Dynamic Collision-Avoiding Trajectory Planning for Tower Crane Operations via Configuration Space Optimization

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Abstract -

In prefabricated construction sites, tower cranes are required to operate safely in confined workspaces where site layouts and surrounding activities change over time. Reliable trajectory planning is therefore essential for maintaining safety margins, ensuring smooth motion, and improving operational efficiency. This paper proposes a Configuration-Space Genetic Algorithm (CSGA) for trajectory planning of tower cranes directly in the configuration space under dynamic site conditions. Instead of planning directly in Cartesian space, the proposed method formulates the trajectory planning problem in the crane configuration space defined by slewing, trolley, and hoisting motions, thereby enforcing kinematic feasibility intrinsically during optimization. The construction environment is abstracted using lightweight geometric bounding models to represent both static structures and moving entities, enabling efficient spatiotemporal collision evaluation. To account for payload swing effects without introducing complex dynamics, a sway-aware safety envelope is incorporated to conservatively expand clearance constraints. Within this formulation, the proposed CSGA searches for smooth and collision-free trajectories by jointly minimizing path length, safety violations, and motion irregularities. Simulation results in representative scenarios show that the proposed approach can generate mechanically executable trajectories with safe clearances and stable convergence in cluttered, time-varying environments. These findings suggest that the framework offers a practical solution when kinematic constraints, safety requirements, and environmental dynamics must be addressed simultaneously.

Keywords -

Tower crane; trajectory planning; configuration space optimization; genetic algorithm; prefabricated construction.

1 Introduction

Prefabricated construction is increasingly recognized globally as a pivotal direction for construction industrialization, offering significant potential to enhance productivity while mitigating energy consumption and environmental impact [1]. As a critical operation within this assembly process, the hoisting of prefabricated components determines project schedules and overall construction quality [2]. Compared to many unstructured on-site activities, hoisting operations exhibit a degree of predictability due to relatively fixed material storage zones and equipment locations [3]. Nevertheless, current practice remains heavily reliant on manual operation and experience-based scheduling. In complex construction environments characterized by dense structures, concurrent machine operations, and dynamic human activities, traditional planning schemes often prioritize material sequencing without systematic consideration of three-dimensional (3D) spatial constraints. Such reliance on experience-driven and static planning often results in suboptimal crane utilization [4]. More importantly, it increases the likelihood of spatial conflicts and operational hazards in dense construction environments.

With the escalating demand for refined construction management, conventional two-dimensional analysis methods and simplified numerical simulations are becoming inadequate, as they fail to capture complex 3D spatial relationships and dynamic environmental changes effectively [5]. Building Information Modeling (BIM) provides structured geometric representations and integrated site information for construction environments [6, 7]. Such information can support trajectory planning by supplying accurate spatial descriptions of static structures and site layouts. However, effectively utilizing this information requires automated trajectory planning algorithms capable of explicit reasoning about spatial constraints and operational feasibility [8]. Consequently, trajectory planning has emerged as a crucial component for enabling intelligent hoisting operations and reducing reliance on static decision-making [9].

Despite extensive research in general robotic path planning, directly applying existing algorithms to tower crane hoisting presents significant challenges. Classical graph-search methods, such as Dijkstra and A*, guarantee global optimality in static environments but suffer from rapid computational explosion in the large-scale, continuous state spaces typical of crane operations [10, 11]. Conversely, reactive approaches like Artificial Potential Fields

(APF) and the Dynamic Window Approach (DWA) are well-suited for local collision avoidance in dynamic settings but are susceptible to local minima and cannot ensure global path quality [12, 13, 14]. However, many existing crane-related studies generate trajectories in the Cartesian workspace without explicitly accounting for the inherent kinematic constraints of tower cranes. Tower cranes are actuated through coupled slewing, trolleying, and hoisting motions, which makes arbitrary Cartesian straight-line paths difficult to execute directly, often requiring substantial post-hoc feasibility corrections before implementation. To address these limitations, this paper presents a trajectory planning framework tailored to tower crane operations in dynamic construction environments. A key methodological distinction of this work is that trajectory optimization is performed directly in the crane configuration space (C-space) [15]. Unlike Cartesian-space approaches, the proposed method intrinsically enforces kinematic constraints during optimization, ensuring that generated trajectories are directly executable. To the best of our knowledge, existing studies on tower crane trajectory planning predominantly rely on Cartesian-space formulations, where feasibility is handled at the execution stage. In contrast, this work directly formulates the planning problem in the configuration space, enabling a more structured and physically consistent optimization process under dynamic environmental conditions.

