3D SIMULATION AND VISUALIZATION OF CRANE ASSISTED CONSTRUCTION ERECTION PROCESSES

Introduction

Many kinds of construction projects involve erection processes performed by cranes. In particular, cranes are essential for lifting and transporting materials and equipment in a construction site and are key elements in the erection processes. In many kinds of projects, such as high rise construction, cranes are one of the most shared commonly pooled resources at the site. Therefore, an efficient and safe operation of cranes is of utmost importance in the safety, schedule and crucial to the overall success of the project.

Over the last 30 years computers have played an increasingly important role in construction. In particular, scheduling, cost estimation and many other planning and management tasks are routinely done today with the assistance of computers. The software implementations like such as the 4D CAD technology, which binds 3D models with their corresponding construction schedules to enhance comprehensibility of representation of constructing procedures, have seen a rapid emergence. This is mainly due to the increasing recognition from the construction industry on the benefits of using the 4D CAD applications for increased productivity, improved project coordination, and optimized use of on-site resources. There are powerful commercial 4D CAD tools have been developed in recent years, examples of which are, such as Common Point's Project 4D, Bentley's Navigator, Intergraph's SmartPlant Review, BALFOUR's FourDscape, and ConstructSim. (Sheppard, 2004). Moreover, much research efforts have been carried out to advanced the 4D CAD technology from simple 4D animation of construction progression to interactive 4D simulation of alternative construction processes (McKinney et al., 1996), and even to nD CAD that integrates 4D models to project information in dimensions other than 3D space and time (Lee et al., 2003; Tanyer...
Four dimensional systems provide a powerful tool to assist construction engineers in planning construction projects. They visualize and display the construction progress by linking three-dimensional 3D computer models of the project developed with commercial CAD software and with a construction schedule developed in commercial project scheduling software. Four dimensional systems then use the project schedule to control the time in which layers or objects in the 3D model are shown allowing visualization of the whole construction of the project or to visualize specific time segments of specific areas of the project. However, in most cases, computer models are developed to show only the final configuration of the project and are not necessarily developed to show how the individual components are assembled. Furthermore, components of the three-dimensional 3D models visualized correspond to construction activities as described in typical construction schedules and therefore lack the necessary detail to be of direct use for detailed visualization of construction operations such as the erection of individual components. More importantly, 4D systems, although allowing visualization of a construction schedule, do not allow the simulation of construction activities.

Since the 70s there has been considerable amounts of research on the simulation and visualization of construction activities. Some examples include CYCLONE (Halpin, 1976 and 1977), a method for modeling job site processes; INSIGHT (Kalk, 1980), an interactive system for the simulation of construction operations using graphical techniques; RESQUE (Chang, 1986), a resource based simulation system for construction process planning; and, STROBOSCOPE (which is a programmable and extensible simulation system designed for modeling construction operations.

Such systems and techniques were developed through describing procedures of construction operations based on various kinds of simulation strategies. A simulation strategy is the conceptual framework that guides model development and determines how the modeler views
the system being modeled (Hooper 1986; Balci 1988). By following these strategies, the construction operations can be simplified and abstracted into routine steps or cycles for simulation and visualization. The modelled tasks could be as simple as a scraper and pusher operation or complex large-scale and specific construction activities.

For an excellent review of these and other simulation and visualization systems developed specifically for the construction industry, the reader is referred to Martinez and Ioannou (1996, 1999).

Many of these systems have been aimed at scheduling and general-planning purposes of repetitive construction activities (e.g., earth moving operations) and therefore include a number of simplifying assumptions such as production rates being assumed constant, simplification of generalizations of construction paths, include other examples of simplifications here and. Visualization was typically very limited often only providing a 2D schematic two-dimensional visualization.

With the advent of more powerful computing power, improved simulation and visualization methods have been developed in recent years. Some examples of recent research includes further-deeper studies about into simulation strategy (Ming Lu, 2003; Hong Zhang et al., 2005; R. Sacks et al., 2007), 3D dynamic construction visualization, automatic constructing simulation, and the method of interference detection in 3D construction environments (Vineet R. Kamat et al., 2001, 2005).

