A Physics Based Simulation for Crane Manipulation and Cooperation

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Abstract

This paper describes an approach to construct a numerical crane model in a computer-generated virtual world. A dual-crane scenario was used to demonstrate. The numerical crane model is divided into two sub-models: a manipulation model and a suspension model. The manipulation model is used to describe the relationship between the crane operations (the movement of each part of the crane) and crane status (the position and orientation of the crane). The suspension model includes the crane cables and rigging object. It can be used to analyze the dynamic behavior of the suspended object caused by the inertial forces during crane operation. To demonstrate the use of the sub-models, a prototype simulation system has been developed. The results show that the prototype system can sufficiently provide visualization details for simulating crane manipulation and cooperation.

Introduction

Crane manipulation and cooperation issues are very important in modern construction. However, these tasks are usually very risky and hence require high accuracy. For example, there is twenty-five percent of the construction budget is directly related to crane resources or their operation tasks on steel structure building. Furthermore, accidents caused by crane operation mistakes unfortunately resulted in more than 500 deaths in the U.S. during the period from 1984 to 1994 (Peurifoy and Schexnayder, 2002). In this research, we aim to develop a general purpose approach to simulate crane-related activities prior to the start of a construction. Using the simulation, we expect to identify and eliminate hazardous situations.

Although computer graphics can significantly help construction simulation, it is still a difficult problem to render realistic visualization and at the same time provide users with the feedbacks according to physics rules. The first difficulty to produce detailed and realistic animation is the high cost. Since an animation is generated frame by frame, it requires a tremendous number of man-hours. Second, to render an animation consumes a great amount of computation power. On average, it may take an hour to render a 60 second animation with an average level of quality. The third difficulty in producing a realistic animation is accuracy. To simulate the operation of a crane requires dynamics feedback. It needs to introduce physics, such as kinematics of dynamic situations.

To automate the generation of visualization and improve the reality of the simulation, researchers, such as Kamat and Martinez (2005) and Kang and Miranda (2004), recently conducted research into automated visualization methods for detailed construction visualization. Simlog (2007) and CMLabs (2007) corporation had produced training simulator with physical reaction and realistic textures. In this paper we will further introduce a manipulation model to simulate the dynamic behavior of the crane during its operation, and a suspension model to facilitate the generation of a physically accurate representation. This model can be broadly used for various simulation purposes, such as simulating detailed erection activities.

A Dual-Crane Scenario

In this research, we use a dual-crane scenario to exemplify crane cooperation (see Figure 1). To build a numerical model, this dual-crane scenario is split into two models, a suspension model and a manipulation model. The suspension model includes cables, hooks, and the rigging object. To properly simulate the dynamic behavior of the suspension model, we followed the principles of constrained dynamics and developed the model mathematically. The manipulation model was developed to compute the relationship between the motions of the crane components manipulated by operators and the position of the end-effector (the tip of boom).

Theories in forward kinematics are introduced to identify the geometrical relationship. In the latter part of the paper, we will explain how to apply constrained dynamics and forward kinematics to model a crane and develop a physics-based simulation environment for construction cranes.

Suspension model

Constrained dynamics, a technique widely used in the field of multi-body modeling in computer graphics, is used to model construction machines in this research. Multi-body modeling methods are used to model those virtual objects only composed of rigid bodies and joints. Since the virtual objects are linkage objects, their motions are constrained by the joints. Therefore, we derive the geometrical constraints for the equation from all joints and attempt to develop a mathematical model that can be used to facilitate the generation of physics-based visualization.

Two types of joints, ball-in-socket joints and slider joints, are introduced to simulate a construction crane. We first explain the ball-in-socket joint. Assume that the l'th joint is a ball-in-socket joint between the two bodies B_i and B_j as shown in Figure 2. A ball-in-socket joint is characterized by the fact that two points, one from each body, are always connected to each other. It means that there are three constraints, equality in the x, y and z dimensions of the two points.

