A Performance Benchmarking Framework for Remote-Controlled Tower Cranes Toward Standardized Specifications

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Abstract –

This paper establishes a performance evaluation framework for Remote-Controlled Tower Cranes (RCTCs), which potentially addresses the growing need for standardized, safe and efficient lifting operations in high-rise building works and large-scale civil infrastructure sites. Specifically, four performance metrics are defined: (1) lifting productivity, (2) system responsiveness, (3) operator wellness and (4) operational safety, derived from regulatory standards and operational requirements. A rigorous performance benchmarking is conducted against conventional tower cranes, through reviewing technical specifications of several RCTC solution providers in Hong Kong and mainland China, field surveys of their operators, and comparative analysis of the operational sensing data of remote-controlled and conventional tower cranes. RCTCs demonstrated 11.1% increase in daily lifting cycles, by recovering 25% non-productive time otherwise consumed by operators climbing up/down high-rise tower cranes every day. The insights shed light on future directions of establishing statutory standards and specifications for wide adoption of RCTCs.

Keywords –

Remote-controlled Tower Cranes (RCTCs), Human-Machine Interface, Performance Metrics, Performance Benchmarking, Harmonized Requirements, Standardized Specifications.

1 Introduction

Tower cranes remain indispensable at worldwide construction sites that require high-intensity vertical transport, but they present significant safety challenges. According to statistics from the Labour Department of the Hong Kong Special Administrative Region, 15.7% of the 299 incidents that occurred between 2011 and 2020 in Hong Kong were crane-related [1], and tower crane incidents account for approximately 8.0% of all construction fatalities over the past five years [2].

The environmental conditions of conventional tower crane cabins are not conducive to the comfort of tower crane operators fundamentally. Climbing tower cranes imposes significant physiological demands on operators, while falls from elevation present substantially elevated fatality risks compared to ground-level incidents. Operators suffer from prolonged isolation in elevated cabins and are exposed to inclement weather involving extreme heat, harsh cold, and limited visibility, exacerbating fatigue and reducing their situational awareness. The blind spot operation also leads to persistent risks of collision in obstacle-filled urban sites, especially when multiple tower cranes are deployed in proximity.

Furthermore, the demographic challenges compound these safety concerns in the construction industry. The lack of sufficient young entrants to replace skilled operators who are familiar with safety standards and operating tower cranes threatens the sustainable development of the entire construction industry.

Recently, remote-controlled tower cranes (RCTCs) emerged as a potential solution to safer lifting operations. As illustrated in **Figure 1**, the operators can perform lifting tasks from ground-based cabins, relying on remote monitoring and control technologies. The adoption of RCTCs potentially brings significant benefits to the construction industry. However, proprietary technologies and products with varying specifications from suppliers led to fragmented practices. Barriers are emerging, including ambiguous safety scope, confusing and low-interoperability system design, and difficulties in procurement and maintenance.

Figure 1: Remote-controlled tower crane cabin

While existing studies have evaluated specific components such as cameras or latency individually, they solely focus on individual components rather than a holistic benchmarking standard, therefore cannot correlate multiple performance metrics. A more standardized framework is needed to identify critical safety and performance parameters. Hence, this study aims to develop a unified evaluation framework through a structured harmonization process, for performance benchmarking of RCTCs against conventional ones.

2 Related Work

To develop a unified performance evaluation framework for RCTCs, related studies are reviewed from three aspects: the comparison of operation characteristics of remote-controlled and conventional tower cranes, representative components with functions of existing auxiliary sensing systems, and quantitative performance evaluation for tower cranes.

When both conventional tower cranes with suspended cabins and RCTCs could serve for vertical transport on construction sites, their operational safety and efficiency were compared. RCTCs show potential superiority in certain circumstances, such as multi-camera visual coverage to eliminate operators' blind spots [3]. A study of tower crane safety accidents in South Korea from 2015 to 2020 [4] revealed that poor operator visibility is a major cause of accidents in the operation of conventional tower cranes, while RCTC-related accidents were primarily due to improper management of lifted loads and inadequate inspection of the surrounding areas.

Figure 2 directly differentiates the system architecture of typical RCTCs against conventional tower cranes, where RCTC-specific components include the human-machine interface displaying sensor information for operators' decision-making. The seamless interaction between operators and the remote-controlled interface replaces direct observation of on-site information. Adopted interaction patterns enabled operators to control remotely, while helping them reduce load swaying and prevent coming collisions [5].

