SEMI-AUTOMATIC LIFTING AND ASSEMBLY PLATFORM (SLAP) FOR MIC TO MITIGATE SAFETY RISKS

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Semi-automatic Lifting and Assembly Platform (SLAP) for MiC to Mitigate Safety Risks

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CERTIFICATE OF ORIGINALITY

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Abstract

With the increasing adoption of Modular Integrated Construction (MiC) in Hong Kong, the demand for safer, more efficient, and precise lifting operations becomes critical. Traditional crane-based lifting methods face significant safety risks, inefficiencies, and operational challenges, especially in the dense and complex urban environments of Hong Kong. These challenges highlight the urgent need for innovative solutions to improve the safety, efficiency, and accuracy of MiC lifting operations. In response, this study aims to develop a Semi-automatic Lifting and Assembly Platform (SLAP), a robotic system specifically designed to enhance module localization and positioning in MiC. The aim of this research is to improve operational efficiency, accuracy, and safety performance, addressing the limitations of existing lifting methods while advancing MiC practices.

To achieve this aim, the study follows three primary objectives:

(a) To identify and analyze the key safety risks in MiC lifting operations across different stages, and to determine specific, measurable gaps that can be addressed through technological solutions.

(b) To design, develop, and validate an SLAP capable of mitigating the identified risks and improving the safety, efficiency, and accuracy of MiC lifting operations.

(c) To assess the practical performance of the SLAP system using a systematic evaluation framework based on industry practices and measurable parameters for safety, efficiency, and productivity.

The research begins by systematically identifying critical safety risks in MiC lifting using a mixed-method approach, including a detailed literature review, semi-structured interviews, and numerical analysis. This process uncovers the most pressing lifting safety risks and provides a clear understanding of the challenges present at various stages of the lifting process. These findings lay a strong foundation for the development of targeted technical solutions. Building on this analysis, the SLAP is proposed as an innovative solution to address these challenges. The platform integrates advanced control mechanisms for horizontal steering, levelling, and translation, supported by a robust sensing system that provides real-time feedback. These features enable the system to meet the safety, precision, and productivity requirements of MiC while ensuring compatibility with the operational demands of the construction industry.

The SLAP's control logic and mechanisms incorporate detailed workflows and pose adjustment principles to optimize its functionality, which is detailed and illustrated in this study. A laboratory-scale prototype is developed to validate the feasibility of the proposed design and methodology. Experimental results demonstrate the SLAP's ability to execute complex lifting tasks with precision. These findings confirm the system's potential to address critical safety risks while significantly improving efficiency and accuracy in MiC lifting operations.

Recognizing the absence of a standardized framework for evaluating MiC lifting platforms, this research develops a comprehensive performance evaluation framework. This framework is established through a rigorous review of academic literature, international standards, and local guidelines, identifying key performance parameters such as Quality, Safety, and Productivity. The SLAP prototype is tested using this framework, and the experimental results validate both the system's functionality and the applicability of the evaluation framework. While the SLAP system demonstrates robust performance, minor limitations, such as theoretical simplifications and human-induced errors during calibration, are identified. These limitations provide opportunities for future refinement and optimization of the system.

The key findings of this study are summarized across four dimensions. First, the research systematically identified and addressed critical safety risks in MiC lifting operations. Nine major safety risks, such as poor communication and operator's nonproficiency, were identified and prioritized. Furthermore, three measurable gaps across six operational stages were identified, which could be effectively addressed through mechanical automation or semi-automation. Second, to bridge these gaps, the SLAP system was developed, integrating three core modules: the Horizontal Steering Control Module (HSCM), the Levelling Control Module (LCM), and the Translation Control Module (TCM). These modules automate key tasks such as module rotation, levelling, and precise positioning, significantly reducing reliance on manual operations. Third, a scaled prototype of the SLAP system was constructed and tested, demonstrating its ability to reduce platform tilt by over 80%, achieve millimeter-level positioning accuracy (errors <3mm), and control roll and pitch angles within ±1°. Additionally, the SLAP system reduced module positioning time to 5 minutes per move (including damping and data recording), compared to the significantly longer durations required by manual methods. Fourth, a comprehensive evaluation framework was developed, confirming the SLAP system's performance in safety, accuracy, and efficiency, and showcasing its potential to address critical safety risks and transform MiC lifting practices.

This research makes original contributions to improving the safety and performance of

MiC lifting operations from both theoretical and practical perspectives. Theoretically, it systematically identifies and prioritizes critical safety risks associated with MiC lifting, providing a structured framework for understanding and addressing these challenges. It also introduces the SLAP system as a novel methodology, integrating advanced automation and precision control to tackle these risks and enhance operational efficiency. The research bridges the gap between theory and real-world application through a comprehensive validation framework, demonstrating the system's feasibility and offering actionable insights for refinement under on-site conditions. Additionally, it advances the MiC lifting knowledge system by developing new methodologies, performance metrics, and validation techniques, laying a foundation for future research and innovation in automated lifting technologies. From a practical perspective, the SLAP system represents an innovative solution that addresses critical safety risks by automating hazardous tasks, reducing workers' exposure to unsafe environments, and mitigating risks such as human error, fatigue, and poor visibility. The system also improves operational efficiency, while significantly reducing physical labor demands. These contributions collectively pave the way for safer, more efficient, and more reliable MiC lifting processes and establish a foundation for future advancements in full automation and robotics within the construction industry.

Publications Arising from the Thesis

Papers:

1. Qian, C., Li, X., Song, C., & Du, Q. (2025). Cable-Driven Parallel Robot for Module Facade Seam Sealing in Modular Construction: Static Workspace Analysis. *Modular and Offsite Construction (MOC) Summit Proceedings*, 9-16.
2. Song, C., Li, X., Du, Q., Jiang, R., & Shen, Q. (2024). Hybrid pose adjustment (HyPA) robot design for prefabricated module control in modular construction assembly. *Automation in Construction*, *168*, 105798.
3. Chen, J., Chi, H. L., Du, Q., Wu, P., 2022. Investigation of operational concerns of construction crane operators: An approach integrating factor clustering and prioritization. *Journal of Management in Engineering*, 38(4).
4. Du, Q., CHI H., Li, X., and Shen, Q. (2020) "Prioritizing Operational Considerations of Crane Operator Training for Modular Integrated Construction". *Construction Research Congress 2020*. Arizona, USA.

Patents:

1. CN 117864958A A Hoisting Mechanism for Active Payload Pose Adjustment. LI Xiao, DU Qianru, SONG Chen, SHEN Qiping Geoffrey, TENG Yue. (PCT/CN2024/120069)
2. CN 117864959A A Control System for Active Payload Pose Adjustment, SONG Chen. DU Qianru, LI Xiao, JIANG Ruiqi, SHEN Qiping Geoffrey (PCT/CN2024/120062)

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I write down these words to commemorate my academic journey over the past seven years.

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I firmly believe that this thesis is not an end, but merely a beginning:

“However difficult it might seem, the challenge will be overcome.”

“The road ahead will be long, our climb will be steep.”

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List of Abbreviations

ArchSD	Architectural Services Department
BD	Buildings Department
BI	Benefit Index
CAVS	Computer Aided Visual System
CI	Cost Index
CIC	Construction Industry Council
CoG	Center of Gravity
CoM	Center of Mass
CoMc	Center of Mass of the Whole Structure
CoMm	Center of Mass of the Moving Part of the Structure During the Module Transitioning
CoMp	Center of Mass of the Stationary Part of the Structure During the Module Transitioning
COPMC	Code of Practice for Safe Use of Mobile Cranes
COPTC	Code of Practice for Safe Use of Tower Cranes
CPC	Cooperative Patent Classification
DoF	Degrees of Freedom
DSR	Design Science Research
FMEA	Failure Mode and Effect Analysis
HKIC	Hong Kong Institute of Construction
HME	Human-Machine-Environment
HMI	Human-Machine Interaction
HPK	Horizontal Position Knob
HSCM	Horizontal Steering Control Module

IMU	Inertia Measurement Units
IPC	International (European) Classification of Patents
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCM	Levelling Control Module
LD	Labour Department
LQR	Linear Quadratic Regulator
MCA	Multiple Correspondence Analysis
MiC	Modular Integrated Construction
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
PCT	Patent Cooperation Treaty
PD	Proportional-Derivative
PI	Performance Index
PID	Proportional–Integral–Derivative
POSS	Position and Orientation Sensing System
RAS	Robotic Assembly Systems
RPN	Risk Priority Number
RPY	Roll-Pitch-Yaw
SAK	Steering Angle Knob
SLAM	Simultaneous Localization and Mapping
SLAP	Semi-Automatic Lifting and Assembly Platform
SLAP-CP	SLAP Control Panel
SLAP-CS	SLAP Control System
STCRs	Single-Task Construction Robots
TCM	Translation Control Module

t-SNE	T-Distributed Stochastic Neighbour Embedding
UI	User Interface
VPK	Vertical Position Knob

Chapter 1 Introduction

1.1 Introduction

This Chapter provides a concise and structured overview of the study, beginning with an exploration of the background surrounding the development of Modular Integrated Construction (MiC). It examines the safety challenges prevalent in local MiC lifting practices and highlights the growing trend of automation within the construction industry. Through this contextual analysis, the research problem is identified as a critical issue requiring attention. Building on this foundation, the research problem is further refined to align with the formulated research questions, which serve as a basis for defining a clear research scope and objectives. These are specifically designed to address gaps in existing knowledge and advance the field. To ensure a systematic approach, the study's structure is outlined in this Chapter, providing a clear roadmap for achieving the research objectives. Transitioning logically from background to problem identification, and then to the research framework, this Chapter sets the stage for the comprehensive research investigation that follows.

1.2 Research Background

1.2.1 The Development of MiC

MiC is a construction method that utilizes free-standing, fully finished modules, manufactured off-site and installed on-site (Buildings Department, 2018a). In Hong Kong, the development of prefabrication and modular construction has been closely tied to addressing housing demands and improving construction productivity. As early as the 1960s, public housing projects began adopting precast components, such as facades and staircases, to accelerate construction timelines and improve quality (Info government, 2018). By the mid-1980s, standard modular design was widely used in public housing, and by the 1990s, the precast ratio in public housing projects reached 18% (Info government, 2018). In the 21st century, precast technology expanded further, with the Housing Authority achieving a 70% precast ratio in public housing by 2019, incorporating volumetric kitchens and bathrooms as standard (HKHA, 2019). The government also promoted off-site prefabrication of steel reinforcing bars, supported by approved prefabrication yards (Buildings Department, 2016; DEVB, 2016).

The promotion of MiC as a higher-level strategy in Hong Kong began after the Chief

Executive highlighted its importance in the 2017 Policy Address (Policy Address, 2017). MiC refers to the use of free-standing integrated modules, completed in prefabrication factories with finishes, fixtures, and fittings, and then transported to construction sites for installation (Buildings Department, 2023). To streamline MiC implementation, the Buildings Department introduced a pre-acceptance system and, by 2023, had pre-approved 72 MiC products, including concrete and steel modules (Buildings Department, 2023). Landmark MiC projects include the MiC Display Center, the Pak Shing Kok residential project, and Innocell, a hybrid MiC development completed in 2020 (CIC, 2023, 2023a, 2023b). MiC also demonstrated its rapid construction potential during the COVID-19 pandemic, with projects such as the North Lantau Hospital Infectious Disease Center and the Tsing Yi Community Isolation Facility, the latter completed in just seven days (CIC, 2023c).

More recently, MiC has been adopted for transitional housing projects, offering flexibility for short-term needs. By 2023, 12 transitional housing projects utilized MiC, allowing for shortened construction timelines and module reuse. For instance, the "Nam Cheong 220" project was dismantled and relocated to a new site in Wong Yue Tan, Tai Po, with installation completed within two weeks (Gov, 2023a, 2023b). The growing adoption of MiC in Hong Kong reflects the industry's demand for faster, safer, and more sustainable construction methods, while also presenting opportunities to explore automation for enhanced productivity and operational efficiency.

1.2.2 MiC Safety in Hong Kong

The construction industry in Hong Kong faces significant safety risks, particularly in crane operations, which are critical for hoisting large, bulky MiC modules. Hong Kong’s congested construction sites, a result of its compact living spaces, exacerbate these risks (Kayhani et al., 2021). In 2020, public housing tenants had an average living space of 13.4 square meters. (Hong Kong Housing Authority, 2020a), reflecting the spatial constraints that complicate crane operations. Over the past decade, crane-related fatalities have occurred annually in Hong Kong, highlighting persistent safety issues. In 2017 alone, three fatalities were reported due to crane operations, including incidents caused by uneven center of gravity, cable failures, and falling jibs (on.cc, 2017a, 2017b; Yeung & Wong, 2017). These incidents underscore the significant challenges in ensuring safety during the lifting of large components, such as MiC modules. For example, in 2017 alone, three fatal crane-related accidents in Hong Kong highlighted critical safety deficiencies in both mobile and tower crane operations. In December 2017, a tragic tower crane accident occurred when an imbalanced center of gravity caused a component to detach from the hook, leading to a fatality as a worker was positioned directly beneath the lifting zone. (Yeung & Wong, 2017). Similarly, in November of the same year, a broken cable caused a component to fall from height, leading to another fatality (on.cc, 2017a). Earlier that year, in January, a mobile crane jib suddenly collapsed, claiming yet another life (on.cc, 2017b). These examples reveal not only the risks associated with crane operations but also the unsatisfactory working conditions and safety performance that further complicate the safe handling of large, heavy, and bulky MiC modules. These challenges emphasize the need for improved safety measures tailored to the unique demands of MiC projects.

