Construction Equipment Collision-Free Path Planning Using Robotic Approach

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Abstract –

Path planning is crucial in constructability analysis and heavy construction equipment scheduling, particularly in industrial plants. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free. The current planning practice, even in industrial projects whose sites are extremely congested, is manual based on the expert judgment. Thus, this sophisticated manual process is not only prone to errors, but also time-consuming. This research presents an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. The proposed methodology finds the shortest path for the planar motion of any convex 2D object. It assumes continuous translational (i.e. X and Y directions) and discretized rotational motions for the object. Two case studies are also presented to illustrate and to validate the proposed methodology.

Keywords –

Construction Equipment; Collision-free Path Planning; Robotics; Automation in Construction

1 Introduction

Dams, bridges, roads, industrial plants, and other construction mega-projects heavily rely on the utilization of heavy construction equipment. Construction equipment planning and management is a sophisticated task due to its interrelationship with dynamic activities (i.e. workspace logistics, material delivery, and equipment allocation) [1]. Thus, improper planning and management of construction equipment would lead to unsafe, inefficient, and unproductive construction projects. Nevertheless, current construction equipment planning practice is manual and extremely depends on engineers' intuition, experience, and imagination and is proceeded by trial and error methods. Thus, this sophisticated manual process is not only prone to errors but also time-consuming. Additionally, complexity, uncertain nature and dynamic conditions of congested construction sites require frequent and short-term re-planning. Therefore, to maximize productivity, developing effective and flexible tools would be necessary to help engineers manage these pieces of equipment.

The movement of mobile construction equipment is one of the principal causes of fatalities on a construction site. A collision-free path for construction equipment can reduce the risk of worker injury and fatality [2]. Such a collision-free path can decrease the probability of workspace conflict, enhance construction equipment management, and increase the productivity of the construction process. As a result, path planning analysis plays a pivotal role in constructability analysis and heavy construction equipment scheduling, particularly in congested industrial plants.

This research aims to present an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free.

The sub-objectives of this research are as follows: (1) developing and enhancing a methodology for finding the shortest path for the planar motion of any convex 2D object.; (2) using the method to determine the shortest collision-free path on a construction site for mobile construction equipment; (3) providing a visualization tool in CAD environment in order to present and evaluate the results and the whole process. Planners should be able to evaluate the user-defined variables and the final output. This research proposed a computer program to meet these goals and provides engineers with a computational, visual, and interactive way of decision making support systems. The proposed method is validated by some pilot case studies to prove that it can provide a visually effective and efficient result.

2 Literature Review

An effective construction equipment planning and control includes (1) site planning, and (2) heavy construction equipment movement control [1]. A lot of studies conducted to make these processes more efficient and flexible particularly by using computer-based automated solutions. For example, type and location optimization [3], resource allocation optimization [4], path checking [5], activity analysis and control [6] concentrate scholars' attention in recent decades.

Path planning is a sub-process in robots' motion planning and aims to find a collision-free path between the initial and goal configuration of the robot. The construction equipment path planning problem is potentially interchangeable to the path planning problem of mobile robots. A fundamental study conceded by Lozano-Pérez [7] proposed a method called "configuration space (C-Space)" to solve 2D motion planning problems for 2D convex mobile robot objects. The pivotal idea of this method is to reduce the dimension of the moving object's shape into one single representing point and to augment the obstacles to configuration space obstacles (C-Obstacles). The most significant advantage of this idea is that dealing with the intersection of a point and a set of obstacles is easier than the intersection of the moving object and the set of obstacles. Figure 1 (A) demonstrates how to convert an obstacle to the corresponding C-Obstacle based on a rectangular moving object without considering the rotations. The central point of the moving object is chosen as the representing point (B), and the obstacle is grown by the shape of that, creating a new area (C-Obstacle) (C). After the creation of the C-Obstacle, the problem of finding a collision-free path for the moving object is equivalent to finding a path for the representing point avoiding the generated C-Obstacle (D). If the moving object rotates, the shape of the created C-Obstacle would be changed. Previous work on construction equipment path planning employs various algorithms to search the created C-Space. However, the main focus is on two main search categories: (1) discretized (node-based) search algorithms (i.e. Visibility Graph [8], Gridding plus A*, GA, Dijkstra's Algorithm [9]), (2) continues (sampling-based) search algorithms. (i.e. RRTs [10], [11], PRM [12]).