To further elaborate on the proposed approach, the trajectory planning problem is formulated directly in the crane configuration space, parameterized by the actuated variables: slewing angle θ, trolley radius r, and hoisting height z. A real-coded Configuration-Space Genetic Algorithm (CSGA) is developed as the global optimization engine, where candidate solutions are encoded as sequences of configuration-space control points. To enable efficient safety evaluation under dynamic conditions, both static structures and moving entities are represented using Axis-Aligned Bounding Boxes (AABBs), which enable rapid distance computation. In addition, a sway-aware safety envelope is introduced to conservatively account for payload swing through geometric margin expansion, eliminating the need for explicit dynamic simulation. Smooth and continuous trajectories are reconstructed using Piecewise Cubic Hermite Interpolating Polynomials (PCHIP) and evaluated through a composite fitness function that balances transport efficiency, safety clearance, and motion smoothness under spatiotemporal consistency.

The main contributions of this study are summarized as follows:

(1) A direct configuration-space trajectory planning formulation for tower cranes is developed, in which optimization is performed over slewing angle, trolley radius, and hoisting height, intrinsically satisfying kinematic constraints without requiring inverse kinematics or post-processing.

(2) A unified spatiotemporal safety evaluation strategy is integrated into the proposed CSGA, enabling robust trajectory generation in environments containing both static structures and dynamic obstacles.

(3) A sway-aware safety envelope is introduced to conservatively account for payload swing effects through geometric margin expansion, enabling efficient safety evaluation without explicit dynamic simulation.

The remainder of this paper is organized as follows. Section 2 details the methodology, including problem formulation, environmental and safety modeling, and the proposed CSGA. Section 3 reports experimental validation results. Section 4 concludes the paper with a summary and future outlook.

2 Methodology

This section presents the proposed methodology for tower crane trajectory planning in dynamic construction environments. As illustrated in Figure 1, the framework combines C-space modeling, geometric environment abstraction, and evolutionary optimization under a unified pipeline. The planning problem is formulated in the crane configuration space, where the decision variables are the actuated coordinates (slewing angle, trolley radius, and hoisting height), such that kinematic limits are enforced intrinsically throughout the search. To handle complex site conditions, the environment is abstracted using lightweight bounding models for both static and dynamic elements, enabling efficient spatiotemporal safety assessments. Based on these models, the proposed CSGA evolves smooth and collision-free trajectories by jointly minimizing transport effort, safety violations, and motion smoothness under dynamic conditions.

2.1 Problem Formulation and Configuration Space Optimization

The objective of this study is to generate a feasible and safe trajectory for a tower crane to transport a payload from a start position P_{start} to a destination P_{goal} in the Cartesian workspace W. The planned motion must simultaneously satisfy safety constraints imposed by the surrounding environment, mechanical limits of the crane, and smoothness requirements to ensure stable operation. Rather than performing trajectory planning directly in the Cartesian space $W \in \mathbb{R}^3$, the problem is formulated in the configuration space (C-space) of the tower crane. The crane state is parameterized by the configuration vector $q = [\theta, r, z]^{\mathrm{T}}$, where θ denotes the slewing angle, r the trolley radial distance, and z the hoisting height. The admissible configuration space is bounded by the crane's