The safety situation in crane operations remained critical in 2023, with lifting-related accidents posing significant risks to workers. By November 2023, 10 lifting-related industrial accidents had resulted in six fatalities (Ling, 2023). Notable incidents included a worker in Tung Chung being struck by falling rebar during a lifting operation on November 10, followed by a steel cable failure at the Central Kowloon Route site the next day, which caused four workers to fall into a pit and sustain injuries (Siu, 2023). These incidents reflect the growing challenges associated with lifting operations, particularly with the increasing use of prefabricated parts and curtain walls in construction, which have made such operations more frequent and complex. Despite reliance on risk assessments and assigning personnel to monitor operations, no effective solutions have been implemented to address these risks.

The situation further deteriorated in 2024, with a series of crane-related accidents highlighting systemic deficiencies in safety management. For instance, in January, a lorry-mounted crane toppled in Wong Chuk Hang due to improper outrigger setup and inadequate ground condition checks, injuring three workers and damaging two trucks (Hong Kong Housing Authority, 2024). In September, structural failure caused the collapse of a crane arm at a construction site in Lok Ma Chau, injuring five workers due to flying debris (South China Morning Post, 2024). Finally, in December, a worker in Yau Ma Tei was fatally struck by a glass panel of a curtain wall during lifting operations, underscoring the risks of handling heavy and bulky materials (Labour Department, 2024). Although no direct accident cases were specifically investigated related to MiC lifting, these incidents underscore the ongoing safety challenges in crane operations. These challenges are largely attributed to inadequate equipment capabilities, outdated technologies, and unsafe working conditions. To address these issues, adopting advanced lifting technologies and optimizing construction workflows to minimize the need for workers' involvement to operate directly beneath suspended loads could significantly improve safety. Without such innovative development, lifting operations will continue to pose risks to workers, particularly in MiC projects, where the precision required for lifting and aligning large, heavy modules makes safety even more critical.

The MiC lifting process faces significant safety challenges, with workers exposed to hazardous conditions and operations heavily reliant on human precision, increasing the risk of accidents and inefficiencies. As a way forward, the adoption of automation has thus emerged as a critical step, paving the way for innovative solutions in the MiC lifting domain to enhance safety and performance in MiC projects. The following section explores the trends and advancements in automation applications within the construction industry, laying the groundwork for addressing the specific risks associated with MiC lifting through cutting-edge technologies.

1.2.3 Automation Trends in Construction

The automation implementation in the construction industry has evolved significantly, with early developments focused on tasks such as heavy lifting, repetitive processes, and precision assembly. Japan led the way in the 1970s and 1980s, introducing single-task construction robots (STCRs) for activities like concrete spraying, welding, and prefabrication of building components (Bock & Linner, 2016a; Gharbia et al., 2020). By the mid-1980s, robotics technology had advanced with the integration of sensors and rudimentary machine vision systems, enabling robots to track and manipulate materials with greater precision (Misiti, 2020). These technologies laid the groundwork for automated on-site factories, where multiple robotic units could coordinate tasks such as distributing materials and assembling frameworks, significantly enhancing productivity and safety during lifting and assembly processes (Bock & Linner, 2016b).

Since the 2000s, automation solutions have increasingly been applied to heavy material lifting and assembly. For example, robotic assembly systems (RAS) have been developed to erect and assemble steel structures off-site, while mobile robots have been deployed for welding column-to-beam and column-to-column connections in steel structures (Carlos et al., 2008; Liang et al., 2017). Robots like Kajima's "Mighty Hand" and Takenaka's "SurfRobo" have also been used for tasks such as concrete floor compacting, while fully automated bricklaying systems have streamlined wall construction, reducing manual labor and improving accuracy (Carlos et al., 2008; Dörfler et al., 2016). These technologies directly address lifting and assembly risks by reducing the need for manual handling of heavy materials and improving precision in high-risk tasks.

More recently, advancements in sensor technology, digital transformation, and Building Information Modelling (BIM) have enabled collaborative robots (Cobots) to perform tasks such as excavation, compaction, and material management (Schöberl et al., 2023). Autonomous construction equipment, such as sensor-equipped excavators and loaders with GPS, Wi-Fi, and lidar, has further enhanced safety by minimizing human involvement in hazardous zones (Melenbrink et al., 2020). These automation trends highlight the potential to mitigate risks in MiC lifting operations, particularly through enhanced precision, reduced manual intervention, and improved control over lifting processes.

1.2.4 Introducing Semi-Automation in MiC Lifting

Automation in production systems is generally classified into three categories: full automation, semi-automation, and manual operation (Groover, 2016). Fully automated systems perform tasks autonomously without human intervention, relying on advanced technologies to ensure consistency, efficiency, and productivity (Carlos et al., 2008; Gharbia et al., 2020). On the other hand, semi-automation combines the advantages of fully automation with human oversight, creating a hybrid approach where certain tasks are automated, while others remain under human control (Cavell, 2017; Chintada & V, 2022; Ishihara & Ohtsuka, 2023; Xu et al., 2019). This intermediate level of automation, as described by Frohm et al. (2008), involves collaboration between humans and technological systems, balancing machine capability with human judgment to achieve tasks effectively. Semi-automation is especially advantageous in complex environments where adaptability, rapidly changing conditions and newly implemented technologies are critical.

MiC modules are typically designed as fully functional spaces, incorporating structural or non-structural walls and ceilings, with a focus on maximizing usable room space and ceiling height (BCA, 2017a). To ensure compatibility with practical layouts across a wide range of projects, module dimensions often reach up to 3 meters in width and 6 meters in length, resulting in a projected area of approximately 18 square meters or more, depending on specific designs (WSP, 2020). The weight of these modules further complicates the lifting process, with steel modules weighing between 15 and 20 tons and reinforced concrete modules weighing between 20 and 35 tons, depending on the design (BCA, 2017a). These characteristics make the lifting and positioning of MiC modules both complex and hazardous, requiring a system that ensures precision, adaptability, and safety.

Facing the challenges of MiC projects, including large module dimensions, heavy weight, and complex designs, fully automated systems are unsuitable due to their high costs, maintenance demands, and inability to adapt to dynamic and unpredictable conditions (Knight, 2025). Moreover, their reliance on the maturity and reliability of advanced technologies leads to significant upfront investment and maintenance costs, making them less accessible for projects with limited budgets compared to semi-automated systems. (HWArobotics, 2024).

Semi-automation, however, offers a practical solution by integrating human expertise into the workflow. It enables operators to monitor and participate in critical operations, ensuring real-time adaptability to changing site conditions. This approach minimizes the risks associated with errors and enhances operational safety, while also being more cost-effective due to reduced reliance on technologies. Semi-automation provides a starting point for automation applications in MiC lifting workflows, enabling the gradual adoption and validation of automated solutions before full deployment. This hybrid approach ensures precision, adaptability, and safety, addressing the complex demands of MiC lifting and positioning.

In the proposed solution developed in this research, tasks are divided between machine automation and human involvement to optimize efficiency and safety. The automated components of the system will mainly focus on precision-driven tasks, including horizontal attitude adjustment, which ensures accurate alignment of the module in the XY plane, and vertical height adjustment on a small scale to achieve precise positioning. Additionally, the automation part also manages translation movement, enabling smooth and accurate module movement relative to the ground. By assigning these tasks to the automation system, workers can be removed from the MiC lifting zone and its immediate surroundings, effectively reducing safety risks associated with falling objects, collisions, or working at height. Therefore, further improving overall safety and quality performance during the lifting process.

On the other hand, certain critical tasks are reserved for human operators to ensure monitoring and adaptability in handling complex or unpredictable situations. Operators are responsible for initial module positioning identification, where they confirm the starting position. They are also responsible for determining and inputting the destination. In the event of sudden disturbances to the system or any risks occurring, operators can intervene by activating the emergency stop or initiating emergency lifting procedures. Before the system executes its decision on the operations, operators can review the results and make manual fine-tuning adjustments if necessary. This hybrid task allocation integrates human judgment into key stages of the process, enabling real-time corrections and adaptability. By combining the precision of automation with the flexibility and decision-making capabilities of human monitoring, the proposed system is well-suited to address the complexities and safety requirements of MiC lifting operations.

Semi-automation strikes a balance between innovation and practicality, addressing the limitations of implementing full automation in MiC lifting. This hybrid framework not only meets the current demands of MiC projects but also lays a solid foundation for future advancements in automation, allowing the industry to gradually build expertise and confidence in fully automated solutions.

1.3 Research Problem Statements

Building on the advancements in MiC and the growing adoption of automation technologies in the construction industry, this study aims to tackle the critical MiC lifting safety risks associated with it, particularly in dense urban environments like Hong Kong. The rapid development of MiC has introduced significant opportunities to enhance construction efficiency, quality, and sustainability. However, the current lifting process for MiC modules, which relies heavily on riggers manually dragging and aligning modules, not only results in low efficiency and accuracy but also poses serious threats to worker safety. While automated systems have demonstrated potential for certain construction tasks, their lack of flexibility, high implementation costs, and incompatibility with dynamic site conditions render them impractical for addressing these challenges at this stage. Semi-automation, combining human oversight with adaptability, is a promising approach to improving safety, precision, and operational efficiency in MiC lifting operations.

This research addresses the key research question of how a novel semi-automated solution can be developed and validated to systematically resolve the intertwined challenges of safety and practical applicability in MiC lifting operations. The study aims to identify critical safety risks, evaluate the limitations of current practices, design a semi-automated solution to enhance safety and efficiency in lifting processes, and validate the effectiveness of the proposed solution. To achieve this aim, the research addresses the following specific research questions:

Q1. What are the critical safety risks in MiC lifting operations, and how can they be systematically identified and prioritized?

This question focuses on recognizing and categorizing the primary safety risks in MiC lifting operations. It seeks to establish a comprehensive understanding of risks that can inform the development of targeted technological solutions.

Q2. How do safety risks and challenges vary across different operational stages, and what measurable gaps can be addressed to improve the final assembly stage?

This question delves deeper into the variation of risks across different operational stages of MiC lifting and breaks them into stage-specific, actionable problems. By prioritizing measurable gaps, particularly in the final assembly stage, the analysis ensures a focused approach to designing semi-automated solutions for improved safety and efficiency.

Q3. What innovative semi-automated solutions can be designed and developed to mitigate the identified safety risks and improve MiC lifting operations?

This question would lead to the design and development of an SLAP to address the identified stage-specific risks. It explores how innovative semi-automated technologies can enhance safety, efficiency, and accuracy in MiC lifting, focusing on an integrated, practical lifting adjustment system.

Q4. How can the performance of the proposed SLAP system be systematically validated to ensure its effectiveness in addressing safety, efficiency, and productivity in MiC lifting scenarios?

This question addresses the validation of the SLAP system, focusing on the development or adoption of a systematic evaluation framework. It seeks to determine appropriate parameters and metrics for assessing the system's performance under both controlled laboratory conditions and real-world scenarios, ensuring its practicality and reliability.

1.4 Research Scope and Objectives

The aim of this study is to develop a **Semi-automatic Lifting and Assembly Platform** (SLAP) to improve the current process of module localization and positioning in MiC, with the aim of reducing safety risks and improving MiC lifting performance. To achieve this aim, the study begins by identifying and prioritizing the critical MiC lifting safety risks. The research further investigates how the safety risks manifest across various stages of the MiC lifting process, identifying specific challenges to propose targeted mitigation strategies.

The SLAP solution is an innovative system specifically designed to enhance the safety and precision of MiC lifting operations. It is composed of several original components, including the Horizontal Steering Control Module, the Levelling Control Module, and the Translation Control Module. These modules work together to address critical aspects of the lifting process, such as alignment, levelling, and controlled movement, ensuring improved lifting performance. The semi-automated nature of SLAP is shown through the integration of automated functionalities and human monitoring.

In the SLAP system, specific tasks, as follows, are automated to reduce operator workload and enhance precision:

- Horizontal Attitude Adjustment: Mitigate the tilt of the module in the XY plane.
- Vertical Height Adjustment (Small-Scale): Adjusts the module's height for accurate positioning.
- Controlled Horizontal Movement: Ensure controlled and accurate movement of the module relative to the ground.

However, SLAP also incorporates human involvement in key areas where monitoring, decision-making, and adaptability are essential to accommodate the complex changes in construction site environments and ensure the operational safety of the site. The major human involvement parts in SLAP are:

- Emergency Response: Operators handle sudden disturbances or risks by activating the emergency stop or initiating emergency lifting.
- Final Execution Confirmation: Before the system executes operations, operators review the results and make manual fine-tuning adjustments if necessary.

This hybrid framework of SLAP underscores its semi-automated nature, effectively balancing the strengths of automation and human expertise. Automated systems are tasked with handling operations that require precision and consistency, while human operators contribute flexibility, adaptability, and real-time problem-solving to address complex or unpredictable situations. By integrating these complementary elements, SLAP offers a practical and efficient approach to overcoming the unique challenges associated with MiC lifting processes.

