Sample of Level 1 Editing

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 ~~a project.

Over the last 30 years computers have played an increasingly important role in construction. ~~In particular, s~~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, ~~has ~~have seen a rapid emergence~~d~~ ~~rapidly~~. 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 p~~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, ~~many ~~much research effort~~s~~ ~~have ~~has ~~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

Comment [SK: CHECK: You need to include a reference for each item.

and Aouad, 2005).

~~4D~~ Four dimensional systems provide a powerful tool to assist construction engineers ~~in~~ with ~~the~~ planning ~~of~~ construction projects. They ~~visualize~~ display the construction progress ~~of construction~~ by linking ~~three dimensional~~3D computer models of the project developed with commercial CAD software ~~and~~ with a construction scheduled developed in commercial project scheduling software. ~~4D~~ 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~~ rendering 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~~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 ~~only~~ allowing ~~to~~ visualization of~~e~~ a construction schedule, do~~, but do~~ not ~~allow the~~ simulat~~e~~ion ~~of~~ construction activities.

Since the 70~~'~~s 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 ~~modelling~~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 ~~modelling~~modeling construction operations.

Comment [SK: CHECK: You need to put a reference here

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

For a~~n excellen~~ thorough~~t~~ 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 ~~a~~toward~~t~~ scheduling and general~~-~~planning purposes of repetitive construction activities (e.g., earth moving operations) and therefore include a number of simplif~~ying assumption~~ications such as production rates being assumed ~~considering~~ constant ~~production rates~~, simplification of generalizations of construction paths, include other examples of simplifications here and. V~~v~~isualization ~~was~~ is typically very limited often only providing a 2D schematic ~~two dimensional visualization~~.

Comment [Ozy3]: CHECK: I'm not sure what this means. Please rewrite it.

Comment [Ozy4]: CHECK: This seems incomplete. Please rewrite it.

With the ~~advent~~ availability of more powerful comput~~er~~ing power, improved simulation and visualization methods have been developed ~~in recent years~~. ~~Some examples of r~~Recent research includes the ~~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 develop~~ed~~ numerical procedures to simulate and visualize construction erection processes, with the intents of~~. It is aimed at p~~ providing detailed planning and visualization in a virtual construction environment ~~as well as for~~and

Comment [Ozy5]: CHECK: One or more numerical procedures. Please check.

assisting crane operators in real-time during erection. Construction cranes are modelled and treated as robots in which motions required in each of the degrees of freedom of the crane are computed as a function of the path to be followed by each component being erected. A physics-based simulation and animation of crane motions was developed to visualize vibrations induced by crane motions. A special emphasis is placed on crane manoeuvring required for significantly diminishing motion-induced vibrations and for increasing safety at job-sites. Examples using tower cranes and crawler cranes for erection of steel and precast reinforced concrete buildings are ~~included~~presented.

Comment [Ozy6]: CHECK: Can you insert a noun? eg...erection of X.

~~Model~~Modeling the ~~a~~ Manipulation of a Crane ~~Manipulation~~

~~In this research c~~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~~that is, the motions~~ controlled by the crane operator to the position of the hook in space.

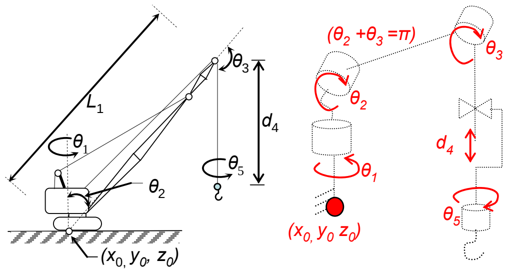
~~For~~ To mathematically describ~~eing~~ the motion of crane, we employ the Denavit-Hartenberg notation (Denavit and Hartenberg, 1955). The notation defines a coordinate system attached to each joint that is used to describe the displacement of each object relative to its ~~neighbors~~neighbours in a general form. Following the rules of the Denavit-Hartenberg notation, there are four parameters, $a_{i\text{-}1}$, d_i, $\alpha_{i\text{-}1}$, and θ_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 $\{i\text{-}1\}$ and $\{i\}$ can be derived. We can transfer coordinate system $\{i\}$ to $\{i\text{-}1\}$ by translating two directions, $a_{i\text{-}1}$ and d_i, and rotating $\alpha_{i\text{-}1}$ and θ_i along $a_{i\text{-}1}$ 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:

$$
{}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} d_i \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

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

As shown in Figure 1, crawler cranes are capable of moving freely around the site sothus that they are also widely used in many construction projects. –This type of crane may be mounted on crawlers, trucks, or wheel carriers to provide the mobility necessary mobility 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, the machine there hasis no actual fixed end in the machine. 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 its the moveable base.