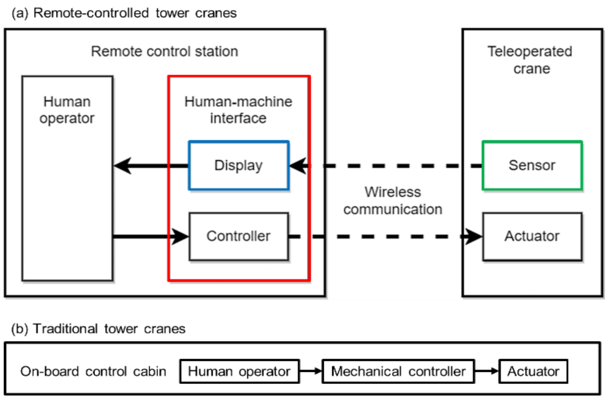

Figure 2: System architecture adapted for RCTCs

RCTC operations relied heavily on auxiliary sensor systems for precise data perception. Fundamentally, cameras are indispensable in auxiliary sensing systems, for estimating the crane components' motion [6], analyzing the spatial statuses of lifting-related objects [7], measure the sway and twisting angle of loads [8], and more. Simultaneously, a wider range of auxiliary sensors were applied. For example, light detection and ranging (LiDAR) is beneficial for reconstructing lifting environments, especially in complex construction scenarios [9]. By installing a series of environmental sensors, including sensors for measuring temperature, air humidity, and wind speed, the most favorable conditions for lifting operations can be explored [10].

Quantitative performance evaluation for tower cranes is multifaceted. Operational safety was addressed through various indicators in [5-10], including safe distances, movement, and speed, etc. Lower-level indicators would be further integrated to form comprehensive performance metrics, such as the capability of operators' situation awareness [11]. Moreover, the adverse effects of communication time latency and potential optimizations receive attention, such as providing more user-friendly control interfaces to reduce psychological and physical stress, as well as incorrect decision-making of operators [12]. Furthermore, cost and efficiency were considered in existing studies, covering the complete lifting cycle time [13], total transportation distance of the load in lifting tasks [14], equivalent energy consumption [15], etc.

Overall, RCTCs are expected to improve performance under specific site conditions compared to conventional ones, freeing operators from suspended cabins through remote interaction. The auxiliary system with multiple sensors is connected to the transmission system, supporting operators to acquire and analyze on-site information. Nevertheless, the reviewed work has not established a unified framework with specifications for RCTCs to collect advantages and coordinate differences in the current fragmented practice.

3 Proposed Methodology

To address the fragmentation in current RCTC implementations, this study establishes a comprehensive performance evaluation framework for RCTCs. Based on our review of tower crane-related literature and regulatory safety guidelines, several performance metrics are proposed to facilitate performance benchmarking of RCTCs against conventional tower cranes. With data and feedback solicited from several real construction sites, performance benchmarking is conducted to evaluate the potential benefits of adopting RCTCs.

Specifically, our proposed evaluation framework integrates multiple performance dimensions to provide a holistic assessment that captures both operational efficiencies and human factors considerations. By establishing quantifiable metrics across four dimensions: (1) lifting productivity, (2) system responsiveness, (3) operator wellness and (4) operational safety.

These four dimensions were derived from a synthesis of various regulatory safety guidelines, operational efficiency requirements, and human-factor literature. Alternative dimensions such as hardware cost were excluded from this technical framework as they are highly project-specific, whereas the selected four dimensions represent universal technical performance characteristics applicable across different scenarios.

The four dimensions are inter-dependent. Operator wellness directly influences lifting productivity through enhanced fatigue management, while operational safety imposes thresholds which may act as a constraint on lifting productivity. System responsiveness enables both safety and productivity, affecting the operator's reaction upon any unsafe scenarios. The framework addresses trade-offs by considering safety and human wellness as mandatory compliance criteria, while the responsiveness and productivity of RCTCs are optimized within those safe boundaries.

3.1 Lifting Productivity

Lifting productivity evaluation centers on operational throughput and time efficiency in real-world construction environments. The primary metric is the number of lifting cycles per hour. Each cycle is defined as completed lifts from hook availability at loading position to hook return ready for the next load. This fundamental measurement captures raw operational capacity while accounting for site-specific variables.