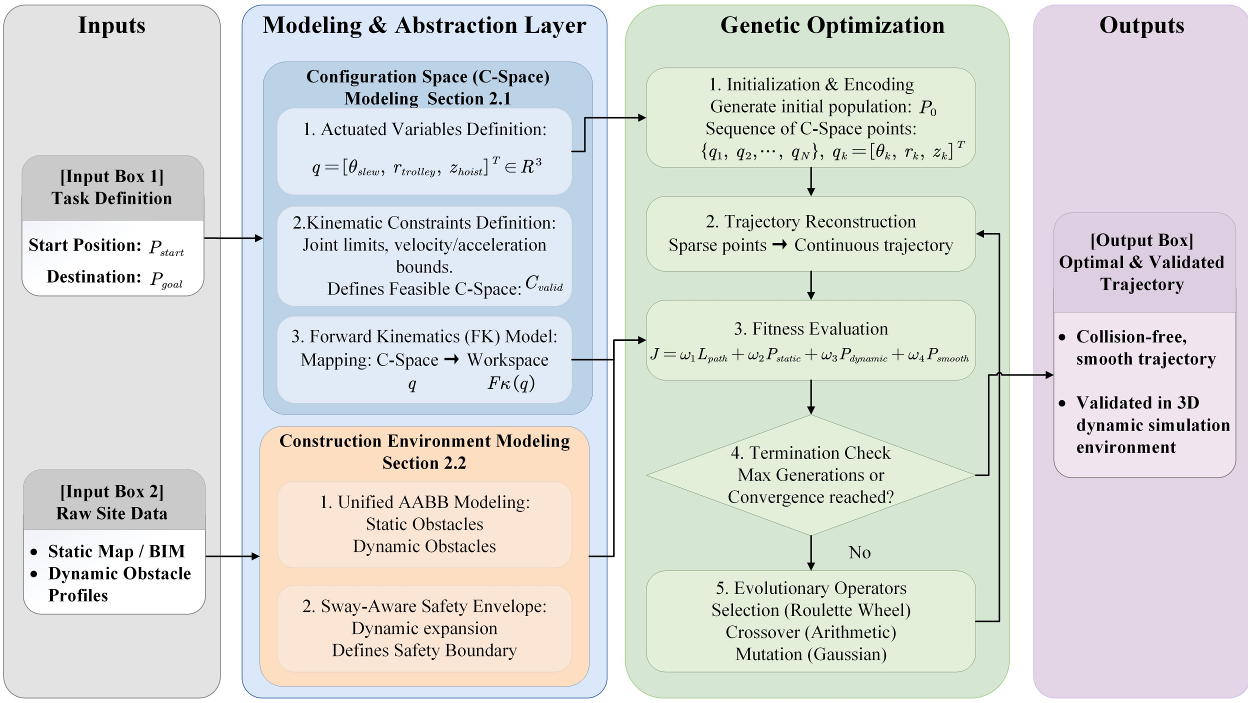


Figure 1. Workflow of the proposed CSGA-based trajectory planning framework.

mechanical limits,

$$C_{\text{valid}} = \left\{ \mathbf{q} \;\middle|\; \begin{matrix} \theta_{\min} \le \theta \le \theta_{\max}, \\ r_{\min} \le r \le r_{\max}, \\ z_{\min} \le z \le z_{\max} \end{matrix} \right\} \tag{1}$$

A sequence of configurations $\mathbf{q}_k$ is mapped to the corresponding hook positions in the workspace through the forward kinematics relationship:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = F(\mathbf{q}_k) = \begin{bmatrix} x_{base} + r_k \cos\theta_k \\ y_{base} + r_k \sin\theta_k \\ z_k \end{bmatrix}, \tag{2}$$

where k denotes the index of the discretized trajectory, and (x_{base}, y_{base}) denotes the crane base location.

Formulating the problem in C-space offers two key advantages. First, kinematic feasibility is inherently guaranteed, as all generated configurations lie within the physical operating limits of the crane, eliminating the need for inverse kinematics. Second, independent actuation variables (θ, r, z) allow for a more structured search space, which facilitates efficient optimization. Based on this formulation, the trajectory planning problem is solved using a global evolutionary optimization framework.

2.2 Construction Environment Modeling

To support efficient collision evaluation during optimization, the construction site is abstracted using simple geometric primitives that enable consistent spatial and temporal safety assessment. Both static and dynamic site elements are represented within a unified framework to facilitate distance-based collision checking.

Static and Dynamic Obstacles. Static structures, such as buildings and material stacks, can be obtained from BIM models in practical applications and subsequently approximated as Axis-Aligned Bounding Boxes (AABBs) to balance geometric fidelity with computational efficiency. Each static obstacle is parameterized by $\{x_s, y_s, z_s, w, l, h\}$, where (x_s, y_s, z_s) denotes the reference corner and (w, l, h) represent dimensions. This representation allows fast computation of Euclidean distances, making it suitable for repeated evaluation within the evolutionary optimization loop. Dynamic entities are modeled as time-varying AABBs with planar motion. Each moving obstacle is assigned a constant velocity vector $v = \left[v_x, v_y\right]^{\mathrm{T}}$, and its position at time t is updated via linear extrapolation. To reflect site confinement, a boundary reflection rule is applied: when an obstacle reaches the workspace limits, its velocity component is inverted, ensuring the entity remains within the valid evaluation domain. While the dynamic obstacle model adopts constant-velocity motion with boundary reflection for computational efficiency, we acknowledge that real construction entities, such as workers and machinery, often exhibit non-linear and reactive behaviors. This simplification enables efficient and consistent evaluation within the evolutionary optimization process, which requires repeated collision checks across

