Automated Method for Checking Crane Paths for Heavy Lifts in Industrial Projects

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Abstract: At present, industrial projects are constructed primarily using a prefabricated approach. The modules are produced in an off-site facility and transported on transport trailers to the construction site where they are lifted by mobile cranes. One of the keys to the success of modular industrial projects is efficient crane planning, which includes path checking to find whether or not a crane has a feasible path through which to lift a module over obstructions in a congested plant. However, due to the large number of lifts, the manual path-checking practice is quite tedious and prone to error. In light of this problem, this paper proposes a methodology for automatically checking the lift paths for industrial projects. The proposed methodology simplifies and represents the three-dimensional site layout using project elevations. For each elevation, the crane feasible operation range (CFOR) is calculated based on the crane’s capacity and clearances, as well as site constraints. The pick area (PA) is calculated by subtracting the ground obstruction areas from the CFOR. The relative positions of the module’s set point, the CFOR, and the PA are checked to determine the feasibility of the lift path on each elevation, as well as the project elevation combination. This approach has been fully automated for path checking of entire sites, and the results are responsive to site changes over time as a project progresses. This proposed methodology is generic and thus can be easily applied to check lift paths for entire industrial plants or similar projects. DOI: 10.1061/(ASCE)CO.1943-7862.0000740. © 2013 American Society of Civil Engineers.

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Introduction

Most industrial projects involve construction using preassembled modules, which are shipped to the site and erected by mobile crawler cranes. Such heavy lifts are costly and difficult to manage, such that effective planning is the key to favorable project outcomes. A considerable volume of research has been conducted into heavy lift planning in the last two decades in various areas, including optimal crane positioning based on capacity and clearances; relocation; and lift path planning (Haas and Lin 1995; Zhang et al. 1999; Al-Hussein et al. 2000, 2001, 2005; Sawhney and Mund 2002; Hasan et al. 2010; Olearczyk 2010; Wu et al. 2011; AlBahnassi and Hammad 2012; Lin et al. 2012; Zhang and Hammad 2012).

Lift path planning is a subtopic of trajectory and path planning in construction. Previous research regarding trajectory and path planning have included path planning for on-site multipiece operations (Tseng et al. 2000); a multiobjective path planning framework for workers and vehicles on construction sites (Soltani and Fernando 2004); use of advanced technology to assist with path planning for construction operations (Teizer et al. 2007; Cheng et al. 2012); and a Google Earth-based system that can optimize the haulage routes for off-road dump trucks in construction and mining sites (Choi and Nieto 2011). Crane lift path planning examines the feasibility of the movement of the lifted object from its pick location to its final location. The current industry practice of lift path planning relies mainly on intuition and experience, thus lacking efficiency and being prone to error. Meanwhile, the nature of heavy industrial projects makes crane lift path planning for these projects particularly challenging: (1) industrial projects usually involve a large number of lifts (often over 100 modules per project), and so the process of manually planning these lifts is laborious; (2) heavy industrial projects are dynamic, and prompt updates of path planning results are necessary; and (3) industrial project sites are complex, usually with more constraints than other types of projects.

The research to date into lift path planning has focused mainly on developing algorithms and computer tools to generate detailed lift paths and reduce the human component in the planning process. The robotic motion planning method (Lozano-Pérez 1983) is still a popular approach for developing lifting path-planning algorithms, where cranes are usually treated as multi-degree-of-freedom robotic manipulators. One of the earliest research efforts to emerge based on the foundation laid by Lozano-Pérez’s research was a system for automated path planning for mobile cranes developed by Reddy and Varghese (2002) using the Configuration Space (C-space) method. Sivakumar et al. (2003) subsequently developed a system to automate path planning of two-crane lifts using hill climbing and A* heuristic search methods. Another method for two-crane path planning was developed by Al et al. (2005) using
a genetic algorithm. Since then, the visualization function has been incorporated into lift path planning. Kang and Miranda (2006) modeled the crane in a virtual environment in which collision-free and time-efficient paths for virtual cranes can be searched through motion planning algorithms. More recently, Chang et al. (2012) have developed a method to plan the erection path automatically for single and dual cranes, which converts the scene of crane erection into a configuration space, and adopts the Probabilistic Road Map (PRM) method to search for collision-free paths.

