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Integrating 3D visualization and simulation for tower crane operations on construction sites

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Abstract

Most high-rise building construction projects rely on tower cranes to perform lifting and hoisting activities. In practice, tower cranes are managed based on demand, urgency, and prioritized work tasks that must be performed within a set period of time in the field. As a computer tool, simulation has proved to be effective in modeling complex construction operations and can be a substantial help in aiding practitioners in construction planning. However, the use of simulation has fallen far below its maximum potential due to a lack of appropriate support tools which would allow construction managers to use simulation tools for themselves. Special purpose simulation (SPS) and 3D visualization of simulated operations are two potential means that enable domain experts, who are knowledgeable in give domains, but not familiar with simulation, to easily model an operation within their domain and analyze the simulation results. This paper presents a practical methodology for integrating 3D visualization with SPS for tower crane operation. An integrated system was built in a 3D Studio MAX environment and tested in the construction of the new civil and environmental engineering building at the University of Alberta. This paper demonstrates that 3D visualization is helpful in the verification and validation of simulation results, and can effectively communicate the essence of a simulated operation, thus improving the accessibility of simulation as a decision making aid.

Keywords: Tower cranes; Special purpose simulation; 3D visualization; 3D animation

1. Introduction

Tower cranes are the most expensive and frequently shared resources on building construction sites. Efficient utilization of tower cranes greatly depends on skilled judgments that account for a number of technical, schedule, and financial factors. As the number of work tasks and the demand for tower cranes increase, planners may be required to make bold decisions on job conditions for a particular situation. A poor decision is likely to have significant negative effects, which will lead to additional costs and possible delays.

Computer simulation proved to be an effective tool for aiding practitioners in modeling complex construction operations. Substantial efforts in the domain of construction were made after the development of the CYCLONE simulation language [1]. However, the use of simulation as a construction planning tool has fallen far below its maximum potential [2]. Construction planners and analysts have long regarded simulation for construction planning with mixed emotions. While acknowledging the benefits of simulation, managers have often viewed simulation as “black art” that can only be performed and understood by computer specialists or highly paid consultants. This delegation of simulation to specialists leads to the separation of decision makers from the simulation process, a situation that often leads to misunderstanding or non-application of simulation results. This, in turn, increases skepticism among construction managers as to the real value of simulation, aside from providing a showy section of simulation results in construction planning reports. The aforementioned problems justify the need for support tools that allow construction managers to construct simulation models and analyze results for themselves. Special purpose simulation (SPS) and 3D visualization of simulated operations are two potential means by which this goal can be achieved.

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1.1. Special purpose simulation (SPS)

SPS aims to facilitate simulation modeling through the creation of building environments tailored to the specific requirements of a given construction domain. The SPS environment provides a set of modeling elements that map to the real physical or logical components of the target construction operation, so that a practitioner who is knowledgeable in a given domain, but not necessarily in computer simulation, may model a project within that domain [3]. The utilization of the SPS concept resulted in the development of a number of special purpose systems, including Ap2Earth [4], CSD [5], and CRUISER [6], and an integrated SPS development and utilization environment, Simphony [7]. As a part of the proposed system, an SPS model that assists practitioners in scheduling tower crane operations based on the priority rating concept was built in Simphony. The details of this SPS model were described elsewhere [8] and are mentioned briefly in this paper (Section 3) to provide continuity.

1.2. Visualization of construction operations

Visualization of simulated construction operations can also be of substantial help in the analysis and communication of simulation results. Firstly, decision makers cannot base their decisions on simulation results unless they fully understand those results. Dynamic graphical depictions, which are able to show the simulated operations in the same way as the operations would be in the real world, give users a better understanding of the simulation results, and the operations as well. Secondly, typical simulation models do not provide sufficient insight into the requirements and/or limitations of the working space; this information is usually crucial for construction operations. In addition, visualization can provide valuable insight into the subtleties of the modeled construction operations and can thus be helpful in establishing the credibility of the simulation models and results [9]. For the past two decades, simulated construction operations have been visualized in several levels of detail and realism. Schematic models [10] and iconic animation on schematic models [11] have been widely used to improve the conceptual understanding of modeled systems, but they do not provide much detail and do not reflect the workspace requirements and/or limitations of the modeled operations. 2D visualization systems illustrate the progression of simulated operations by continually describing the movements of resource elements on 2D layouts [12]. Although, in many cases, 2D visualization is effective in communicating the simulation models, it cannot accurately depict complex construction operations that involve vertical movements, such as crane operations. Recently, efforts have been made in 3D animation of modeled construction operations, including the development of general purpose 3D visualization tools and methods for simulated construction operation [9,13], and the 3D animation of discrete event construction process models for construction equipment [14]. In fact, 3D visualization has already been extensively utilized in crane planning to experiment with the operation process and check for physical interference or clearance problems to avoid costly errors. These efforts include, but are not limited to, developing a visualized environment for heavy lifts planning [15,16], planning analysis using a 3D model [17], and integrating databases with 3D CAD models [18,19]. However, none of these systems are able to be linked with construction simulation tools.

