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Modeling approach of simulation for dual-crane lift system

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ABSTRACT

Lifting objects with extra weight and large span are more and more common in large-scale lift projects and it becomes more and more difficult for a single crane considering the limit of its lift capacity, which urges the wide use of dual-crane who can deal with the large-scale lift easily by the cooperation of two cranes. However, dual-cranes' cooperation may be much more dangerous compared with single crane lift. To identify and avoid the potential danger during lifting, this paper focuses on 3D simulation of typical dual-crane cooperative lift and describes its model and basic motion expression. An effective simulating approach which follows the principle of space geometric constraints is put forward and an actual lift case validates the feasibility of the developed approach.

Key words: Dual-crane lift; simulation; Modeling

INTRODUCTION

Lifting objects with extra weight and large span are more and more common in large-scale lift projects. And for a single crane, some problems, such as the limitation in crane's lift capacity and the load's turning, always lead to the task too hard to complete. Maybe there are some cranes capable of performing these erections, but such cranes are not always available in the construction sites and the cost of rental is usually very high. Therefore, the use of two cooperative cranes available on-site is a wise alternative [1]. However, compared with single crane lift, dual cranes' cooperation may be much more dangerous [2]. Even a little improper collaboration may lead to collision, overturning, boom crash, casualties and so on.

3D simulation is an effective and low-cost way to identify potential danger in actual lifts. The planners can observe the overall lift process by simulation and identify potential risks in advance. So lots of scholars have deeply studied the lift simulation in the past. Some of them researched on tower cranes lifting process [3,4] and various simulation and visualization tools have been developed to plan the crane's location or optimize the lifting sequence. Others cared about the lift simulation of mobile cranes. Some researchers [5,7-8] proposed some approaches which were implemented in simulating systems based on CAD. Sang Hyeok Han, et al. utilized of 3d visualization of mobile crane operations for modular construction on-site assembly [10]. Hermann U. R., et al. [6] improved the lifting sequence for single crane by simulation. Amin Hammad, et al. [9] Improved lifting motion planning and re-planning of cranes. Mohamed Al-Hussein, et al. studied a methodology for mobile crane lift path [11]. These approaches are mainly concerned with single crane lifts.

There are many studies of handling a single object by multiple mobile cooperative manipulators in robotics domain [12-16]. The system of multiple mobile manipulators handling a single object is analogous to that of multiple mobile cranes lifting the same object, but they are not exactly the same. The connection between mobile manipulators and the object handled is a rigid bar that can support the load, while the connection between mobile cranes and payload is a group of cables that can be pulled but not support the load.

However, only a few studies have focused on cooperative lift simulations for two or more cranes. Souissi et al. developed a model for the closed chain motion of two rotary cranes holding a rigid object in a two-dimensional workspace [17]. Zhang et al. proposed a simulation method based on agent [18] to enhance communication between two cranes. But lifting processes simulated by these methods can not always live up to expectations for the agents' autonomy and the cranes' traveling is always neglected in these researches.

Also existing methods for dual-crane simulation fail to deal with typical cooperative erection. As linked by heavy load, the two cranes usually act according to an easy operated mechanism rather than moving arbitrarily so that the object can be transported to the expected location successfully. And we call such lift as typical dual-crane cooperative lift. This cooperative strategy derives from engineers' experience in long-term practice and is widely used in actual lift. Since it is difficult to visually determine which motions of the two cranes need to carry out with the expected path of lifting object given, and existing approaches always cope with this problem with the help of the 'cut-and-try' method. So it is impossible to simulate such dual-crane lift for these methods.

Therefore, this paper develops a feasible strategy of dual-crane cooperation which is easily operated and can simulate the typical dual-crane lift process exactly. In our research, we first build a dual-crane model and give an expression of the lifting state. And then a novel dual-crane lift simulating method based on special geometric constraints is presented in this paper.

DUAL-CRANE MODELING AND EXPRESSION OF LIFTING STATE

Dual-crane Modeling. Two cranes and single lifting object can be regarded as a complex lift system. Previous research usually treats cranes and loads separately, and discusses their motions respectively. In our research, we take the system combined with two cranes and lifting object as an integral whole which is linked by flexible lifting cables. And it is a rigid-flexible coupling and single closed-loop system which consists of two cranes, a load and the ground, as shown in Fig. 1. At a time, one of the cranes executes a motion with a small step length while another one needs to do the cooperation by carrying out another motion. Then the load was transported from the former state to next one, in which process, the cranes' lifting capacity must not be over their rated loads respectively.