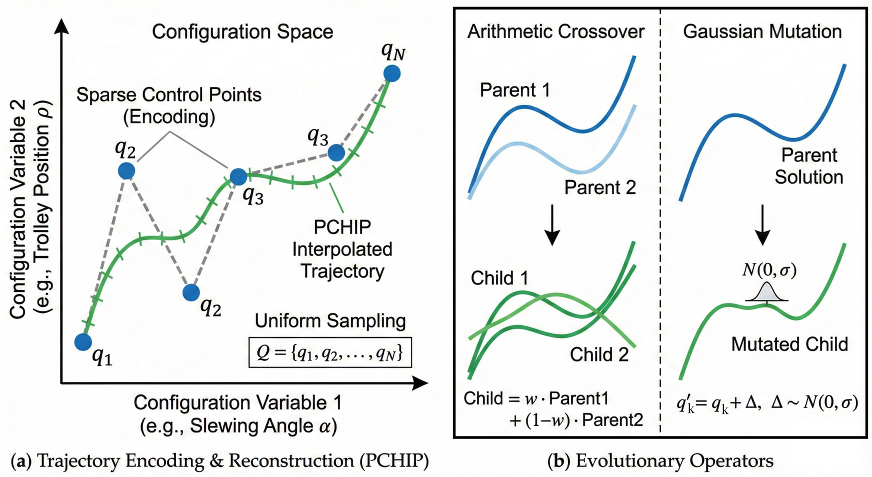


Figure 2. Schematic workflow of the GA-based trajectory optimization.

multiple trajectories and time steps. The primary objective of this work is to validate the effectiveness of the configuration-space-based trajectory planning framework rather than to model complex motion patterns of dynamic entities. In practical applications, the proposed framework can be extended to incorporate more realistic motion models, including stochastic behaviors or data-driven predictions, which will be explored in future work.

Payload Sway-Aware Safety Envelope. In practical lifting operations, collision risk is not solely determined by nominal payload geometry. Acceleration and deceleration can induce pendulum-like sway, causing lateral deviation from the vertical cable line. Relying solely on static dimensions may underestimate required clearance in cluttered environments. To address this without incurring the computational cost of a full dynamics model, a sway-aware safety envelope is incorporated. The clearance threshold used in collision checking is inflated by a kinematics-induced sway buffer:

$$d_{safe} = r_{load} + \delta_{sway} = r_{load} + L_{cable} \sin\left(\phi_{\max}\right), \quad (3)$$

where r_{load} denotes the effective payload radius, L_{cable} is the maximum cable length, and $\phi_{\max}$ is the allowable sway angle determined by operational limits. The use of a constant $\phi_{\max}$ provides a conservative upper bound for potential payload deviation. In practice, sway angles vary dynamically depending on hoisting speed, slewing acceleration, and cable length. However, by adopting the maximum allowable operational sway angle (typically restricted to a few degrees), the framework introduces a kinematics-induced safety buffer. This formulation enables efficient safety evaluation without requiring explicit dynamic modeling, making it suitable for repeated trajectory evaluations within the CSGA. As a result, bounded dynamic sway is approximated as an equivalent geometric margin, yielding a conservative separation criterion.

During fitness evaluation, safety is assessed using the minimum Euclidean distance $d_{\min}$ between the payload and obstacle bounding boxes. A penalty is triggered whenever $d_{\min} < d_{safe}$, providing a robust and computationally efficient criterion for collision avoidance under both static and dynamic site conditions.

2.3 Genetic Optimization

A real-coded GA is employed to search for feasible and safe trajectories within the configuration space defined in Section 2.1. As shown in Figure 2, the optimization is carried out directly on the crane's actuated variables. Consequently, kinematic feasibility, collision avoidance, and motion smoothness are simultaneously incorporated into a unified evolutionary framework.

(1) Trajectory Encoding in Configuration

Individuals in the population represent complete candidate trajectories encoded as an ordered sequence of configuration control points,

$$Q = \{q_1, q_2, \cdots, q_N\}, q_k = [\theta_k, r_k, z_k]^{\mathrm{T}}. \quad (4)$$

This representation aligns naturally with the actuated degrees of freedom of the tower crane, enabling direct reasoning over feasible operational motions. By performing the optimization in configuration space, all generated trajectories are mechanically executable by design, eliminating the need for inverse kinematics or post-hoc feasibility checks.