This paper presents a practical approach to integrating 3D visualization and the simulation of complex construction operations through the development of a visualization tool, SimAnim, for simulated tower crane operations. The core of SimAnim is a post-simulation module, which was developed in the 3D Studio Max (3DS) environment based on the concept of 3D object transformations. An integrated system for the simulation and visualization of tower crane operations at the Natural Resources Engineering Facility (NREF), constructed in Edmonton, AB, Canada, was used as a generic case study to illustrate the validity and advantages of the proposed methodology.

2. System architecture and information flow

In practice, tower crane operation can be broken down into separate activities called work packages (WPs), which represent a set of uninterrupted lifts to be performed by the tower crane. Each WP has the following features: (1) source location; (2) destination location; (3) weight and size; (4) assigned crane; (5) priority setting. The operation schedules are managed based on demand, urgency, and prioritized work tasks that must be performed within a set period of time in the field. In the construction planning stage, a particular configuration of tower crane is chosen to yield the required heights, reaches, and capacities. The travel speeds for hoisting, radial, and horizontal trolley movements also vary for each crane type. A system database, consisting of three databases for tower crane specifications, site geometry data, and WP data, and two 3D object libraries, designated for tower cranes and project objects, was developed to store all

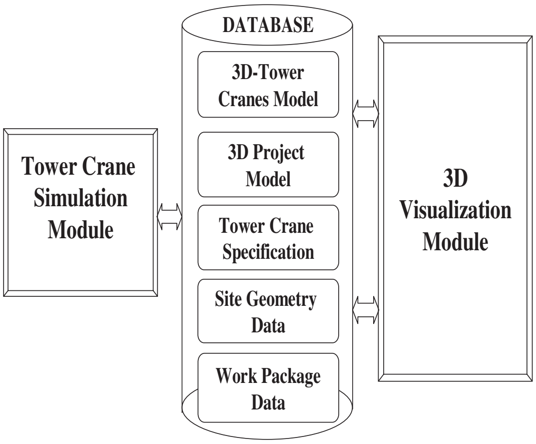


Fig. 1. System components.

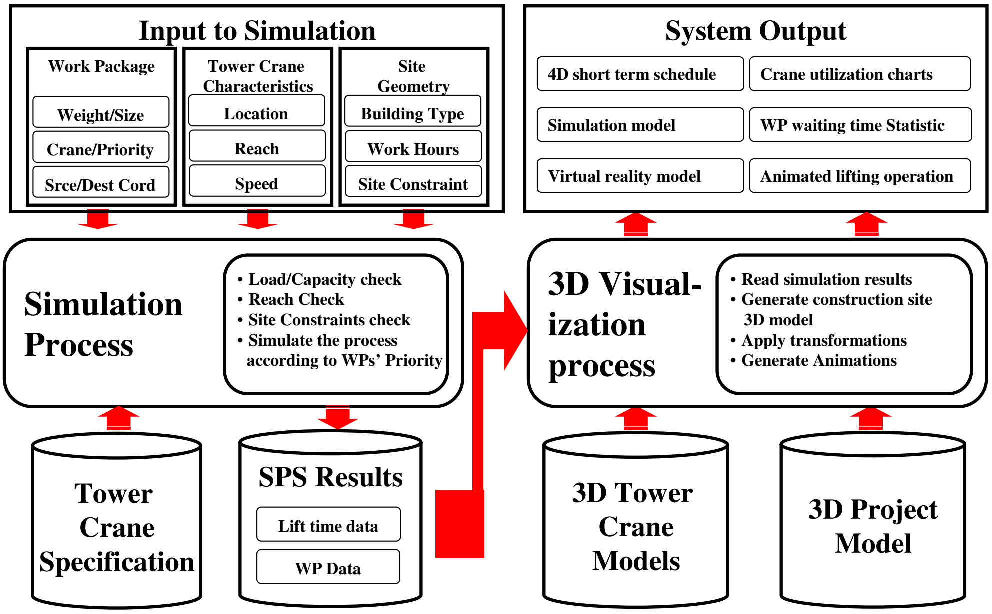


Fig. 2. System information flow diagram.

the information needed for operation simulation and visualization. Fig. 1 shows the architecture of the proposed system. Both the priority rating SPS module and the 3D visualization module share the information stored in the system database. Fig. 2 illustrates the information flow within the system. After retrieving the required data from the WP database and the crane specification database, the SPS module checks all the constraints and simulates the lifting process until all the lifting WPs are completed. The geographic data and lifting time of each lift are then exported into a log file. By using the simulation outputs and the 3D models stored in the object libraries, the 3D visualization module creates a construction site 3D model and renders the animation frames using the Inverse Kinematics (IK) procedure.