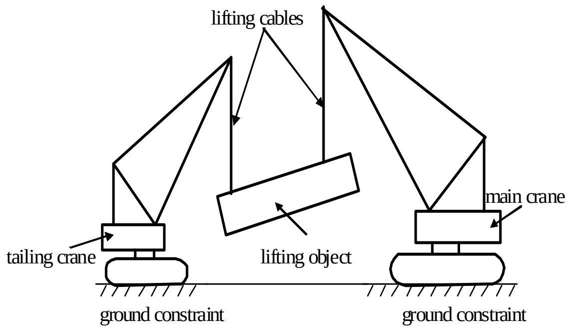


Fig. 1: Geometrical model of dual-crane system

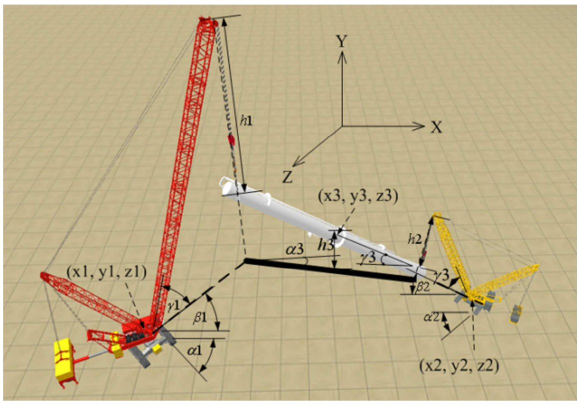


Fig. 2: Configuration space of dual-crane system

Therefore, from a macro perspective, the movement of object is an internal motion of system driven by the two cranes, and dual-crane's cooperation is the movement of the system itself. That is, dual-cranes' cooperating lift can be described as the complex system's own movement. Movement of a system is often accomplished by the perfect combination of several basic motions. For example, a car accomplishes its running by going straight or turning, and a crawler crane accomplishes its single erection by traveling, turning, slewing, luffing, or lifting. As a result, to simulate dual-crane erection, we should describe basic motions conformed to the system's cooperating mechanism.

Lifting State Expression of Dual-crane System. Lifting state is a basis in the study of dual-crane cooperation and simulation. To express the lifting state with consideration of actuality, the following simplified assumptions are made：(1) All the crane components are assumed to be rigid body so that they have no shape changing during erection. (2) Since the cable's swing is much more influential to cranes [2], both the two cranes' cables are assumed to be vertical.

All the state of dual-crane system in erection can be described as $(x1, y1, z1, \alpha1, \beta1, \gamma1, h1, x2, y2, z2, \alpha2, \beta2, \gamma2, h2, x3, y3, z3, \alpha3, \gamma3, h3)$, which is also referred to as configuration of the system. Interpretation of each variable is shown in Fig. 2, where ($x1$, $y1$, $z1$)is coordinate value of main crane's slewing center. $\alpha1$ is angle between main crane's crawler direction and positive X-axis which ranges from -180o to 180o. $\beta1$ is angle between main crane's upper part and positive X-axis which ranges from -180o to 180o. $\gamma1$ is main crane boom's angle which ranges from 0o to 90o. $h1$ is height from pulley block center of main crane's boom head to the lifting points of object. ($x2$, $y2$, $z2$) is coordinate value of tailing crane's slewing center. $\alpha2$, $\beta2$, $\gamma2$ and $h2$ of tailing crane are same as main crane's. ($x3$, $y3$, $z3$) is coordinate value of lifting object geometrical center. $\alpha3$ is angle between object and positive X-axis which ranges from -180o to 180o. $\gamma3$ is object's angle which ranges from -90o to 90o. $h3$ is height of object geometrical center which ranges from the height of the lowest point during lifting to the tailing crane's limited height.