The peak working timeframe of the crane is first identified, such that the lifting cycles estimated reflect the maximum productivity each tower crane supports. This ensures a fair performance comparison between different cranes (excluding the idle time). Then, a workflow is proposed to automatically extract the lifting cycles from a batch of timestamped motion data:

1) Detect change in lifted load by the load sensor mounted at the hook, where positive change denotes "loading", negative change denotes "unloading".
2) Detect change in lifting height of the hook logged by the position encoder, where positive change denotes "lifting", negative change notes "lowering".
3) Detect change in rotational angle of the arm, which denotes "moving";
4) Detect change in lifting radius of the arm, which denotes "slewing".

Upon identifying the operational patterns over the timestamps, the raw sensing data are automatically converted into discrete actions reflecting the dynamic motion change of the tower crane, which enables inference of how many lifting cycles are performed.

A critical differentiating factor between remote-controlled and conventional tower cranes is the potential time-saving through eliminating the operators' climbing requirement, which denote certain portion of non-productive time during a daily operation shift. Hence, our evaluation framework also accounts for shift transition efficiency and operational continuity. RCTCs potentially enable near-instantaneous shift transitions (within 1-2 minutes, for workers entering and leaving the ground cabin). This metric becomes increasingly important on projects with multiple shifts within a workday, where cumulative time savings can substantially offset per-cycle productivity differences.

3.2 System Responsiveness

The network architecture should have redundant bandwidth to ensure stable signal transmission to the remote-control cabin. Signal latency is measured as the visual feedback time lag between physical events and their display representation, captured through synchronized input detection and response sensors. Redundancy in data transfer bandwidth is also assessed.

The cognitive ease of adaptation when operators move from conventional to remote-control interfaces is assessed via surveying the on-site tower crane operators, including subjective assessments of intuitiveness, spatial awareness retention and depth perception capabilities.

Visual feedback quality is evaluated, since consistent visual clarity is essential during challenging conditions such as low-light operations scenarios that frequently occur on construction sites. Metrics include frame rate consistency, image resolutions and waterproof capability under varying ambient conditions, e.g. strong sunlight or heavy rain which may degrade the camera image quality.

3.3 Operator Wellness

The wellness dimension particularly emphasizes factors that differentiate RCTCs from conventional tower cranes: elimination of climbing requirements, protection from extreme weather conditions, improved access to facilities, and reduction in physical strain. These factors collectively influence operator retention, recruitment potential, and long-term operational sustainability in an industry facing significant demographic challenges.

Environmental metrics quantify cabin conditions including temperature stability, supply of air-conditioning and lighting for human comfort, isolation from surrounding noises or debris on construction sites. These measurements correlate operator alertness, decision-making capability, and long-term human health.

Qualitative assessments capture operator subjective experiences through structured surveys focusing on physical comfort, mental workload, stress levels, and job satisfaction. Key factors include visual fatigue upon looking at multiple display screens for a long time (considering the blue-light emission), convenience/accessibility to toilets and rest areas (conventional tower crane operators often limit fluid intake to avoid climbing descents, leading to dehydration and associated performance degradation).

3.4 Operational Safety

Operational safety metrics evaluate both preventative capabilities and functional designs that mitigate safety risks. Camera view coverage among critical lifting zones (including jib ends, trolley positions, hook approach paths, and ground-level loading areas) is assessed to ensure sufficient cameras are installed to avoid blind spots that obstruct the operators' decision. The provision of anti-collision mechanisms is also assessed (e.g. AI algorithms embedded into the cameras for object proximity alerting), ensuring RCTCs' ability to compensate for human limitations in spatial awareness during remote operations.

Moreover, the sufficiency of structural and environmental sensors (including wind speed, structural deflection, load weight, lifting height and radius) is also evaluated. Emergency protocols are also analyzed, e.g. automatic shutdown/slowdown functions when the sensor readings exceed any design limits. These can determine the RCTCs' real-time responsiveness to changing conditions, particularly for rapidly developing environmental hazards that require immediate operator awareness and response.