Building on the development of SLAP, this study also introduces a comprehensive and systematic framework for evaluating the performance of MiC lifting systems. This evaluation framework is directly applied to the lab-scale prototype to validate the SLAP's design concept. Moreover, the validation of the SLAP prototype itself verifies the rationality and practicality of the proposed framework, ensuring its applicability in real-world scenarios. By combining innovation in system design with a robust validation methodology, this study not only provides an effective solution for addressing the risks associated with MiC lifting but also establishes a solid foundation for future development in lifting robotics.

The objectives of the research are:

(a) To identify and analyze the key safety risks in MiC lifting operations across different stages, and to determine specific, measurable gaps that can be addressed through technological solutions.

(b) To design, develop, and validate an SLAP capable of mitigating the identified risks and improving the safety, efficiency, and accuracy of MiC lifting operations.

(c) To assess the practical performance of the SLAP system using a systematic evaluation framework based on industry practices and measurable parameters for safety, efficiency, and productivity.

The research objectives are closely aligned with the research questions, ensuring a systematic approach to addressing them. Specifically, Objective (a) is designed to address Q1 and Q2 in a progressive manner. Q1 focuses on identifying and prioritizing the key safety risks in MiC lifting operations, while Q2 builds on this by analyzing how these risks vary across different operational stages and identifying measurable gaps. Together, these questions guide the achievement of Objective (a) in providing a comprehensive understanding of the risks and actionable insights for solution investigation. Objective (b) corresponds to Q3, as it focuses on designing, developing, and validating the SLAP system to mitigate the identified risks and enhance safety, precision, and efficiency. Finally, Objective (c) addresses Q4 by systematically evaluating the SLAP system's performance using measurable parameters for safety, efficiency, and productivity. The objectives are formulated to systematically address the research questions, ensuring a logical progression from identifying challenges to delivering practical, validated solutions.

1.5 Structure of the Thesis

A total of nine chapters are included in the thesis, with the structure presented as follows:

Chapter 1 provides an overview of the study, introducing its background, motivation, objectives, and significance.

Chapter 2 conducts a comprehensive literature review of relevant robotic patents and current related robotic technologies, identifying key research gaps to guide the study.

Chapter 3 provides a comprehensive framework for the research methodology and elaborates on the specific methods used in the study to systematically address the research objectives.

Chapter 4 investigates crane operational risks, clustering and prioritizing the identified risks, and breaking down work procedures to pinpoint specific pain points, which lay the foundation for proposing solutions to address these issues in subsequent Chapters.

Chapter 5 proposes a system (SLAP) to address MiC lifting safety risks by introducing the basic structure design and functionality of the system.

Chapter 6 details the control mechanism, logic, and UI design developed for the proposed system, aligned with real-world lifting procedures.

Chapter 7 demonstrates the feasibility of the mechanical and control systems through a scaled prototype, demonstrating their feasibility for construction applications.

Chapter 8 presents a performance evaluation framework for MiC lifting platforms and applies it to the SLAP lab-prototype to assess safety, efficiency, and productivity, confirming both the practicality of the system and the rationality of the framework.

Chapter 9 summarizes the thesis by highlighting key findings, contributions to knowledge and practice, limitations and proposing future research directions.

1.6 Summary of Chapter

This Chapter introduces the research problem identified in current MiC lifting practices, beginning with a brief review of the development of MiC in Hong Kong and the growing trend of automation in the construction industry. Based on these challenges, four research questions are proposed, along with three corresponding objectives to guide the study. The aim is to design an SLAP to address safety risks associated with MiC lifting in Hong Kong. The main contribution lies in validated insights into SLAP design and implementation that improve lifting safety and operational performance.

To achieve this aim and the associated objectives, the thesis is organized into nine interconnected Chapters. This Chapter outlines its content and explains how each chapter contributes to resolving the identified research questions.

Chapter 2 Literature Review

2.1 Introduction

In order to tackle the research issues introduced earlier, this chapter conducts an extensive review of existing literature, focusing on the critical aspects of safety risks, technological advancements, and research gaps in MiC lifting operations. First, it examines safety risks associated with MiC lifting and crane operations, providing a foundational understanding of the hazards that the proposed system aims to mitigate. Second, it reviews relevant patents for construction lifting robots, offering insights into existing innovations and practical technologies adopted in the industry. This analysis not only highlights technological advancements but also informs the design of the SLAP system by identifying proven solutions and areas for improvement. Third, the Chapter explores current robotic technologies, particularly recent advances in lifting, assembly systems, and collaborative control mechanisms, along with challenges in their application to modular construction. Finally, the Chapter identifies key research gaps by synthesizing findings from the safety risk analysis, patent reviews, and technology evaluations. These insights create a solid theoretical basis for the design and development of the SLAP system, ensuring that the proposed solution is aligned with industry needs and state-of-the-art innovations.

2.2 Review of MiC Lifting Safety Risks

2.2.1 MiC Lifting Safety Risks

Crane-related accidents in Hong Kong over the years have highlighted the persistent safety challenges in lifting operations. Despite advancements in construction methods, incidents involving crane failures continue to expose workers to significant risks. As mentioned in the previous section, multiple fatalities were reported due to issues such as equipment malfunctions and structural failures in the year 2017. Similarly, in 2023, 10 lifting-related accidents resulted in six fatalities, while in 2024, several high-profile incidents—including crane collapses and falling objects—caused injuries and fatalities.

The Yuen Long accident on September 22, 2023, underscores the risks associated with handling heavy materials in construction, including prefabrication projects. A 62-year-old driver tragically died when a three-tonne precast concrete slab (5 x 0.5 x 1.5 meters) fell during superstructure works at a Housing Society project in Hung Shui Kiu/Ha Tsuen. Although investigations confirmed the incident was unrelated to the prefabrication method, it underscored the dangers of on-site assembly and transporting heavy materials (The Standard, 2023).

The Yuen Long case revealed that although prefabrication methods or MiC have significantly improved safety, the consequences of any safety incident can still be very severe. The module positioning process in MiC projects is particularly hazardous due to the extreme weight and size of the modules (Du et al., 2020), which increase the likelihood of collisions and make motion adjustments more difficult during the final positioning phase due to the modules' high inertia. In most MiC operations, riggers are tasked with guiding these modules into place by manually pulling ropes attached to the modules, adjusting their orientation, and aligning connection points. This process often requires riggers to work in high-risk environments, such as standing on lower floors and looking upward to monitor the module above, exposing them to dangers such as falling objects, falling from height, and physical strain. Additionally, the high precision required during module descent further increases the complexity and risks of MiC lifting operations. Connection methods such as bolt and nut connections, grouting coupler lapping rebar, and semi-wall lapping rebar demand exact alignment, with tolerances often as low as 17.08mm (Enshassi et al., 2019). Achieving this level of precision places significant physical and cognitive demands on workers, leading to three key risks: (a) the danger of riggers being struck by heavy and bulky modules, (b) the risk of falls from height during orientation guidance, and (c) muscle strain and injuries caused by the high level of precision required for adjustments. These challenges compromise worker safety and reduce the efficiency of MiC construction processes.

2.2.2 Crane Lifting Safety Risks

As MiC is a relatively new construction method, limited literature specifically addresses the MiC lifting safety risks. To gain a more thorough understanding of these risks, this study broadens its scope to include an examination of safety hazards related to general crane lifting operations, aiming to extract valuable insights and lessons applicable to MiC lifting scenarios. Consequently, this section explores the safety challenges inherent in crane lifting, drawing on both scholarly research and local industry standards to provide a practical, context-specific analysis.

The literature review involved a broad search of articles, books, and theses using keywords such as *"crane operation considerations," "crane operation risks,"* and *"crane fatalities."* Among the reviewed works, Shapiro et al. (2011) categorized potential crane operation risks into nine broad categories, covering all stakeholders involved in construction activities, from project designers to on-site operators. William (1994) narrowed the focus to operational risks, identifying twenty-three risks commonly associated with cranes. These were grouped into four key areas: mechanical issues, preparatory tasks, inspection requirements, and operational risks. Within the operational category, seven specific risks were highlighted, such as limited visibility during lifts, accidental dropping of detachable weights, inadequate load control, hazards from pinch points, swinging objects, two-blocking incidents, and instability caused by overloading.

For practical regulatory and guideline review, the study compiled information from key government authorities, including the Labor Department (LD) and the Buildings Department (BD), as well as insights from industry professionals. Crane operations in Hong Kong are regulated under various mandatory frameworks. For instance, the Construction Sites (Safety) Regulations (Cap 59I) outline requirements for the safe operation of cranes (hoists) and the proper securing of loads, with detailed instructions provided in Parts II to V (Department of Justice, 2006a). Similarly, the Factories and Industrial Undertakings (Lifting Appliances and Lifting Gear) Regulations (Cap 59J) govern the use of lifting equipment, including chains, ropes, and gears, in crane operations (Department of Justice, 2006b). Beyond these legal requirements, two key Codes of Practice, namely the Code of Practice for Safe Use of Tower Cranes (COPTC) and the Code of Practice for Safe Use of Mobile Cranes (COPMC), provide comprehensive operational guidelines to further enhance crane safety. Furthermore, the Construction Industry Council (CIC) has published the "Guidelines on Safety of Tower Cranes" to provide supplementary guidance on good practices for appliance inspection, site supervision, and the qualification of operational personnel. While Cap 59I and Cap 59J focus on setup and general descriptions, the COPTC and COPMC provide detailed requirements for safe working loads and on-site operational conditions. These requirements were consolidated and summarized into different aspects, as shown in Table 2-1 (Labour Department, 2017a, 2017b).

Table 2-1 Operational Regulatory Requirements and Corresponding Safety Risks

Category	**COPTC Requirements**	**COPMC Requirements**	**Key Safety Risks**
Operation and Control	Mode of operation and control	Mode of operation and control	Ensuring a clear line of sight and stable control mechanisms.
Load Handling	Safe working loads	- Safe working loads - Near maximum	Adhering to safe working load limits,

		working loads	including near-maximum capacity.
Proximity to People	Handling of loads near persons	-	Avoiding crossover, overhead, and proximity risks to personnel.
Suspended Loads	-	Traveling with suspended loads	Ensuring stability and safety when moving with suspended loads.
Carrying Personnel	Carrying of persons by crane	Carrying of persons by crane	Prohibiting or strictly managing the transport of people using cranes.
Communication	Communication system	Communication system	Establishing effective communication systems during operations.
Weather Conditions	Weather conditions	Weather conditions	Monitoring and adapting operations to account for weather effects.

After synthesizing findings from academic research and regulatory guidelines, five key operational risk considerations were identified based on their repeated appearance across multiple sources, as summarized in Table 2-2. Among the consolidated considerations, weather conditions were excluded from this study because crane operations are suspended during Typhoon Signals or other extreme weather events (Labour Department, 2019).

Table 2-2 Hong Kong Crane Operational Safety Risks

Category	**Operational Risks**	**Description**
Safety	**Blind Lifting**	Avoid performing rigging operations in areas of the construction site that cannot be visually monitored.
	High Payload	Avoid conducting rigging activities in zones requiring high payloads, which demand significant rigging moments.
	Overhead and Crossover	Avoid moving loads over nearby structures, workers, or construction equipment to minimize

		risks.
Effectiveness	**Direction Changes**	Limit the frequency of directional changes during rigging to improve efficiency and reduce complexity.
Productivity	**Short Path**	Optimize lifting trajectories by minimizing the distance between the starting point and the destination.

By reviewing the causes of MiC lifting safety risks and extending the analysis to crane operation safety risks for broader insights, this section identifies three common categories of lifting safety risks frequently encountered in Hong Kong. However, the relative importance of these risks in the context of MiC lifting and whether they represent the most critical issues requiring attention remain areas for further investigation. To address this, Chapter 4 will develop deeper into analyzing these MiC lifting safety risks, ranking their criticality based on the findings from the review, to better explore potential semi-automation-based solutions to mitigate these risks effectively. Naturally, identifying feasible solutions requires a thorough examination of existing patented technologies and research efforts. Therefore, the next section will review related patents to uncover the current state of technological advancements, draw on similar experiences, and reveal the research gaps between existing patents and potential solutions. This investigation will provide valuable insights and lay the groundwork for proposing innovative approaches to address the identified MiC lifting safety risks.

2.3 Relevant Robotic Patents for Construction Lifting

2.3.1 Scope of the Patent Reviews

The research begins with a patent review to identify existing technologies relevant to or likely to contribute to addressing the research questions. Recognizing the critical importance of similar product designs to the solution proposed in this study, a two-stage comprehensive review process was adopted to ensure the inclusion of as many relevant findings as possible. This systematic approach enables a thorough investigation of prior patent applications within the market.

The two-stage review process can be elaborated as follows:

In the first stage, two keyword sets, “Construction Lifting Robot” and “Construction Hoisting Robot,” were entered into the search engine to retrieve relevant patents. To refine the results, duplicate findings were removed by family. This step accounted for patents registered in multiple regions or filed under the Patent Cooperation Treaty (PCT). Only patents explicitly appearing under the specified keywords were included in the analysis. During this stage, a total of 19,236 patents were retrieved using the keyword "Construction Lifting Robot," while 17,716 patents were identified under the keyword "Construction Hoisting Robot."