BASIC MOTION DESCRIPTION OF DUAL-CRANE SYSTEM CONSIDERING SPACE GEOMETRIC CONSTRAINTS

Analysis of Dual-crane Lift Cooperative Strategy. As analyzed above, it is critical to define basic motions for the system to describe the dual-crane lift process. In fact, the problem is seeking for some motions satisfying with not only cranes' kinematics constraints but also space geometric constraints under cranes' capacities. Cranes' kinematics constraint involves that movement relating cranes must follow the rules of single crane, such as crawler's differential traveling etc. Space geometric constraint of dual-crane system involves the keeping of a closed loop which formed by the end to end connection of the following three: two cranes, load and ground, as is shown in Fig. 1. Also in the loop the cables is always plumb.

To meet the two constraints mentioned above, we analyze dual-crane system movement from another point of view. The movement of mechanic system aims to change its state and for the dual-crane system we are discussing, its movement aims to change the position or configuration. And what it only focuses on is the results after state changing. So there is no fixed driving part or driven part in dual-crane system and any motion that can accomplish expected state changes will be a feasible one. Hence, for a specific motion, we can select an appropriate driving part for it and then the driven parts' movement can be expressed with consideration for the two constraints referred to above.

In actual lift process, large numbers of typical dual-crane cooperative ways have been found during long-time practice. And these ways follow some special geometric constraints different from both the two mentioned above. As a result, dual-crane system's basic motion can be defined as these cooperative ways and then a correspondence between basic motions and system states can be established. Particularly, to move object along an expected path exactly, object and crawler have prior opportunity to become driving parts and other parts' movement can be expressed by the variation of driving parts.

Dual-crane System Basic Motion Description. In order to transform basic motions into system state and visualize it, we describe basic motions of the system mathematically in this subsection.

As is known from previous analysis, the state changing of dual-crane system is its movement. So its basic motion can be formalized as follows：

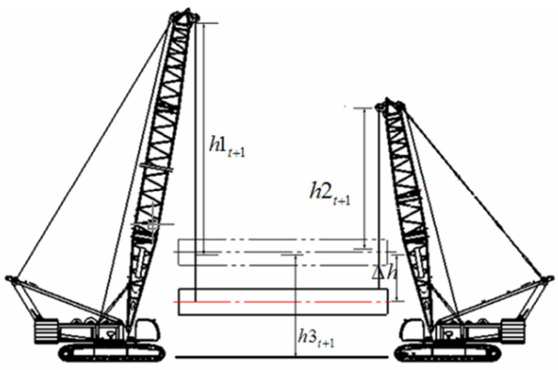
$$CS_{t+1} = f(u, CS_t) \quad (1)$$

where CS_t , CS_{t+1} is lifting state of dual-crane system at time t, t+1. That is CS_i ($x1_i$, $y1_i$, $z1_i$, $\alpha1_i$, $\beta1_i$, $\gamma1_i$, $h1_i$, $x2_i$, $y2_i$, $z2_i$, $\alpha2_i$, $\beta2_i$, $\gamma2_i$, $h2_i$, $x3_i$, $y3_i$, $z3_i$, $\alpha3_i$, $\gamma3_i$, $h3_i$), $i = \{t, t+1\}$. Vector u is the motions' variation from time t to time t+1. f is space geometric constraint of the motion. Then dual-crane system basic motion is converted into the function expression f and vector u . And we can get CS_{t+1} from CS_t .

MOTION SET BUILDING OF DUAL-CRANE SYSTEM

This section describes basic motion definition and motion set building in detail. In actual lift, especially for petrochemical construction lift, it is common to turn and raise tower equipment from level to vertical orientation by using two cranes, and then to locate it on foundations or frames by using main one of the two cranes, in which process, the two cranes' close cooperation is necessary. And to accomplish this task, there are many cooperative strategies drawn from engineers' practice. For example, the two cranes finish the object's vertical lift by raising or dropping motion simultaneously. Another example is that the two cranes finish the object's parallel movements by slewing or luffing motion, etc. From these strategies, we conclude that trajectory of the object can be predicted intuitively and each strategy follows a special geometric constraint. The rest of this section gives the definition of dual-crane's motion which includes hoisting, level moving, tailing traveling, non tailing traveling, and main hook rotating on its vertical axis. And also every motion's function expression f and its vector u are described.

Hoisting. Hoisting is that two cranes complete the object's vertical lift by raising or dropping hook simultaneously. It is always used when unloading lifting object from transport vehicle or before turning and raising object to vertical orientation, as shown in Fig. 3.