3.5 Data Collection and Analysis

Regarding methodological validity, the framework employs a multi-criteria comparative approach rather than a weighted aggregation strategy. No normalization or weighting is applied to combine dimensions into a single score, as this could mask critical deficiencies (e.g., high productivity masking poor safety). Instead, effectiveness is ensured by evaluating each dimension against established baseline measurements from conventional tower cranes. Results are interpreted both quantitatively (e.g., cycle times and latencies from sensor logs) and qualitatively (e.g., operator surveys), ensuring a balanced assessment where compliance in safety and wellness is prerequisite to productivity evaluation.

The framework incorporates baseline measurements from conventional tower cranes to establish comparative benchmarks. For each deployment site, we collect the operational logs that capture the continuous operational patterns of tower cranes (both remote-controlled and conventional ones). Moreover, site visits are conducted to review the on-site operations, which are also compared against the technical specifications documented by the solution providers.

Our data analyses employ both descriptive statistics to characterize performance patterns and inferential statistics to identify significant differences between remote-controlled and conventional tower cranes, with particular attention to contextual factors that might influence performance comparisons. This comprehensive approach ensures evaluations reflect real-world operational conditions while maintaining scientific rigor in performance assessment.

4 Validation and Discussion

The technical specifications of five leading solution providers in Hong Kong and mainland China are thoroughly reviewed, with actual field visits conducted to multiple construction sites adopting their RCTCs. Data were collected from field observations, operator feedback surveys, and the timestamped operational logs of their tower cranes. A snapshot of data logged for the tower cranes are shown in **Figure 3** (logged by structural sensors, slewing angle sensors and wind sensors, etc.). The lifting cycles performed by the tower crane are then extracted by analyzing the recorded motions.

Data_start	moment	Load	Radius	Angle	Height	WindSpeed	Safeload
9/21/2025 15:49	1.41	0.44	10.41	12.46	74.68	0	14
9/21/2025 15:52	1.16	0.32	11.69	10.91	74.6	0	14
9/21/2025 16:41	9.74	3.41	9.2	33.37	74.82	0	14
9/21/2025 16:44	1.05	0.34	9.82	35.94	75.42	0	14
9/21/2025 17:00	6.3	0.87	23.33	-41.5	68.86	0	13.81
9/21/2025 17:03	2.69	0.29	28.47	-46.93	64.2	0	10.71
9/27/2025 9:40	9	0.52	40.79	364.54	-6.06	0	5.75
9/27/2025 9:50	8	0.49	39.39	379.38	-4.94	1.8	6.15
9/27/2025 10:05	20.99	1.01	44.39	365.72	-5.53	1.5	4.81
9/27/2025 10:15	38.57	2.09	42.01	365.38	-4.62	1.2	5.43
9/27/2025 10:27	29.26	1.42	44.2	364.73	-4.8	2.7	4.86
9/27/2025 10:49	36.31	1.9	42.77	369.89	-5.51	1.05	5.23

Figure 3: Sample operational logs of tower cranes

4.1 Lifting Productivity

The comparative study was conducted on a construction site in Hong Kong, comprising works in a waste treatment plant. The conventional tower crane and

RCTC are next to each other, serving similar works in the same area. The conventional tower crane operator needs to climb approximately 50 meters to reach the onboard cabin, during which he/she must stop climbing when the neighboring tower crane is performing material lifting works simultaneously, prolonging the overall shift time.

Two months of continuous operational logs are analyzed (actual data collected from two RCTCs and one conventional tower crane, working on the same construction site in Hong Kong). From the sensing data, the lifting cycles are extracted (illustrated in **Figure 4**), based on our automatic workflow proposed in Section 3.1.

Table 1: Performance evaluation for lifting productivity

Metric \ Crane Type	Remote	Traditional
Non-productive time per day	/	2 hours
Effective work time per day	8 hours	6 hours
No. of cycles per hour	8.75	**10.5**
No. of cycles per day	**70**	63

Table 1 explicitly compares the productivity between remote-controlled and conventional tower cranes. Overall, the RCTCs achieved 11.1% higher daily cycle counts (70 vs 63 by conventional one). A critical trade-off is revealed if the daily throughputs are normalized by an 8-hour daily shift, where the RCTCs operated at 8.75 cycles/hour compared to 10.5 cycles/hour for conventional tower cranes. Despite a reduction in per-hour throughput during active lifting phases, RCTCs increase the net lifting throughput per day by 11.1%.