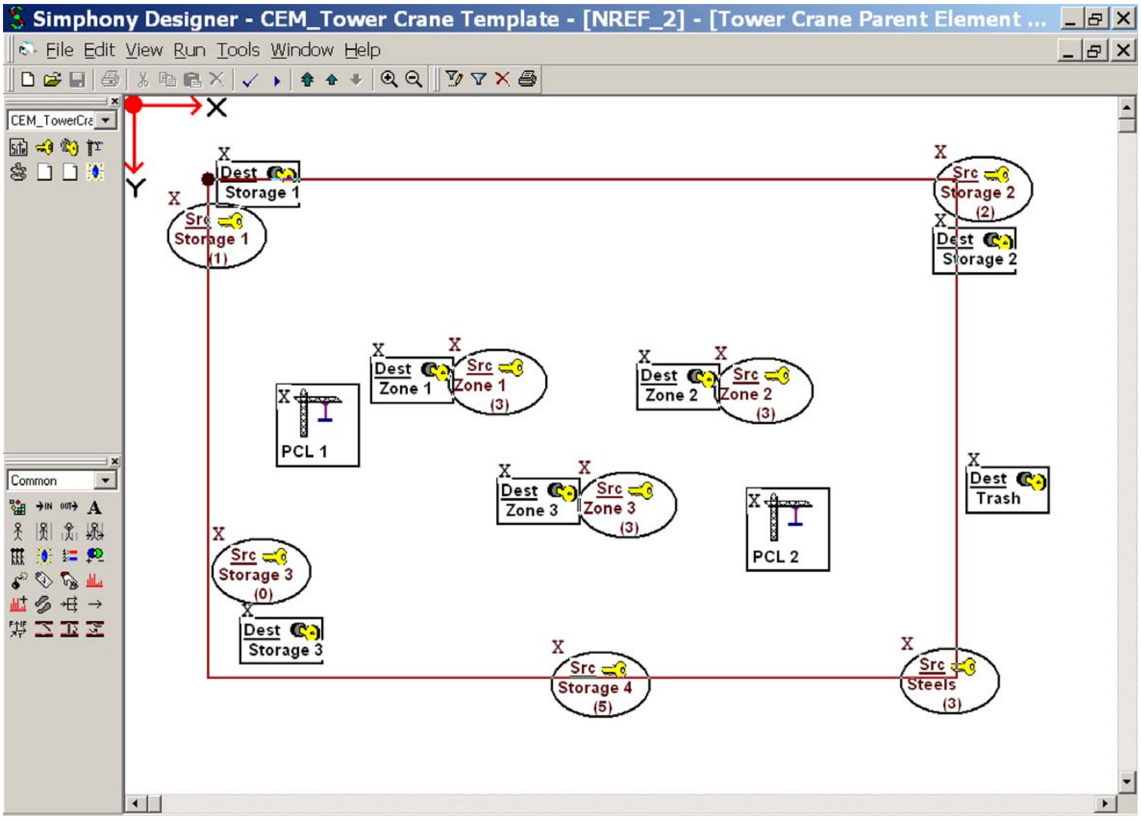


Fig. 3. Tower crane simulation model layout for NREF construction (typical floors 2–7).

3. SPS module for tower cranes

The SPS module of the proposed integration system was developed using Simphony's tower crane template (Fig. 3). Five kinds of elements were used to create the simulation model: (1) parent element, (2) source element, (3) destination element, (4) tower crane element, and (5) work element. The parent element is used to prepare a layout on which other elements are placed and interacted to simulate the operation. The source and destination elements are used to represent the geographic locations of loading and releasing for a given WP. One or more tower crane elements can be selected from a library of tower cranes and placed in the layout. The work elements, which are created inside a source element, drive the simulation in the tower crane SPS module. They create WP entities, capture resources, calculate hookup, unhook, and travel time, and record statistics.