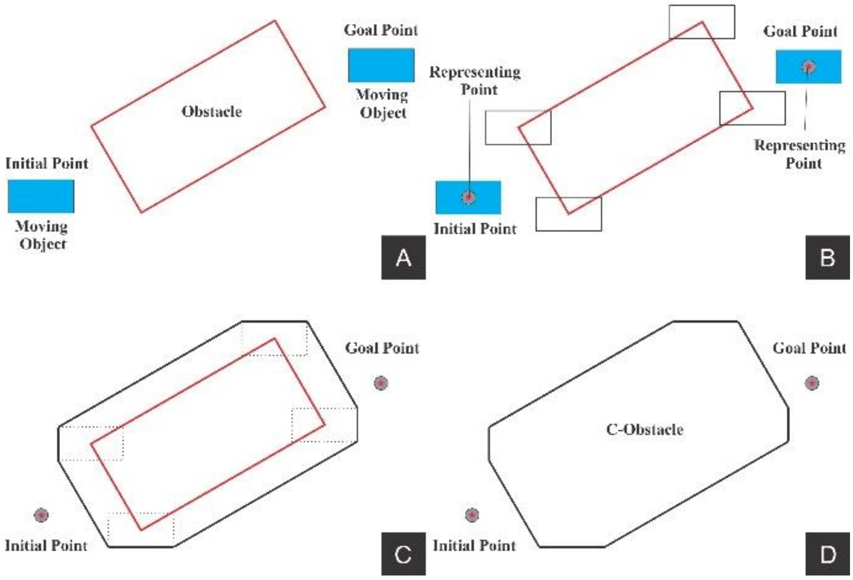

Figure 1- C-Space Generation Steps

3 Proposed Methodology

This research is based on the limitation enhancement of a research work done by Lei et al [13]. They neglected full discretization for rotation as the third degree of freedom for moving object. Mixed rotation-transition movement not only affects the optimality of the solution adversely, but also it restricts the developed system to 2D path planning. By exemption of this limit, this paper combined the robotic motion planning with the construction equipment path planning to reach a more flexible and developable methodology. Figure 2. Illustrates the proposed methodology which consists of several components. The system is developed in VisualBasic.Net employing MS Access database.