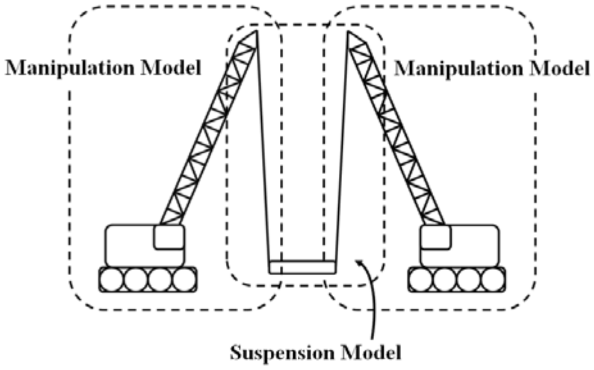


Figure 1. A dual-crane scenario

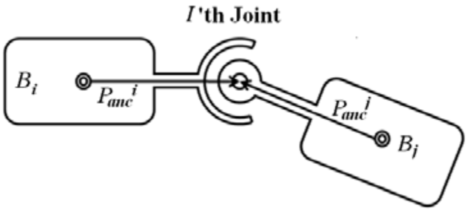


Figure 2. A ball-in-socket joint

According to above constraints, we can form equations as follows:

$$\Phi_m(P) = \left[\left(P_i + R \cdot P_{anc}^i\right) - \left(P_j + R \cdot P_{anc}^j\right)\right]_m = 0 \qquad (1)$$

where $m = \{x, y, z\}$, R is the corresponding rotation matrix of body's orientation, P^i_{anc} and P^j_{anc} are anchor vectors which represent the body's center of mass to the connected point, P_i and P_j are the position vectors of B_i and B_j respectively. The equations $\Phi_x(P)$, $\Phi_y(P)$ and $\Phi_z(P)$ are the geometrical constraints according to the spatial vector *P* that is composed by the position and orientation of B_i and B_j.

Therefore, ball-in-socket joints can be expressed in vector form:

$$\Phi(P) = [\Phi_x(P) \quad \Phi_y(P) \quad \Phi_z(P)]^T = 0 \tag{2}$$

By differentiation with respect to time, we derive velocity-based formulation:

$$\frac{d}{dt}\Phi(P) = \frac{\partial\Phi}{\partial P}\frac{dP}{dt} = \frac{\partial\Phi}{\partial P}Sv = J_\Phi v = 0 \tag{3}$$

where the matrix J_Φ is Jacobians; it describes relations between velocities in different coordinate representations. The vector v represents velocity and matrix S, derived from Newton-Euler equation, and represents the relationship composed by angle velocity and orientation.

Finally, we have the constraint equations of ball-in-socket joint:

$$J_{\Phi\, ball-in-socket} v = 0 \tag{4}$$

By using the same approach, we can derive the constraint equation for slider joint. The slider joint can only be moved in one specific direction, so there will be five constraint equations, two for position and three for orientation, which keep the joint movement correct. After developing Jacobians for both joints, we can use the following equation to compute the velocity of the rigid bodies in the crane system.

$$v^{t+\Delta t} = v^t + M^{-1}(f_{constraint} + \Delta t f_{ext}) \tag{5}$$

where Δt is the increment of time step, M^{-1} represents the inverse matrix of mass, $v^{t+\Delta t}$ is the velocity and angle velocity condition next to v^t with Δt skip, f_{ext} represents external forces, torques, and velocity-dependent forces, and $f_{constraint}$ is calculated by using the Jacobians developed for every joint type.

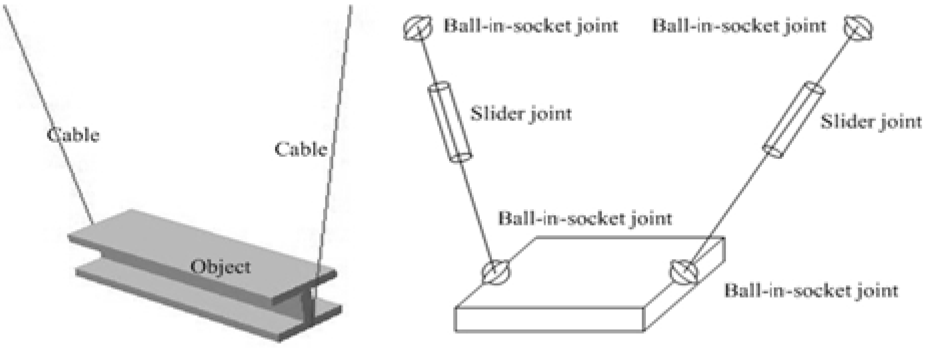
From velocity, we can determine the geometrical properties of the rigid bodies:

$$P^{t+\Delta t} = P^t + \Delta t S v^{t+\Delta t} \tag{6}$$

where P^t includes the position and orientation of two bodies connected by the joint at time frame *t*, and $P^{t+\Delta t}$ is the position and orientation condition next to P^t with