The following steps describe the simulation process performed in the SPS module:

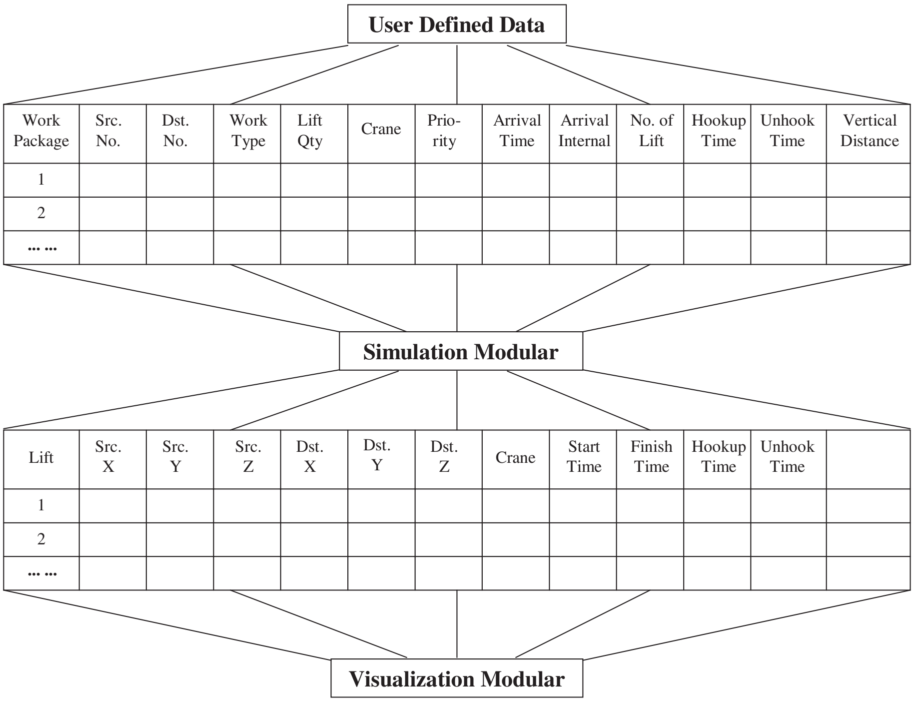
(1) WPs are created in the work elements and the radial, horizontal, and vertical distances are calculated.
(2) The created WPs go into the waiting file of the assigned cranes and wait for the next available tower crane.
(3) When the crane is available, the WP with the highest priority rating in the waiting file captures the crane.
(4) A delay is assigned for the tower crane's movement from the last destination location to the source location of the next WP to be carried out.
(5) A delay is assigned for the WP lift hookup time.
(6) The WP lift travel time is calculated and a delay is assigned.
(7) A delay is assigned for the WP lift unhook time.
(8) Steps (5)–(7) are repeated until the count (number of lifts performed) is equal to the quantity of lifts required to complete the WP.
(9) The tower crane resource is released. The WP is completed.
(10) Steps (3)–(9) are repeated until there are no WPs left in the waiting file.
(11) Simulation finishes.

A typical SPS model in Simphony outputs its results in the form of pre-designed tables and charts, but it also can be instructed to output results and process data into files. In the proposed integration system, the SPS module stores all required data in an ASCII file, which is then processed by the visualization module (Fig. 4).

4. Technical approach for integrating 3D visualization and simulation

4.1. Problem description

As two different computer modeling methods, discrete event simulation and 3D visualization abstract and represent real world operations in completely different ways. In general, the primary objective of computer simulation is to better understand certain aspects of a complex system, and to predict its performance following various decisions. Hence, the specific purpose and scope of a study governs the level of abstraction from reality. On the other hand, 3D visualization tries to help viewers to more quickly and easily understand the states and changes of the modeled system through a realistic representation of the milieu. In order to create a natural scene, the visualization model must be built with a high level of detail.



Work Package	Src. No.	Dst. No.	Work Type	Lift Qty	Crane	Prio-rity	Arrival Time	Arrival Internal	No. of Lift	Hookup Time	Unhook Time	Vertical Distance
1												
2												
………												

Lift	Src. X	Src. Y	Src. Z	Dst. X	Dst. Y	Dst. Z	Crane	Start Time	Finish Time	Hookup Time	Unhook Time	
1												
2												
………												

Fig. 4. Data input and output of the simulation module.

The huge information gap between these two models can be summarized in the following five aspects:

(1) The discrete event simulation model focus only on a set of discrete, but possibly random, time points, at which the state of the model changes. 3D animation, on the contrary, is a continuous description of the modeled operation. Although, technically, we assign the settings discretely at some specific time points and assume smooth movement in between, much more detail must be considered to make the animation real.
(2) Typical simulation models only need relative spatial data, such as distances. However, geometric information, such as the coordinates of the start and end points of activities, is necessary to visually depict the construction operation.
(3) In the simulation model, only the target object's movement is important, but in the visualization model, every element in the system must be considered. For instance, in tower crane simulation, the only movement that we consider in simulation is that of the lifting load, but in visualization, we have to define the movements of rigging, trolley, and boom as well.
(4) There is no time-scale problem in simulation, but a proper time scale factor, the ratio of the animation time to the time of the real process, is crucial for a good animation. Sometimes more than one factor is adopted for different activities in one animation. For example, in SimAnim, the time scale factor for lunch time is smaller than that for hoisting to avoid long time intervals between movements.
(5) In simulation, the input parameters normally follow probability distribution; we perform numerous simulation runs and obtain statistic results. However, the visualization model is basically a one-time deterministic model.