However, most studies in the past have considered individual lift-path-planning scenarios, while overlooking the question of how generally to manage lift paths for large-scale industrial projects. Industrial megaprojects require the lift-path-checking system to be more generic in order to facilitate module path checking of the entire site. Given this, the University of Alberta has been working closely with PCL Industrial Management, Canada’s largest general construction contractor, to develop methods and systems to improve the efficiency of heavy lift planning for industrial projects, including an algorithm to lift long items using mobile cranes (Hermann et al. 2011); resource scheduling for the lifted modules (Taghaddos et al. 2012); mobile crane positioning on-site (Safouhi et al. 2011); and a detailed algorithm for path checking based on the module’s set elevation (Lei et al. 2013). This paper presents the most recent progress as part of this research initiative, an extension of the work by Lei et al. (2013), which extends the path-checking algorithm from only checking on one elevation to checking on multiple project elevations. In this research, fully automated path checking is achieved and implemented in an ongoing industrial project, which reduces human components involved in the planning process.

Proposed Methodology

Main Process

For the purpose of timely data communication and sharing, PCL Industrial Management’s crane management programs are integrated and linked to a central database, where the project information and crane information is stored. PCL Industrial Management’s crane management program made up of three components: Advanced Crane Planning and Optimization (ACPO) (Hermann et al. 2010), Advanced Simulation in Industrial Crane Operations (ASICO) (Taghaddos et al. 2012), and the program based on the methodology proposed in this paper. ACPO calculates the possible crane locations for each module at its set position, considering the crane’s boom clearance and lifting capacity, whereas ASICO generates the lifting sequence of the modules based on the lift logic issues (e.g., the top module is the successor of the lower module). Following that, the crane locations and the lifting sequence are recorded in the database and serve as inputs for the path checking.

As for the path-checking approach, it is assumed that the project structure is constructed by modules simplified as box shapes (see Fig. 1 for a typical industrial module and its simplification as a rectangular box). In addition, since the project structure comprises stacked components that can be simplified as rectangular boxes, the three-dimensional (3D) site layout can be described and represented in terms of site elevations, where the project structure is assumed to remain invariant between adjacent elevations (Fig. 2). Based on this, the proposed methodology investigates the feasibility of lift paths at each specific elevation (i.e., path checking). The investigations begin from the highest elevation down to the module’s set elevation, and each investigation is performed on one elevation at a time. In addition, if the module does not have a lift path after all the elevations have been checked individually, the methodology subsequently checks the feasibility of the lift path through the overlaid elevation combination. The main process of the proposed path-checking approach follows the flowchart shown in Fig. 3. In this process, there are three primary functions: (1) determination of elevations; (2) path checking on individual elevations; and (3) path checking on the overlaid elevation combination. The function “path checking on individual elevations” consists of three subalgorithms: (1) elevation determination algorithm; (2) crane feasible operational range (CFOR) algorithm; and (3) pick area (PA) algorithm. These algorithms will be explained in detail in the following section, “Designed Algorithms.”

Designed Algorithms

The elevation determination algorithm identifies the elevations that can represent the project site layout. Ideally, all of the modules’ elevations will be taken into consideration. However, a trade-off needs to be considered: too many elevations can increase the computation workload, and thus result in inefficiency; too few elevations can lead to oversimplification of the site layout. Therefore, an elevation tolerance is provided as a user-defined parameter which determines the minimum height difference between two adjacent elevations. In this paper, the values of all elevations are calculated satisfying Eq. (1):

$$ET \leq |E_i - E_{i+1}| \quad (i = 0, 1, 2, \ldots, n - 1)$$

where $ET$ = elevation tolerance; $E_i$ = the elevation $i$; and $E_{i+1}$ = the elevation $i + 1$; and there are total $n$ elevations.

A CFOR is calculated for each determined elevation which represents an area where the crane can perform the lift without any collisions. The CFOR is calculated following three steps:
1. The mobile crane’s minimum and maximum radii (referred to in this paper as $R_{\min}$ and $R_{\max}$) are used to define an area where the crane can lift the module without exceeding its lifting capacity. $R_{\min}$ and $R_{\max}$ are usually calculated according to the crane’s capacity chart such that they satisfy the boom clearance and minimum required rigging height requirements.

2. The $R_{\min}$ and $R_{\max}$ are then modified, considering the crane’s boom clearance together with the obstruction and tail-swing equipment constraints. Fig. 4 presents a situation in which the boom conflicts with the obstruction at the $R_{\max}$ position; the CFOR is then modified accordingly (shown as the gray area in the Fig. 4). Fig. 5 shows how the existence of tail-swing equipment impacts $R_{\min}$ and $R_{\max}$, where an area is erased from $R_{\min}$ and $R_{\max}$ due to the tail-swing collision with the obstruction.

