Advances in Engineering Software 65 (2013) 1–11

Contents lists available at SciVerse ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Configurable model for real-time crane erection visualization

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ARTICLE INFO

Article history:
Received 4 April 2012
Received in revised form 30 June 2012
Accepted 14 April 2013
Available online 7 June 2013

Keywords:
Crane
Cooperative
Erection
Multibody
Physics Engine
Simulation
Visualization

ABSTRACT

Detailed simulation and visualization of crane activities have been recently introduced to help engineers identify potential problems with critical erection tasks; however, the development of real-time erection visualizations for different types of cranes and lifting objects is time-consuming, and usually requires a certain amount of effort in modeling and setting up the environment. This research proposes a configurable model which is reusable, fast-prototyping, and extendable to support real-time visualization of the erection process. The developed model of the crane is divided into three modules which can be reconfigured for different erection tasks. Each module is defined using multiple rigid bodies and the joint constraints of multibody dynamics. The proposed modeling method can also be easily adapted to existing physics engines. To evaluate the feasibility of the proposed method, we observed the processes involved in a common erection activity and compared this with the visualization results obtained using proposed method. We also simulated a cooperative cranes scenario taken from an actual construction project to demonstrate its usability. We found that the proposed modeling method was easily able to visualize various erection activities with different cranes and configurations.

1. Challenges of crane erection activities in modern construction

The increasingly versatile use of cranes in modern construction projects has introduced new challenges along with it: rigging objects have become larger, heavier, and more diverse, and yet shorter erection times are expected. Most objects that cranes work on are in the critical path for that project and thus a delay in these tasks often results in a delay for the whole project. Furthermore, some erection tasks involve high levels of risk, requiring high accuracy during the planning stage [9].

In order to increase the efficiency and precision of crane erections, engineers try to use cranes that are more mobile and versatile, and perform cooperative erections at construction sites where possible. Mobile cranes are equipped with wheels or tracks, are easier to transport between sites, and are more flexible as they can be deployed at different places on the construction site according to the schedule demands. However, they are generally more difficult to control than tower cranes. Operators need to control the rigging mechanism as well as the motion of the crane, ensure that the crane is stable during the erection process, and also avoid any collisions.

The increased use of cooperative erections is another trend seen in modern construction projects. Large cranes are not always available and site rental fees can be very high. Moreover, assembly and dismantling of large cranes requires more time. Thus, a cheaper alternative is the cooperative use of standard cranes that are available on-site [1]. The two cranes can also be used individually on site, which reduces the overall time cost and allows project managers more flexibility when scheduling the erection project, resulting in a more efficient plan; however, performing cooperative erections is challenging, even for experienced operators. The erection plan needs to be completed and checked before the actual erection to ensure that the load does not exceed the lifting capacity of each crane at any time. The erection paths and crane operations will affect the share of the load handled by each crane. Operators need to work cooperatively to be able to solve these problems and complete the task successfully.

Rigging methods are also becoming increasingly versatile, especially in fast-tracked projects. Engineers now use a variety of lifting devices to stabilize the erection of decks, windows, pipes, equipment, and even irregularly-shaped objects. "Christmas tree" rigging (rigging of several objects in one erection cycle) and dress-up rigging (rigging of large equipment that has many accessories) are now common. Christmas tree rigging can reduce the number of erection cycles required, and dress-up rigging transfers workload from the post-erection phase to the pre-erection phase, which can reduce the risks involved in working at heights. While utilizing these erection methods can significantly reduce the time required for a task, they increase the complexity of the task itself. Many recent studies have applied visualization technologies for the identi-

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http://dx.doi.org/10.1016/j.advengsoft.2013.04.013

fication of potential problems in complicated erection activities involving versatile lifting configurations and devices [37,10,18]. However, there is a need for an efficient and systematic method of fast prototyping crane erection visualization to reduce the time cost involved. In this way, the benefits of crane erection visualization and simulation can be realized and adapted for different types of erection tasks.

In this study, we propose a configurable crane modeling method that allows engineers to efficiently prototype a crane erection activity through real-time visualization and simulation. By modularizing a crane model, this method allows engineers to easily visualize cranes with different lifting devices. We implement an real erection project to be performed with dual mobile cranes to verify the feasibility of the proposed method.

2. Related works

Crane modeling and simulation has been an active area of research for several years. Researchers have used mathematical methods to model cranes and estimate duration and cost of erection task scheduling. Tam et al. [36] were able to predict the hoisting time for tower cranes using a nonlinear model. Zhang et al. [38] simulated construction operations by applying the fuzzy logic method. Kim and Park [22] applied the multiple traveling salesman problem method (mTSP) to schedule tasks for quay cranes in ship operation planning. Attempting to move towards automated construction, Ali et al. [1], Cheng and Admin [8], Kang and Miranda [20] utilized computational methods to generate collision-free paths automatically for cooperative crane operations.