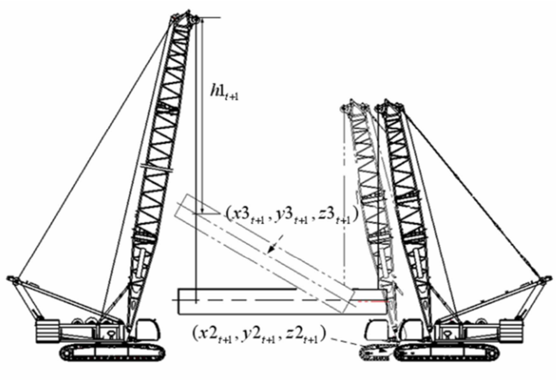


Fig. 3: Hoisting of dual-crane system **Fig. 4: Tailing traveling of dual-crane system**

In this cooperation, none variables have changed other than the cable length and the height of lifting object above ground. So this height is selected to be driving variable of this motion which causes the change of cable length. Here, the movement of lifting object is Δh, while the motion inputs vector is $u = [\Delta h3]$, and the function f can be expressed as Eq. (2).

$$\begin{cases} h2_{t+1} = h2_t + \Delta h3 \\ h1_{t+1} = h1_t + \Delta h3 \\ h3_{t+1} = h3_t + \Delta h3 \\ \text{other variables of } CS_{t+1} = \text{corresponding variables of } CS_t \end{cases} \tag{2}$$

Level Moving. In actual lift, the load often needs to be moved horizontally to the final destination of a frame or concrete foundation by two cranes' slewing, luffing or lifting cooperation. This cooperative strategy is named level moving in this paper, and it is often used in installing, unloading or uninstalling objects.

In this cooperation, all the following variables may be changed, including the object's X-coordinate or Z-coordinate value, the two cranes' slewing angle, their booms angle and cables length. For convenience of description, we select object's X-coordinate and Z-coordinate values as active variables. Their variations are $\Delta x3$ and $\Delta z3$, and the motion inputs vector is $u = [\Delta x3, \Delta z3]^T$. Since dual-crane system abides the space geometric constraint of closed loop, a crane's slewing or boom angle and cable length at time t+1 can be obtained as following: First, the object's position is determined according to $\Delta x3$ and $\Delta z3$, then the coordinate of its two lifting points is got. Second, the cranes' slewing angle is determined according to its position and the coordinate value of the object's lifting points, then its boom angle is got. Last, the length of the cables can be obtained. The expression of geometric constraint function f is shown as Eq. (3).

$$\begin{cases} x3_{t+1} = x3_t + \Delta x3 \\ z3_{t+1} = z3_t + \Delta z3 \\ \beta 1_{t+1} = \arctan((-(z3_{t+1} - 0.5L3\sin\alpha 3_t) + z1_t)/((x3_{t+1} - 0.5L3\cos\alpha 3_t) - x1_t)) \\ \gamma 1_{t+1} = \arccos((R1_{t+1} - x1_{offset})/L1) \\ h1_{t+1} = y1_{offset} + L1\sin\gamma 1_{t+1} - y3_{t+1} \\ \beta 2_{t+1} = \arctan((-(z3_{t+1} + 0.5L3\sin\alpha 3_t) + z2_t)/((x3_{t+1} + 0.5L3\cos\alpha 3_t) - x2_t)) \\ \gamma 2_{t+1} = \arccos((R2_{t+1} - x2_{offset})/L2) \\ h2_{t+1} = y2_{offset} + L2\sin\gamma 2_{t+1} - y3_{t+1} \\ \text{other variables of } CS_{t+1} = \text{corresponding variables of } CS_t \end{cases} \quad (3)$$

where $L1$ and $L2$ are boom length of main crane and tailing crane respectively. $x1_{offset}$ is longitudinal offset between main crane's boom pivot and its slewing center. $x2_{offset}$ of tailing crane is same as the main crane's. $y1_{offset}$ ($y2_{offset}$) is vertical offset between main (tailing) crane's boom pivot and its slewing center. $L3$ is longitudinal distance between two lifting points of object. $R1_{t+1}$ and $R2_{t+1}$ are work radius of main and tailing cranes at time t+1 which are calculated as the following equations:

$$R1_{t+1} = \sqrt{((x3_{t+1} - 0.5L3\cos\alpha 3_t) - x1_t)^2 + (-(z3_{t+1} - 0.5L3\sin\alpha 3_t) + z1_t)^2}$$
$$R2_{t+1} = \sqrt{((x3_{t+1} + 0.5L3\cos\alpha 3_t) - x2_t)^2 + (-(z3_{t+1} + 0.5L3\sin\alpha 3_t) + z1_t)^2}$$