4.2. Technical approach

The fundamental purpose of this research is to develop a practical methodology that can be used to bridge the information gap between simulation and 3D visualization, so that the essence of simulation can be effectively conveyed in 3D visualization. As such, the authors did not develop a visualization engine, but built the visualization module in the environment of a commercial 3D animation tool, 3D Studio Max (3DS). The authors attempted to take advantage of existing technologies and focus on using them creatively to solve practical problems.

The basic idea behind creating animation in 3DS is creating a series of key frames on timeline to define the start and end of major actions. Each of these key frames reflects the state of the modeled system at a designated point in time. To smoothly model the tower crane operation, we further divided one lift cycle into the following eight actions.

(1) Move hook block from the final location of the last lift to the initial location of the new lift.
(2) Lower the hook block down to the source position.
(3) Hook up the target load.
(4) Hoist the lift to the desired height.
(5) Move the lift to the destination location.
(6) Lower the lift to its final position.
(7) Unhook the target load.
(8) Move hook block up to the desired height.

The simulation model has a lower level of detail than does the visualization model; thus, it only provides information about

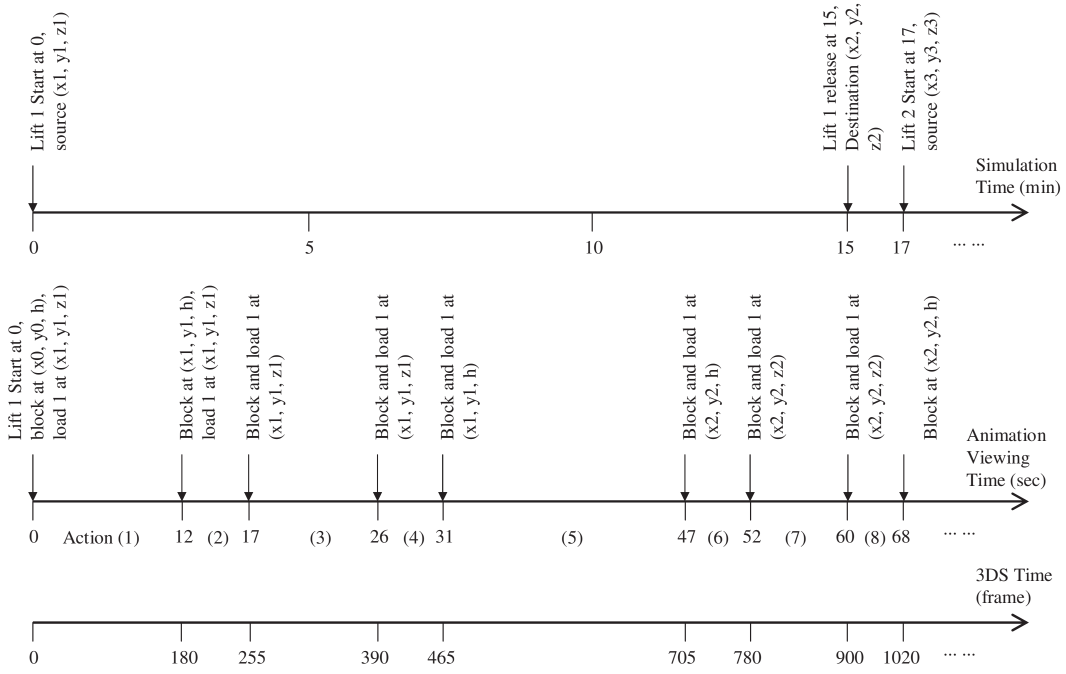


Fig. 5. Relationship between the simulation outputs and animation frames.

high level large activities. The visualization module calculates data from sub-activities encapsulated within the large activities based on the tower crane specifications and site conditions. Fig. 5 graphically explains the relationship between the simulation outputs and the animation frames. The time scale factor used for lift activities is 1/15 making 15 min of real time into 1 min of computer simulation time, and for any stationary period that lasts longer than 15 min, a 1-min animation time is adopted. In fact, 3DS enables the viewer to control the animation speed by changing the frame rate (frame per second).