3. The motion planning method (Lozano-Pérez 1983) is applied in order to simplify the layout on the selected elevation. However, the rotation of the lifted module along the lift path is not considered. The PA for the lifted module is calculated satisfying Eq. (2), fulfilling three requirements: (1) the PA should overlap with the CFOR and the site boundary so that the crane can reach the module; (2) within the PA, the lifted module should not have any conflicts with the surrounding structures at the ground elevation; and (3) the PA should also overlap with potential pick areas (PPAs), which are specific areas, such as roads for delivery trailers, which have been pre-defined for module pick up. Once the CFOR and PA have been calculated, the feasibility of the lift path is checked employing Eq. (3):

$$PA = (CFOR \cap SB \cap PPA) - SOA_i$$

where PA = pick area; CFOR = crane feasible operational range; SB = site boundary; PPA = potential pick area; and $SOA_i$ = area of site obstruction $i$ ($i = 1, 2, \ldots, m$); there are a total of $m$ site obstructions.

Path checking result = \[
\begin{cases}
0 \ (\text{There is a path}) & \text{CFOR} \cap \text{PA} \neq \emptyset \ \text{and} \ \text{SP} \in \text{CFOR} \\
1 \ (\text{No path}) & \text{CFOR} \cap \text{PA} = \emptyset \ \text{or} \ \text{SP} \notin \text{CFOR}
\end{cases}
\]

Case Study and Validation

**General Information**

The proposed methodology is implemented as a program in Visual Studio 2010 to achieve automatic path checking of the entire site. The “Case Study and Validation” section is based on the results generated by the built program and consists of two parts:

1. Case 1 presents a path-checking example for one elevation that serves to demonstrate calculation of the CFOR and PA, based upon which path checking is performed on individual elevations; (2) Case 2 focuses on how the overlaid elevation combination is formed and on its application in checking the lift path, together with the final results of path checking for the project and the application of the current system.

The case study is based on an ongoing industrial project by PCL Industrial Management, located in Alberta, Canada, which involves lifting 200 modules and heavy vessels. The employed heavy mobile crane for this project is the Demag CC 2800, equipped with a 660-t capacity and a superlift tail-swing. The possible crane locations for each module are calculated by the ACPO program, and the lifting sequence is generated by the ASICO program (see the “Proposed
locations. For this project, ACPO has generated a total of 89,252 possible crane locations for all the modules, and each module has multiple potential crane locations. ASICO, based on the results of ACPO, performs schedule planning, primarily considering the lift logic issues. The logic issues are defined based on the precedential relationships among modules, which further generate a complete lift sequence. Fig. 6 presents all the calculated crane locations for the module and the site layout. The inside and outside boundaries define the inaccessible areas for crane settlement and the site boundary, respectively. The objective of employing the proposed methodology in this project is to automatically check the lift path for every crane location, and filter out the locations without feasible lift paths.

The project elevations are determined based on the modules' installation elevations and the elevation tolerance. The elevation tolerance is given as a user-defined parameter that defines the minimum height difference between two adjacent elevations. Since there is no industry standard for elevation tolerance, this value is determined by engineers based on their experience; in this project, 1.5 m (5 ft) is used as the elevation tolerance. Based on the calculations of project elevations made using Eq. (1), a total of 11 project elevations are generated.

**Case 1 (Single-Elevation Path Checking)**

In Case 1, the module PR-075, with a gross weight of 30.53 t (67,305 lb), is selected for path-checking analysis. The ACPO
has generated 354 potential crane locations for this module (Fig. 7 shows the module at its set position with all the selected crane locations), among which one location is selected for the path checking. The module’s set elevation is used to demonstrate the calculation of the CFOR and PA. Fig. 8 presents the calculated $R_{\text{min}}$ and $R_{\text{max}}$ at the selected crane location, based on which the CFOR in Fig. 9 is calculated. At Area A, a sector is removed from $R_{\text{min}}$ and $R_{\text{max}}$ due to the superlift tail-swing constraint, and at Area B the $R_{\text{max}}$ is modified due to the installed modules. The generated CFOR represents the area where the crane can perform the lift without any collision at the module’s set elevation. Fig. 10 presents the PAs (outlined in blue), which represent the areas where the crane can pick the module. Since the CFOR overlaps with the PAs and the lifted module set position falls within the CFOR, the

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**Fig. 6.** Case study site layout

**Fig. 7.** Module set position and crane locations

**Fig. 8.** $R_{\text{min}}$ and $R_{\text{max}}$

**Fig. 9.** CFOR for Case 1

**Fig. 10.** PA for Case 1
path-checking program determines using Eq. (3) that there is a lift path for the target module.