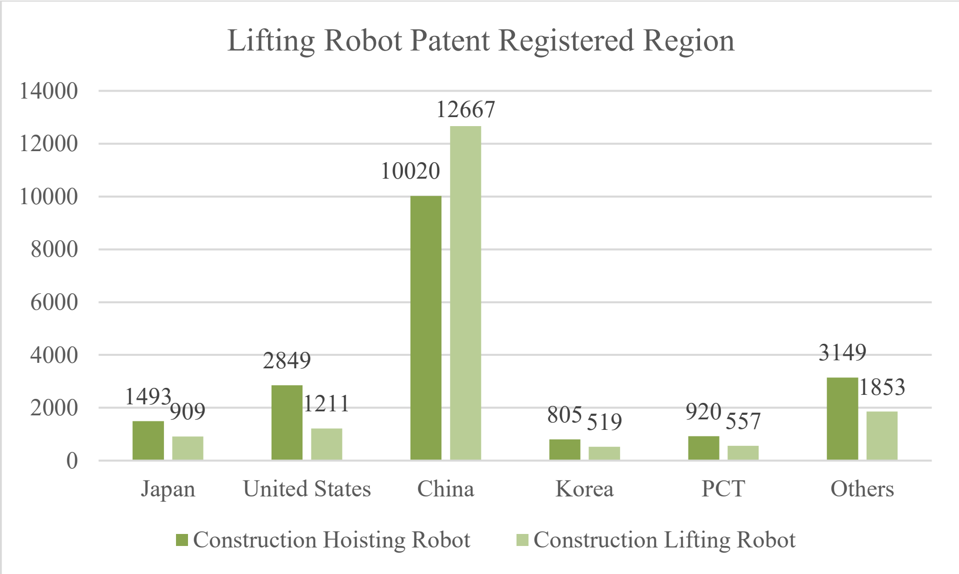


Figure 2-1 Lifting Robot Patent Registered Region Distribution

The search results are categorized by registration location and presented in Figure 2-1, which clearly shows that China holds the highest number of registered patents, at least three times more than other regions. Specifically, two keyword searches yielded 10,020 and 12,667 Chinese patents, respectively, highlighting the dominant volume compared to countries such as the United States and Japan. While some overlap may exist between the two search processes, the keyword "Construction Lifting Robot" produced approximately 2,000 more patents than "Construction Hoisting Robot," with this trend being particularly pronounced in China. This underscores the region's dominance in patent activity within this field.

Following Stage 1, the research advanced to Stage 2 for further refinement. In this stage, all results were sorted by relevance using Google's algorithm. It is assumed that the correlation between patents and the keywords decreases gradually as the ranking lowers, as lower-ranked results often include patents with little or no relevance to construction. To enhance both accuracy and review efficiency, only the top 25 patents for each keyword were retained for further analysis. This resulted in a total of 50 top-ranked patents.

These 50 patents were then subjected to a rapid screening process by reviewing their titles and abstracts. During this step, 4 duplicate results were identified and omitted, leaving 46 patents for detailed discussion in this study. This systematic approach ensures that the most relevant and high-quality patents are included in the analysis, providing a strong foundation for addressing the research questions. This structured approach ensures that the review captures a broad range of existing technologies while maintaining focus on patents directly relevant to the research objectives.

2.3.2 General Analysis of the Patents

1. Development Trend Analysis

The construction lifting robot, as a key tool for automating the hoisting process of buildings, represents an important branch of on-site construction automation (Cai et al., 2018). The earliest patent in this study dates to 1992, when Nippon Steel developed a material handler equipped with rails and arms. However, this application was later withdrawn (Kato, 1992). Following this, Kajima Corporation applied for a patent in 1993 for a machine designed to facilitate the lifting process, featuring a gripper equipped with a force sensor at the tip (Uchimura & Hirose, 1993). In the same year, Mitsubishi collaborated with Takenaka to apply for a patent for tunnel segment installation equipment (Asai et al., 1993). These three patents mark the beginning of patent applications in the field of construction lifting robots.

Despite this early activity, the pace of patent applications in this field slowed considerably over the next 16 years, with only 7 patents filed between 1994 and 2009. However, this trend reversed after 2010, when the field experienced a surge in interest. From 2010 onwards, there has been a significant increase, with 36 patents filed in this area to date.

It is worth noting that, over the past 30 years, only 34 out of the 46 patents analyzed in this study have been granted. Several factors may explain why certain patents remain ungranted:

Some patents are still under review, such as the drilling robot claimed by Daming Gec and Samsung C&T, as well as the climbing frame system claimed by Bozhilin (Fukase & Kurita, 1994; Qiang et al., 2019).

Others were withdrawn after filing, such as the lifting platform patent applied for in 1994 and Nippon Steel’s 1992 application (Jong-man et al., 2021; Kato, 1992).

The historical development trends of construction lifting robot patents are highlighted in this analysis. These trends are depicted in Figure 2-2, Figure 2-3, and Figure 2-4, showing an early period of experimentation, followed by a long stagnation, and culminating in a recent surge in innovation and patent activity, underscoring the growing importance of construction lifting robots in advancing construction automation.

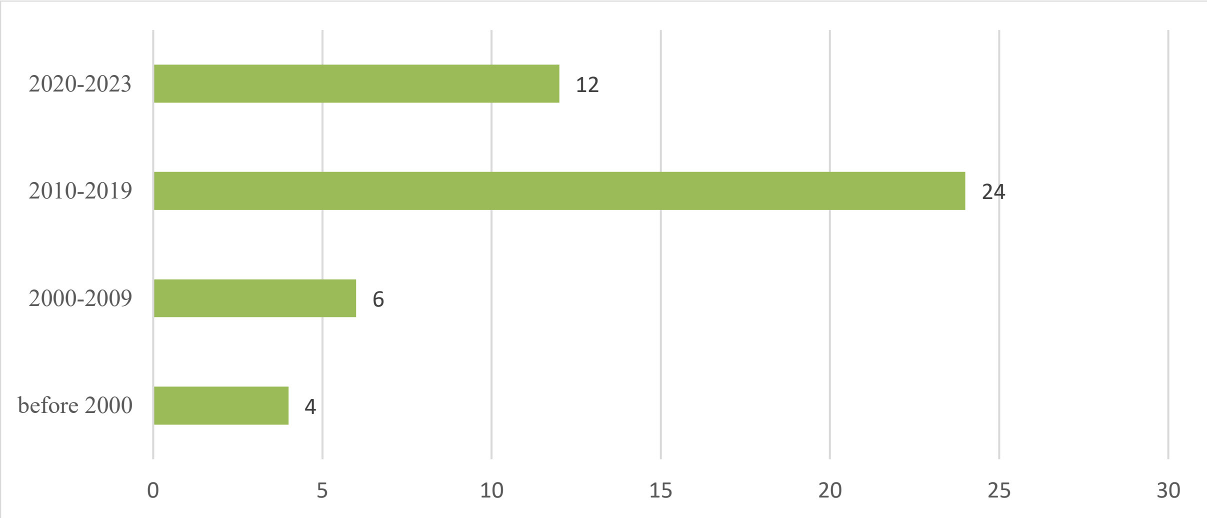


Figure 2-2 The Patent Application Summary (By Year)

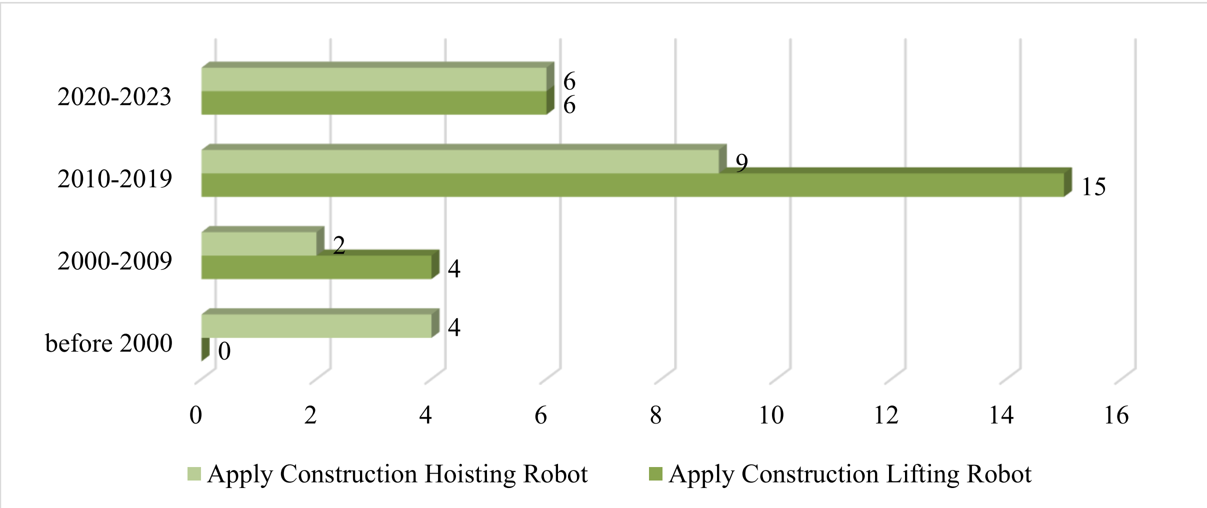


Figure 2-3 Date of Patent Appearance (By the Year of Applicant)

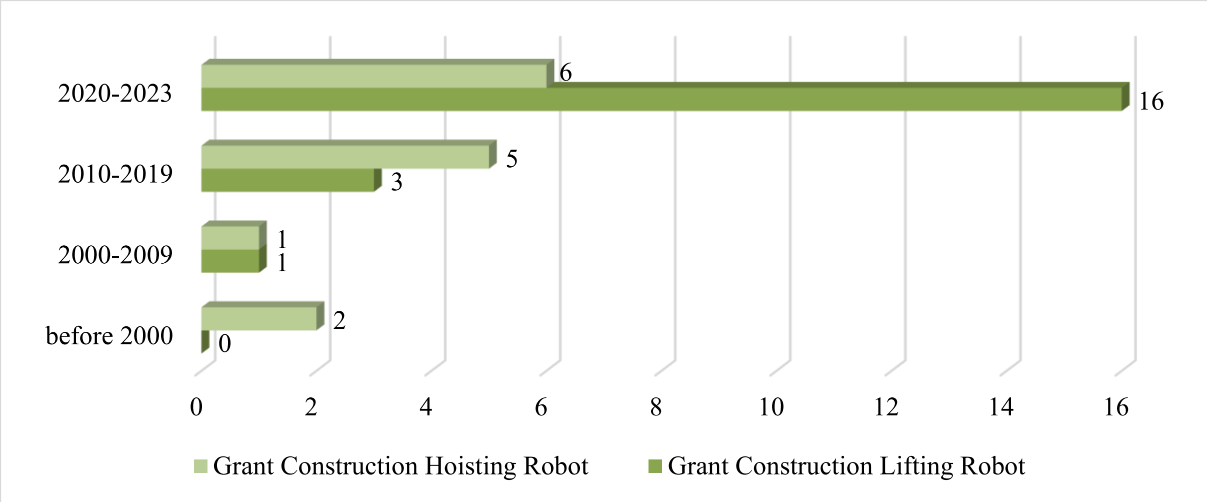


Figure 2-4 Date of Patent Appearance (By the Year of Grant)

2 Registration Location Analysis

As shown in Figure 2-5, the patents are distributed across four regions: China (46%), Japan (17%), Korea (15%), and the United States (15%), and patents protected under the Patent Cooperation Treaty (PCT), which account for the remaining 7%. Together, these categories encompass all 46 patents analyzed. Although China is the most popular region for patent registration, not all inventors or assignee companies are based in China. For instance, the Korean company Daming Gec Co., Ltd. and Samsung C&T registered a patent in China for a ceiling anchor bolt hole-drilling and insertion robot in 2021 (Jong-man et al., 2021). Similarly, Kawasaki Motors from Japan registered a substrate conveyance apparatus for lining (Hirohiko et al., 2016), while Boeing in the United States filed a patent for an automated aircraft panel assembly facility incorporating movable cradles (Eric Bramwell Britcher et al., 2012).

Among the 21 patents registered in China, Guangdong Bozhilin Company stands out, holding 6 patents. This not only makes Bozhilin the company with the highest number of patents registered in China, but also the highest across all regions in this study. These patterns reflect the significant role of China in patent activity while also demonstrating the global nature of innovation in this field.

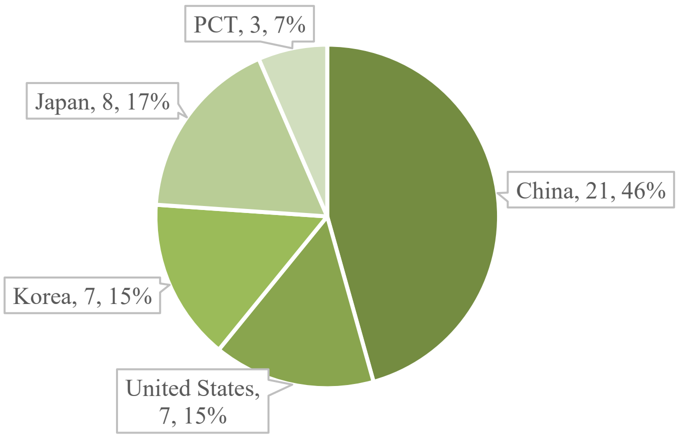


Figure 2-5 Region of Patent Registration

3. Filed Classification Analysis

Similar to the use of keywords in academic publications, patents are required to indicate one or more classification codes during the application process. These codes facilitate efficient searching and retrieval of patent documents and also provide a quick understanding of the technology field to which the patent belongs (S. Li et al., 2018). To standardize patent classification, the International (European) Classification of Patents (IPC) system was introduced in 1954, with the first edition formally published in 1968 following the signing of the Strasbourg Agreement. The most recent version, IPC (2023.01), came into effect on January 1, 2023, replacing the previous version published in 2022. As an extension of the IPC, the Cooperative Patent Classification (CPC) system, jointly managed by the European Patent Office and the United States Patent Office, includes approximately 250,000 classification entries. The CPC will be further discussed in the latter chapters of this study (WIPO, 2023). Since classification codes are determined by the applicant, analyzing these codes is particularly valuable as they reflect the technical details and core innovations identified by the patent inventor.