Tailing Traveling. Among all of them aiming at object's turned and raised to a vertical orientation, the most common one of cooperative strategies is that the main crane attaches to the top of the object and lifts slowly while the tailing crane attaches to its bottom to keep the distance between tailing lifting point and ground fixed. By traveling along the object's projection, the tailing crane moves it forward cooperating with the main crane. This strategy is defined as tailing traveling of dual-crane system in this section, as shown in Fig. 4.

This cooperation turns and raises the object to a vertical orientation by tailing crane's traveling and moving forward on condition that the tailing crane is a crawler crane that can travel with main crane and whose crawler direction is in accordance with the direction of object's longitudinal axis. This motion can bring the change of lifting object's configuration, main cable length and tailing crane's position. We select the main cable length as active variable in this motion and its variation is $\Delta h1$ while the motion inputs vector is $u = [\Delta h1]$. Since the system abides space geometric constraints, the other states' variation can be determined by the following steps: 1) to get the main hoisting point's coordinate value according to $\Delta h1$, 2) to get object's angle and location by its length, and 3) to get the tailing crane's location according to tailing point's location. The expression of geometric constraint function f is shown as Eq. (4).

$$\begin{cases} h1_{t+1} = h1_t + \Delta h1 \\ x2_{t+1} = x2_t - \Delta d\cos\alpha 3_t \\ z2_{t+1} = z2_t + \Delta d\sin\alpha 3_t \\ \beta 3_{t+1} = \arcsin((L3\sin\beta 3_t - \Delta h1)/L3) \\ x3_{t+1} = x3_t - \Delta d\cos\alpha 3_t \\ z3_{t+1} = z3_t + \Delta d\sin\alpha 3_t \\ y3_{t+1} = y3_t + 0.5L3(\sin\beta 3_{t+1} - \sin\beta 3_t) \\ \text{other variables of } CS_{t+1} = \text{corresponding variables of } CS_t \end{cases} \quad (4)$$

where Δd is the variation of tailing lifting point along the direction of object's longitudinal axis after turning, which is calculated as follows:

$$\Delta d = L3(\cos\beta 3_t - \cos\beta 3_{t+1})$$

Non Tailing Traveling. Although it is easy for the last motion to accomplish the object's turning or erecting, it requires the tailing crane's traveling. For a tailing crane that can not travel when lifting object, to accomplish the object's turning or erecting, it can move the object forward by its slewing, luffing or lifting motion to cooperate with the main crane. Such a strategy is named non tailing traveling in this section, which can avoid traveling dynamic impact. This motion can bring change of the configuration of lifting object, the main cable length, the tailing's slewing angle, boom angle and cable length. We select the main cable length as the active variable and its variation is $\Delta h1$, while the motion input vector is $u=[\Delta h1]$. The determination of the other variables is similar to that of tailing traveling except tailing slewing angle, boom angle and cable length. According to the geometric constraint of dual-crane system, we can get the expression of function f, as is shown in Eq. (5).

$$\begin{cases} h1_{t+1} = h1_t + \Delta h1 \\ x2_{t+1} = x2_t - \Delta d \cos\alpha 3_t \\ z2_{t+1} = z2_t + \Delta d \sin\alpha 3_t \\ \beta 3_{t+1} = \arcsin((L3\sin\beta 3_t - \Delta h1)/L3) \\ x3_{t+1} = x3_t - \Delta d \cos\alpha 3_t \\ z3_{t+1} = z3_t + \Delta d \sin\alpha 3_t \\ y3_{t+1} = y3_t + 0.5L3(\sin\beta 3_{t+1} - \sin\beta 3_t) \\ \text{other variables of } CS_{t+1} = \text{corresponding variables of } CS_t \end{cases} \quad (5)$$

where $R2_{t+1}$ is working radius of the tailing crane at time t+1. $(x_{ass}, y_{ass}, z_{ass})$ is coordinate value of the tailing lifting point of the object. $R2_{t+1}$ and $(x_{ass}, y_{ass}, z_{ass})$ are calculated as follows:

$$R2_{t+1} = \sqrt{((x3_{t+1} + 0.5L3\cos\alpha 3_t) - x2_t)^2 + (-(z3_{t+1} + 0.5L3\sin\alpha 3_t) + z1_t)^2}$$

$$\begin{cases} x_{ass} = x3_{t+1} + (0.5L3\cos\beta 3_{t+1})\cos\alpha 3_t \\ y_{ass} = y3_{t+1} + 0.5L3\sin\beta 3_{t+1} \\ z_{ass} = z3_{t+1} + (0.5L3\cos\beta 3_{t+1})\sin\alpha 3_t \end{cases}$$

Main Hook's Rotating. In some actual lifts, it's difficult for limited location of tailing crane to finish turning or erecting lifting object directly without main crane's hook rotating around its vertical axis. And this strategy, which is called main hook's rotating in this paper, is composed two steps. One is main hook's rotating so as to make applicable location relationship between object and tailing crane by tailing's slewing, luffing or lifting, as is shown in Fig. 5. The other is the two cranes' cooperation with tailing traveling,. This motion can bring change of lifting object's location or angle and the tailing crane's slewing angle, luffing angle or cable length. We choose the slewing angle of tailing crane as the driving variable and its variation is $\Delta\beta 2$ while its motion input vector is $u=[\Delta\beta 2]$. The other changed variables can be got in the following process: First, the tailing crane's slewing angle is got according to $\Delta\beta 2$, which determines its boom direction. Second, the location of tailing lifting point is determined by drawing arc whose center and radius are main lifting point and lifting object's length respectively. Third, the tailing crane's luffing angle and cable length are got according to tailing lifting point's location. The expression of the geometric constraint function f is shown in Eq. (6).

$$\begin{cases} \beta 2_{t+1} = \beta 2_t + \Delta\beta 2 \\ \gamma 2_{t+1} = arc\cot((d\cos\theta - \sqrt{L3^2 - d^2\sin^2\theta})/L2) \\ \alpha 3_{t+1} = \alpha 3_t + \arccos(\dfrac{L3^2 + d^2 - R2_t^{\ 2}}{2L3d}) - \arccos(\dfrac{L_0^{\ 2} + d^2 - R2_{t+1}^{\ 2}}{2L3d}) \\ h2_{t+1} = h2_t + L2(\sin\gamma 2_{t+1} - \sin\gamma 2_t) \\ \text{other variables of } CS_{t+1} = \text{corresponding variables of } CS_t \end{cases} \quad (6)$$