To validate the results, a 3D lift study has been conducted. The total module weight is calculated, including the module gross weight, load block weight, rigging weight, and other additional weight. The calculated total module weight at the set position is 78.48 t (approximately 173,019 lb). By checking the capacity chart provided by the crane manufacturer, the maximum radii at the pick point and the set point for this weight are 54 ft (177.2 m) and 85.3 ft (26 m), respectively, and the corresponding chart capacities are 100.92 t (approximately 222,490.55 lb) and 259 t (approximately 571,997.36 lb). The crane is proven to have enough capacity at its pick location and set location. At the pick location, the crane consumes 77.8% of its full capacity, while at the set location, only 30.3% of its full capacity is used. In addition, the boom clearance check is performed to guarantee sufficient clearance for the lift path.
At the pick location, the crane has a boom clearance of 64 ft 5 in (19.6 m), while at the set location the clearance is 10 ft 9 in (3.3 m). The lift study also checks the lifting surroundings to ensure that the lift path is valid.

**Case 2 (Overlaid Elevation Combination)**

In Case 2, another module, PR-011A, with a gross weight of 111.92 t (approximately 246,741.41 lb), is selected to demonstrate how the overlaid elevation combination is used for path checking (Fig. 12 presents the module set position and selected crane location). For different project elevations, the crane’s operation range varies due to the boom clearance, rigging height, and capacity requirements. The CFORs and PAs are calculated for each project elevation (shown in Figs. 13 and 14 with different colors). According to the results, the CFORs on higher elevations represent more constrained operation ranges due to the boom clearance and rigging height requirements, but meanwhile they involve fewer obstructions than at the lower elevations; similarly, the crane encounters more feasible operation ranges at lower elevations, but more obstructions. By overlaying the CFORs and PAs from different elevations (Fig. 15), the OCFOR and OPA are obtained, which represent the feasibility of lifting and picking the module from different elevations. The obtained OCFOR and OPA are used for path checking using Eq. (4), such that a feasible lift path is found to exist for the selected crane location. The corresponding lift study by professional engineers for this module shows that the crane consumes 67 and 64% of its full capacity at its pick position and set position, respectively. The study also gives a boom clearance of 10 ft 5 in. (3.2 m) and 11 ft (3.35 m) at the pick position and set position, respectively. Automatic path checking is performed for the entire site using the built program. Selected for the modules are 155 crane
positions, and the results show that there are 122 crane locations (78.71%) that have lift paths and 33 crane locations (21.29%) that do not have lift paths, considering fixed crane locations (Fig. 16). For the failed crane locations, the writers are currently developing alternative solutions, such as crane walking with load.

Conclusions and Future Research

This paper proposes a generic methodology for mobile crane lift path checking in large-scale industrial construction. The proposed methodology considers the general constraints that appear on industrial projects and can be used to perform path checking for similar projects. A computer program has been developed based on the proposed approach that achieves automatic lift-planning calculations. The developed program is linked to the company’s central database and communicates dynamically with other developed programs.

The path-checking process begins with determining elevations for the representation of the industrial plant. The determination of elevations is based on the modules’ respective elevations coupled with an elevation tolerance to establish an appropriate balance between computation workload and oversimplification. Based on the defined elevations, the feasibilities of lift paths have been investigated for each elevation. This investigation has consisted of the three steps described earlier in greater detail: (1) the CFOR, an area where the mobile crane can perform the lift without any conflict, is calculated based on the crane’s capacity, boom clearance, tail-swing constraint, and site obstruction constraints; (2) the module’s PA is calculated by subtracting the obstruction areas on the ground elevation from the CFOR; and (3) the CFOR is checked for overlap with the PA as well as to determine whether or not it contains the module’s set point (if so, the module has a lift path; otherwise, other elevations need to be checked or alternative solutions need to be provided). A case study based on an industrial project has been presented to demonstrate the capabilities and flexibilities of the proposed approach, in which the path-checking approach was applied to investigate the feasibilities of lift paths for preselected crane locations. However, it should be noted that the functionality of the proposed approach is not limited to this case, as it can be employed to assist in solving other heavy lift-planning problems. This approach benefits practitioners by automatically providing accurate path-checking results, which can be updated promptly to respond to changes to the given project. However, the limitations of the current work are (1) it is assumed that only one mobile crane performs the lifting, without any simultaneous crane operation; simultaneous crane operation on a given lift is a possible additional constraint for path planning that is not incorporated into the current algorithm; (2) the project elevations assist in simplifying the site layout, but meanwhile ignore the possible obstructions between elevations; (3) the number of elevations is determined by the elevation tolerance, which needs to be further tested in different projects to obtain a standard value; and (4) alternatives for crane locations without lift paths need to be added. In subsequent research, the writers wish to utilize path checking to identify the logic constraints of a given lift sequence. In addition, the writers expect to develop a model that can automatically generate detailed crane operation animations for the entire project for the purpose of visualization and collision detection.

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