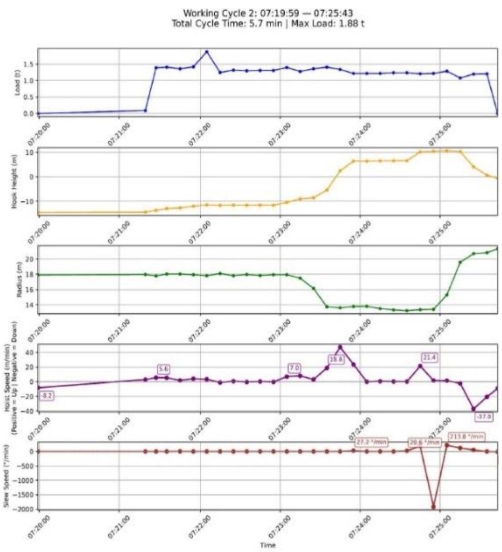

Figure 4: Sample of actual lifting cycles extracted

Our preliminary analysis suggests a narrative: RCTCs effectively compensate the non-productive climbing time along conventional tower cranes. Based on field surveys to the operators (approximately 2 hours, including climbing up/down the tower crane for each shift, dining and toilet breaks), enabling near-instantaneous shift transitions for extended operational windows. For construction sites with tight schedules and multi-shift operations, such time recovery provides greater schedule reliability than marginal improvements in cycle speed.

Furthermore, RCTC cabins sustain higher operational continuity under adverse weather conditions (e.g. rain or intense sunlight), whereas conventional tower cranes are frequently suspended due to unsafe climbing conditions or operator discomfort in exposed cabins.

Essentially, our evaluation with 2-month operational logs only provide initial insights for RCTC performance. During early adoption, RCTCs may not inherently accelerate individual lifting cycles, due to the delayed visual and control feedback to the RCTC operators. As the operators accumulate more operational experience with the remote-control interfaces, the lifting efficiency will further improve. Hence, RCTC data over longer timeframes across different project sites should be analyzed in future studies, for a more conclusive performance benchmarking.

4.2 System Responsiveness

Table 2 compares the signal latencies among different RCTC solutions. Significant variations in system responsiveness characteristics are observed.

Table 2: Signal latencies among the solutions reviewed

Solution	Latency
A	100-150 ms
D	80-100 ms
E	100 ms

The reviewed solutions implementations exhibited latency ranging from 80–150 milliseconds, via dedicated industrial-grade network bridges with around 1 gigabyte per second. Based on several benchmarking human-machine interfaces, the maximum latencies range from 190ms [16], 200ms [17], 250ms [18], suggesting that the RCTC solutions surveyed have acceptable system latency of below 150ms.

Acceptable visual feedback quality was reported by the operators, as the display screens have consistent frame rate at minimum 30 frames per second. Operator feedback indicated that latency directly influenced control confidence and operational behavior. The RCTC operators reported that when the system feels delayed, more conservative or slowed-down operations are adopted especially during precision placement tasks.

The on-site operators for Solution A were surveyed, which revealed additional insights about system performance. Their operators reported "almost equivalent feeling among conventional and remote-control cabins" but noted significantly improved visibility during heavy rainfall due to the hydrophobic coating on their camera lenses, while conventional cabin windows rapidly deteriorate in visibility.

4.3 Operator Wellness

Operator feedback across all sites consistently highlighted significant improvements in operator wellness with RCTCs compared to the elevated cabins in conventional tower cranes.

A thematic analysis of operator feedback is conducted to categorize human wellness improvements into four dimensions:

(1) Environmental Comfort: All the five solutions have sufficient air-conditioning and lighting in a well-protected cabin. The operators for Solutions A and C reported reduction in heat stress exposure with the air-conditioned remote-control cabin, protection from construction site dust and particulate matter, which are essential to human health.

(2) Accessibility: The elimination of climbing requirements universally improves operator welfare, with RCTC operators reporting elimination of physical fatigue from climbing and no longer needing to limit fluid intake to avoid climbing descents, with improved access to restroom facilities and rest areas, maintaining better hydration of the operators.

(3) Mental Wellness: Ground-based cabins also reduce cognitive load of the RCTC operators, as they reported higher sustained attention levels due to thermal comfort and reduced physical stress, providing a theoretical anchor for the observed improvements in operational continuity.

(4) Physical Ergonomics: RCTC operators for Solution A highlighted the ergonomic seat design (mimicking a 7-person vehicle driver seat) which directly reduced lumbar strain compared to standard cabin chairs.

