A Framework of Lift Virtual Prototyping (LVP) Approach for Crane Safety Planning

Y. Fang[a] and Y. K. Cho[a]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology
E-mail: yihaifang@gatech.edu, yong.cho@ce.gatech.edu

Abstract –

Many crane accidents occur due to a lack of understanding of potential constraints present on lift sites, especially the spatial conflicts with inadequate clearance to surrounding obstructions. Even the most thorough lift plans can be compromised by changes in lift sites such as a newly-erected frame in the crane workspace or a sudden presence of another equipment. Therefore, it is critical for the lift crew (i.e., planner, rigger, signalman, operator) to be aware of the condition and potential constraints in the as-is lift settings prior to conducting the actual lift job. This study proposes a framework of Lift Virtual Prototyping (LVP) approach to assist quick lift planning based on actual site settings. This is achieved by rapid modeling, simulating, and analyzing crane lifting operation by reconstructing as-is site conditions and incorporating the characteristics of individual operator. The proposed LVP approach was implemented in a case study and the results showed that the LVP approach is effective in familiarizing the lift crew with potential constraints existing in the lift site and improving the operator's confidence in conducting the lift job safely and efficiently. Implementing this approach in daily lifting operations will facilitate the recognition of operation constraints that are difficult to be identified in the planning phase, and thus advance the crane operational safety and efficiency.

Keywords –

Lifting Virtual Prototyping (LVP); obstruction recognition; spatial conflicts; Crane safety planning; Lift safety and efficiency

1 Introduction

A crane is one of the most essential and commonly used construction machinery present on the various construction sites of buildings, plants, and bridges. Given the magnitude of a crane's weight and the workspace it occupies, the potential loss of property and life due to incidents related to cranes is tremendous. From 1997 to 2013, 1171 fatalities were observed in crane-related accidents in all industry sectors in the US, among which construction industry alone was responsible for 544 fatalities accounting for nearly half of the deaths in all sectors combined (Bureau of Labor Statistics (BLS) 2015). Many of these accidents are were due to inadequate lift planning or failures to identify lift constraints existing on complex and changing construction sites.

Virtual prototyping (VP) originated from the manufacturing industry especially in the automobile and aerospace fields. During product development, VP helps to validate a design before committing to making a physical prototype. Through computer-aided design (CAD) and computer-aided engineering (CAE) software, the designers and engineers can test the mechanical motions and functions, and simulate the behavior of the product in the real world. The manufacturing industry and the construction industry share many similarities and thus the construction industry has benefited from many concepts adopted from manufacturing industry such as lean construction and prefabrication. Recently, the VP method has drawn much attention from the academics and practitioners in the construction industry.

As an early attempt in this direction, Huang et al. introduced the concept of VP in the construction industry, termed construction virtual prototyping (CVP) [1]. They envisioned that CVP will enable project teams to model, simulate, and analyze the construction processes before the commencement of the project. The CVP, therefore, allows them to check constructability and safety issues in advance so that rework and construction defects can be minimized. Li et al. introduced a framework for efficient implementation of CVP in the construction planning phase [2]. They reported the application of the CVP in an office building project and the findings shows that the CVP can reduce construction risks and enhance the communication and collaboration between construction stakeholders. Dong et al. adopted a virtual prototyping environment as it provides a configurable setting to evaluate the augmented reality-assisted method for building damage reconnaissance [3].

In light of the CVP concept, this study proposes a lift virtual prototyping (LVP) approach to enhance lift safety and efficiency on construction sites. This paper starts with a review of the practices and techniques used in traditional lift planning. Then, a framework of the LVP approach is introduced with details in the steps of modeling, simulation, and analysis. It is followed by a case study and validation of the LVP approach in a real world implementation. The last sections discuss the limitations and envision the future work in the LVP approach.

2 Related Work

Within the huge workspace of cranes, the presence of built structure components, overhead power lines, and the workspace of other equipment induce massive spatial conflicts during crane lift operations. Suruda et al. reported that 40% of the deaths in crane-related accidents were related to spatial conflicts [4]. Among 632 crane-related deaths from 1992 to 2006, 61% of all fatalities involved crane parts or loads colliding with obstructions (e.g., power lines, personnel, structure) [5]. Therefore, designing crane locations [6], calculating the lift range and crane boom reach based on load chart [7], and planning a collision-free lift path [8] are important planning tasks in order to mitigate the collision hazards and improve lift efficiency in crane operation.