After summarizing and analyzing the classification codes retrieved from Google for all 36,952 patents (19,236 + 17,716), the top 10 most popular classification codes are presented in Figure 2-6. 10 codes account for 61.9% of the total citations, with “B25J – manipulators; chambers provided with manipulation devices” ranking the highest at a citation rate of 19.85%. This indicates that around 20% of the patents claim innovations in the manipulator devices area in all patents searched.

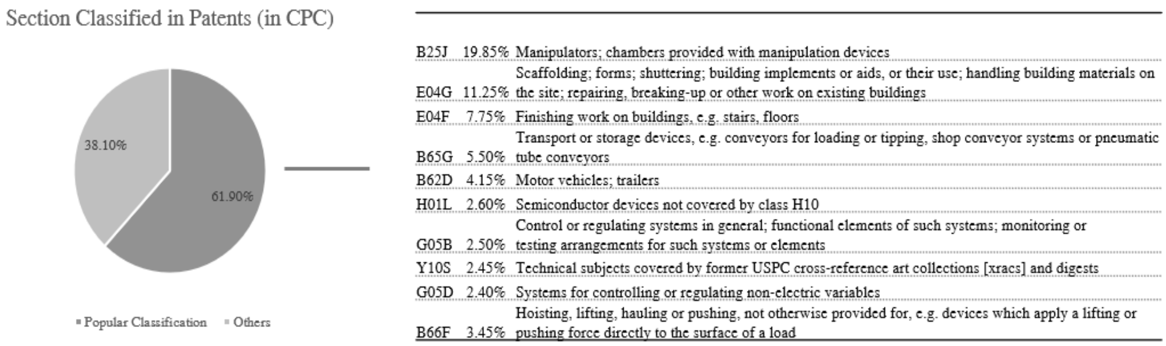


Figure 2-6 Top 10 Popular Classification Codes (All Patents Identified)

Focusing on the 46 selected patents, “B25J” and “E04G” emerge as the most frequent classification codes, highlighting significant industry interest in manipulators, chambers with manipulation devices, and scaffolding or handling building materials on-site. Beyond these two codes, three additional popular subclass codes are outlined in Table 2-3. Across these 46 patents, a total of 234 different codes are cited, averaging 5.5 codes per patent.

Among the five most popular classification codes, “B25J,” “H01L,” and “B66C” primarily describe the mechanical design features of the patents, while the other two reflect the application scenarios. This distribution underscores the balance between technological innovation and its practical applications in the field of construction automation. Within the group and sub-group under “B25J”, the sub-group “B25J 9/xx” is cited 35 times. This sub-group primarily focuses on program control methods, including learning-based approaches, redundant control, compliant control, and force and torque control, as well as the mechanical design of actuators and arms. The high citation rate of “B25J” underscores the frequent adoption of mechanical arms in the structural design of these inventions, highlighting their critical role in advancing the functionality and precision of construction automation technologies.

Table 2-3 Top 5 Popular Classification Codes by Frequency (Selected 46 patents)

Subclass	Frequency	Description (WIPO, 2023)
B25J	75	Manipulators; chambers provided with manipulation devices
E04G	24	Scaffolding; forms; shuttering; building implements or aids, or their use; handling building materials on the site; repairing, breaking-up, or other work on existing buildings
H01L	19	Semiconductor devices not covered by class H10
B66C	18	Cranes; load-engaging elements or devices for cranes, capstans, winches, or tackles
E04F	8	Finishing work on buildings, e.g. stairs, floors

2.3.3 Patent Categories

To enhance the clarity and relevance of research findings, it is critical to organize the review of patents using a well-structured taxonomy. Such categorization not only provides coherence but also facilitates the identification of feasible solutions to address specific problems. In this research, two criteria are adopted to categorize the patents: application scenarios and mechanical structure. By systematically analyzing patents using this taxonomy, valuable insights into potential technologies can be derived, offering inspiration for developing a feasible solution to address MiC lifting scenarios.

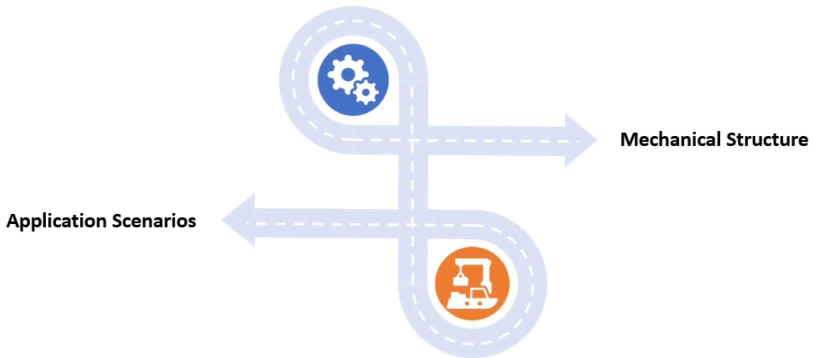


Figure 2-7 Selected Patent Review Categories

Figure 2-7 illustrates the selected taxonomy used for patent analysis. The following sections outline the categorization of patents based on application scenarios and mechanical structures, with an emphasis on their relevance to MiC lifting technologies.

1. Categorize the Patent by Application Scenario

The 46 reviewed patents span 20 application subcategories, covering specific tasks such as bricklaying, facade installation, and object grasping. Among these, five key application areas—object transfer, lifting, positioning, facade installation, and object grasping—are closely related to the mechanical design of apparatuses for MiC lifting. While some mechanisms lack defined functions, their designs may still inspire solutions for MiC lifting. However, this does not mean that patents in other application fields are irrelevant; the study considers all 46 patents holistically, with particular attention to those closely aligned with MiC needs. A summary of the application scenarios is shown in Table 2-4.

Table 2-4 Application Scenario Consolidated from the Selected Patents

Application Scenario	Total	Relevancy to MiC Lifting	Relevant Patent Number
Object Transfer	10	✓	CL 1,7, 9,13,15,18,20,21,24; CH2
Object Lifting	7	✓	CL 6, 24 ; CH 2,6, 7, 19; 24;25
Bricklaying	7		CL 3,4,14; CH 3,4,8,16
Mechanism/Algorithm	3		CL 8,16; CH 25
Part of System without Specific Purpose	3	✓	CL 11,12; CH1
Drilling Robot	3		CL 2, 22; CH 21
Object Positioning	3	✓	CH 6,10,13
Façade Installation	2	✓	CL 17; CH 22
Object Grasping	1	✓	CH 5
Others	11		

Besides six patents focus on innovations in control algorithms or general foundations that enable versatile applications by adding different end effectors, other patents are tailored to specific construction trades. For instance:

Liebherr proposed a system with at least three support columns and a cable system connected by high-strength fiber ropes, designed to manipulate workpieces with increased positioning accuracy (R. Bramberger, 2021).

Pearson introduced a movable gantry robot, which combines an extendable gantry crane, earth-moving equipment, and laser scanning, intended for sea wall construction (Pearson Jr, 2021).

Yaskawa Electric Corp developed a mechanical arm concept featuring a horizontal arm unit and three joint units with links and a turning mechanism (Figure 2-8) (Sueyoshi, 2014).

These patents represent three mechanical structure concepts—Gantry, Mechanical Arm, and Cable—each offering unique advantages. To determine which structure is most suitable for MiC lifting, these patents are further categorized based on their structural designs to identify commonalities and extract inspiration.

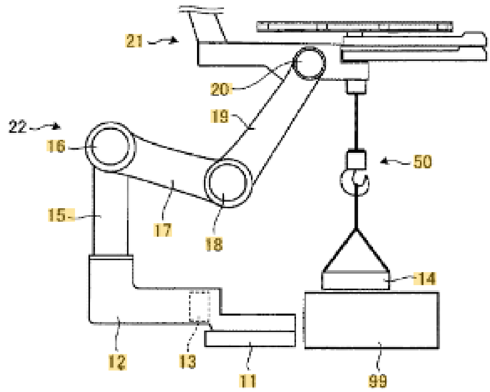


Figure 2-8 Yaskawa Lifting System Concept Design (Sueyoshi, 2014)

2. Categorize the patent by Mechanical Structure Adopted

The patents employ two primary structural mechanisms: Serial Mechanisms and Parallel Mechanisms, each with distinct characteristics and applications, as summarized in Table 2-5.

Serial Mechanisms, including the Mechanical Arm and Gantry concepts, consist of a series of links connected by motor-actuated joints, forming a kinematic chain. These mechanisms are versatile and offer a wide range of motion but sacrifice precision and payload capacity (Pandilov & Dukovski, 2014). Among the 46 patents, 26 utilize mechanical arms as the primary structure, making it the most popular choice. Mechanical arms are well-suited for tasks requiring significant motion range but moderate payloads, such as bricklaying (Jiwen, 2020; Jun, 2021; Moo-rim et al., 2012; Xiaoyang et al., 2019). Larger payloads, however, necessitate structural scaling, as seen in the Gantry concept. Gantry systems, adopted in 6 patents, are designed for higher payload capacities and greater stability, making them ideal for heavy lifting and facade installation (Choi, 2004; Oberoi et al., 2015; Tang et al., 2016).

Parallel Mechanisms, such as Cable Robots, utilize multiple actuators to drive a single platform, offering greater precision, speed, and payload capacity while limiting motion range (Ming et al., 2019; Qiang et al., 2019; Tian et al., 2019). Cable robots, a unique form of parallel mechanism, are described in 3 patents (Qian et al., 2018; Zi et al., 2008). They excel in applications requiring large motion ranges and high efficiency in force transmission while maintaining a lightweight structure (Bramberger, 2021; Pott, 2013). For example, Changwon University implemented a parallel mechanism on an excavator for precise gripper control (Lee & Park, 2003).

In addition to these two mechanisms, Hybrid Parallel-Serial Mechanisms are proposed in some patents as a compromise, integrating the wide motion range of serial systems with the precision and speed of parallel systems (Zhou et al., 2019). These hybrid designs effectively address the limitations of single-mechanism systems, delivering balanced performance for complex construction tasks. While the dominance of mechanical arms highlights their versatility, particularly in end-task manipulation, the specialized use of gantry and cable systems underscores their strength in heavy-duty and high-precision operations. This categorization emphasizes the potential to combine these mechanisms, paving the way for innovative solutions tailored to MiC lifting scenarios.

Table 2-5 Mechanical Structure Adopted in the Selected Patents

Mechanical Structure	Number	Patent Related	Control Mechanism
Gantry Concept	6	CL 1,24; CH 6, 18, 19, 24	Serial Mechanism
Arm Concept	26	CL2,3,4,5,10,11,12,13,14,15,17,20,21,22; CH1,2,3,4,8,9,13,14,16,19,21,22	Serial Mechanism
Cable Concept	3	CL 6, 19; CH22	Special Parallel Mechanism
Mechanism/Algorithm	3	CL 8,16; CH 25	Not applicable
Others	8		

2.4 Current Robotic Technologies in Construction

After reviewing the patents in Section 2.2, which focused on construction lifting and hoisting robots for practical applications, it was evident that no solutions were found to address the research questions outlined in Chapter 1. This highlights the need for further exploration into existing technologies to either identify directly applicable solutions or uncover gaps in current approaches that could be improved to resolve the identified challenges.

This section shifts attention to the latest advancements in robotics technologies from both academic literature and industry. By analyzing these advancements, we aim to assess whether existing technologies can be directly adapted to address the challenges of MiC lifting or whether they require further enhancement to bridge the identified gaps. The aim is to find innovative solutions that improve safety, accuracy, and efficiency in MiC lifting operations. The following subsections begin by examining the latest developments in crane and robotic lifting systems, emphasizing their potential contributions to MiC challenges. Subsequent sections will delve into collaborative control methods and precision compensation mechanisms to identify solutions for specific sub-tasks within the larger MiC lifting problem.

2.4.1 Recent Advances in Lifting and Assembly Systems

1. Crane Control Systems

Traditional crane designs, which are typically under-actuated systems, face significant challenges in achieving precise manipulation of payloads. To address this, Sorensen et al. (2007) proposed a controller that integrates feedback and input shaping techniques. This controller comprises three modules: one for compensating positioning errors, another for rejecting disturbances, and a third for mitigating motion-induced oscillations. In a controlled environment, the system was tested on a 10-ton bridge crane and demonstrated improved payload positioning accuracy and disturbance suppression. However, this approach requires integration into crane control systems, limiting its applicability to other crane manufacturers. Additionally, the controlled testing environment lacks the dynamic challenges encountered by tower cranes operating on construction sites.