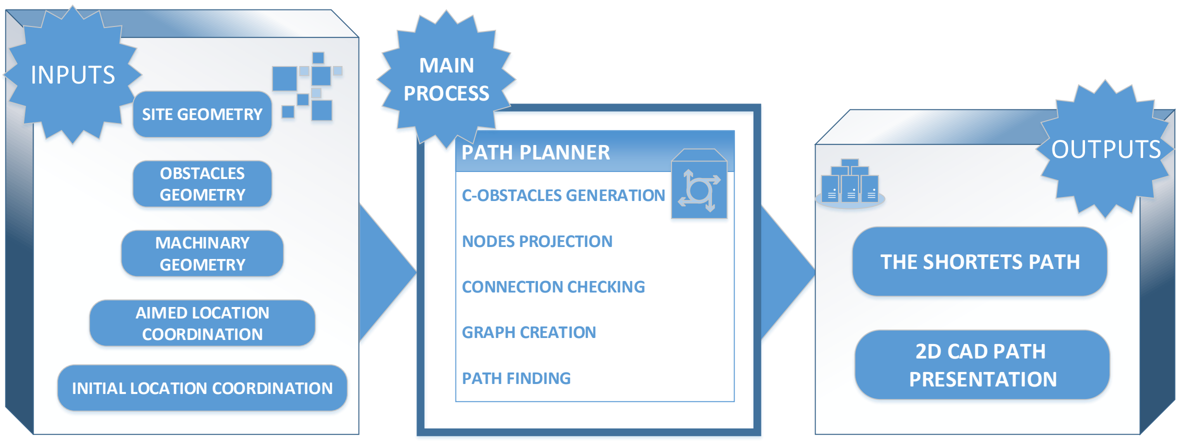

Figure 2- Proposed Methodology

3.1 C-Space Generation

As mentioned above, the shapes of the generated C-Obstacles would be changed as the moving object rotates. Therefore, the ideal modeling approach is to generate the C-Obstacles while considering the continuous rotation of the moving object. Nonetheless, in order to make the model computationally feasible and efficient, finite rotation steps are assumed. In this regard, for each rotation step of the moving object, the C-Obstacles are generated and kept on a separate corresponding rotational plane by their vertices. (Fig 3.) In this regard, it is needed to rotate the geometrical shape of the moving object by the 2D rotation matrix and proceed the augmentation process for each obstacle. Finding the shortest collision-free path for a convex 2D object through obstacles is now changed to finding the shortest collision-free path for the representing point through grown obstacles (C-Obstacles) between its initial and aimed location. Indeed, the moving object will avoid obstacles, if and only if the corresponding representing point is located out or on the perimeter of the C-obstacles.

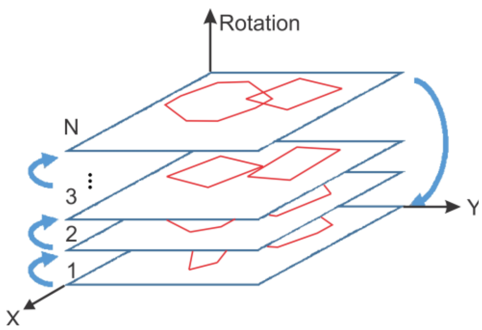

Figure 3- Discretized rotational planes in the generated C-Space

3.2 Corresponding Graph's Node Generation

Based on visibility graph, a collision-free path for a set of points and obstacles in the Euclidean plane is an array of feasible connections between the points (i.e. obstacles' vertices, start point, and aimed point) which starts from the initial point and ends to the aimed point. In fact, a visibility graph is a graph in which each node represents the representing point location, and each edge represents a visible connection between them. Two nodes will be connected, if and only if their connector segment does not have any intersects with any obstacles.

In order to implement this idea, it is necessary to introduce the nodes at the first stage. In this study, two types of nodes are introduced for each rotational plane: (1) Internal nodes; and (2) External nodes. Internal nodes initially consist of vertices of corresponding C-Obstacles for that rotation. Initial and aimed location of the representing point are two extra internal nodes which are added to their corresponding rotational planes. External nodes are introduced in this study to complete the full-discretized modeling of the moving object rotation. External nodes within any rotational planes are those nodes that are added from other rotational planes via continuous projection. The continues projection process proceeds in the negative and positive manner for clockwise and counter-clockwise rotation of the moving object for the amount of a single rotation step, respectively. During this process, each individual internal node within each rotational plane is projected to the next successive rotational plane negatively/positively. By so doing, the object ability to rotate around the representing point is investigated. For example, an internal node N(x,y) within plane j positively projected to plane j+1 and added to it as an external node N'(x,y), given that the projected node will not be placed inside of new plane's C-Obstacles. For the next step, N' would be projected to j+2. The positive projection will be continued unless projected nodes are placed inside the planes' C-Obstacles. In that case, the projected point will not add to that plane, and the positive projection process will be stopped for N(x,y). Right after that, N(x,y) will be negatively projected to plane j-1 to obtain N''(x,y). Similarly, the negative projection would be continued unless projected nodes were placed inside the planes' C-Obstacles.

make an inter-plane connection if they have the same coordination (i.e. X, Y). It is necessary to define a metric to assign a weight for any connections. In this work, the distance and length of motion is simply used. Finally, each connection and its weight treated as the corresponding weighted graph's edge.