In crane lift planning, lift path planning is an important task to ensure lifting safety and efficiency. The goal of path planning is to plan a collision-free and efficient lift path based on load data and site geometry constraints. Traditionally, the lift path was planned largely depending on the planners' intuition and experience and thus this process is often labor intensive and error prone [9]. Recently, researchers have adopted the knowledge and techniques in robotic motion planning in lift path planning trying to automate the lift planning process. In this approach, a crane was treated as a multi degree-of-freedom robotic manipulator and various searching algorithms were tested to optimize the lift path to ensure a collision-free travel for the lifted load while guaranteeing a respectively short lift path [9]. To validate the advantage of computer-aided path planning , researchers have extensively investigated different algorithms including Heuristic Search [10], Ant Colony Algorithm [11], Probabilistic Road Map (PRM) [12], and Rapidly Exploring Random Tree (RRT) [13]. Findings from these research efforts have demonstrated that using computer-aided path planning techniques can greatly improve the accuracy and efficiency in path planning.

It should be noted that computer-aided path planning only works when provided with accurate and comprehensive site geometric information. Site geometric information, however, is not always available or accurate in the early planning phase. In addition to static obstructions, when analyzing crane-related spatial conflicts, one must consider the dynamic crane motions and condition changes in the surrounding environment as the project proceeds [14]. Design changes occur throughout the planning phase and even during the construction phase. It is not practical, however, to re-plan the lift path for every design change. In addition, site drawings or models used for lift path planning can hardly represent all the geometric constraints existing in the actual lift site. For instance, temporary structures such as scaffoldings and formworks are often not included in the design model and thus won't be considered in the path planning. These variances between the planned and actual site conditions will inevitably compromise the validity of the planned lift paths. Furthermore, the lift job will be eventually performed by a crane operator who might not prefer or not be able to follow the exact planned path. Although the operator is required to be involved in the lift planning and be familiar with the lift plan, he or she will most likely execute the lift job based on their judgements in the actual situations. Therefore, it is critical for the lift planning to consider the actual as-is condition of the lift site and to involve the operator in the planning by incorporating their individual operation preference and tendency.

3 Lift Virtual Prototyping (LVP) Framework

The objective of the Lift Virtual Prototyping (LVP) approach was to plan the lift based on actual site settings and the actual capabilities of the lift crew. This was achieved by rapid modeling, simulating, and analyzing crane lifting operations with as-is site conditions and the characteristics of an individual operator. Figure 1 shows the framework of the proposed LVP approach and the following sections will introduce the details in each part of the framework.

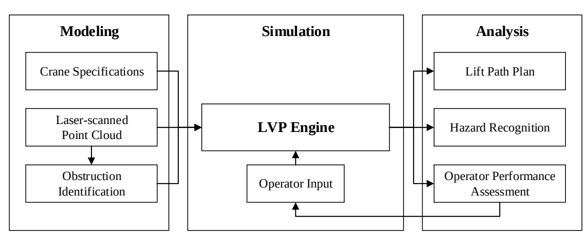

Figure 1: Framework of the Lift Virtual Prototyping (LVP) approach

3.1 Lift Scenario Modeling

Cranes are different in types, size, and capacity, and thus it is important in the LVP to model the critical crane configurations according to the actual crane. This can be accomplished by modifying an existing crane model according to specification of the actual crane that will be used for the job. A major limitation in traditional lift planning approach is the lack of information to represent the as-is lift site condition. Recent advances in rapid geometry data acquisition makes it possible to obtain massive 3-dimensional (3D) geometric data in a short amount of time with minimal effort. This study adopted laser scanning technology that can rapidly and accurately capture the shape and geometry of a physical scene. The scanned scene is represented by a dense point cloud comprised of millions of points, each of which contains position (XYZ) and color (RGB) data. This technology, therefore, is suitable for wide range measurement given only a limited amount of time.