(2) Trajectory Reconstruction

The discrete control points evolved by the GA provide only a sparse description of the motion. To obtain a continuous and physically meaningful trajectory, a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) scheme is

Table 1. Qualitative comparison between Cartesian-space planning and the proposed CSGA

Aspect	Cartesian-space Planning	Proposed CSGA
Planning space	Workspace (x, y, z)	Configuration space (θ, r, z)
Kinematic feasibility	Requires inverse kinematics or post-processing	Intrinsically satisfied
Trajectory executability	Not guaranteed	Directly executable
Handling of constraints	Enforced after planning	Embedded in optimization
Adaptation to crane motion	Limited	Explicitly modeled

applied to reconstruct a dense path between control points. PCHIP is selected for its shape-preserving characteristics, which effectively prevent overshoot and unintended excursions between control points. The reconstructed trajectory is then uniformly sampled to support high-resolution safety evaluation and motion quality assessment.

(3) Fitness Evaluation

Each candidate trajectory is evaluated using a composite objective function that balances efficiency, safety, and operational smoothness:

$$J = \omega_1 L_{path} + \omega_2 P_{static} + \omega_3 P_{dynamic} + \omega_4 P_{smooth}. \quad (5)$$

The path length term L_{path} encourages efficient material transport. The penalty terms P_{static} and $P_{dynamic}$ enforce clearance requirements with respect to static structures and moving entities based on the safety envelope defined in Section 2.2. To ensure stable crane operation, the smoothness term penalizes large variations in successive configuration values, discouraging abrupt slewing, trolley motion, and hoisting changes that may induce payload excitation.

(4) Spatiotemporal Consistency with Dynamic Obstacles

To account for dynamic site conditions, the reconstructed trajectory is associated with discrete time instances. During fitness evaluation, the hook position at each time step t_k is evaluated against the predicted positions of dynamic obstacles at the same instant. This spatiotemporal consistency ensures that collision avoidance is enforced jointly in space and time, preventing unsafe temporal overlap between the crane and moving site entities.

(5) Evolutionary Operators

The population evolves through standard real-coded evolutionary operators. Individuals are probabilistically selected according to their objective values, favoring higher-quality solutions. For crossover, an arithmetic operator is applied to two parent trajectories ${q_k}^{(1)}$ and ${q_k}^{(2)}$ to generate an offspring trajectory:

$$q_k^{(\text{child})} = \omega q_k^{(1)} + (1-\omega) q_k^{(2)}, \quad \omega \in [0,1], \quad k = 1, \dots, N. \quad (6)$$

For mutation, Gaussian perturbations are injected into randomly selected genes to preserve population diversity:

$$q'_k = q_k + \Delta, \quad \Delta \sim \mathcal{N}(0, \sigma). \quad (7)$$

To ensure feasibility, mutated variables are bounded within the admissible limits by projection:

$$q''_k = \Pi_{C_{valid}}(q_k), \quad (8)$$

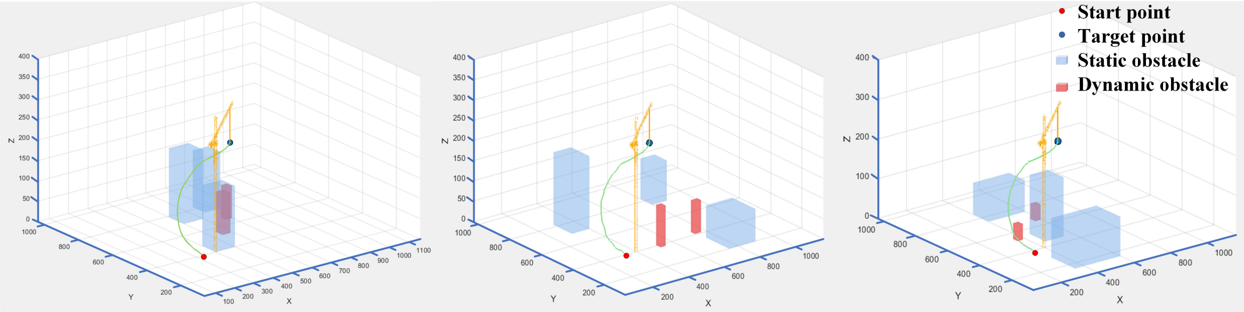
where $\Pi_{C_{valid}}(\cdot)$ clips each element of q_k to its corresponding mechanical limits. This operation guarantees that all offspring trajectories remain mechanically executable. These operators jointly maintain exploration capability while preventing premature convergence, enabling robust search for collision-free and smooth trajectories under dynamic constraints.