**Research Goal**

The overall goal of the research conducted by the authors was to here we developed numerical procedures to simulate and visualize construction erection processes, with the intentions of it is aimed at providing detailed planning and visualization in a virtual construction environment as well as...
Modeling the Manipulation of a Crane

In this research, construction cranes are treated as robots in order to facilitate a mathematical description of their motion. In particular, this approach permits the formal mathematical linkage of the individual controls in the crane's control panel that control each independent movement of the crane (that is, each degree of freedom of a crane), which includes all motions from those controlled by the crane operator to the position of the hook in space.

To mathematically describe the motion of a crane, we employ the Denavit-Hartenberg notation (Denavit and Hartenberg, 1955). The notation defines a coordinate system attached to each joint that is used to describe the displacement of each object relative to its neighbours in a general form. Following the rules of the Denavit-Hartenberg notation, there are four parameters, $a_{i-1}$, $d_i$, $\alpha_{i-1}$, and $\theta_i$, used to describe the relationship between two coordination systems in a general form. By identifying these four parameters, the transformation matrix between coordinate system \{i-1\} and \{i\} can be derived. We can transfer coordinate system \{i\} to \{i-1\} by translating two directions, $a_{i-1}$ and $d_i$, and rotating $\alpha_{i-1}$ and $\theta_i$ along $a_{i-1}$ and Axis i-1. Similarly, this is a general way to describe any other type of connection. The general form of a transformation matrix can be presented as follows:
\[
\begin{bmatrix}
\cos \theta_i & -\sin \theta_i & 0 & a_{i,1} \\
\sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -\sin \alpha_{i-1} d_i \\
\sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & \cos \alpha_{i-1} d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1)

where \( ^{i-1}T_i \) maps the coordinate system \( \{i\} \) relative to coordinate system \( \{i-1\} \).

As shown in Figure 1, crawler cranes are capable of moving freely around the site \textbf{thus that they are also} widely used in many construction projects. \textbf{This type of crane may be mounted on crawlers, trucks, or wheel carriers to provide the mobility necessary for different purposes. When analyzing this type of crane, it can be treated as a moveable luffing crane. The schematic representation is essentially the same as that of luffing crane except that in this case the base is movable instead of fixed.} Since the base of the mobile crane is moveable in space, \textbf{the machine has no actual fixed end}. Three variables, \( x_0, y_0 \) and \( z_0 \), can be added to represent the translation of the base with respect to a reference point. Here we can find that the forward kinematics matrix of the mobile crane is exactly the same as that of the luffing crane with exception of the position terms (the top three elements in the fourth column in the homogeneous matrix). The only difference between a mobile crane and a luffing boom crane is that mobile cranes have three additional variables to represent the moveable base.
Plan the Motion Planning for Crane Erections

Current Efficiency of crane utilization can be significantly improved by optimizing the moving path and crane operation. These days, the cranes are manipulated by the operator’s technique mainly depending on their experiences or even their intuition. This empirical manipulation can be inefficient and often result in some unsafe movement. Since crane operators cannot always find optimal motion paths for manipulating a crane, particularly optimum simultaneous movement involving three or four degrees of freedom, the time is wasted due to follow the inefficient paths. Although the waste of time due to the duration of inefficient operation in an erection cycle (e.g., for erecting one component) may be small, it can accumulate to a significant amount of time when the hundreds or thousands of erection cycles involved in a project are considered. Hence, it is important to develop a reliable method that can help crane operators optimize crane usage by using computer analysis can be used to find the optimum erection sequence and optimal path for each piece that needs to be lifted.

However, due to the complexity of construction projects, currently employed manual methods make it difficult to produce precise and detailed erection schedules. Therefore, automatic methods, which facilitate the visualization and simulation to visualize and simulate of detailed erection activities in the computer, are needed. Herein lies the motivation behind this research. Developing a detailed erection plan requires a great amount of geometrical analysis, consideration of...
the crane operation, and identification of the most efficient and safest path for each element that needs to be erected, and identification of the best erection sequence for all elements in the projects. The solution to these problems can be facilitated by the techniques in motion planning and computer graphic, two of the most rapidly developing areas of computer science in recent years. Choosing from the large pool of available techniques, it is very important to select appropriate techniques, as is develop ways on how to adapting these the chosen techniques for our purpose, improving crane operations.