Comment [Ozy7]: CHECK: Why in this case? Is it special for your research? Perhaps remove this phrase.



$$\begin{bmatrix} c_{1-5} & s_{1-5} & 0 & x_0 + \frac{1}{2}L_1(c_{1-2} + c_{1+2}) \\ s_{1-5} & -c_{1-5} & 0 & y_0 + \frac{1}{2}L_1(s_{1-2} + s_{1+2}) \\ 0 & 0 & -1 & z_0 + -d_4 - s_2 L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(c)

Figure 1.The model of a mobile crane: (a) illustration; (b) schematic

> **Comment [Ozy8]:** CHECK: How about (c)?

Plan the Motion ~~Planning~~for Crane Erections

~~Current e~~Efficiency of crane utilization ~~can~~ could be significantly improved by optimizing the moving path and crane operation. ~~Today~~These days, ~~the~~ cranes are manipulated by ~~the~~ the operator,~~s~~ with technique ~~mainly~~ depending mainly on their~~ir~~ experiences or even ~~by their~~their intuition. This empirical manipulation can be inefficient and often ~~cause~~ result in ~~some~~ unsafe movement. Since crane operators cannot always find optimal motion paths~~s~~ for manipulating a crane, particularly optimum simultaneous movement ~~of~~ involving three of four degrees of freedom~~s~~, ~~the~~ time is often~~crane may~~ waste~~d time 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 into ~~grow~~ 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.~~s by using c~~Computer analysis can be used to find the optimum erection sequence and optimal path for each piece that needs to be lifted.

~~However, d~~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 ~~us to visualize and simulate~~of detailed erection activities ~~in the computer~~, are needed. Herein lies the motivation behind this~~, so they motivate the~~ 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~~ each element~~s~~ in the project~~s~~. The solution to ~~T~~these problems can be facilitated by ~~the~~ techniques ~~in~~ of motion planning and computer graphic, ~~s,~~ two of the most rapidly ~~-~~developing areas of computer science in recent years. Choosing from the large pool of available techniques~~Because there are large amount of techniques developed in these fields, it~~ is ~~very important~~critical ~~to select appropriate techniques~~ as is ~~and 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~~ for automatinge ~~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~~ begun 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 ~~in~~ 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 focuses~~d~~ only 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 ~~to~~ with minimal~~mize the~~ computation cost.

QuickLink is the most inexpensive algorithm but has the lowest success rate ~~in~~ for finding a collision-free path among the three methods. ~~The~~ 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.

Comment [Ozy9]: CHECK: Inexpensive in which sense?

RandomGuess is the most expensive method among the three path-finding methods but offers the greatest possibility of finding a collision-free path ~~if there is any~~should one exist. This method keeps ‘‘guessing1,’’ ~~i.e.~~that is, sampling, random points in Cspace 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~~is 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-

Comment [Ozy10]: CHECK: This phrase is unclear. What is being compromised for what?

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~~ finding~~. This research ~~implements~~uses the QuickGuess method ~~by using~~with 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~~To compute an erection path, we sequentially used QuickLink, QuickGuess and RandomGuess methods for finding paths. ~~Since the function uses the~~This procedure ~~guarantee~~ensures the use of ~~path planning~~computation methods~~,~~ ~~going goes~~moves from the one with ~~less~~ least computational ~~cost~~ load to the ~~more~~ one with the most~~costly one~~, so the ~~efficiency of the function~~overall performance ~~can be~~is maximized. ~~We tested~~~~According to~~In a previous test (Kang and Miranda, 2006) ~~in GeneratePath function on~~on a 12-story building with 2105 structural elements~~.~~, ~~. I~~it was ~~and~~ found that 62% of the paths were found by QuickLink, 35% were found by QuickGuess, and 3% were found by RandomGuess. ~~In addition, we alsot~~The ~~estimated~~ computation efforts (computational times) ~~between~~among the three motion planning methods ~~are~~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 ~~ten~~10 ~~to~~ and ~~one hundred~~ 100 times more expensive than QuickGuess. The results showed that the application ~~GeneratePath function~~sequence~~, which integrates~~ (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 time~~s~~.

