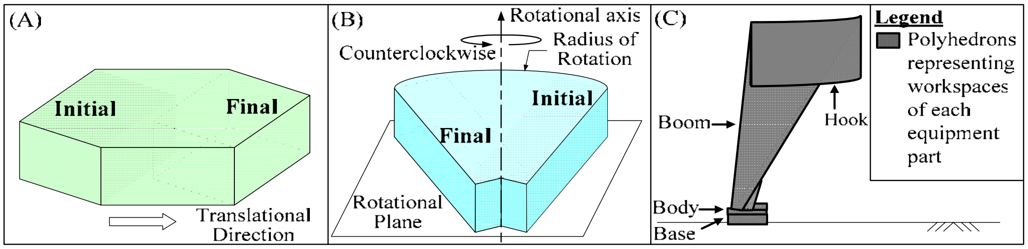

Figure 2: Polyhedrons Enclosing Spaces Occupied By Equipment Part (A) During Translation and (B) During Rotation and (C) Collection of Polyhedrons Representing Equipment Workspace During Operation

SIMULATION-BASED IDENTIFICATION OF POSSIBLE CRANE LOCATIONS

This section describes an approach for identifying possible locations for cranes to perform operations with minimal relocation and without encountering spatial conflicts. The developed approach builds on discrete-event simulation of crane operations and utilizes workspaces of cranes in identifying possible spatial conflicts related to crane operations. It identifies an initial set of alternative crane locations by dividing an entire ground surface of a site into a finite number of grids, whose corners represent locations, at which a crane can be situated. Then, it assesses the possibility for spatial conflicts while a crane is operating at those locations. Unfeasible locations, where a crane cannot reach building components, and where it can possibly have spatial conflicts, are eliminated. After such elimination, the remaining crane locations are considered to be the *possible* locations for a crane to perform a given operation. Moreover, the developed approach assesses whether the possible locations for one crane operation can be used as the possible locations for other crane operations utilizing the same crane in the sequence. By incrementally eliminating the possible locations where cranes cannot perform multiple crane operations, it is possible to identify possible locations for cranes that also minimize relocation.

Although discrete-event simulation of crane operations can be used to identify possible spatial conflicts accurately, it is time-consuming, when used to simulate crane operations that take place at every location. This research minimizes the simulation of crane operations by utilizing simple geometric intersection tests to eliminate unfeasible crane locations that are within the footprint of or close to building structures that are expected to be in place during the operations. These intersection tests do not account for dynamic motions of cranes during operations in identifying possible spatial conflicts, but check for intersections between building structures and the boom of a crane while a crane is placing a piece of material. Hence, the efficiency of identification of possible crane locations increases.

IMPLEMENTATION AND VALIDATION

In this research, we implemented a prototypical visualization environment to graphically display outputs of the developed approach and to assess their validity. This prototype allows a user to navigate through a building environment from different view angles and at different points in time during construction and to visualize possible locations for mobile cranes to perform a sequence of operations. Figure 3(A) shows screen dumps of a building structure modeled as a testbed for validating the approach and Figure 3(B) shows a set of possible locations, where a mobile crane can be situated to install a single beam. Based on a set of possible crane locations, the user can select specific locations of cranes and view their movements and corresponding workspaces during operations. Screen dumps of animations showing movement of a crane while operating at a selected location are shown in Figure 3(C). Such graphical outputs of the prototype provide an easier way for users to plan crane operations at construction sites and validate the approach described in this paper.

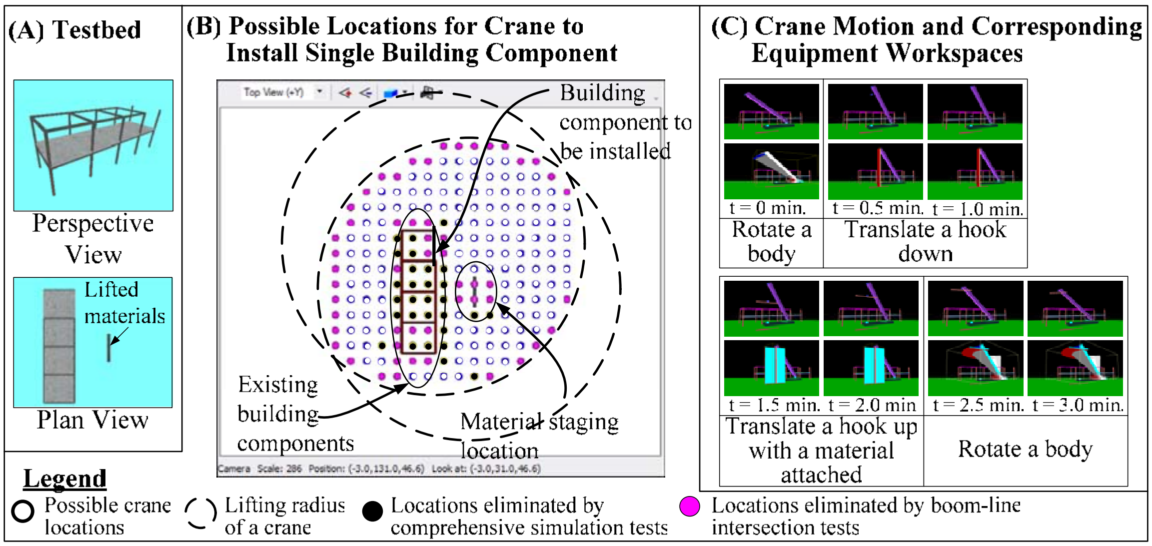

Figure 3: (A) Testbed, (B) Possible Locations for Crane to Install Building Component, and (C) Motion of Crane When Operating at Selected Location and Corresponding Workspaces

During validation, we assessed the accuracy and the efficiency of the developed approach with respect to a comprehensive discrete-event simulation and time-space conflict detection of crane operations. We implemented two collision detection mechanisms: a conventional approach and a workspace-based approach. The conventional approach checks for collisions between cranes and building structures at each discrete time step whereas the workspace-based approach identifies spatial conflicts between workspaces of cranes and building structures. In our implementation, it is found that the workspace-based approach is less computationally intensive and hence more efficient than the comprehensive simulation tests when spatial conflicts detected using those two approaches are equally accurate. Therefore, workspaces of mobile cranes represented and generated in this research can potentially be used to increase the efficiency of spatial conflict detection and identification of possible crane locations. Detailed discussion on validation can be found at Tantisevi (2006).

CONCLUSIONS

The research described in this paper focuses on the need for representing and reasoning about dynamic behaviors of mobile cranes in creating plans for mobile crane operations. It enhances the benefits of using 4D visualization tools by developing an approach for automating the generation of workspaces of mobile cranes and identification of possible crane locations. The approach described in this paper identifies possible locations where cranes can be situated to operate with minimal relocation and without encountering spatial conflicts. Such an approach reduces errors and time spent in modeling the dynamic movement of cranes and the corresponding workspaces. As a result, it could enable project engineers to determine possible locations of a crane more efficiently and effectively.

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