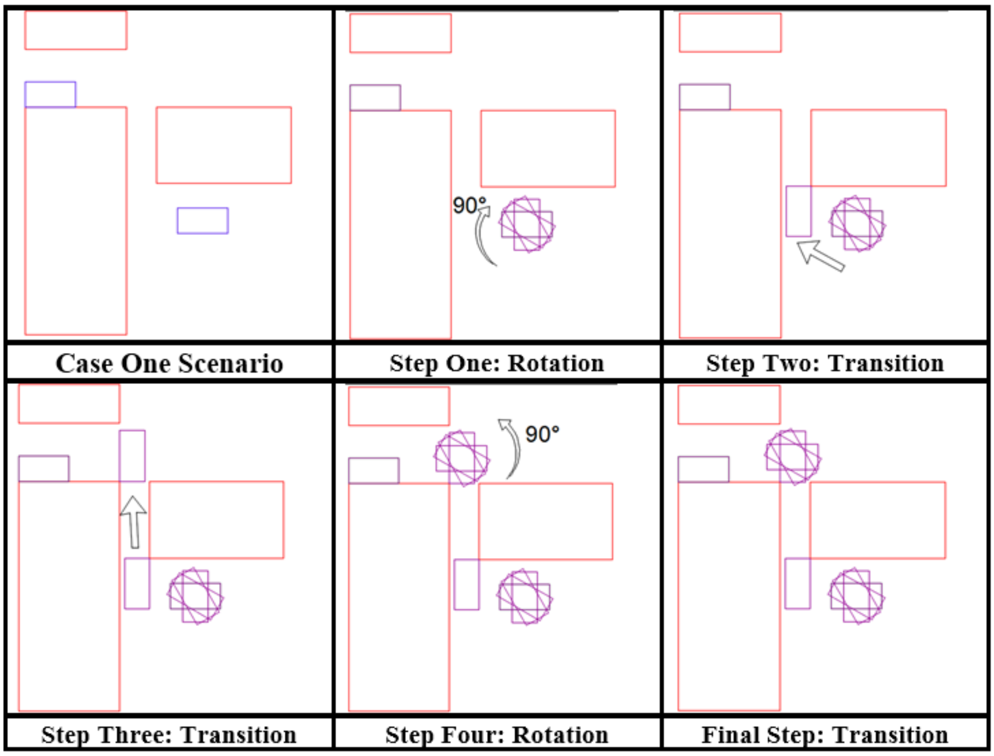

Figure 4- The shortest path in case one

3.3 Corresponding Graph's Edge Generation

When two nodes are connected, it implies that there is a feasible motion between the two positions represented by the nodes. This research proposed two types of connections between nodes: (1) in-plane connections; and (2) inter-plane connections. For instance, a connection between two nodes from the same rotational plane j represents that the moving object can transit without any rotations from one node to the other using a straight line; and a connection between two nodes from two successive rotational planes (e.g. j and j+1) implies the rotation of the moving object. This rotation is equal to one single rotation step.

Two nodes within the same rotational plane will be connected if the segment connector does not collide with the existing C-Obstacles. The connection for two nodes from successive layers is checked to guarantee that the rotation to the amount of a single rotation step will not collide with the existing obstacles. Hence, two nodes will

3.4 Path Finding

Dijkstra's algorithm is employed in this study to find the shortest path in the generated corresponding graph. The principal idea of Dijkstra's algorithm is to calculate the minimum cumulative weight of connections to reach any nodes such as the aimed node from the initial node in a weighted graph G= (V, E). [14]

4 Case study

4.1 Case One

Case one presents an illustrative example in which a moving object is supposed to move through three obstacles in five steps. (Figure 4) In each step the moving object is able to either transit or rotate, but there is no mixed movement for it. The proposed path is safe and collision-free.