To further clarify the distinction between the proposed configuration-space formulation and conventional Cartesian-space planning strategies, a qualitative comparison is provided in Table 1. As shown in Table 1, the proposed method intrinsically enforces kinematic feasibility and avoids post-processing, which is a key advantage for tower crane trajectory planning.

3 Experiments

To evaluate the effectiveness and practical feasibility of the proposed CSGA framework, experiments were conducted under multiple scenario configurations with varying static layouts and dynamic obstacle conditions. The primary objective is to verify the method's capability to generate collision-free, smooth, and kinematically executable trajectories under diverse operating conditions, thereby demonstrating its generalizability rather than performance in a single fixed environment.

A three-dimensional virtual construction environment was established to emulate typical prefabricated component hoisting tasks. To assess the robustness of the proposed method, multiple scenario configurations with different static layouts and dynamic obstacle conditions were considered. The tower crane was fixed at a designated base location, and the task required transporting a payload from a start position to a target position across a cluttered workspace. Several static obstacles, representing existing buildings or structural elements, were distributed within the environment. Additionally, multiple dynamic obstacles were introduced to simulate moving site entities, such as ground vehicles or equipment. Consistent with the environment abstraction described in Section 2.2, all static and dynamic obstacles were modeled using AABBs. Dynamic obstacles followed predefined planar motion patterns with



Scenario 1 Scenario 2 Scenario 3

Figure 3. Three-dimensional crane trajectory planning results using the proposed CSGA.

boundary reflection to ensure containment within the operational domain throughout the simulation.

As illustrated in Figure 3, the proposed method is evaluated under different scenario configurations with distinct obstacle distributions and dynamic conditions. The three-dimensional trajectory planning results are integrated with dynamic simulation. The optimized trajectory successfully guides the payload from the start to the target location while maintaining safe clearance from both static structures and moving obstacles throughout the entire motion duration. No collisions or unsafe proximity events were observed, demonstrating the effectiveness of the proposed spatiotemporal safety evaluation mechanism. The resulting trajectory exhibits smooth variations in slewing, trolleying, and hoisting motions, devoid of abrupt directional changes or oscillatory behavior. This confirms that the smoothness term incorporated into the fitness function effectively suppresses aggressive configuration changes that might otherwise induce payload instability. Notably, the planned path naturally deviates from a straight-line Cartesian trajectory, reflecting the inherent influence of crane kinematic constraints and necessary obstacle-avoidance detours. Such behavior is consistent with realistic tower crane operations, where feasible motions are governed by coordinated actuated movements rather than direct linear displacement. Furthermore, dynamic simulation verifies that the sway-aware safety envelope provides sufficient margins under dynamic conditions. Even when moving obstacles pass near the nominal payload path, conservative separation is maintained, indicating that the geometric safety inflation effectively captures potential swing-induced deviations at the planning level.

The convergence behavior of the proposed CSGA is illustrated in Figure 4. The best fitness value decreases rapidly during early generations, indicating efficient exploration of the solution space and swift elimination of infeasible or unsafe candidates. As optimization progresses, the convergence rate gradually slows and stabilizes, reflecting refinement (or exploitation) toward smoother and more efficient trajectories under the imposed constraints. This pattern suggests that the genetic algorithm achieves a reasonable balance between global exploration and local exploitation without exhibiting premature convergence (or stagnation). Importantly, stable convergence was maintained even in the presence of dynamic obstacles and strict spatiotemporal safety constraints. This demonstrates that the proposed encoding, reconstruction, and fitness evaluation strategies yield a robust optimization process suitable for complex construction environments. To provide a quantitative assessment, Table 2 reports trajectory length, minimum clearance, average velocity change, and final fitness value across different scenario configurations.