Motion planning is one of the most important techniques to automating the erection activities in a construction. The motion-planning problem is to find the operational path of a construction crane in a given three-dimensional environment from an initial configuration to a target configuration. The paths do not only require collision-avoidance between the crane and all obstacles in the given environment but also must consider the capacity of the crane and the ability of operators in construction practice.

The following sections describe the crane model that was developed in this research and describe the motion-planning methods and algorithms.

Path-planning and motion-planning methods have been developed in computer science and robotics in the last 30 years (L.E. Kavraki, and J.C. Latombe, 1998). Previous methods have mainly focused on the topics related to computer games and robots. Recently, because of the significant improvements in computation power, some research has started using path-planning methods for medicine and engineering purposes. To the best of our knowledge, little research has been done to develop path-planning methods specifically for cranes. A major challenge in finding the erection paths for a crane is to consider both geometrical obstacles and operation problems. Unlike many other applications in which the obstacles remain constant over time, in this application, every piece that is erected subsequently becomes an obstacle for the erection of the following pieces.

This research separates the problem into two parts. The first part focused on efficiently finding a collision free path efficiently, and the second part focuses on refining and optimizing the path for
better crane operations.

Inherent to the nature of path-planning methods, the methods that have a higher success rate in finding a collision-free path generally have a higher computation cost than those with a lower success rate. For this reason, we have developed and implemented three different path-planning methods, QuickLink, QuickGuess and Random-Guess, to handle different path-planning problems with minimal computation cost.

QuickLink is the most inexpensive algorithm but has the lowest success rate for finding a collision-free path among the three methods. An illustration of the procedure can be found in Figure 2. The basic idea of QuickLink is to build up two trees starting from both an initial point and an end point by adding random points above those two points. QuickLink then attempts to link the end points in the two trees from the bottom up. If the connection between the points is found to be collision-free, a collision-free path is returned by linking the trees passing the connection.

RandomGuess is the most expensive method among the three path-finding methods but offers the greatest possibility of finding a collision-free path if one should exist. This method keeps “guessing,” i.e., sampling, random points in C-space until finding a path. If the guessed points can be linked to the initial tree without any collision, we can add the point to the initial tree. Similarly, the end tree is grown by using the same process. If one or both of the trees are changed, the RandomGuess method will call the QuickLink function to examine whether the two trees can be linked without any collisions. This process is repeated until a path is found. Because the method needs to blindly guess random points in configure space (C-space) of the crane and perform collision-detecting tests, the method can be extremely computationally expensive in some cases. However, if there is at least one collision-free path in the given configuration, in theory, RandomGuess will eventually find the path after a sufficient amount of attempts.

QuickGuess compromises the computation and completion by quickly guessing a random point in C-space.
space. This method is essentially a middle point between the two trees. If the guessed point can reach both the initial tree and the end tree without collision, then we can connect the two trees by passing the guessed random point to obtain a collision-free path. Adding more middle points can improve the success rate of finding a path.

This research implements the QuickGuess method by using both single and double middle points. The QuickGuess method with a single middle point is shown in Figure 3.

The GeneratePath function, which integrates the tree path-planning methods, is implemented in the iCrane system. The function GeneratePath computes an erection path, we sequentially used QuickLink, QuickGuess, and RandomGuess methods for finding paths. Since the function uses the QuickLink, QuickGuess, and RandomGuess methods, going moves from the one with least computational cost (load) to the more one with the most costly one, so the efficiency of the function overall performance can be maximized.