4.2 Case two

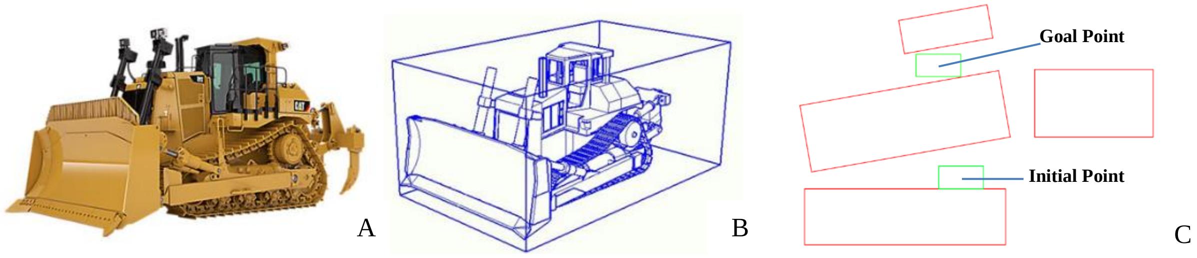

Figure 5- (A) CAT-D9 dozer; (B) Boundary box envelope; (C) A congested scenario

To apply the proposed methodology in finding the shortest collision-free path between initial and aimed location of construction equipment, it is needed to simplify that machinery to a 2D convex. Hence, a boundary envelope is used to guarantee that the mobile construction equipment will avoid obstacles. The boundary for a CAT-D9 dozer (Figure 5(A)) is shown in Figure 5(B); it is a box that completely encloses it. In other words, no points of the dozer will be placed outside of the boundary box.

Additionally, case two presents a more congested scenario with four obstacles (Figure 5(C)). In this case, a complex environment considered to challenge the proposed methodology. However, it is designed to be trackable for any individuals to easily validate the shortest path.

As shown in (Figure 6(A)) rotational planes and their C-obstacles are generated. Meanwhile, in-plan and inter-plane connections are made afterward (Figure 6(B)). The final result is shown in Figure 7 as below.

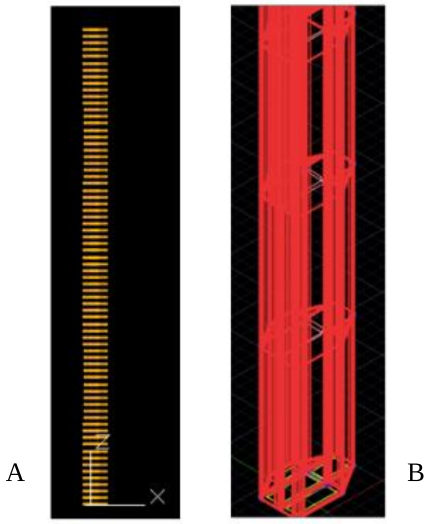

Figure 6- Case two; (A) Rotational Planes; (B) Connections and corresponding graph