These features collectively result in better concentration to conduct safer and more precise throughout the lifting operations. It also potentially addresses the industry demographic challenge by making tower crane operation more accessible to broader age groups and genders, training up more diverse workforce.

4.4 Operational Safety

Camera system configurations varied across implementations (8–14 units per installation), with resolutions ranging from 2MP to 4K. All systems achieved IP66 environmental protection ratings. Comprehensive coverage of critical zones—jib ends, trolley positions, hook approach paths, and ground loading areas—was universally implemented. Advanced implementations incorporated AI-assisted features including automatic hook tracking, real-time worker proximity alerting within statutory 7-meter danger zones.

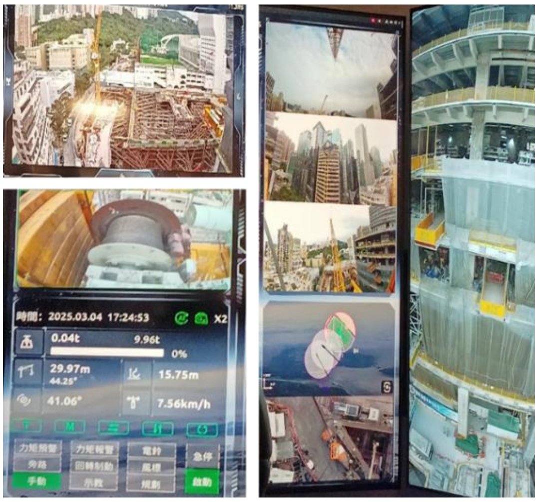

Figure 5: RCTC interface of one solution visited

Anti-collision capabilities were universally deployed through either 2D planar synchronization of multiple crane envelopes (shown in **Figure 5** where the overlapping circles denote the cranes' locations and their lifting radii), or with 3D LiDAR-based point cloud processing enabling obstacle-aware speed modulation available in Solution E.

Environmental monitoring capabilities were universally implemented to measure wind load, lifted load and lifting height of the crane components. Tilting angle sensors are commonly used to measure vibration and structural deflection of crane components. Solution C even monitored the ambient temperature and humidity, for more human-centric alerting of the site conditions.

All the five solutions include automatic operational restrictions when environmental thresholds are exceeded (e.g. automatic shutdown if wind speed reaches 72km/h, overload alarm when reached 90% capacity). All their RCTCs commonly implement emergency protocol with fail-safe mechanisms, e.g. one-click immediate switching to conventional on-board manual control at any time, auto-switched when latency exceed a threshold.

4.5 Recommendation toward Standardization

Our analysis leads to following directions for developing RCTC standards and regulatory requirements.

System Architecture: While RCTCs offer enhanced visual coverage, remote operations may induce additional risks upon excessive signal latency, packet loss or loss of somatic feedback. Unlike conventional operators who rely on the physical intuition (e.g. mechanical vibration of the cabin), RCTC operators depend mainly on visual and auditory cues embedded in the remote system. Hence, the proposed standard may require strict latency thresholds to ensure synchronized visual feedback, redundant communication architecture with automatic failover mechanisms, enhanced visual alerting systems for compensating haptic feedback, etc.

Safety Protocols: Require minimum standards on camera (e.g. minimum image resolutions, comprehensive coverage of critical operational zones like jib ends, trolley positions and loading areas); Specify core sensor requirements including load monitoring, wind speed detection, structural deflection measurement, and real-time environmental assessment; Implement progressive safety intervention protocols with defined warning thresholds and automatic shutdown mechanisms.

Inspection Regime: Mandate inspection procedures with documentation based on standardized checklists for essential RCTC components; Daily inspection may cover camera image quality, network signal stability, testing simple motions before actual lifting works, etc.; Weekly inspections may encompass structural integrity assessments of the tower crane itself, camera/sensor alignment, redundant storage of data logging system, etc.

Operator Wellness: Establish minimum cabin environmental standards addressing thermal comfort, air quality, noise levels, and visual ergonomics to prevent operator fatigue. More importantly, human-centric cabin interface designs should be mandated to enhance the attention of operators, reducing their stress and discomfort, which results in safer lifting operations.

Operator Training and Certification: Develop dual-certification requirements where operators must maintain conventional tower crane certification plus specialized RCTC-specific training (e.g. mandate a minimum operational hours); Implement periodic re-certification requirements with emphasis on new safety features and system updates.