The fundamental mechanism used in 3DS for animation is a process called Inverse Kinematics (IK). Kinematics is the science of motion; it considers the geometric properties of motion independently of the forces causing it [20]. The core concept in kinematics is a hierarchical structure called family hierarchy. It contains parent and *child* links, where the child is linked to the parent. As a result, the child will inherit the parent's motion when the parent moves. When the parent object controls the child object, the hierarchy is known as Forward Kinematics. Inverse Kinematics, by contrast, is the means by which a desired child object position, called an end effector, is used to determine the movement of parent objects in the chain. Simply stated, IK means that the end effectors' movement will affect each member up the hierarchy. When an end effector is moved, all object positions up the hierarchy are calculated in relation to that end effector. In tower crane visualization, each tower crane, in terms of IK, can be considered as an open chain, having the following hierarchy: fixed tower→boom→trolley→hook block. Each joint that connects the objects in the chain has one degree of freedom.

- Fixed tower and boom: rotational joint in Z axis;
- Boom and trolley: sliding joint in X axis;
- Trolley and hook block: sliding joint in Z axis.

To describe the position of system elements mathematically, we attach a unit vector coordinate frame to each element on its connection joint, as shown in Fig. 6. Then, in IK, each action of the chain can be defined using a homogeneous transform matrix, which is a 4 × 4 matrix that comprises 2 parts: a 3 × 3 rotation matrix R and a 3 × 1 dimensional translation vector P.

$$T = \begin{bmatrix} R & P \\ 000 & 1 \end{bmatrix} \tag{1}$$

For instance, the first step of the lift, moving the hook block from the final location of the last lift (x_0, y_0, h) to the initial location of the new lift (x_1, y_1, h), can be expressed using Eq. (2).

$$\begin{bmatrix} x_1 \\ y_1 \\ h \\ 1 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1-\theta_0) & -\sin(\theta_1-\theta_0) & 0 & 0 \\ \sin(\theta_1-\theta_0) & \cos(\theta_1-\theta_0) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & d_1-d_0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ h \\ 1 \end{bmatrix} \tag{2}$$

Wherein, $\theta_0 = \tan^{-1}\left(\frac{y_0}{x_0}\right)$, $\theta_1 = \tan^{-1}\left(\frac{y_1}{x_1}\right)$, $d_0 = \sqrt{x_0^2 + y_0^2}$, $d_1 = \sqrt{x_1^2 + y_1^2}$.

The second step of the lift, hook block moves down to source position (x_1, y_1, z_1), can be expressed using Eq. (3).

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z_1-h \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ h \\ 1 \end{bmatrix} \tag{3}$$

From the above equations, for any given initial and final positions and orientations of the lowest level child object –

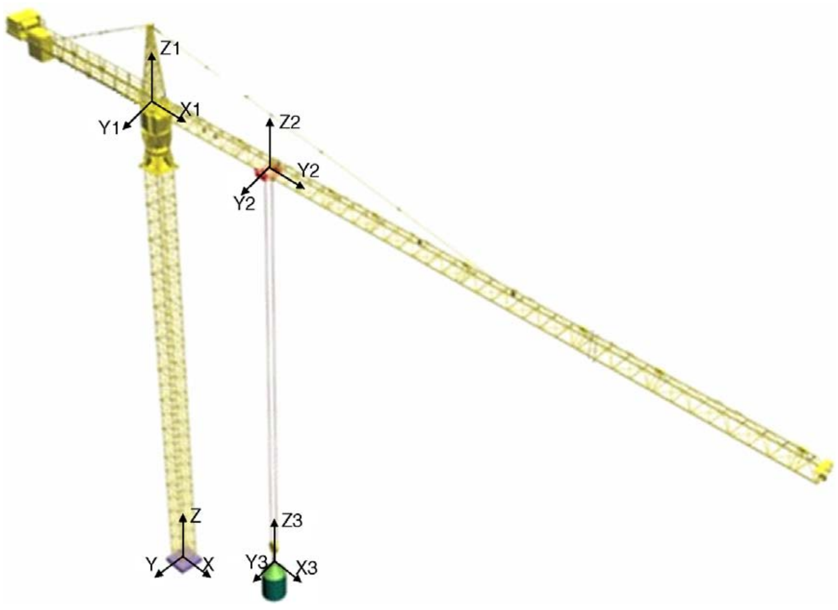


Fig. 6. Schematic of a tower crane.

hook blocks – one or multiple homogeneous transform matrixes can be obtained. Once the homogeneous transform matrix has been designated, the 3DS can compute the transformations of other parent elements in the kinematical chain using the IK procedure.

Another important issue in the development of the proposed integration system is data transformation between the simulation module and the visualization module. Spatial and geometric lift information is generated in the simulation module based on the users' input and then stored in its output file, although it is not necessary for the simulation. The lift start and release times used in visualization are the mean values of the simulation results, but it is feasible to instruct the simulation module to provide other percentile values, for example, 80th percentile values.

