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Classification and Improvement Directions for Mobile Crane Path Planning Algorithms: A Comprehensive Review

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Abstract: Efficient path planning for mobile crane lifting operations in the construction industry is essential for ensuring smooth machinery operation, worker safety, and the timely completion of projects. The inherently complex construction sites, characterized by dynamic environments, constantly changing conditions, and numerous static and mobile obstacles, underscore the necessity for advanced algorithms capable of generating optimal paths under various constraints. Mobile crane path planning algorithms have been researched extensively and possess the potential to resolve the challenges presented by construction sites. However, the application of these algorithms in actual construction sites is rare, suggesting a need for ongoing research and development in this field. This paper begins by systematically identifying and analyzing relevant research papers using predetermined keywords, providing a comprehensive review of the current state of mobile crane path planning algorithms. Specifically, it categorizes mobile crane path planning algorithms into four main groups: Graph search-based algorithms, Sampling-based algorithms, Nature-inspired algorithms, and Newly developed algorithms. It performs a critical analysis of each category, offering guidance to researchers exploring path planning solutions suitable for the dynamic and complex environments of construction sites. Through this review, we affirm the need for continued interest and attempts at new methodologies in mobile crane path planning, suggesting improvements for further research and practical application of these algorithms.

Keywords: Mobile crane Path Planning, A* Algorithm, RRT Algorithm, Genetic Algorithm

1. INTRODUCTION

In the dynamic and complex world of construction, cranes play a crucial role [1]. They are not merely tools for lifting and moving heavy materials but are essential for the timely and efficient execution of projects [2]. Among the various cranes used in construction, mobile cranes are distinguished by their exceptional versatility and ability to quickly adapt to different project requirements and site conditions [3]. This versatility makes them indispensable for a wide range of construction activities, enabling them to effectively perform tasks from simple to complex [4].

Mobile crane path planning has become a critical factor in determining the efficiency and safety of such operations [5]. Path planning involves considering spatial constraints and interactions with other equipment or structures on site, enabling the mobile crane to follow the optimal route for efficient operation. This process optimizes the use of mobile cranes in complex construction environments and supports the success of projects [6].

Past path planning for mobile cranes primarily utilized simple heuristic methods and empirical approaches [7]. These methods failed to adequately consider the diverse variables and situations present in complex construction sites, leading to inefficient route selection, increased work times, and potential safety hazards, thereby not delivering the expected level of performance or full benefits. However, recent advancements in mobile crane path planning have enabled more precise positioning and route optimization [8]. Such technological progress and its dissemination are becoming increasingly significant elements within the construction industry [9]. Therefore, continued interest and investment in this field are essential for the future of the construction industry.

Despite the introduction of various algorithms and methodologies for designing optimal lift paths for mobile crane operations, widespread application is still hindered by the long duration required for path design, limitations in realistically reflecting the natural mobility of mobile cranes, and the absence of sufficient analysis for selecting the optimal algorithm tailored to the characteristics of construction projects [10]. These issues indicate that the field of mobile crane path planning is still in a developmental stage, and continuous research is needed to meet these requirements.

The primary objective of this paper is to contribute to the advancement of the field by conducting a comprehensive review of the path planning developed so far for mobile cranes, identifying the limitations of existing technologies, and suggesting directions for future research. This paper is organized as follows: Initially, the methodology used for this literature review study is described, followed by a summary of the findings from the reviewed literature. Subsequently, the conclusion of the research and directions for future studies are discussed.

2. RESEARCH METHODOLOGY

To conduct this study, a systematic review of research on mobile crane path planning was undertaken. In this process, a detailed literature review was performed targeting papers published in major academic journals. The procedure for selecting research papers was organized into three main steps.

In the first step, academic papers were identified using predefined search terms based on prior literature, including keywords such as ‘crane’, ‘path planning’, ‘lift planning’, and ‘algorithm’. These keywords were selected to identify relevant literature in the field, and papers that included these keywords in the title, abstract, or keyword section were considered for review in this study. Academic information search engines like Google Scholar were utilized to identify journals that have made significant contributions to the construction sector.

In the second step, research papers focusing on the technology of path planning for mobile cranes were selected. Among the papers found through the initial search, those most closely related to the research topic were chosen based on their abstracts.

Finally, the selected papers were analyzed in depth, and their contents were summarized. Through this process, the technological advancements and current research trends in the field of mobile crane path planning were identified, with a focus on suggesting directions for future research.

3. PATH PLANNING ALGORITHMS

In this paper, algorithms used to solve the path planning problem for mobile cranes are classified into four main categories: Graph search-based algorithms, Sampling-based algorithms, Nature-inspired algorithms, and Newly-developed algorithms. This classification provides a foundation for systematically understanding and comparing the various approaches and techniques for path planning problems.