The experimental results confirm that the proposed method effectively generates kinematically feasible and collision-free trajectories for tower crane hoisting tasks in dynamic environments. By conducting optimization directly within the configuration space, the planner inherently avoids infeasible motions common to Cartesian-space approaches. The utilization of lightweight geometric modeling and conservative safety envelopes enables efficient collision evaluation without resorting to computationally intensive dynamic simulations. While these experiments are conducted under a limited set of scenario configurations rather than exhaustive benchmarking, the underlying planning framework is generic. Both obstacle layouts and motion patterns are parameterized and readily adaptable to diverse construction settings. These results indicate that the proposed approach provides a practical and reliable planning solution for tower crane operations under dynamic site conditions.

4 Conclusion

This study addressed trajectory planning for tower cranes operating in dynamic and spatially constrained construction environments. To overcome the limitations of conventional Cartesian-space planning methods, the proposed CSGA directly plans crane motions in the configu-

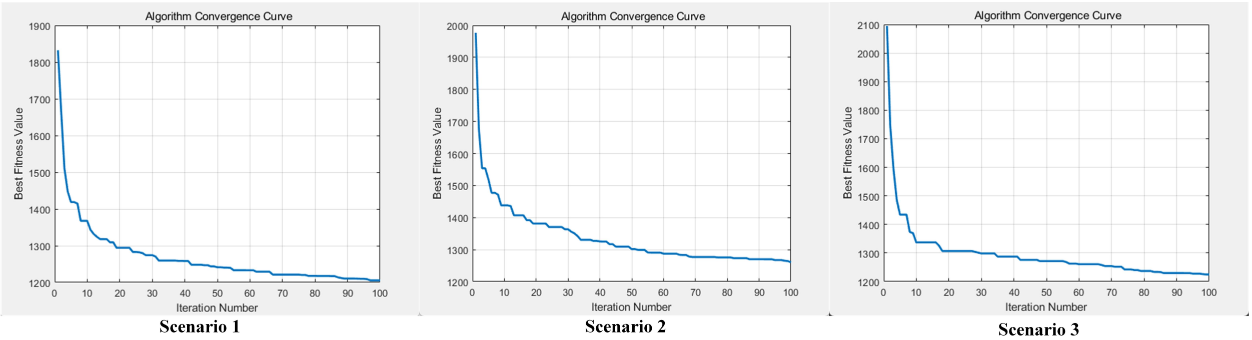


Figure 4. Convergence behavior of the CSGA optimization over successive generations.

Table 2. Quantitative evaluation across different scenario configurations

Metric	Scenario 1	Scenario 2	Scenario 3
Path length (m)	6.16	6.27	6.13
Minimum clearance to obstacles (m)	0.69	1.50	0.39
Average velocity change	0.0147	0.0371	0.0148
Final fitness value	1244.83	1253.76	1222.73

ration space using slewing, trolley, and hoisting variables. This formulation inherently satisfies kinematic constraints and avoids post-processing feasibility corrections. The construction environment was modeled using lightweight geometric representations for both static and dynamic obstacles, enabling efficient spatiotemporal collision evaluation. A sway-aware safety envelope was further incorporated to conservatively account for payload swing effects without introducing complex dynamic simulations. Within this framework, the proposed CSGA was employed to search for feasible trajectories under unified safety and feasibility criteria. Simulation results demonstrate that the proposed method generates executable and smooth crane trajectories with safe clearances in cluttered and dynamic environments, while the convergence behavior indicates stable optimization performance under non-convex constraints. Overall, the proposed approach provides a practical and consistent planning framework for tower crane operations where kinematic feasibility, safety, and adaptability must be considered simultaneously. Despite its effectiveness, several limitations should be acknowledged. The dynamic obstacle model adopts a simplified constant-velocity assumption, and payload sway is approximated using a fixed maximum angle, which may not fully capture complex real-world behaviors. In addition, the current validation is conducted under a limited set of simulated scenario configurations, and further evaluation in more diverse and real-world construction environments is required to fully assess the generalizability of the proposed method. To further enhance practical applicability, future research will incorporate data-driven behavior models via real-time site perception to better handle complex environmental dynamics. Additionally, extensions to multi-crane coordination will be investigated to support large-scale collaborative operations.

References

[1] Giovanni Tumminia, Francesco Guarino, Sonia Longo, Marco Ferraro, Maurizio Cellura, and Vincenzo Antonucci. Life cycle energy performances and environmental impacts of a prefabricated building module. *Renewable and Sustainable Energy Reviews*, 92:272–283, 2018. doi:10.1016/j.rser.2018.04.059.

