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Automating motion trajectory Of crane-lifted loads

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ABSTRACT

Crane Lifting Path Planning (CLPP) is an important task, especially in congested construction sites. This activity becomes extremely complex since, as the project advances, new (and sometimes unpredicted) constraints may occur. These constraints force lift engineers to explore the possibility of alternative paths for the objects still to be moved. Under severe time constraints, manual analysis of such paths is practically impossible, which makes it necessary to rely on computer implementations in order to avoid project delays. From a mathematical standpoint, if the crane payload trajectory is to be defined analytically, the polar coordinate system,(r, θ), is naturally the most suitable. As a result, this paper proposes an algorithm for CLPP in which the path is represented as a piece-wise continuous function where each portion is defined either by constant radius (rotation of the load) or a constant angle (translation of the load). In other words, rather than forcing a crane to adapt to unnatural rectilinear trajectories as obtained by traditional path searching procedures, it is the trajectory that is adapted to the crane motion. In fact, even though (mathematically) a precise balance between the rates of rotation and translation of the jib (or boom) will make the payload follow any continuous path (regardless of its complexity), the coupling between the rotations and translations increases the difficulty of the lifting activity. However, a crane lifting path in which these motions are uncoupled will lead to less stringent requirements in terms of controlling the balance between rotations and translations.

1. Introduction

Using computer technology to design construction equipment has brought changes to equipment functionality, productivity, and the construction industry. Mobile cranes, in particular, have increased in size, capacity, manoeuvrability, and versatility. The significance of misusing or improperly planning a crane lift can be severe. The preparation and planning of heavy lifts (usually 85% of crane lift capacity or more) can be complex and involve challenges during lift analysis. Fast-tracked construction projects involve frequent changes to the construction plan, thereby requiring a number of what-if scenarios and modifications to the lift plan. Due to these factors, lift engineers rely on complex computer algorithms to make informed decisions in which there is no room for guess work. Virtual reality, combined with an interactive planning environment that explores human potential, is an efficient alternative for spatial integration. In a well-known article introducing spatial integration in construction [2], has presented the historical advancement and objectives of this technology. In other studies, researchers have borrowed concepts from the field of robotics, e.g., configuration space (C-Space), which has opened a new approach for generating crane lifting paths [7].

Generating the shortest collision-free paths for crane lifting operations is an important challenge for the (heavy) construction industry, especially since it moved toward modularization as one of its major project delivery paradigms. As a result, there is a growing need for mathematical models and technologies that can help managers to precisely and easily plan crane operations, regardless of the level of congestion encountered on site. From the point of view of technological innovation, the introduction of sensing devices to improve safety and efficiency of crane operations has opened new research opportunities, especially in the context of sites with multiple cranes where coordination is paramount. In this context, Lee et al. [5] have developed a laser-based lifting-path tracking system for a robotic tower crane system. However, although this technology is expected to improve productivity by as much as 50%, further investigations are needed in order to determine its robustness when subject to the harsh conditions of construction sites, e.g., dust, vibrations and rainfall. In a subsequent

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contribution, the sensing technology introduced by these authors was integrated within a Building Information Model (BIM) in order to extend its application to the case where a tower crane is operated in the presence of blind spots, i.e., blind lifts [4]. In terms of mathematical modeling and algorithms, the importance of Crane Lifting Path Planning (CLPP) in the construction industry has drawn the attention of many researchers, who have proposed a variety of procedures allowing lifted objects to be moved around obstacles. These algorithms, known collectively as motion planning, path finding, or path searching, have been well developed in the field of computer science and can be viewed as graph traversal methods in which some form of optimality is sought. Among the most widely used procedures for optimal path finding are: (*i*) Dijkstra's [10,12]; (*ii*) the A* (A star) [10,9]; (*iii*) evolutionary algorithms including Genetic algorithm optimization [10]; (*iv*) the Configuration Space (C-space) [7,3]; and (*v*) Rapidly-exploring Random Trees (RRT), not to mention the numerous variations that were built on top of the above listed algorithms. In the specific context of CLPP, it is worth noting that Soltani et al. [10] have evaluated the performance of three of the above algorithms, namely Dijkstra's, A* and GA. They concluded that: (*i*) Dijkstra's method can find an optimal path, but that its efficiency deteriorates as the complexity of the problem at hand increases; (*ii*) the A* approach, being essentially an optimal form of Dijkstra's, is relatively more efficient than its predecessor but still becomes impractical for large-scale problems; and (*iii*) GA based path searching is naturally probabilistic, which means that its solutions may be less accurate than the first two, but that it has the ability to remain efficient even in the case of problems with large dimensionality. More recently, Zheng and Hammad [13] have developed a remarkable variation of the RRT algorithm, referred to as RRT-Con-Con-Mod, which allows paths to be generated dynamically as a means to improve efficiency and safety, especially when unexpected changes are encountered on construction sites. A smoothing procedure is applied to the paths generated by the RRT-Con-Con-Mod algorithm in order to reduce their roughness, which allows unnecessary movements to be avoided.