Similarly, Rauscher and Sawodny (2020) introduced a dynamic model for top-slewing tower cranes, conceptualizing them as flexible multibody systems. This model considers the dynamic interactions among the steel structure, load movement, system actuators, and the suspension cable. Using this model, a two-DoF control method with active sway damping was developed, combining a flatness-based nonlinear feedforward controller coupled with a gain-scheduled linear quadratic regulator (LQR) feedback regulator. While the method was successfully deployed on a full-size operational tower crane system, its lifting capacity of 1.65 tons at the jib tip is considerably smaller than the requirements for MiC projects, which typically demand capacities of 10 to 30 tons. Furthermore, integrating this control method requires significant system modifications and adjustments tailored to individual crane modules.

In another study, Zhu et al. (2022) explored a novel human-in-the-loop approach to anti-sway control for double-pendulum tower crane payloads. This method employs haptic devices connected to a 3D-printed pole to provide real-time feedback to operators about the payload's balance status. Operators use counterbalance forces on the pole to reduce sway, demonstrating superior performance compared to traditional automatic methods. This approach highlights the potential of human-machine collaboration to enhance crane stability and safety, offering a promising direction for integrating operator input into MiC crane systems.

Takahashi et al. (2022) proposed a time-optimal, sensor-less control method to suppress load-sway and boom-twist vibrations in crawler cranes. By analyzing vibrations in an actual crawler crane, the authors developed a dynamic model and a vibration mitigation strategy based on a cycloidal motion trajectory. This strategy simplifies implementation by using only the boom's horizontal motion to suppress two-dimensional load-sway. The experiments demonstrated its effectiveness in mitigating vibrations and enhancing safety. However, the method is designed for crawler cranes and may not directly address the unique challenges of tower cranes applied in MiC construction environments, such as higher payload requirements and dynamic construction site conditions.

Although these advanced control systems demonstrate improvements in precision, stability, and operator interaction, they are not directly feasible for solving MiC lifting problems on-site due to limitations such as inadequate payload capacity, the need for significant system modifications, and limited adaptability to the dynamic conditions of construction environments.

2. Material Lifting and Assembly Systems

Beyond crane control systems, ergonomic and vacuum material lifting machines offer advantages in human-machine collaboration (Hayakawa et al., 2022; Lu et al., 2018). For example, ergonomic lifting machines use force sensors to amplify operator input, enabling precise lifting and payload positioning. These machines typically handle loads ranging from 100 to 400 kg at speeds of 0.762 m/min to 6.096 m/min (Ergonomic Partners, 2024). While their precision and ease of use are commendable, their load capacities fall far short of the 10 to 30 tons required for MiC projects.

In industrial assembly systems, companies like Mercedes-Benz and Zoomlion have implemented innovative lifting technologies. Mercedes-Benz's Factory 56 employs flexible assembly systems capable of handling vehicles of different designs and drive systems, emphasizing precision and efficiency (Mercedes-Benz, 2020). Similarly, Zoomlion introduced a rigid rack host with grippers equipped with sensors to monitor and adjust the rack’s height, minimizing displacement and swinging issues during transportation (FU et al., 2022). However, these systems are designed for controlled factory environments and may lack compatibility with crane systems or the dynamic conditions of construction sites.

Existing crane systems generally rely on under-actuated designs, which struggle to resist external disturbances and make precise pose adjustments. In contrast, rigid-body robotic lifting systems excel in precision control and disturbance resistance but are limited by their low payload capacities and reliance on controlled environments. While innovations such as human-in-the-loop control methods, dynamic modeling, and ergonomic lifting machines offer promising advancements, they require adaptation to meet the unique demands of MiC projects.

The review of current technologies underscores the need for hybrid solutions that combine the high precision and adaptability of robotic systems with the strength and load capacity of traditional cranes. These insights provide a foundation for developing a novel device capable of addressing the challenges of MiC lifting, improving accuracy, safety, and operational efficiency.

2.4.2 Collaborative Control and Precision Compensation

Building on the overview of the latest developments in crane systems and other material lifting and assembly technologies, this section shifts its focus to specific technological components. It examines collaborative control methods and precision compensation mechanisms aimed at addressing the sub-tasks involved in MiC lifting. While the previous section highlighted the limitations of existing systems in directly resolving MiC lifting challenges, this section explores whether individual robotics technologies can offer effective solutions for the sub-tasks identified in MiC lifting. By analyzing these technologies, the objective is to identify suitable strategies that enhance system precision, stability, and efficiency for heavy module lifting in dynamic construction environments, laying a solid foundation for identifying research gaps and proposing innovative solutions in following sections.

1. Horizontal steering control

Horizontal steering control technologies for crane lifting hooks have reached a relatively high level of maturity after decades of development. Inoue et al. (1998) introduced a device incorporating active and passive control modes, both leveraging the gyroscopic effect of a high-inertia flywheel spinning at high velocity. In the active mode, the gyroscopic moment generated by a constant torque regulates the payload's orientation, enhancing the safety and efficiency of construction material transportation. The passive mode uses the gyroscopic effect to maintain stability during operation. However, for heavy payloads, the method requires substantial flywheel inertia, necessitating both a larger weight and higher spinning speed. This limits its feasibility for large payloads, as it is neither energy-efficient nor practical for heavy module lifting.

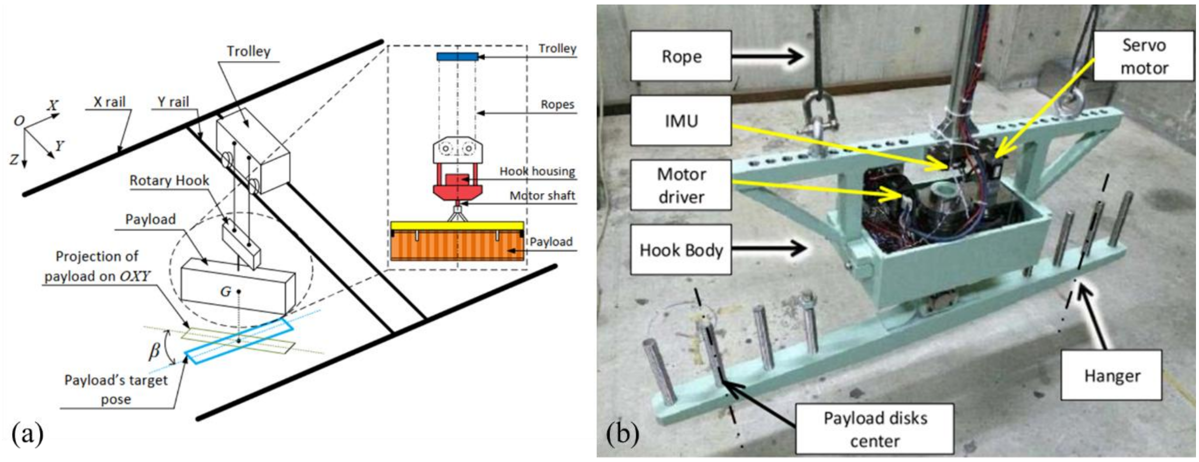


Figure 2-9 (a) The Rotary Hook Device for Adjusting Payload's Skew Orientation (Ho et al., 2018), and (b) Structure of the Experimental Testbed (Ho & Terashima, 2018)

Ho et al. (2018) introduced a nonlinear sub-optimal time control for crane payload skew rotation (steering) within actuator limits. Their experiments confirmed the method's effectiveness in achieving precise orientation with minimal oscillation, Figure 2-9 (a). Further improvements were made in Ho and Terashima (2018) with a robust nonlinear integral sliding mode control (ISMC) method for mitigating vibrations during the skew rotation process, as indicated in Figure 2-9 (b). ISMC demonstrated superior stability and robustness compared to traditional H∞ control, making it a promising approach. However, these methods were tested in controlled environments using line-format payloads, and their applicability to modules with a center-of-mass offset in dynamic construction environments remains uncertain. Additional testing under real-world conditions is essential to assess their feasibility for MiC lifting operations.

Recent studies have explored other methods to facilitate the steering control and precise placement technologies. Yue et al. (2025) proposed mammalian-like legged robots inspired by healthcare robotics to achieve high precision in heavy lifting and placement. These robots improve safety by reducing manual handling. However, their limited payload capacity for extremely heavy loads, combined with high development and maintenance costs, presents challenges for scalability in large-scale modular construction tasks.

Forcael et al. (2025) investigated the integration of robotic assembly with BIM for Cross-Laminated Timber panels. Their approach showed significant reductions in assembly time and improved accuracy. Despite these advancements, operator involvement remains significant, and challenges with alignment and levelling persist. Moreover, this method is more effective for panel-style payloads rather than large modular units, leaving a gap in addressing the specific needs of MiC lifting operations.

2. Cable-driven pose control

Cable-driven systems provide an innovative approach to controlling the Cartesian pose (position and orientation) of payloads, significantly reducing the system's weight and enabling larger workspaces compared to rigid-link mechanisms (Picard et al., 2020). These systems typically use multiple cables (six or eight) attached to a mobile platform, with each cable (or multiple cables) imposing a specific actuation or constraint on one degree of freedom (Pott, 2013). However, the low stiffness of cables and the need to maintain positive tension present unique control challenges, requiring specialized kinematic and dynamic controllers (Qian et al., 2018; So-Ryeok & Agrawal, 2005). Kinematic controllers, such as proportional-derivative (PD) controllers, regulate cable positions based on inverse kinematics to achieve desired trajectories (Aflakian et al., 2018; Antonelli et al., 2000). In contrast, dynamic controllers account for the nonlinear dynamics of cable-driven manipulators to enable precise manipulation and synchronization of cable motions (Gangloff et al., 2020; Jia et al., 2019; Zarei et al., 2018). Advanced techniques further enhance control performance, which improves robustness and accuracy under model uncertainties and external disturbances (Jabbari Asl & Janabi-Sharifi, 2017; Meziane et al., 2019). These efforts focus on maintaining cable tension while optimizing trajectory tracking and reducing vibrations, with approaches such as robust Proportional–integral–derivative (PID) control, trajectory shortening for oscillation damping, and methods to avoid cable interference (Inel et al., 2021; Khosravi & Taghirad, 2014; Meziane et al., 2019; Zake et al., 2020).

Some studies have also explored dynamic modeling methods to address specific challenges in cable-driven systems. For instance, inverse kinematics approaches have been used to account for cable mass and elasticity, which significantly influence control performance in large-scale systems. These methods include hybrid position/force control to reduce wind-induced vibrations in cable-driven manipulators (Tang & Shao, 2013; Zi et al., 2008). Dynamic models incorporating lumped mass or elastic cable properties have also been developed to improve control accuracy and robustness (Babaghasabha et al., 2016; Caverly et al., 2015). Advanced approaches, such as decoupling nominal dynamics from vibration dynamics, help reduce undesired vibrations and improve trajectory tracking (Jamshidifar et al., 2018).

Despite these achievements, challenges remain. Cable elasticity, stiffness, and mass substantially affect control performance, particularly for payloads exceeding 20 tons, as required in MiC projects (Jamshidifar et al., 2021; Tang & Shao, 2013). Current systems also rely on mass poles for cable attachment, making them impractical for dynamic construction environments. Additionally, the precision offered by existing systems is insufficient for accurately positioning large MiC modules. To address these limitations, future research must develop control strategies that account for mass substantially, improve vibration suppression, and explore practical implementations for construction sites.

3. Mass distribution adjustment control

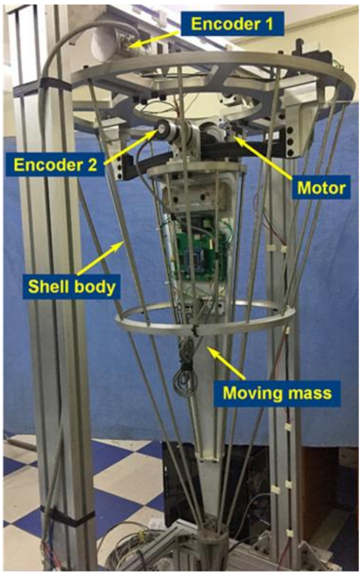
Moving mass control, also referred to as mass redistribution or internal mass manipulation, is widely employed in various airborne and underwater vehicles (J. Li, C. Gao, C. Li, et al., 2018). This technique adjusts the internal mass distribution of an object to shift its center of mass, influencing its dynamics and stability. By altering the position of the center of mass, the object can achieve and maintain a desired orientation.

Rogers and Costello (2008) explored a vibrating internal mass control mechanism for use in both fin- and spin-stabilized projectile configurations. They demonstrated that substantial control authority could be achieved by vibrating a relatively small internal, translating mass perpendicular to the axis of symmetry, particularly when synchronized with the roll rate frequency. This approach effectively uses a small internal mass relative to the total mass of the projectile, making it efficient and practical.

A decade later, J. Li, C. Gao, C. Li, et al. (2018) reviewed the development and challenges of moving-mass control for space vehicles, rotating munitions, submersible systems, unmanned aerial vehicles, and re-entry vehicles. The study highlighted that mass redistribution can significantly enhance attitude control and disturbance mitigation. However, implementing this mechanism requires careful layout design, as the moving-mass actuator occupies a substantial portion of the available internal space, which may interfere with other system components and operations.

To address these challenges, J. Li, C. Gao, C. Li, et al. (2018) proposed an innovative moving-mass configuration for flight vehicles, see Figure 2-10. This configuration, featuring a large mass ratio, offers enhanced maneuverability compared to traditional point-moving mass systems. The study also introduced an adaptive controller with excellent command tracking capabilities, effectively mitigating the coupling issues caused by moving masses with high inertia. Through comprehensive theoretical and experimental validation, this research demonstrated the feasibility of using mass redistribution to adjust an object’s pose while addressing the challenges of layout design and coupling effects.