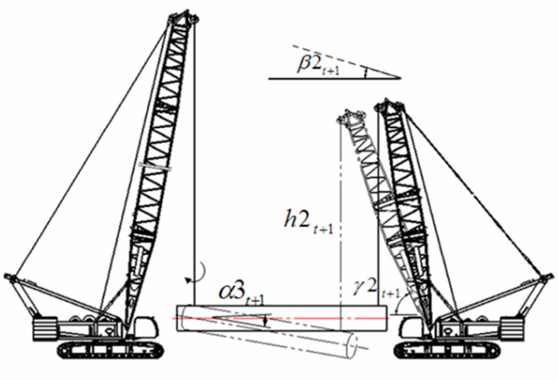


Fig. 5: Non tailing traveling of dual-crane system

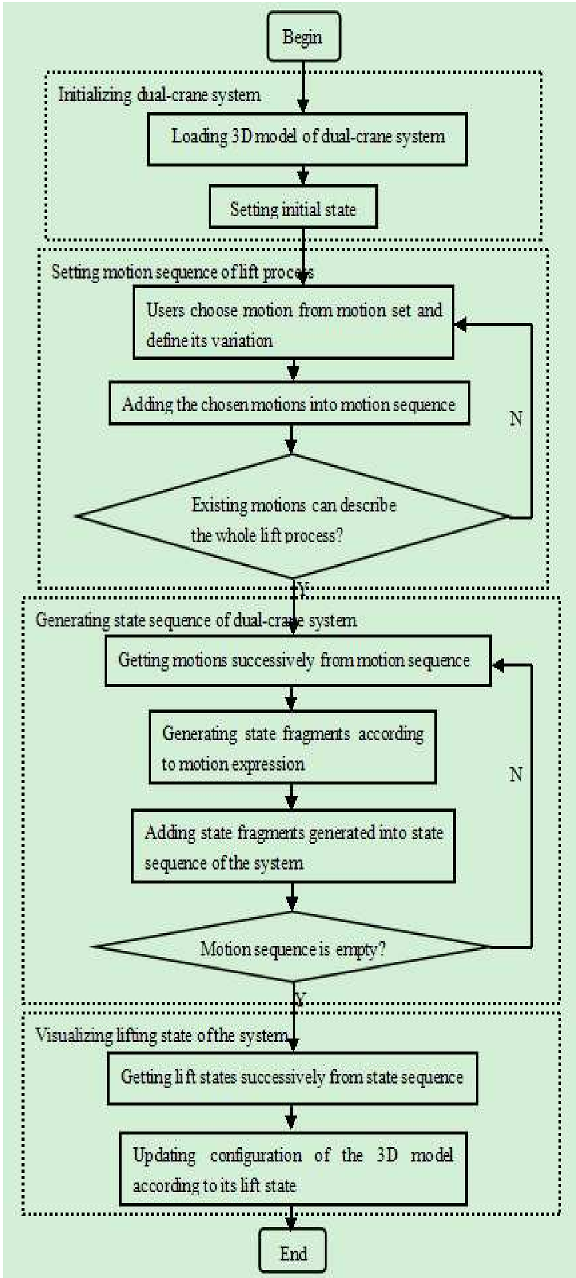


Fig. 6: Simulation flow chart for cooperative lift of dual-crane system

where d is distance between the main crane's slewing center and the tailing crane's. $R2_t$ and $R2_{t+1}$ are working radius of the tailing crane at time t and t+1. $R2_t$, $R2_{t+1}$, d and θ are calculated as follows:

$$R2_t = x2_{offset} + L2\sin\gamma 2_t$$
$$R2_{t+1} = x2_{offset} + L2\sin\gamma 2_{t+1}$$
$$d = \sqrt{(x2_t - x1_t)^2 + (y2_t - y1_t)^2 + (z2_t - z1_t)^2}$$
$$\theta = \arccos(\frac{R2_t^{\ 2} + d^2}{L3^2}) - \Delta\beta 2$$

In the flow, the key parts are motion sequence setting and state sequence generating of lift process, in which the basic motion as well as its geometric constraint should be defined in advance.

CASE STUDY

To illustrate the effectiveness and usability of the proposed approach, an actual case is presented. The case here involves the lift of propylene tower in petrochemical construction project in Beihai, Guangxi, China. The propylene tower weighs 500t and has 4.0m diameter and 84m length. Restricted by the site size, the propylene tower is located as Fig. 7 before lifting. The task of lifting is to raise the propylene tower to a vertical orientation by two cranes, and to move it to the final destination by a main crane. Here, we select CC8800 crawler crane as main crane and LR1400-2 crawler crane as tailing crane. The location of dual-crane system is shown in Fig. 7, in which the grid areas of foundation are strengthen to bear the weights of dual-crane system, and cranes can travel with object in these areas.