5. 3D visualization module for tower cranes (SimAnim)

SimAnim was developed using 3D Studio Max's scripting language, MaxScripts. The inputs of the visualization module come from two sources. One is the simulation module output file, which stores the spatial configuration of the modeled operation along with the performance time, as shown in Fig. 4. The other resource is the 3D model library of SimAnim. Although 3DS provides a built-in 3D modeling capacity, for sophisticated 3D models like tower cranes and buildings, it is more convenient to construct the 3D model using more powerful 3D CAD applications, such as AutoCAD and MicroStation. The visualization module imports 3D models from the 3D library, including the tower crane model and the 3D site model, according to the construction stage designated, and assembles them in 3DS. Then the 3D animation engine uses the data retrieved from the simulation results file to create the key frames and render the animation.

Since SimAnim was developed using the 3DS MAXScripts language, it inherited the strengths and weaknesses of 3DS and possesses the following characteristics:

- It uses the 3DS clock; the speed of animation can be controlled by the viewer by changing the frame rate.
- Navigation in 3D space is simplified and any desired view can be obtained by controlling the position and configuration of the "camera".
- The user can jump ahead or back to any desired location in the animation by specifying a future or past time-value.
- Animation can be stopped or paused at any time to make static observations in the modeled system.
- The system supports numerous file formats, including DWG, DXF, AI, WRML, XML, FBX, STL, IGS, and AVI. The ASCII text file format is used as the simulation data import format. This provides the SimAnim with the necessary flexibility to be used in combination with a wide range of different 3D modeling and simulation systems.

6. Case study

The proposed methodology has been tested in the case of the construction of the seven-storey Natural Resources Engineering Facilities (NREF) on the University of Alberta campus. The project was constructed based on the design-build fast-track project delivery system, and used two tower cranes. PCL Constructors Inc. is the general contractor for the project. The many different uses of the tower cranes in each stage of the construction made simulating the entire tower crane operation very difficult. The case study presented here focuses on the construction of the second floor (L2). The primary tower crane operations on site are the lifting of large formwork panels, reinforcing bars, and concrete buckets. For these three

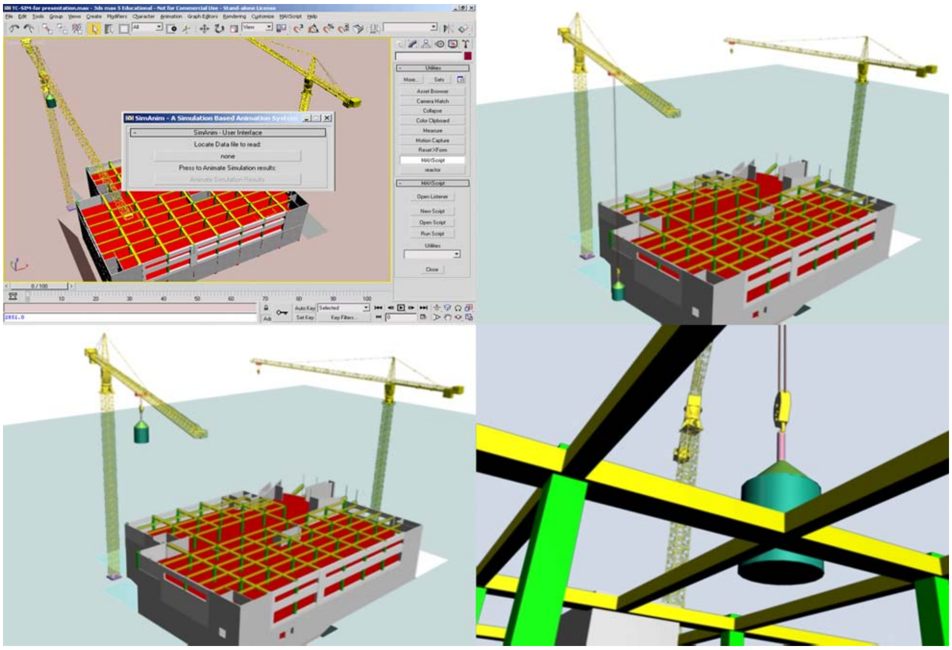


Fig. 7. SimAnim screen snapshots.

operations, a simulation model was built in Simphony using a tower crane SPS template based on the geographical locations of the crane, source, and destination elements on the model layout. This simulation model was run for 50 iterations to simulate the various conditions reflected by the input parameters. Then SimAnim imported the data file and generated the animation in the 3DS environment according to the results of the simulation, as illustrated in the screen snapshots in Fig. 7. Considering viewing time and the size of the animation file, the tower crane operation was visualized on a daily basis. The viewing time for visualizing 8 h of the discussed tower crane operation is, for example, 30 min; the animation file, in 3DS format, is about 50 M. If we export the animation to general movie file format AVI, the size of the file will be around 540 M.