Δt skip. For a detailed explanation of constraint dynamics, Erleben et al. (2005), has summarized related work.

To develop the suspension model of the system in the dual-crane scenario we used four ball-in-socket joints and two slider joints (see Figure 3). Considering the natural attribute of connections between the top of boom and cable, we use ball-in-socket joints to simulate their behaviors and connections between cables and erected object. Due to the capacity of cables to extend, we use slider joints to simulate lengthening and shortening.



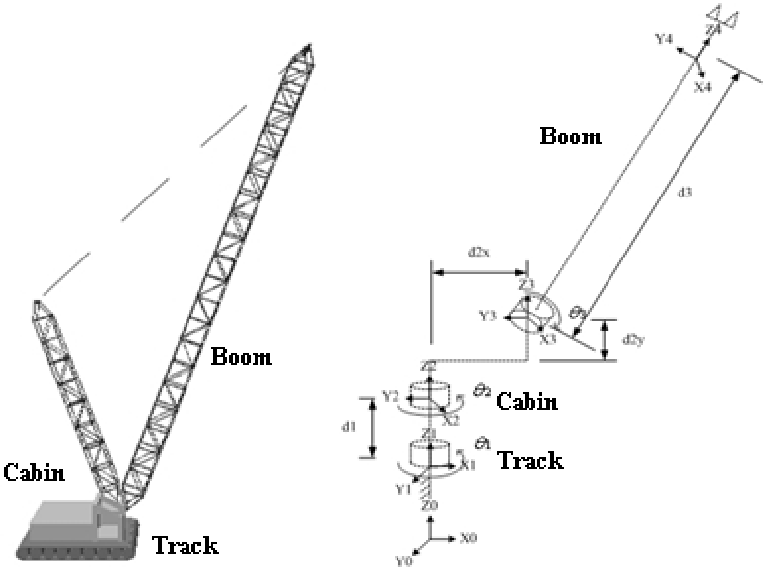
(a) Overview of suspension model (b) The configuration of joints

Figure 3. Joints setting on the dual-crane scenario

Manipulation Model

A manipulation model is used to connect the operator’s manipulation (the relative movement of each part of the crane) and the attitude of the crane (the position of each part of the crane) in a virtual world. In this paper, we employed forward kinematics to achieve this goal. Forward kinematics provides a way to connect rigid bodies together as an ordered chain structure. The movement of a rigid body in this chain will affect adjacently connected bodies. In order to construct a numerical model, we need to determine the relationship between the bodies.

Denavit-Hartenberg notation (Denavit and Hartenberg, 1955), a notation broadly applied in robotics applications, is used for finding the transformations matrix between the connected chains. It has been used for building tower crane model described by Kang and Miranda (2006). By following this method, we built a numerical model for a mobile crane. Figure 4 shows that crane model in a virtual environment described using Denavit-Hartenberg notation where the coordinate system $\{0\} = \{x_0, y_0, z_0\}$ represents the global environment, another coordinate system is for the local view of each piece of the crane model, *d* is mount of translate between two coordinate, and θ represents the mount of rotation angle in each connection in the crane.



(a) Overview of the manipulation model (b) Relationship between crane bodies

Figure 4. Numerical model built using Denavit-Hartenberg notation

According to this figure, we can formulate the transformation matrix between every coordination system. For example, the transformation matrix T_4^0 map the coordinate system {*4*} relative to the coordinate system {*0*}, which means that the local coordinate {*4*} of the top of the boom can be represented by global coordinate {*0*} by multiplying this matrix. Using the general form:

$$T_m^n = T_{n+1}^n T_{n+2}^{n+1} \cdots T_m^{m-1} \tag{7}$$

we can figure out any local position of the crane mapped to the global position. That makes the numerical model easy to implement in this system.