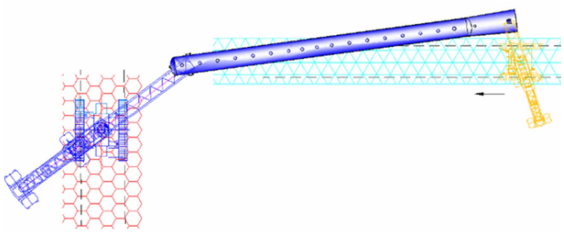


Fig. 7: Location of dual-crane system

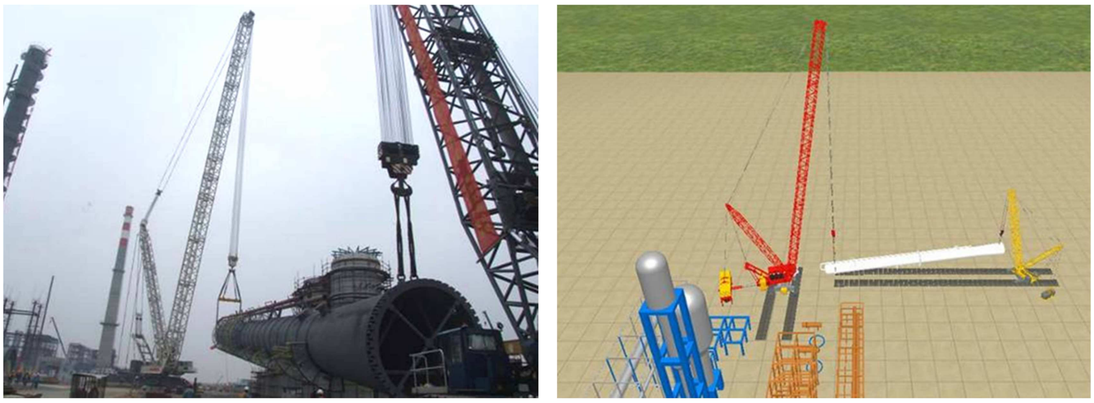
In this actual case, because of limitation of site size, the tailing crane is located not along the object's longitudinal axis (Fig. 7), which is difficult to plan motion strategy. By analyzed, the tailing crane should firstly turn the tower to the tailing crawler's longitudinal direction by slewing, and secondly travel with the main crane's lifting. Finally, the two cranes can raise the propylene tower to a vertical orientation successfully. For this process, it is easy to simulate the lift by using the modeling method developed in this paper. The lifting process description is as follows: The system carries out hoisting by 1m, and carries out main hook's rotating by 60o, and carries out tailing traveling by 89m.

After that, we integrate the modeling method into a 3D Lifting Simulation System which is developed by our team and simulate the lift process. The comparisons between the photos of real scene and the screen shots of simulation are shown as Fig. 8-10.

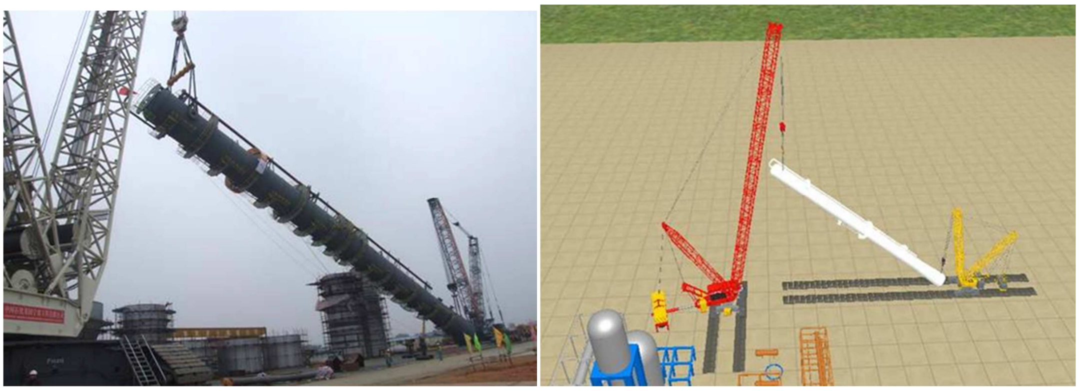
CONCLUSION

For the problem of dual-crane lift simulation with the lifting object's expected trajectory given, this paper focuses on the cooperation of the two cranes, A dual-crane system model is built, and its basic motions are defined and described. After that, a simulation flow facing typical lift is designed. At last, we validate the proposed approach's feasibility by an actual lift case.

The major contributions of this research are as following: (1) Two cranes and single object are treated as an integral complex lift system. Then, dual-crane's cooperation is deeply analyzed, and a new prospective for other cooperative strategy is proposed. (2) Dual-crane system's basic motions are defined with using space geometric constraint, by which lifting process with object's expected path is described.



(a) Photo of real scene (b) Screen shot of simulation
Fig. 8: State of dual-crane system during hoisting and main hook's rotating



(a) Photo of real scene (b) Screen shot of simulation
Fig. 9: State of dual-crane system during tailing traveling

(a) Photo of real scene (b) Screen shot of simulation
Fig. 10: State of dual-crane system when completing turning and erecting the object

It is necessary to be noted that the simulation flow introduced in this paper is mainly for common and typical lifting problems. For some special issues, some new motions should be added to accomplish its special simulation. In addition, some cooperative strategies' description is beyond certain space geometric constraint, so the simulating flow in this study may fail to simulate such dual-crane lifting. Those are our future research.

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