3D visualization provided several non-quantifiable details and made the verification and validation of the simulation model much easier. Verification is the process of identifying the difference between the actual model and the intention of the modeler, and updating the model to conform to this intention; validation is determining whether the simulation model correctly represents the target real-world operation in the study aspect [21]. In simulation practice, the differences between the model and modeler's intention are ubiquitous and some of them are very difficult to detect. For instance, the SPS model used the same logic to simulate the two-crane system used in this case as the logic used for a single-crane system. This meant the potential collision of two cranes when their lifting routes crossed or when they had to reach adjacent resources or destinations at the same time. Fig. 8 shows an animation snapshot of the scenario. The reason for this is that the SPS module basically simulates each tower crane independently and then overlaps the results. Because it is hard to modify the intrinsic logic of the SPS template to reflect the interaction of the tower cranes, in practice, we changed the priority of the work packages that caused the collision. This changed the sequence of lifts and thus avoided the collision scenario. After a modified simulation is executed, a new animation should be generated to check whether the possibility of the collision was, in fact, eliminated. Thus, the integration of simulation and visualization ensures the validity of the simulation results.

In addition, with the assistance of 3D visualization, the viewers were able to examine the simulated construction operation in a very realistic and detailed manner. This can be of substantial help in communicating the simulation results to domain experts. During the NREF construction planning stage, the integrated system was used to simulate lifting operations in typical floor (second to seventh) construction. Because the SPS and 3D visualization were easy to use and understand, the developed system was used by project management to simulate and analyze different scenarios for optimizing the construction schedule and the lifting package priority. In the lifting plan approval procedure, PCL's engineers were provided with a lifting plan report along with 3D animation files depicting simulations of a typical week's tower crane operations. This information expedited the work of safety officers and facilitated the approval of the lifting plan.

7. Conclusions

The purpose of using computer simulation to model construction operations is to assist decision makers in better understanding planned operations and predicting the performance resulting from alternative decisions. To achieve this goal, the simulation models should be credible and fully comprehensible to construction practitioners. This paper described and discussed the challenges met and the approach adopted in an effort to develop an SPS and 3D visualization

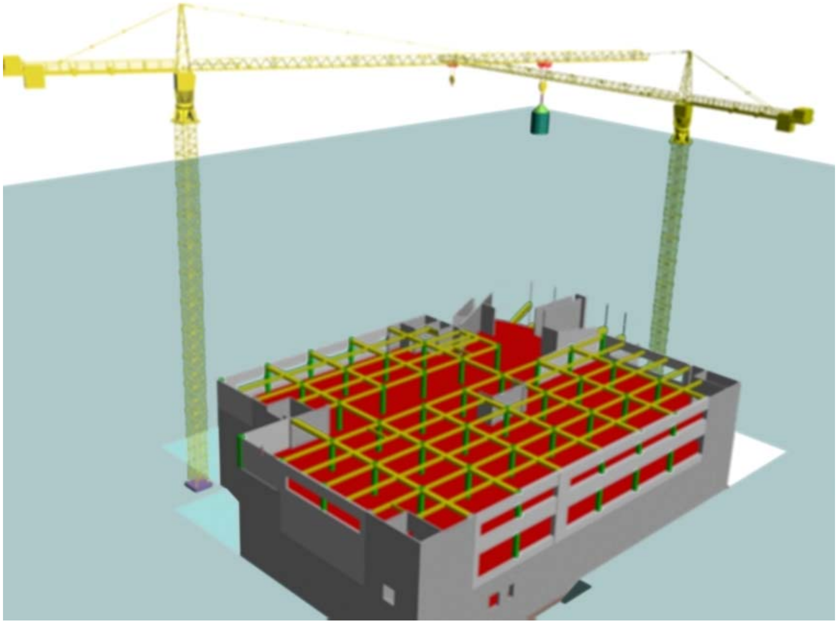


Fig. 8. Modeling flaw: crane lifting route collision.

integration system to improve the credibility and communication of simulated construction operations. An integrated system was developed for the simulation and 3D visualization of tower crane operations. The NREF case study was used to validate the effectiveness of the proposed methodology and to illustrate the essential features of the developed integrated system.

This paper demonstrated the effectiveness of utilizing 3D visualization and simulation modeling in better understanding construction operations. This is particularly helpful for simulation verification and validation. Furthermore, the dynamic graphical depiction generated by the 3D visualization module clearly communicates the simulated operation and provides detailed information to decision makers.

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