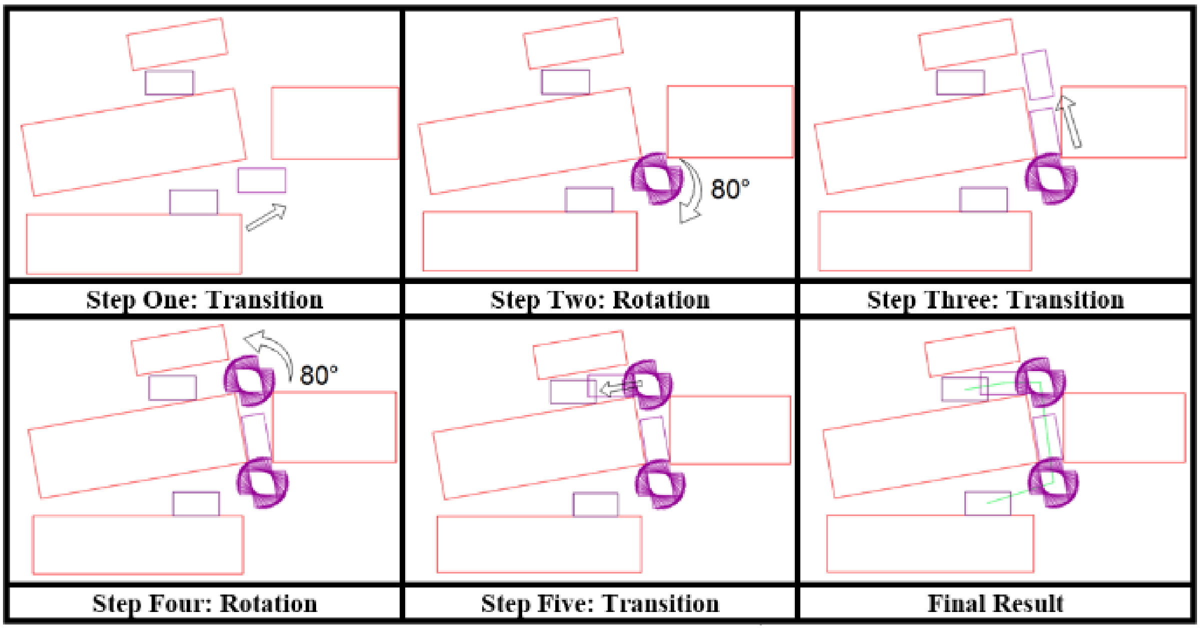

Figure 7- The shortest path in Case Two

5 Conclusion

Path planning is crucial in constructability analysis and heavy construction equipment scheduling, particularly in industrial plants. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free. The current planning practice, even in industrial projects whose sites are extremely congested, is manual based on the expert judgment. Thus, this sophisticated manual process is not only prone to errors but also time-consuming. This study presents an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. This research enhanced the limitation of the other scholars' efforts. However, the proposed system only considered the shortest path, but it can consider ease of operation, machinery movements, and other constraints in future studies. This research work will be further extended into heavy lift path planning of mobile cranes.

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References

[1] Lin JJ-C, Hung W-H, Kang S-C. Motion Planning and Coordination for Mobile Construction Machinery. Journal of Computing in Civil Engineering, 29(4):4014082, 2014.

[2] Cheng T, Mantripragada U, Teizer J, Vela PA. Automated Trajectory and Path Planning Analysis Based on Ultra Wideband Data. Journal of Computing in Civil Engineering, 26(2):151-160, 2012.

[3] Taghaddos H, Hermann U, Abbasi A. Advanced Crane Planning and Optimization for Modular Construction. Journal of Construction Engineering and Management (Submitted).

[4] Taghaddos H, AbouRizk S, Mohamed Y, Hermann U. Simulation-Based Auction Protocol for Resource Scheduling Problems. Journal of Construction Engineering and Management. 138(1):31-42, 2012.

[5] Lei Z, Taghaddos H, Hermann U, Al-Hussein M. A methodology for mobile crane lift path checking in heavy industrial projects. Journal of Automation in Construction. 31:41-53, 2013.

[6] Cheng C-F, Rashidi A, Davenport MA, Anderson D V. Activity analysis of construction equipment using audio signals and support vector machines. Journal of Automation in Construction. 81(June):240-253, 2017.

[7] Lozano-Perez T. Spatial Planning: A Configuration Space Approach. IEEE Transactions on Computers. c(2):108-120, 1983.

[8] Asano T, Asano T, Guibas L, Hershberger J, Imai H. Visibility-polygon search and Euclidean shortest paths. In: 26th Annual Symposium on Foundations of Computer Science (SFCS).:155-164. 1985.

[9] Soltani AR, Tawfik H, Goulermas JY, Fernando T. Path planning in construction sites: Performance evaluation of the dijkstra, A*, and GA search algorithms. Advanced Engineering Informatics. 16(4):291-303, 2002.

[10] Kuffner JJ, LaValle SM. RRT-connect: An efficient approach to single-query path planning. Proc 2000 ICRA Millenn Conf IEEE Int Conf Robot Autom Symp Proc.;2(April):995-1001, 2000.

[11] Lin Y, Yu H, Sun G, Shi P. Lift Path Planning without Prior Picking/Placing Configurations: Using Crane Location Regions Journal of Computing in Civil Engineering. 30(1):4014109, 2014.

[12] Chang Y-C, Hung W-H, Kang S-C. A fast path planning method for single and dual crane erections. Journal of Automation in Construction. 22(March 2012):468-480, 2012.

[13] Lei Z, Behzadipour S, Al-hussein M. Application of Robotic Obstacle Avoidance in Crane Lift Path Planning. The 28th International Symposium on Automation and Robotics in Construction (ISARC 2011), pages. Seoul, Korea, 2011.

[14] Dijkstra EW. A note on two problems in connexion with graphs. Numerische Mathematik. 1(1):269-271, 1959.