Historically, path finding methods have been developed primarily in the context of robotics and have been geared toward determining the shortest obstacle-free path between two points. As a result, these paths are often represented as polylines, i.e., piece-wise continuous linear functions, since straight lines are very simple yet well adapted trajectories for a moving robot. However, while such a topology is coherent with respect to the way robots move, it is unnatural for a crane payload, since at a fixed elevation its trajectory regardless of its complexity is generated by rotating and translating selected components of the crane. In other words, a rotation and translation can be viewed as a basis that can be used to describe a crane lifting path in the same way as $\overrightarrow{i}$ and $\overrightarrow{j}$ are used to describe any vector in a 2-D plane. Interestingly, Kang & Miranda [3], who developed a procedure based on the C-space, raised the issue of polyline trajectories and devised a procedure to smooth the piece-wise linear path in order to obtain more realistic trajectories. However, although this smoothing process yields a curvilinear path, the crane operator may still require a great deal of control in order to balance the rotation and translation speeds in order for the payload to follow this path. The main objective of this contribution is to provide a CLPP alternative that contributes to solving the problem of rectilinear crane lifting paths. Indeed, rather than using standard robot path planning algorithms and then adapting (to some extent) the resulting trajectory to the specifics of a crane, the proposed algorithm seeks a trajectory that can be expressed as a sequence of simple rotations and translations in which smoothness—i.e., the number of rotation-to-translation transitions—is minimized. This approach is fundamentally different from previous work.

In the section which follows, this paper presents the two basic building blocks underlying the algorithms described in this work: (*i*) the decomposition of a crane lifting path in terms of the basic motions of a crane; and (*ii*) a brief review on developing and merging polygonal envelopes around obstacles. In Section 3, we review some fundamental properties of the A* algorithm, which has been selected for this research because of its simplicity. Issues related to the topology of the paths obtained using robot path planning procedures are also discussed in the context of CLPP. In Section 3.1 an initial (and less efficient) algorithm using rotations and translations is proposed. It starts by building around obstacle envelopes shaped in the form of circular sections whose centers are the crane locations. Once overlapping areas are merged, a path following the contours of these circular sections is constructed by means of a binary tree. Although useful on sites with little congestion, this algorithm may fail to find a lifting path when the congestion increases. This is due to the fact that merging the circular sections, which often are much larger than the obstacles, tends to unnecessarily exclude large portions of the construction site. The second algorithm, described in Section 3.2, is developed to solve this very issue. In the context of this CLPP procedure, the envelopes around the obstacles are constructed in such a way as to exclude the least area of the construction site. A circular grid centered on the crane location is overlaid on the construction site and then mapped onto a matrix where cells containing obstacles receive an infinite weight. This matrix is used for path searching using the A* algorithm. Finally, we provide a case study in which this algorithm was used to assess its practical usefulness.

2. Methodology

Over the past few decades, modular construction has emerged as the paradigm of choice for heavy industrial construction, allowing practitioners to reduce the uncertainty related to harsh and unpredictable weather conditions. Module fabrication, which relocates construction activities to controlled environments (i.e., fabrication plants), has become increasingly efficient as optimization techniques such as lean manufacturing are utilized. As expertise in modularization has improved, construction professionals have sought to increasingly integrate modular construction technologies into their projects. Meanwhile, the fabricated modules have become heavier and more voluminous, thus requiring high capacity cranes for on-site assembly. Consequently, minute planning of crane lifts has become a crucial activity for managers in order to ensure safe, timely, and economical project delivery. This is particularly important on congested sites where the risk of collisions between the payload and the surrounding obstacles is high. In essence, for a given load which is to be moved, at a fixed elevation, from its Pick Point (PP) to its Set Point (SP), the optimal path (in the absence of obstacles) can be described by Fig. 1, in which the object's trajectory is represented by a dotted line.

Under the fixed elevation assumption, the path of any object can be represented by a sequence of rotations and inward or outward translation. For instance, the path $\wp(PP \rightarrow SP)$ from the pick point PP to the

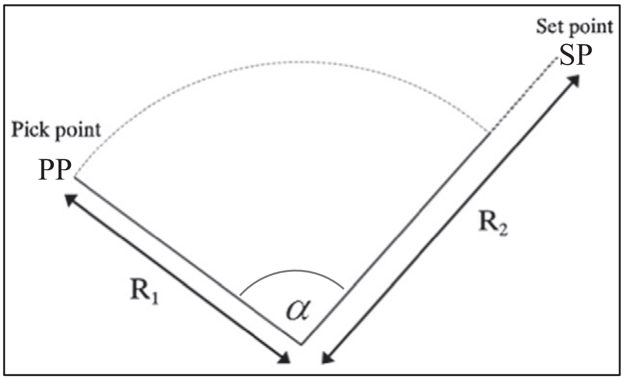

Fig. 1. Crane lifting path for a load picked at PP and set at SP in the absence of obstacles. The path is represented as a dotted line.