3.1. Graph search-based algorithms

The Graph search-based algorithm approaches path planning problems by utilizing graphs. In this method, each point on the graph represents a location, and the lines represent possible paths from one location to another. The key feature of this approach is to examine all possible movement paths within the given environment and to find the optimal or near-optimal path among them [11].

The A* algorithm and the Dijkstra algorithm are quintessential examples of graph search-based algorithms for solving path planning problems. These algorithms effectively identify the shortest path between the start point and the target by calculating the cost to each vertex in the graph [12].

Research on the efficiency and optimization potential of graph search-based algorithms has been conducted through various approaches. Soltani et al. [13] demonstrated that the A* algorithm tends to find more optimal solutions compared to the Dijkstra algorithm. However, both algorithms do not produce efficient results for large-scale problems. The study by Sivakumar et al. [14] covered a case where the A* algorithm was applied to the automatic path planning of cooperative crane lifting tasks, reporting that the algorithm was able to find paths close to optimal. Nonetheless, the long execution time that occurred during this process emerged as a major factor limiting the algorithm's efficiency. Recent studies have extended the application scope of the A* algorithm, focusing on optimizing the operation of large mobile cranes [15]. This has led to the development of new frameworks aiming to reduce operational costs and the risk of failures and accidents. Furthermore, the development of improved A* algorithms, focusing on minimizing energy and time consumption, represents a significant advancement in research in this field [16].

These studies demonstrate the potential for development and the expansion of application scopes of graph search-based algorithms, particularly the A* algorithm. However, a significant limitation of the A* algorithm remains its lengthy compurtation time. Future research will be crucial in developing methodologies that can overcome these limitations and further enhance the efficiency of such algorithms.

3.2. Sampling-based algorithms

Sampling-based algorithms provide an alternative approach to solving path planning problems. These algorithms can be effectively used in high-dimensional and complex environments and, unlike graph search-based algorithms, generate and analyze the search space through random sampling. The main features of this method lie in its computational efficiency and applicability in large-scale spaces [17].

Prominent sampling-based algorithms include the PRM (Probabilistic RoadMap) and RRT (Rapidly-exploring Random Tree). PRM operates by sampling random points within the environment to use as nodes and connecting these to plan paths, making it particularly effective in static environments with little change [18]. Conversely, RRT is suited for dynamic environments, creating a tree that randomly expands from the starting point to explore paths to the target location [19, 20].

Research on the practical application and computational speed improvement of sampling-based pathfinding algorithms is being actively pursued. Chang et al. [21] developed a method for near real-time installation path planning using PRM, achieving rapid computational speeds and practical outcomes. Lin et al. [22, 23] proposed a bi-directional RRT-based path planning method that quickly identifies the optimal path without collisions, considering the lifting and mobility of cranes. Zhang and Hammad [24] created a method that combines bi-directional RRT and DRRT to efficiently generate safe and smooth crane operatin paths, taking into account engineering constraints and path quality. Recently, Zhou et al. [25] introduced an improved RRT algorithm that incorporates generalized distance methods and cell methods to enhance nearest neighbor searches. Additionally, another improved RRT algorithm was developed to increase the visibility of the existing RRT* and reduce motion adjustments [26].

The utilization of sampling-based algorithms in the path planning of mobile cranes is currently a significant area of research. However, given that these algorithms do not always guarantee the optimal solution, future research should focus on exploring methodologies that can further improve the efficiency and optimality of these algorithms.

3.3. Nature-inspired algorithms

Nature-inspired algorithms provide another approach to solving path planning problems, developed based on mechanisms found in nature. These algorithms solve complex optimization issues by mimicking biological processes and natural phenomena [27]. Specifically, genetic algorithms stand out as a widely used example in this domain.

Genetic algorithms represent potential solutions as populations in path planning problems and proceed with optimization through evolutionary processes such as natural selection, crossover, and mutation. In this process, each generation of the population is evaluated, and the most fit individuals are carried over to the next generation, thereby finding the optimal or near-optimal path. The advantage of this algorithm lies in its ability to explore multiple solutions simultaneously and provide effective solutions to global optimization problems [28].

Meanwhile, the Ant Colony Optimization (ACO) algorithm is another example of a nature-inspired algorithm, mimicking the way ants find the optimal path to food based on the pheromone trails they leave behind. ACO is particulary applied to path optimization problems in complex networks and, alongside genetic algorithms, can contribute to improving the efficiency and accuracy of path planning [29].