Technological Promotion: Advanced technologies should be encouraged to create market incentives for technological advancement while maintaining safety imperatives requirements. Advanced technologies, including LiDAR or photogrammetry scanning for 3D environmental reconstruction [19, 20], multimodal AI-assisted safety monitoring[21, 22], can be recognized as differentiating features meriting industry recognition through tiered certification schemes. While not mandated for baseline compliance, these performance-based specifications may effectively qualify RCTC solutions for regulatory approval or preferential procurement.

5 Conclusion and Future Work

This paper establishes a comprehensive framework for evaluating remote-controlled tower cranes through systematic performance benchmarking against conventional tower cranes. Our proposed evaluation framework is validated through extensive review of solution providers in Hong Kong and mainland China, with field surveys of their on-site operators and actual operational logs of their tower cranes. RCTCs offer significant advantages in operator welfare, safety management, and operational continuity. As for productivity, RCTCs show higher daily lifting efficiency through conversion of non-productive climbing time into operational availability. The time recovery (approximately 2 hours/day) compensates the reduction in hourly cycle rates during the operators' adaptation period, yielding 11.1% higher daily lifting productivity. Our evaluation framework provides foundation for developing statutory standards as the industry-wide operational guidelines. The insights are generalizable to different countries/regions worldwide, while adaptation to local regulations is necessary.

The preliminary validation relies on 2-month RCTC operational data from a construction site in Hong Kong. Potential bias may arise from site-specific practices (e.g., shift scheduling, safety protocols, difference in climbing height). For instance, for a construction site working on high-rise buildings, the climbing height for the conventional tower crane can be much higher than that for civil infrastructure works. Dependent on specific site arrangement, different work schedule may be assigned to each tower crane, which can affect the shift intervals during different periods. Future research should expand data collection across diverse sites and operator cohorts to evaluate long-term productivity as the operators gain proficiency in RCTC, ensuring the benchmarking outcomes are robust against site-specific variables.

Future work can also expand along economic analyses to include comprehensive lifecycle costing that accounts for reduced insurance premiums, lower training turnover costs or decreased incident-related expenses. Regulatory development should progress toward standardized RCTC requirements that mandate essential features or measures, including safety-oriented system design, regular inspection, operator training, etc. Meanwhile, emerging technologies should be encouraged, such as more advanced AI algorithms for real-time obstacle avoidance and automatic crane speed regulation), which can support lifting safety monitoring and decision-making of RCTC operators.

Acknowledgment

The authors would like to acknowledge the project (No. BTRI/RDC/2025/WO003) funded by Building Technology Research Institute, Hong Kong Special Administrative Region. The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

[1] Work Safety Alert, Hong Kong, 2021. https://www.labour.gov.hk/eng/news/work_safety_