To reconstruct as-is lift scenario, the laser scanned point cloud need to be converted to bounding boxes to represent these site obstructions. The pipeline of obtaining oriented bounding boxes for various objects in a point cloud involves the steps of segmentation, clustering, and orientation estimation. The input point cloud is first down-sampled to 10% of its original size by performing voxel grid filtering. Next, ground plane segmentation is performed using Random Sample Consensus (RANSAC) [15]. Points from the ground plane are filtered out so that object points can be separated nicely in the clustering step. The ensuing clustering step involves grouping points that are contained within the same neighborhood together and labeling each group as an individual cluster. The threshold parameter can also be manually adjusted so that points belonging to the same object would not be split into separate clusters and points belonging to different objects would not be grouped into the same cluster. Finally, an oriented bounding box is computed for each point cluster by considering the physical spread of points in the z-axis (vertical axis) and the x-y-plane. Principal Component Analysis (PCA) [16] is used to determine the two principal directions in which points in the cluster vary the most in the x-y-plane. The principal directions are used to determine the orientation of the object's bounding box in the x-y-plane. The final bounding box is then computed by determining the maximum and minimum length along the vertical axes and the horizontal principal axes. The total computation time for this process largely depends on the down-sampling ratio but it only takes a couple of minutes for a down-sampled point cloud with around 10,000 points.

3.2 Lift Simulation

The crane model, site point cloud, and the bounding boxes of the identified obstructions were imported into a LVP engine powered by Unity 3D game engine. The LVP engine can simulate actual lighting and wind conditions, customize data input/output, and support close-to-reality physics simulation, such as load pendulum motion. A major advantage of using LVP in lift planning is that the variances among the skill and experience of different operators are considered in the prototyping process so that the results can reflect actual proficiency of individual operator in executing a particular lift task. The operator can practice and rehearse the lift task in the LVP engine with the presence of actual constraints. As such, their ability to recognize and react to hazards is incorporated and will influence the prototyping results. From a training perspective, the operator can continuously rehearse the lifting until a satisfying safety and efficiency results is achieved.

3.3 Safety and Efficiency Analysis

One major objective of the LVP approach was to introduce as-is site conditions, especially geometry constraints, in order to advance the accuracy and practicality of traditional lift planning. The results of the LVP approach was analyzed from different safety and efficiency perspectives. The safety analysis is enabled by continuously monitoring and measuring the proximity of the lifted load to surrounding obstructions and lift capacity by comparing the actual lifted load to the rated allowable capacity. Two measurements (i.e., $I_{clearance}$, $I_{overload}$) are automatically recorded during the LVP process to reflect the ability to maintain a safety clearance to obstructions and the ability to maintain a safe load capacity:

$I_{clearance}$ – Incidence that the load is within dangerous clearance (2m) to obstructions.

$I_{overload}$ - Incidence that the capacity is beyond 75% of the rated capacity.

The efficiency of the lift job is evaluated by the overall ability to efficiently complete a task and the ability to select an efficient lifting path. They are indicated by the following two measurements:

T_{total} - Total time spent for the lifting task.

D_{total} - Total distance the hook travels during the lifting task.

4 Case Study

The proposed LVP approach was implemented in a real world lift task to evaluate its effectiveness in lift planning. This lift task adopted a 70-ton telescopic boom mobile crane to lift a 25 ton load from its original location to a trailer. A telescopic boom crane model downloaded from 3D Warehouse was modified according to the specifications of the actual crane in order to model critical geometries such as boom length, boom slewing pivot point, and load shape and size.

As-is geometric data of the lift site was acquired by using a commercially available laser scanner. Six scans in low resolution setting was conducted around the site which took 40 minutes in total. These scans were then registered as a single point cloud and converted to PTS format. This point cloud was processed by the obstruction identification algorithm and as a result 92 bounding boxes were automatically generated. Finally, the crane model, point cloud, and the bounding boxes of the identified obstructions were visualized in the LVP engine (see Figure 2).

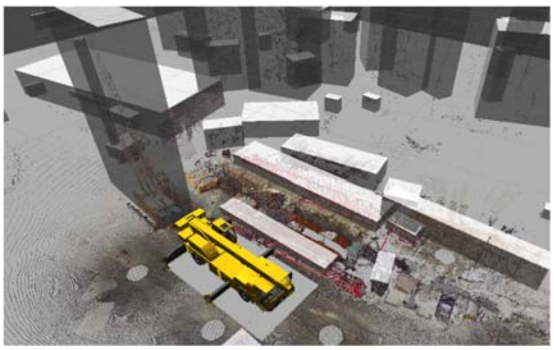

Figure 2: Reconstructed virtual lift scenario with laser scanned point cloud and bounding boxes generated for identified obstructions.

Operator involvement in the prototype was realized by providing the operators an immersive and interactive game type virtual environment where they can rehearse the lift in the simulated as-is lift site condition. To maximize the immersive feel of the operator in the prototyping, a head-mounted display (HUD) was adopted as the primary user interface (see figure 3). A gamepad was used to simulate the actual crane control where two joysitcks replace the levers and trigger buttons replace the pedal (see Figure 4).