Typically, the moving mass is installed internally within the controlled object, which can disrupt the internal structure and take up valuable space. In the case of MiC modules—designed as functional areas such as apartments, hospital wards, or hotel rooms—permanently integrating this technology could reduce the usable space within the module. Therefore, future research should explore innovative methods to apply moving mass control externally to the lifting object, i.e., the MiC module, while minimizing its impact on lifting capacity. This approach would enable the advantages of mass distribution adjustment to be utilized without compromising the functionality or usability of the modular units.

(a)


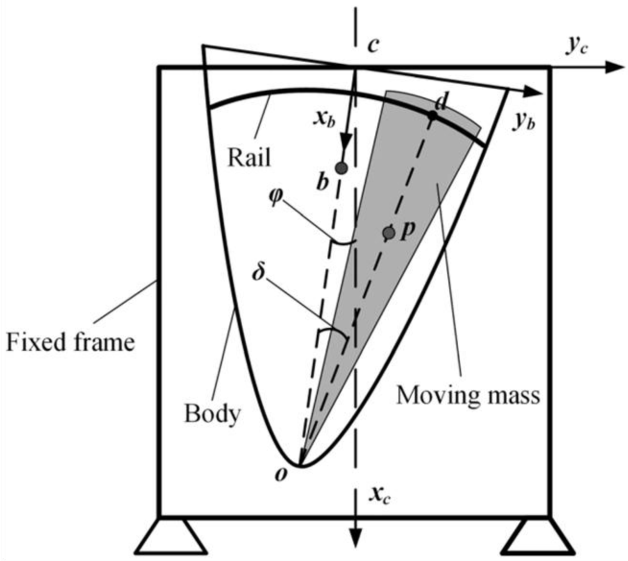
(b)


Figure 2-10 (a) Experimental Setup of the Moving Mass System, and (b) Schematic of the Moving Mass System Experiment Setup (J. Li, C. Gao, T. Feng, et al., 2018)

2.4.3 Challenges in Current Technologies

While significant advances have been made in robotic systems and control mechanisms for lifting and assembly tasks, their application in MiC lifting operations is still full of critical challenges and limitations. Existing research and technologies provide valuable insights and solutions in areas such as horizontal rotation control, cable-driven pose control and mass distribution. However, the unique demands and constraints of MiC lifting expose gaps in their practical applicability and effectiveness. These challenges hinder the progression toward safer, more efficient, and fully automated lifting systems.

One of the primary challenges lies in the integration of robotic systems with under-actuated crane operations, which are widely used in construction. Current cranes are inherently limited in their control authority, particularly in manipulating payload position and orientation with precision. This limitation necessitates substantial manual intervention, including ground crew efforts to align and position modules, resulting in labor-intensive and time-consuming operations. While advanced robotic solutions, such as mobile manipulators or cable-driven devices, have been explored, they are often incompatible with the dynamic and congested nature of construction sites and require extensive modifications to existing equipment.

Another critical challenge is the lack of gross adjustment and stability control mechanisms to address issues such as X-Y plane levelling and sway mitigation. Suspended loads in crane-based systems naturally sway during transport, especially when sudden stops or directional changes occur. Current methods rely heavily on manual dampening by ground crews, which increases safety risks and operational inefficiencies. Although alternative solutions, such as passive dampers or gyroscope-based systems, have been proposed, they remain underexplored in real-world MiC operations, particularly for heavy modules that require robust, scalable systems.

Furthermore, minor positioning and alignment adjustments present substantial difficulties in MiC lifting. Current cranes are not designed to achieve the sub-centimeter-level precision required for module installation. Operators depend on experience and manual guidance from ground crews to achieve alignment, relying on iterative trial-and-error processes that are prone to misalignment and delays. While certain control models, such as LQR controllers, have shown promise in enhancing crane accuracy, with minimal practical deployment in construction environments. While certain control models, such as LQR controllers, have shown promise in enhancing crane accuracy, their feasibility for high-payload applications remains largely theoretical, with minimal practical deployment in construction environments.

Beyond these functional limitations, existing technologies often lack seamless integration and adaptability, leading to disruptions to on-site workflows. Many proposed solutions require extensive modifications to cranes or the addition of bulky external systems, which are impractical in crowded and dynamic assembly sites. For example, certain advanced control models, while theoretically promising, demand substantial changes to tower crane control programs, making them incompatible with a plug-and-play approach. These upgrades also incur high costs and are not feasible for all tower cranes, further limiting their practical application. Moreover, current technologies provide limited automation of hazardous tasks and fail to address common safety risks that expose workers to the risk of accidents. These challenges highlight the critical need for solutions that can integrate seamlessly into existing workflows while effectively mitigating these safety risks and improving operational efficiency.

Collectively, these challenges underscore the inadequacy of existing technologies in addressing the complex demands of MiC lifting. As highlighted in prior reviews, no comprehensive solution currently exists that can effectively integrate advanced control mechanisms, automate critical tasks, and minimize manual intervention without disrupting existing workflows. These limitations set the stage for the next section, where the research gaps are systematically identified and analyzed. This research builds upon these gaps by making original contributions from both theoretical and practical perspectives.

2.5 Research Gaps

The Chapter 1 introduces the development and characteristics of MiC as an innovative construction method, as well as the safety challenges faced in its application in Hong Kong. In the earlier sections, a review was conducted on the relevant patents, literature, and industry development. However, the review revealed that existing solutions fail to adequately address the safety issues specific to MiC lifting and assembly. To develop a technological solution that effectively addresses the safety and performance challenges of MiC lifting in the local context, the following research gaps need to be addressed:

Gap 1: Limited Identification and Prioritization of Safety Risks

While crane operations are widely recognized as one of the most hazardous activities in construction, existing studies often fail to systematically analyze the safety risks specific to MiC lifting. The modular nature of MiC lifting introduces unique challenges, such as heavy payload handling, precise module alignment, and the high reliance on manual intervention.

To date, limited research has comprehensively identified and prioritized safety risks across the distinct stages of MiC lifting operations. Existing safety assessments are often fragmented or overly generalized, lacking stage-specific hazards analysis such as hooking, lifting, and alignment, as well as analyzing practical industry practices and requirements. Moreover, the absence of a system risk ranking impedes the development of targeted solutions and the efficient allocation of resources to improve safety.

Gap 2: Lack of Integrated Technological Solutions for Stage-Specific Challenges

Although significant advances have been made in robotic systems and control mechanisms, their application in MiC lifting operations remains limited. Existing technologies, such as horizontal steering control, cable-driven pose control, and mass distribution adjustment systems, face critical limitations in addressing the unique demands of MiC lifting. These include handling heavy payloads, achieving sub-centimeter alignment precision, and adapting to the dynamic and congested nature of construction sites.

Moreover, these technologies often focus on isolated problems rather than offering integrated solutions that address the full spectrum of stage-specific challenges in MiC lifting. For instance, current solutions may reduce swaying during lifting but fail to address fine alignment during module placement. Additionally, many technologies require extensive modifications to existing crane systems, making them impractical for widespread adoption.

Gap 3: Limited Evaluation of the Practical Performance of Technical Solutions

Despite the growing interest in automated systems for construction, there is a lack of mature tools or frameworks to evaluate the practical feasibility of such solutions in MiC lifting scenarios. Existing validation methods are often borrowed from related fields, such as robotics or manufacturing, and fail to account for the unique constraints of MiC lifting, such as heavy payloads, dynamic environments, and diverse construction conditions.

Without a systematic evaluation framework, it is difficult to evaluate the safety, precision, and efficiency of proposed solutions or to ensure their alignment with industry standards and best practices. This gap not only limits the adoption of innovative technologies but also creates uncertainty regarding their real-world applicability and impact.

To strengthen the connection between the identified research gaps and the subsequent chapters addressing them, the following mapping is explicitly outlined. Gap 1, concerning the identification and prioritization of safety risks, is systematically addressed in Chapter 4, where a structured methodology is developed to analyze and rank stage-specific risks in MiC lifting operations. Gap 2, which highlights the lack of integrated technological solutions for stage-specific challenges, is tackled in Chapters 5, 6, and 7, where the SLAP system is proposed, designed, and detailed as a comprehensive solution to automate and optimize critical MiC lifting tasks. Finally, Gap 3, focusing on the limited evaluation of technical solutions, is addressed in Chapter 8, where a tailored evaluation framework is applied to assess the SLAP system's performance in terms of safety, precision, and efficiency. This explicit mapping ensures clarity in how each gap is systematically resolved throughout the thesis, providing a cohesive narrative that bridges the gaps and their corresponding solutions.

2.6 Summary of Chapter

The Chapter 2 begins with a detailed review of 46 patents from both domestic and international sources, categorizing them based on their applications and mechanical structures. Despite the breadth of this review, no existing patent was found to offer a direct solution to the specific challenges of MiC lifting. This underscores the inadequacy of current patented technologies in addressing the safety, precision, and efficiency demands of MiC lifting operations.

Following the patent analysis, the review expands to academic literature and industry practices. The first area of focus is the development and innovation of crane system control methodologies, reviewing advancements in control technologies that could inspire mechanisms tailored to MiC lifting operations. The second area examines individual technologies designed to address sub-tasks frequently encountered during MiC lifting processes, including precision positioning, levelling control, and payload handling. This comprehensive review helps identify existing technologies' strengths and limitations in addressing MiC-specific challenges.

From this analysis, three major challenges are identified in the context of current literature and industry practices. These challenges highlight the need for innovative solutions that can address the safety and operational inefficiencies of MiC lifting. In response, the Chapter identifies and elaborates on three critical research gaps. These gaps include the lack of a dedicated control platform for MiC lifting, a suitable validation framework for proposed technologies, and limitations in existing solutions to meet the precision and payload requirements of MiC operations.

By systematically analyzing patents, academic literature, and industry practices, Chapter 2 effectively establishes the current state of knowledge and technology in MiC lifting. It provides a comprehensive framework for identifying unmet needs and challenges, laying a solid foundation for the research explored in subsequent chapters. This structured approach ensures that the research is well-positioned to address the identified gaps and contributes to the development of solutions aimed at enhancing MiC lifting performance.

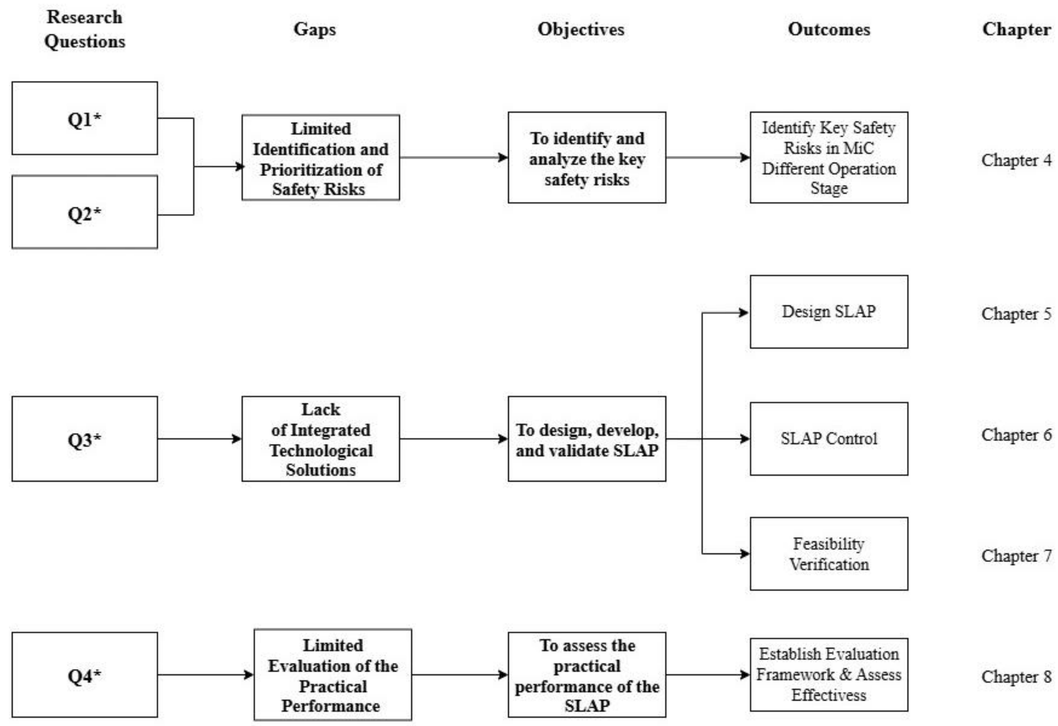
Chapter 3 Research Methodology

3.1 Introduction

This Chapter outlines the principal methods and tools employed in this research. The primary aim is to identify the specific safety challenges associated with the on-site MiC lifting process and to propose precise solutions that minimize workers' involvement while effectively addressing these challenges. To achieve this, the research adopts a combination of scientific methodologies, incorporating both qualitative and quantitative approaches. These include mixed-method reviews, semi-structured interviews, prototype design, laboratory validation, and case studies. The subsequent sections of this chapter provide a detailed explanation of each methodology, emphasizing their contributions to the overall research process.