alert.htm (accessed January, 2026).
[2] Occupational Safety and Health Statistics Bulletin, Hong Kong, 2025. https://www.labour.gov.hk/eng/osh/content10.htm (accessed in January 2026).
[3] A. Shapira, A. Elbaz, Tower crane cycle times: case study of remote-control versus cab-control operation, Journal of Construction Engineering Management. 140 (2014) 05014010. doi:10.1061/(ASCE)CO.1943-7862.0000904.
[4] J. Y. Kim, D. S. Lee, J. D. Kim, G. H. Kim, Priority of accident cause based on tower crane type for the realization of sustainable management at Korean construction sites, Sustainability. 13 (2021) 242. doi:10.3390/su13010242.
[5] T. A. Sitompul, Human–machine interface for remote crane operation: A review, Multimodal Technologies and Interaction. 6 (2022) 45. doi:10.3390/mti6060045.
[6] H. Luo, M. Wang, P. K. Y. Wong, J. C. P. Cheng, Full body pose estimation of construction equipment using computer vision and deep learning techniques, Automation in Construction. 110 (2020) 103016. doi:10.1016/j.autcon.2019.103016.
[7] R. Gutierrez, M. Magallon, D. C. Hernández, Vision-based system for 3D tower crane monitoring, IEEE Sensors Journal. 21 (2021) 11935–11945. doi:10.1109/JSEN.2020.3042532.
[8] J. Ye, J. Huang, Analytical analysis and oscillation control of payload twisting dynamics in a tower crane carrying a slender payload, Mechanical Systems and Signal Processing. 158 (2021) 107763. doi:10.1016/j.ymssp.2021.107763.
[9] L. Huang, S. Dutta, Y. Cai, Laser scanned real environment for intelligent virtualization of crane lifting, Virtual Reality and Intelligent Hardware. 2 (2020) 87–103. doi:10.1016/j.vrih.2020.04.003.
[10] Z. Liu, Z. Guo, W. Tang, X. Yuan, Digital twin-based safety risk coupling of prefabricated building hoisting, Sensors. 21 (2021) 3583. doi:10.3390/s21113583.
[11] T. Cheng, J. Teizer, Modeling tower crane operator visibility to minimize the risk of limited situational awareness, Journal of Computing in Civil Engineering. 28 (2014) 04014004. doi:10.1061/(ASCE)CP.1943-5487.0000282.
[12] T. Fahlén, T. A. Sitompul, R. Lindell, Evaluating graphical user interfaces for handling latency in remote crane operation, BCS HCI '23: Proceedings of the 36th International BCS Human-Computer Interaction Conference. (2023). doi:10.14236/ewic/BCSHCI2023.21.
[13] M. Ahmadnia, R. Ghanbari, M. Maghrebi, Optimized multi-tower crane layout planning: determine height, location and type to improve operational safety, Engineering, Construction and Architectural Management. (2025). doi:10.1108/ECAM-10-2024-1401.
[14] C. Zhou, F. Dai, Z. Xiao, W. Liu, Location optimization of tower cranes on high-rise modular housing projects, Buildings. 13 (2023) 115. doi:10.3390/buildings13010115.
[15] F. Zhang, C. Zhang, Y. Fu, J. Liu, J. Bu, P. Duan, S. Chen, A parameterized model for tower crane energy consumption was developed based on theoretical formulation and field data, Scientific Reports. 15 (2025) 10453. doi:10.1038/s41598-025-94875-5.
[16] T. Hatano, T. Shimada, T. Yoshida, T. Kawano, Evaluation of end-to-end delay requirement for remote, precise pick-up action of miniature crane, IEICE Communication Express. 12 (2023) 242. doi:10.1587/comex.2023XBL0017.
[17] A. Duz, F. Negrello, A. Rucodainii, D. Lanzoni, M. Corsanici, A. Iapichino, A. Vitali, D. Regazzoni, V. Birolini, R. Signori, R. Ceresoli, G. Grioli, A. Bicchi, M.G. Catalano, From construction machines to remote construction robots: control, interfaces, and usability of the Cranebot, Frontiers in Robotics and AI. 11 (2024) 1504317. doi:10.3389/frobt.2024.1504317.
[18] S. B. Kamtam, Q. Lu, F. Bouali, O. C. Haas, S. Birrell, Network latency in teleoperation of connected and autonomous vehicles: A review of trends, challenges, and mitigation strategies, Sensors. 24 (2024), 3957. doi:10.3390/s24123957.
[19] Z. Liang, L. Yang, Z. Liang, J. C. F. Chan, Z. Zhang, M. Wang, J. C. P. Cheng, Optimized UAV view planning for high-quality 3D reconstruction of buildings using a modified sparrow search algorithm, Advanced Engineering Informatics. 65 (2025) 103344. doi:10.1016/j.aei.2025.103344.
[20] Z. Liang, J. C. F. Chan, J. Zhang, Z. Liang, B. Wang, M. Wang, J. C. P. Cheng, Multimodal LLM-driven language-embedded 3D gaussian splatting for semantic and realistic digitization of historical buildings, Automation in Construction. 181 (2026) 106628. doi:10.1016/j.autcon.2025.106628.
[21] X. Guo, P. K. Y. Wong, J. C. P. Cheng, C. F. Chan, P. H. Leung, X. Tao, Enhancing visual-LLM for construction site safety compliance via prompt engineering and bi-stage retrieval-augmented generation, Automation in Construction. 179 (2025) 106490. doi:10.1016/j.autcon.2025.106490.
[22] C. F. Chan, P. K. Y. Wong, X. Guo, J. C. P. Cheng, P. H. Leung, X. Tao, Context-aware vision-language model agent enriched with domain-specific ontology for construction site safety monitoring, Automation in Construction. 177 (2025) 106305. doi:10.1016/j.autcon.2025.106305.