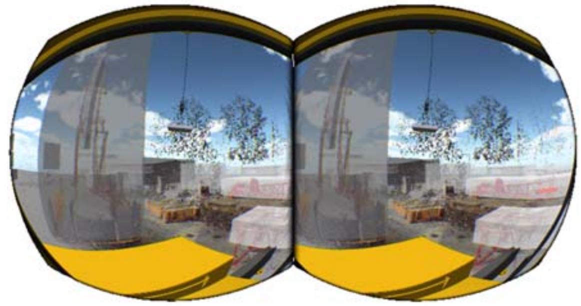

Figure 3: Simulated lift scenario in an HUD interface

Figure 4: Operator input in the VLP process

To validate the effectiveness of LVP approach in identifying constraints existing in the lift job, the analysis results in the LVP approach were compared to the results of analysis based on traditional 2D drawings and experience. Two crane operators were asked to perform the lift. They had similar levels of training and

Table 1: Planning result comparison between traditional planning and LVP approach

	Traditional planning	LVP approach
Safety Analysis	• Potential proximity hazards: crawler crane, spare jibs, trailers • Boom reach < 32m	• Time and location of proximity and overload incidents • Recorded incidents for review
Efficiency Analysis	• Rough lift time estimation: 4 min	• Simulated lift time: 3 min 35 sec • Simulated lift path: 95.3m • Recorded lift path for review

experience in operating this particular type of crane. As such, we assumed that they hadsimilar proficiency in crane operation, hazard recognition, and decision making. The hazards to be identified were limited to proximity between the load and surrounding obstructions and the cases when load was beyond 75% percent of the rated capacity. Table 1 shows the comparison between the LVP and traditional planning results.

Based on limited site information, traditional planning provides subjective judgements and rough estimations of potential hazards that might occur during the lift operation. LVP approach, taking advantage of as-is site information, provides a more accurate simulation of the actual site conditions. As such, the lift simulation is closer to real lift performance and thus provides more detailed planning results such as the exact time and location that potential hazards might occur, which offers the lift crew an opportunity to take action in advance or pay more attention during the lift. In addition, the hazards and efficiency constraints identified in the simulation can be reviewed in a virtual environment that allows further investigation (see Figure 5).

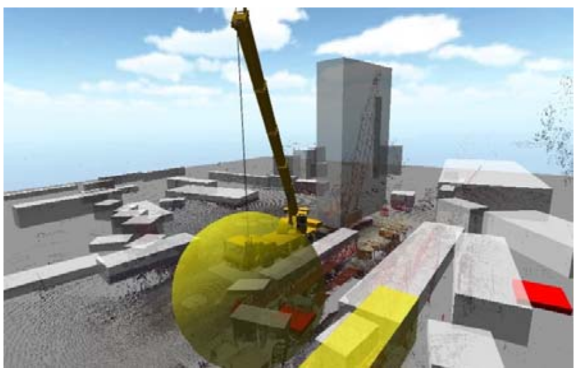

Figure 4: Hazard identification in LVP

5 Conclusions

Traditional lift planning is a manual process based on outdated information and thus can hardly address the actual lift site constraints. This study proposed a Lift Virtual Prototyping (LVP) approach to plan the lift based on actual site settings. This is achieved by rapid modeling, simulating, and analyzing crane lifting operation by incorporating as-is site condition and the characteristics of individual operator. The benefits of the LVP approach over conventional crane lift simulation are in twofold. First, it takes the as-is environment into the prototyping process so that constraints, which are not identified by conventional simulation, can be recognized. Second, it emphasizes more on human-operation interaction by involving the same operator that will perform the lift in the prototyping. The simulation, therefore will not only identify hazards that are more prone to this operator, but at the same time familiarize the operator with the lifting process in advance. The LVP approach was implemented in a real world lift operation and its effectiveness was validated by comparing the prototyping results to conditional planning results. Although the test results show a great potential of the LVP approach in crane lift planning, the current state of the LVP approach is not fully-automated and the preparation of the LVP engine requires an expensive laser scanner that might not be available for small projects and personnel with limited knowledge and experience in data acquisition and processing. Future work will be directed toward exploring technologies that are less labor-intensive in data collection and automating the process of LVP engine preparation.

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