We tested the GeneratePath function on a 12-story building with 2105 structural elements. It was found that 62% of the paths were found by QuickLink, 35% were found by QuickGuess, and 3% were found by RandomGuess. In addition, we also estimated the computation efforts (computational times) between the three motion planning methods were estimated and compared by counting the number of times that the collision-detecting function was called in each of the three path-finding methods. QuickGuess was approximately ten times more computationally expensive than QuickLink; and RandomGuess was between 10 to 100 times more expensive than QuickGuess. The results showed that the application GeneratePath sequence (i.e. QuickLink first, QuickGuess second and then RandomGuess third) can successfully adopt different methods and effectively find collision-free paths within reasonable. Can potentially minimize the overall computation times.
The purpose of path-refining methods is to optimize a given path and make this path more realistic and easier to follow, either by robotic cranes or by crane operators. Although the aforementioned three path-planning methods may generate collision-free paths, which they may involve redundant movements or awkward crane motions. A path-refining method was therefore developed to optimize a path generated by the aforementioned path-planning methods. It makes the path become more realistic and easier to follow, either by robotic cranes or by crane operators. After testing and fine-tuning various alternatives, we developed and implemented an effective path-refining method to eliminate these problems. As shown in Figure 4, the path-refining method is composed of three steps: the first step is to remove redundant nodes in the path; the second is to soften sharp angles, and the last step is to make the path easier for crane operations. These steps are detailed in the following paragraphs.

The RemoveRedundantNodes algorithm is an effective method of removing the redundant points within a given path. The basic concept of in this the first step method is to examine each of the nodes in the path and identify the farthest node that the examined node can reach directly without collisions. If the farthest reachable node is not the next node in the path, we remove the redundant nodes between the examined node and the farthest node. This process is then applied to all the remaining nodes in the path, and usually in most cases, the original path is quickly refined into a shorter and more efficient one. After eliminating redundant nodes, the resulting path is not necessarily an optimal path, especially when the path includes many unnecessary sharp angles.

Because sharp angles in the path may result in longer and less efficient paths, the second step in the refining method which is to eliminate the any wasteful of crane movements during from the planned operations. In SoftenSharpAngles is an algorithm to eliminate these sharp angles. This algorithm step, first picks a random point is selected as a temporary node within a line segment between two nodes is selected as a temporary node and then connect the temporary node and the next node are connected to form a temporary new path. If this path is free of collisions, then the
temporary node replaces the original node and the temporary path replaces the original path. As in Similar to the RemoveRedundantNodes algorithm first step, this process is applied to all the nodes in the path, and thus usually results in a smoother and more efficient path very quickly. In addition, the algorithm can be repeatedly applied to a path for an increasingly better result. We found that applying the method three times is generally sufficient to obtain a satisfactory outcome.

RemoveRedundantNodes and SoftenSharpAngles The first two steps in the path-refining method can only avoid the redundant nodes and inefficient paths but do not take into account the special nature of crane motions. The main problem of what in Cartesian space appears to be an “efficient path,” in reality, may involve unnecessary crane motions, especially for trolley translation and jib rotations. For example, a straight line is usually the shortest path to move an object between two points in a space. However, to rotate a crane following a straight line may require the trolley to move inward and outward resulting not only in unnecessary motions, but may also result in slower erection times. The third step in the path-refining method algorithm OptimizeCraneRotate developed in this research can effectively targets to improve the path so that it is specifically better suited for crane operations. In previous investigations (Kang and Miranda 2006), Figure 4 presents the path refining procedure. From the left to right figures, we applied the path-refining method by the sequence of RemoveRedundantNodes, SoftenSharpAngles, and OptimizeCraneRotate. It was found that following the sequence has a high likelihood of generating a realistic path with relatively low computation cost.

Comment [Ozy15]: CHECK: Which sequence? Please specify for clarity.

Comment [Ozy16]: Can you put the figure closer to the relevant text? It would then be easier to follow.
Simulation of Vibrations Induced By Crane Motions

One of the challenges in visualizing erection activities is to simulate the vibrations induced by crane motions. When a crane rotates its jib, for example, the crane cable and the rigging object vibrate due to the multiple inertial forces caused by the jib rotation. In this research, we introduce the physics principles of constraint-based rigid body dynamics and describe how to formulate the motions of the suspension model using this principle system.