[2] Xiaonong Guo, Zhengang Sui, Zhengning Li, Jindong Zhang, Yujian Zhang, and Shaohan Zong. Efficient analysis and evaluation method for overall lifting of large-span spatial grid structures. *Journal of Building Engineering*, 96:110657, 2024. doi:10.1016/j.jobe.2024.110657.

[3] Jing Yin, Ran Huang, Hao Sun, and Shunyao Cai. Multi-objective optimization for coordinated production and transportation in prefabricated construction with on-site lifting requirements. *Computers & Industrial Engineering*, 189:110017, 2024. doi:10.1016/j.cie.2024.110017.

[4] Jinchi Han, Chen Chen, Robert Lee Kong Tiong, and Kan Wu. Smart multi-project scheduling and multi-skilled workforce assignment for prefabricated bathroom unit production. *Automation in Construction*, 166:105626, 2024. doi:10.1016/j.autcon.2024.105626.

[5] Chiemela Victor Amaechi, Ahmed Reda, Salmia Binti Beddu, Daud Bin Mohamed, Agusril Syamsir, Idris Ahmed Ja'e, Safi Ullah, Deng Xiaopeng, Bo Huang, Chunguang Wang, and Xuanze Ju. A systematic literature review on knowledge management for project risk management in construction. *Journal of Building Engineering*, page 114261, 2025. doi:10.1016/j.jobe.2025.114261.

[6] Humayun Kabir Biswas, Tze Ying Sim, and Sian Lun Lau. Impact of building information modelling and advanced technologies in the AEC industry: a contemporary review and future directions. *Journal of Building Engineering*, 82:108165, 2024. doi:10.1016/j.jobe.2023.108165.

[7] Muhammad Muddassir, Tarek Zayed, Ali Hassan Ali, Mohamed Elrifaee, Sulemana Fatoama Abdulai, Tong Yang, and Amr Eldemiry. Automation in tower cranes over the past two decades (2003–2024). *Automation in Construction*, 170:105889, 2025. doi:10.1016/j.autcon.2024.105889.

[8] Rongyan Li, CHI Hung-Lin, Zhiqi Hu, Du Li, Wen Yi, and Ioannis Brilakis. Data-driven lifting-centered construction site layout planning decision approach with BIM. *Automation in Construction*, 179:106467, 2025. doi:10.1016/j.autcon.2025.106467.

[9] Zhiqian Zhang and Wei Pan. Multi-criteria decision analysis for tower crane layout planning in high-rise modular integrated construction. *Automation in Construction*, 127:103709, 2021. doi:10.1016/j.autcon.2021.103709.

[10] Keyu Chen, Beiyu You, Yanbo Zhang, and Zhengyi Chen. Automatic lift path planning of prefabricated building components using semantic bim, improved A* and GA. *Engineering, Construction and Architectural Management*, 32(6):4100–4124, 2025. doi:10.1108/ECAM-11-2023-1119.

[11] Zhiqian Zhang, Mun On Wong, and Wei Pan. Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction. *Automation in Construction*, 150:104848, 2023. doi:10.1016/j.autcon.2023.104848.

[12] Jiahui Wang, Jun Wang, Ruofan Chen, Kai Yang, Baolei Wu, and Yongqiang Qi. Formation collaborative obstacle avoidance with multiple UGVs in restricted environments based on adaptive DWA. *Expert Systems with Applications*, 265:125870, 2025. doi:10.1016/j.eswa.2024.125870.

[13] Donghao Xu, Jie Yang, Xueqian Zhou, and Haitong Xu. Hybrid path planning method for usv using bidirectional A* and improved DWA considering the manoeuvrability and COLREGs. *Ocean Engineering*, 298:117210, 2024. doi:10.1016/j.oceaneng.2024.117210.

[14] Xiutao Gu, Liaoxue Liu, Lu Wang, Zhaobao Yu, and Yu Guo. Energy-optimal adaptive artificial potential field method for path planning of free-flying space robots. *Journal of the Franklin Institute*, 361(2):978–993, 2024. doi:10.1016/j.jfranklin.2023.12.039.

[15] Boyu Ma, Zongwu Xie, Zainan Jiang, Yang Liu, Yiming Ji, Baoshi Cao, Zhengpu Wang, and Hong Liu. Robotic redundancy via arm angle self-adaptation through nullspace resolution: Offset poses a challenge. *The International Journal of Robotics Research*, 45(5):801–836, 2026. doi:10.1177/02783649251371735.