Comment [Ozy11]: CHECK: Please rewrite this sentence.

Comment [Ozy12]: CHECK: This suggests you only use this method, but in the next paragraph you mention all three methods. Please clarify.
Perhaps 'Both single and double middle point QuickGuess methods are used in this research'.

Comment [Ozy13]: or 'optimized'?

~~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. T~~Although the ~~aforementioned~~ three path-planning methods may generate collision-free paths, ~~which~~ they may involve redundant movements or awkward crane motions. A ~~P~~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~~ 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~~ third step is to make the path easier for crane operations. These steps are detailed in the following paragraphs.

Comment [Ozy14]: CHECK: This clause doesn't match with the beginning of the sentence. Please rewrite it.

~~The RemoveRedundantNodes algorithm is an effective method of removing the redundant points within a given path.~~ The basic ~~concept~~ process ~~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~~ 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. T~~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 ~~connects~~ the temporary node and the next node are connected to form ~~as~~ a temporary new path. If this path is free ~~from~~ 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 ~~a~~ 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. We~~it ~~is~~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.

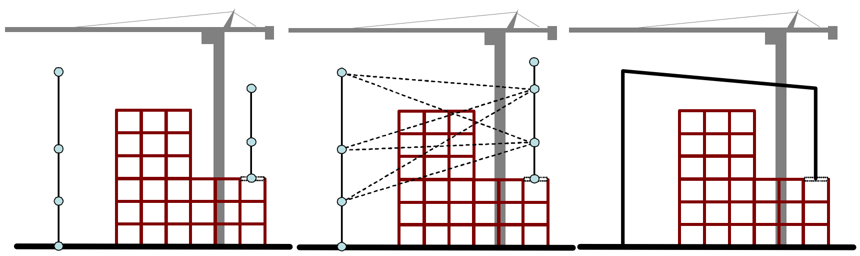


Figure 2. Procedure of the QuickLink method~~.~~

Comment [Ozy16]: Can you put the figure closer to the relevant text? It would then be easier to follow.

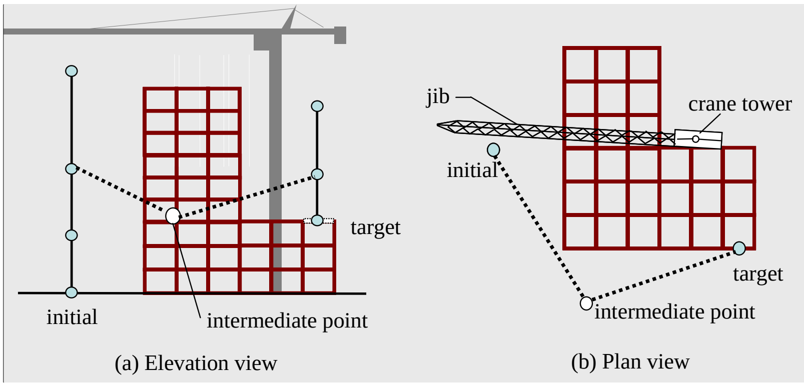


Figure 3. Illustration of the QuickGuess method

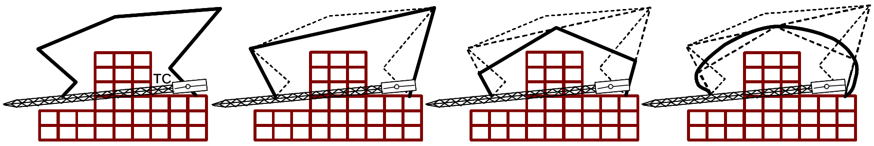


Figure 4. ~~An example~~The procedure of the path refining process (top view).

Comment [Ozy17]: The word 'initial' cannot stand along. Perhaps 'initial point' or 'start'.

Simulation of Vibrations Induced By Crane Motions

~~T~~One of the challenges ~~to~~in visualizing~~e~~ 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 job rotation. ~~his section~~In this research, we ~~introduces~~use the physics principles ~~of constraint-based rigid body dynamicsphysics and describes how toand~~to formulate the motions of the suspension ~~model using this principle~~system.

Comment [Ozy18]: CHECK: 'jib rotation'?