Contemporary research aimed at enhancing the efficiency and optimization capabilities of genetic algorithms is exploring various strategies. Ali et al. [30] introduced a new GA-based method for the automatic path planning of dual crane lifting operations. Cai et al. [31] introduced a GPU-optimized Master-Slave Parallel Genetic Algorithm (MSPGA) to solve the path planning problem for crane lifting tasks, aimed at improving computational efficiency in complex environments. These methods have enhanced the computational speed of Gas and facilitated rapid solutions to complex path planning problems. Additionally, Wang et al. [32] applied the ACO to include safety in planning the shortest path.

Although these nature-inspired algorithms have significantly contributed to improving efficiency, the length of computation time remains a major limitation. Overcoming this drawback will require further additional research.

3.4. Newly developed Algorithms

In recent years, the introduction of newly developed algorithms to solve path planning problems has expanded the scope of research in this field. These new algorithms, while not fitting into traditional classifications, offer more efficient or specialized solutions in specific situations.

Aghajamali et al. [33] introduced a new algorithm for planning the walking path of mobile cranes in congested industrial construction sites, addressing the problem of navigating obstacles while carrying loads. This approach utilizes obstacle avoidance techniques from robotics to optimize crane operation and ensure safety, efficiency, and collision prevention. Han et al. [34] presented a 3D visualization-based method for planning the movement of mobile cranes in heavy industrial projects. By combining 3D visualization with mathematical algorithms, they designed crane operations without collisions. Mousaei et al. [35] introduced an innovative method for planning the path of mobile cranes in discretized polar spaces with the goal of optimizing crane movement for efficiency and safety. This approach focuses on dividing the crane's operating area into a grid to avoid obstacles and ensure the most effective path. Kayhani et al. [36] explored a robotic approach to planning the lifting path of heavy mobile cranes in congested modular industrial plants, developing methods to navigate narrow spaces and obstacles, thereby enhancing safety and efficiency. This approach optimizes crane movement to address the complexities of the industrial environment.

These newly developed algorithms are making significant contributions to the field of mobile crane path planning by overcoming the limitations of traditional methodologies and offering effective solutions tailored to specific situations. However, practical application of these algorithms requires further research and improvement, with ongoing exploration into methods that can further enhance efficiency.

4. ANALYSIS

In section 3, the classification of path planning algorithms for mobile cranes is described, with concise summaries for each category as follows:

Graph search-based algorithms utilize nodes and edges of a graph to explore all possible paths and find the optimal or near-optimal route. Prominent examples includes the A* algorithm and Dijkstra's algorithm, which offer high accuracy and efficiency. However, for large-scale problems, these algorithms have the drawback of increased computational costs and memort requirements.

Sampling-based algorithms are effectively used in high-dimensional and complex environments, creating and analyzing the search space through random sampling. PRM and RRT belong to this category, each being suitable for path planning in static and dynamic environments, respectively. Characteristics include computational efficiency and the applicability in large-scale spaces.

Nature-inspired algorithms solve complex optimization problems by mimicking biological processes and natural phenomena. Genetic algorithms and Ant Colony Optimization algorithms are notable examples, capable of exploring multiple solutions simultaneously and offering effective solutions to global optimization problems.

Newly developed algorithms provide new approaches not fitting into traditional classifications, offering more efficient or specialized solutions in specific situations.

These classifications aid in understanding the characteristics and pros and cons of various algorithms applicable to mobile crane path planning. Table 1 categorizes the algorithms mentioned in this paper.

Table 1. Classification of path planning algorithms for mobile cranes

Method	Reference
Graph search-based	Soltani et al. [13]
	Sivakumar et al. [14]
	Bagheri et al. [15]
	Zhang et al. [16]
Sampling-based	Chang et al. [21]
	Lin et al. [22, 23]
	Zhang and Hammad [24]
	Zhou et al. [25]
Nature-inspired	Ali et al. [30]
	Cai et al. [31]
	Wang et al. [32]
Newly Developed	Aghajamali et al. [33]
	Han et al. [34]
	Mousaei et al. [35]
	Kayhani et al. [36]

5. CONCLUSION

Optimization of crane path planning has been a long-standing research topic of interest within the academic community. This review paper aimed to conduct a comprehensive survey on mobile crane path planning, and the findings indicate progress in algorithm development within this field, yet also suggest the need for further research and development. Practically, existing algorithms have not been fully utilized in field applications, which reflects the reality. Despite not being a new topic, the area of mobile crane path planning continues to receive sustained interest and attempts at new methodologies.

This study makes a significant contribution to the development of mobile crane path planning algorithms and greatly highlights the potential for advancement in this field. It provides motivation for researchers to explore various methods in upcoming studies and offers guidelines to overcome current limitations and future research directions. The major drawbacks identified for each algorithm in this study represent important tasks for future research. Continued research and efforts for improvement are required.

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