Implementation

A computer program was developed to implement above mentioned manipulation model and suspension models. By using forward kinematics, the movements of crane bodies can be transferred to the position of each part of the crane with respect to the global coordinate system in the virtual world. It simplifies the procedure to identify the position and orientation of each part of crane and make relative reactions when operator controls the movement of the manipulation model. The suspension model with the introduction of constrained dynamics can simulate the dynamic behavior of the rigging object.

In the developed system, users can experience a realistic visualization and physically accurate representation as if they are manipulating a real crane in the physical world. The developed system is implemented on the .NET platform and uses OpenGL, a computer graphic language, to render the virtual environment. Open Dynamic Engine (ODE) (2006), a well-known physics engine with constrained dynamics solvers, is also integrated.

System demonstration

To demonstrate the system, here we present selected snapshots taken from the simulation system. These snapshots show part of an erection activity of two cooperative cranes rigging a beam in a virtual construction site. From time 0 to time 60 in Figure 5, the operator pulls the cable of crane on the left-side, and does the same movement on the right-side during time 60 to time 120, then rotates the boom of the right-side crane from time 180 to time 300.

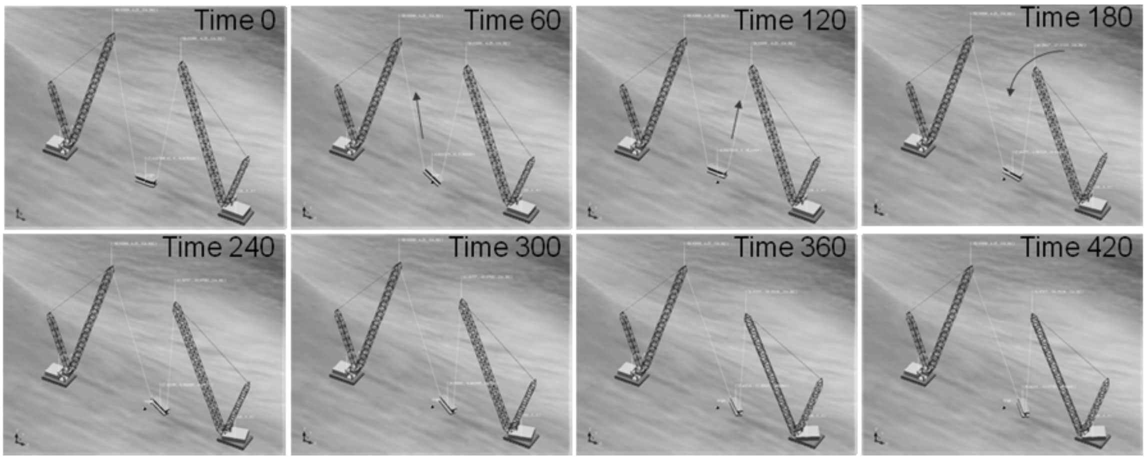


Figure 5. Snap shots of the visualization of cooperation

Conclusion and Future Work

In this research, we found that forward kinematics and constrained dynamics greatly improve the reality and automation when we develop an animation for crane usage. Forward kinematics method allows us to identify the relationship between each part of the crane, so that we can manipulate articulated bodies, and the system will compute accurate positions and orientations of the articulated bodies in real time. Constrained dynamics used for modeling the suspension scenario can be used to perform physical simulation. In this research, we use ball-in-socket joints to represent connections between boom and cable and between cable and the rigging object. We use slider joints to simulate the change of cable length.

Compare with other related works, this approach has been integrated the feature of reality into the simulation of crane-related activities and it is not only for the case of operator training course but also practical construction scenario. In the future, the prototype system can be extended for detailed erection simulation. The detailed erection simulation includes the detailed steps during an erection cycle, including securing, moving, releasing, and repositioning motions. The high-fidelity simulation generated by the system can also be used to support decision-making, safety analysis, layout planning, crane selection, and logistics planning.

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