Many investigators have employed graphical technologies for visualizing and simulating crane activities. This is a low-cost and effective method for identifying potential problems before real construction. O'Connor et al. [32], Liu [25], Amatucci et al. [2], Bernold et al. [3], Stone et al. [35] developed various simulation and visualization tools for crane operations. Lipman and Reek [24] used Virtual Reality Modeling Language (VRML97) to develop 3D web-based technologies for managing, accessing, and viewing construction project information. Kamat and Matinez [17] generated automatic dynamic 3D animations of construction processes using discrete-event simulation (DES) tools. Huang and Gau [16] designed an interactive visual simulation that used a cluster of desktop computers for mobile crane training. Kang and Miranda [21] developed a numerical method to automatically simulate and visualize crane activities in detail.

Recently, some researchers and corporations have utilized physics engines to improve the accuracy of crane simulations. Chi et al. [9] proposed a physics-based simulation for crane manipulation and cooperation using constraint-based dynamics and closed-form forward kinematics methods. They modeled a crane using two sub-models, a manipulation model and a suspension model, and to simulate the main types of cranes. They assumed that the bodies of the cranes were static (i.e. no vibrations were present and the position and orientation were directly controlled by users), which meant that the dynamic motion of a mobile crane could not be simulated. Many corporations have also developed simulators and training systems that compute real-time physical behavior and show a realistic rendering of a scene [11,14,33]. These works have demonstrated that integrating graphical technologies and physics engines is effective in enabling accurate and realistic real-time interaction in crane simulations. However, as these systems and software are commercial products, the details of their implementation are not known. Therefore an extensible and modularized method must be proposed and developed to improve the crane erection simulation and visualization method.

3. Research goals

In this work, we aim to develop a configurable model for real-time crane erection visualization. The proposed method should meet the following goals.

1. It should support the simulation of various types of mobile cranes. Moving platforms, such as the truck and the track, should be simulated. The interaction between the rigging system (the crane) and the moving platform needs to be modeled and visualized.
2. It should be able to simulate the mechanisms of different lifting devices and rigging objects. The attachment and release of lifting devices and objects needs to be simulated, along with complicated rigging mechanisms such as Christmas tree rigging.
3. It should be able to visualize cooperative erections. The model must be extendable and configurable and be easily adapted to erection scenarios involving single or multiple cranes.
4. It should support real-time visualizations efficiently. This will allow future engineers to simulate physics-based virtual cranes in a virtual environment for construction planning and scheduling.

4. Crane simulation method

A crane is composed of multiple rigid bodies and connections, irrespective of its type and scale. A mobile crane includes additional degrees-of-freedom for the moving platform. In order to model a crane, generally we need to model the connections and rigid bodies numerically. The connecting relationships between rigid bodies have to be represented using equations that account for the laws of physics. In this study, we model a crane by firstly defining a crane as a multibody structure, and then using a multibody dynamics solver to calculate results based on that definition. Multibody dynamics is primarily used to compute physical feedback between multiple bodies either in mutual contact or connected with each other through joints [13]. It combines rigid body dynamics and constraint conditions (connections between the bodies). By solving the equations of motion (which describe dynamic behavior in multibody dynamics), the motion of each body can be computed at each time interval. This is a widely used method for simulating the dynamic motions of articulated mechanisms or equipment.

As a crane, apart from the rigging system, is essentially an articulated mechanism, we can define it using multibody dynamics, and then simulate the rigging system using certain assumptions. The boom, cabin, wheel, cable, and lifting object can be represented by rigid bodies, called *actor* actors in this work. The motion between two actors, such as the rotation between the boom and base of a mobile crane, are represented by a *joint* (the constraint condition for two rigid bodies). An actor has geometrical properties, such as position, centre of mass, and tensor, and its motion can be calculated from rigid body dynamics. A joint provides six degrees of freedom, including translation and orientation, between two actors. Four basic types of joints are described in this research: *spherical*, *revolute*, *prismatic*, and *distance joints*. Table 1 lists the details of these joints and their symbols, which are used in later sections.

The spherical joint attaches two actors at one point on each actor. This joint ensures that the two points are always connected (i.e. the global position of one point is the same as the global position of the other). Therefore there are three constraints between these two points. An example of a spherical joint is the simulation of a simple pendulum.

The revolute joint attaches two actors with a hinge structure. It retains one rotational degree of freedom but removes all other degrees of freedom. The two actors can only rotate along one axis.