3.2 Research Framework

To accomplish the research objectives outlined in the previous chapter, a comprehensive and well-structured framework of research methods and analysis techniques is essential. The research framework, illustrated in Figure 3-1, offers a diagrammatic overview of the research framework adopted in this study. It systematically addresses the research questions by identifying existing gaps, formulating specific objectives, and linking them to expected outcomes. This framework integrates qualitative and quantitative approaches to thoroughly investigate the research questions, ensuring cohesive, methodical progression from identifying safety risks to developing and validating the SLAP system, and finally assessing its practical performance. The methods and analysis techniques employed are further summarized in Table 3-1.



**Q1 to Q4 could refer to Chapter 1.3.*

Figure 3-1 Research Framework

Table 3-1 Research Methodology Adopted for Corresponding Objectives

No.	Research Objectives	Research Methods	Analysis	Elaboration
1	To identify and analyze the key safety risks in MiC lifting operations across different stages, and to determine specific, measurable gaps that can be addressed through technological solutions.	1. Mix method review; 2. Semi-structured interview; 3. Site observation.	1. Content analysis; 2. Empirical analysis; 3. Engineering analysis; 4. Numerical analysis.	Chapter 4
2	To design, develop, and validate an SLAP capable of mitigating the identified risks and improving the safety, efficiency, and accuracy of MiC lifting	1. Mix method review; 2. Design science research; 3. Experiment.	1. Functional decomposition analysis; 2. Engineering analysis; 3. Task and workflow analysis.	Chapter 5 Chapter 6 Chapter 7

	operations.			
3	To assess the practical performance of the SLAP system using a systematic evaluation framework based on industry practices and measurable parameters for safety, efficiency, and productivity.	1. Mixed method review; 2. Design science research; 3. Experiment.	1. Comparative analysis; 2. Mathematical calculation; 3. System dynamics.	Chapter 8

3.3 Research Methods

3.3.1 Mixed Method Reviews

A mixed-method review, as defined by Greene et al. (1989), combines quantitative and qualitative analyses to enhance the credibility of research findings by allowing them to support or complement each other. This approach helps researchers develop a broader and more integrated understanding of the problem. Its increasing popularity is partly due to advancements in computer-assisted analysis software, which efficiently analyzes qualitative data and identifies statistical relationships (Hesse-Biber, 2010). This study adopts a mixed-method review to achieve diverse objectives and uncover exemplary experiences that inform further research development.

For the first objective, this study employs a traditional literature review method. Initially, a systematic review of fatal cases in Hong Kong from 2017 to 2023 was conducted, focusing specifically on incidents related to crane operations. This analysis identifies potential safety hazards that could lead to fatalities during the construction site lifting process. The review then delves deeper into safety hazards in crane operations by examining records from both academic literature and industry guidelines. This analysis highlights safety risks unique to Hong Kong's construction sector, offering a strong foundation for further validation and the development of tailored solutions.

For the second objective, the study explores appropriate semi-automated solutions to address the identified and ranked safety hazards. To determine which technologies are applicable to this study, it is essential to review previous work in construction-related fields, particularly in areas such as safety risk avoidance, heavy-duty lifting, and delivery management.

In this context, a comprehensive literature review is an indispensable part of achieving the research objectives. Traditional literature reviews often rely on expert opinions, which may introduce subjective biases influenced by the reviewers' backgrounds (Mulrow, 1994; Petticrew & Roberts, 2008). This investigation incorporates practical industry solutions derived from registered patents worldwide, as well as academic papers. To enhance the practicality of the findings, patents are the focus during the review. Both qualitative and quantitative methods are used during the patent review to identify potential solutions that the industry has already explored for hazard mitigation. The patent review follows a two-stage, content analysis-based approach, a well-recognized method in construction and engineering research, to ensure comprehensive technological coverage. To broaden the scope, the "Google Patent Advanced Search" engine is used instead of the "United States Patent and Trademark Office" database, allowing for the inclusion of innovations from various regions. Statistical analysis is then performed on the results to identify the most frequently filed classifications, popular technologies, and research trends, which inform the design and proposal phases of the study. Similarly, a review of feasible technologies is conducted in the academic domain, with a focus on robotics and automation. The first scope of this review is "Lifting and assembly robotic systems," aiming to identify configurations that can be directly applied to the identified problems. Additionally, individual technologies such as "horizontal steering control," "cable-driven control," "thruster sway damping," and "mass distribution adjustment control" are explored. By analyzing these technologies, the study assesses their advantages and challenges to solve the current research problem.

For the third objective, a similar literature review approach is adopted as in the previous objectives. The study reviews both academic literature and industry standards to identify the parameters and criteria most relevant to real-world construction site operations and machine performance, thereby supporting the establishment of feasible evaluation metrics. In the academic review, keywords such as “robot cost-effectiveness,” “construction robot cost-benefit,” "robot performance validation," "construction robot performance," "performance measurement," and "performance validation” are used. The primary aim is to emphasize the core aim of validating the performance of proposed solutions. By narrowing the scope to the construction discipline, the findings are better aligned with real-world practices, making the validation more representative of on-site environments. On the industry side, the review heavily relies on the International Organization for Standardization (ISO), a globally recognized authority operating in 171 countries with 25,426 standards covering a wide range of technological areas (ISO, 2024). ISO standards play an important role in ensuring that the research aligns with internationally accepted practices and performance benchmarks.

3.3.2 Semi-structured Interviews

After conducting the literature review, safety hazards on construction sites and their severity from the perspective of frontline practitioners were identified. To validate these hazards and explore practical obstacles faced by the industry, interviews were chosen as the research method.

Interview methods range from structured to unstructured formats (Berler, 2019). Structured interviews follow a standardized protocol with closed-ended questions that leave little room for open-ended responses, while unstructured interviews allow participants to respond freely, resembling casual conversations (Karatsareas, 2022). Semi-structured interviews, combining elements of both, are widely used for qualitative data collection due to their flexibility and adaptability (Kallio et al., 2016). This approach uses a pre-developed interview protocol with open-ended questions but allows interviewers to adapt based on participant responses or emerging areas of interest (Knox & Burkard, 2014). Semi-structured interviews are well-suited for this study as they balance objective selection with subjective exploration. They also ensure that all questions are fully answered without external assistance (Austin, 1981; Bailey & Garralda, 1987).

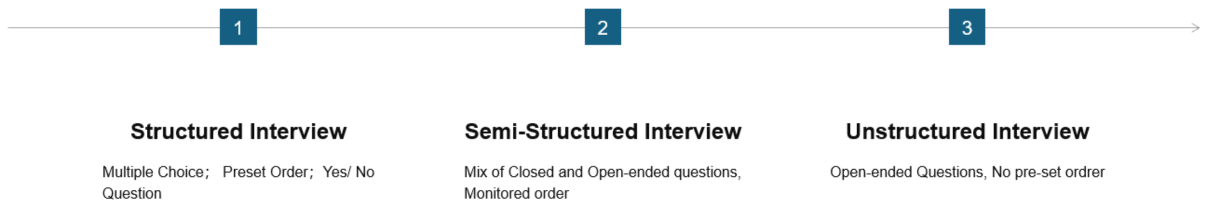


Figure 3-2 Different Interview Experiments Classification (Karatsareas, 2022)

This study employs a semi-structured interview with two expert groups, consisting of seasoned crane operators and training instructors, to verify the concerns outlined in the proposed list. This method is more practical than other methods during the initial stage of identifying safety risks, as it leverages the benefits of insights derived from the literature review, facilitates the smooth verification of consolidated findings from past studies, and prevents the oversight of recent developments on construction sites. Furthermore, it provides control over the scope of respondents' answers, reducing the likelihood of overly speculative or scattered responses.

The semi-structured interview is organized into three main phases, combining a questionnaire with subsequent discussions to comprehensively address the study's objectives. The first phase gathers detailed information about participants' professional experience, along with their assessments and prioritizations of the listed concerns. In the second phase, the concerns are evaluated through pairwise comparisons, following a methodology influenced by the NASA-Task Load Index to determine their relative significance with reduced bias (Hart & Staveland, 1988). To streamline the process and ensure consistency, the questionnaire presents fifteen binary options, simplifying responses while minimizing variability in the results. The final phase explores any additional critical concerns that were not initially included, allowing for further refinement and completeness of the analysis. By asking both closed-ended and open-ended questions, this format allowed for the exploration of motivations, attitudes, and beliefs while verifying the validity of the findings (Austin, 1981; Smith, 1975). The closed-ended questions were used to identify and rank the safety factors identified in the literature review in the questionnaire. Meanwhile, the open-ended questions were posed based on respondents' feedback, focusing on additional precautions to consider on-site, informed by their latest experiences. The questions were carefully designed to clearly reflect the research purpose, and their sequence was logically structured to demonstrate the progression of the study's exploration (Galletta & Cross, 2013).

When designing semi-structured interviews, ethical considerations should also be carefully addressed, particularly as the questions may involve sensitive aspects of participants' daily behaviors. It is crucial to ensure that participants feel comfortable and respected throughout the interview process (Karatsareas, 2022; Smith, 1992).

3.3.3 Design Science Research

Design Science Research (DSR) is a research methodology that focuses on solving real-world problems through the creation and evaluation of innovative artifacts (Hevner et al., 2004). These artifacts, which may include models, frameworks, tools, or technologies, are designed to address specific challenges within a domain while simultaneously contributing to theoretical knowledge (Hevner et al., 2004; Vom Brocke et al., 2020). DSR is characterized by an iterative process that involves problem identification, artifact development, demonstration, and evaluation, with the ultimate goal of bridging the gap between theory and practice (Gregor & Jones, 2007).

In the context of engineering and construction management, DSR has been widely adopted to address complex and high-risk challenges through technological innovation. Researchers emphasize that DSR is particularly well-suited for domains that require the integration of technical, human, and organizational factors to achieve practical and impactful solutions (Baskerville et al., 2015; Peffers et al., 2007). This approach is particularly suited for addressing complex challenges in the modular construction industry, where technological innovations can significantly enhance safety and efficiency.

The development of the SLAP device aligns well with the objectives and principles of DSR. In MiC, the risks associated with lifting and positioning heavy modules, including worker injuries and inefficiencies, present a significant challenge. The SLAP device is conceptualized as an innovative study artifact designed to mitigate these risks by enhancing safety, precision, and efficiency during lifting operations. Designing and investigating SLAP are the two major activities for research development (Wieringa, 2014a).

Empirical validation, which involves collecting and analyzing evidence to evaluate the performance and applicability of technologies, aligns with the fourth step of the DSR research method—artifact demonstration and evaluation (Nowak, 2012; Schneidewind, 1992). Unlike controlled experiments, which primarily focus on testing causal relationships, empirical validation takes a broader approach by observing and verifying the real-world applicability of the proposed artifact. This alignment ensures that the SLAP device is rigorously tested not only for its theoretical soundness but also for its practical effectiveness in addressing the challenges of MiC lifting operations. By incorporating empirical validation into the demonstration and evaluation stage of the DSR process, this research systematically evaluates the proposed solution in a comprehensive and scientifically grounded manner.

The research follows a structured DSR process with integrated empirical validation, as outlined below:

1. Problem Identification and Motivation

Chapter 4 investigates the MiC lifting safety risks, identifying critical safety hazards and inefficiencies during the lifting and positioning of heavy modules. This Chapter provides a detailed analysis of these challenges, establishing the motivation and the specific objectives to be solved for developing a semi-automated solution such as the SLAP device. The identification of these real-world problems forms the foundation for subsequent artifact development and validation (Hevner et al., 2004).

2. Proposed Solution

The SLAP device is proposed to address the identified challenges. The solution is composed of two main components, as detailed in Chapters 5 and 6:

• Mechanical System Design (Chapter 5): This component involves the conceptualization and development of hardware systems to facilitate critical functions such as steering rotation along the Z-axis, module levelling, and micro-positioning.

• Control Principle Design (Chapter 6): Building on the mechanical system, this component introduces control principles, logic, and a user interface (UI) design to enable efficient Human-Machine Interaction (HMI). Together, these designs integrate human oversight and adaptability, ensuring precision and safety during lifting operations.

3. Prototyping and Testing

Chapter 7 focuses on the development of a lab-scale prototype of the SLAP device to simulate real-world conditions. This prototype serves as a proof of concept, enabling the feasibility of the design tested in a controlled environment.

4. Empirical Validation

Empirical validation is a cornerstone of the DSR evaluation process in this research. It systematically assesses the SLAP device's performance and verifies its practicality in addressing the identified challenges. Drawing from the empirical validation frameworks proposed by Briand et al. (1995), Flood and Issa (2010), and Wieringa (2014b), this process incorporates the following steps:

(a) Developing a Validation Strategy: Based on a comprehensive review of academic literature, industry standards, and guidelines, a validation strategy is formulated to ensure that the evaluation is both rigorous and relevant.

(b) Defining Evaluation Metrics: Key performance indicators (KPIs), such as lifting accuracy, safety performance, and task completion time, are identified and refined using relevant literature and industry benchmarks.

(c) Applying Measurement Methods: The validation framework is applied to assess the SLAP prototype. Observational and experimental data are collected, including measurements of lifting precision, safety performance, and operational efficiency under lab-simulated conditions.

(d) Analysing Collected Data: The collected data are analysed to evaluate both the functional effectiveness of the SLAP device and the validity of the evaluation framework itself.

This dual focus ensures that the artefact is rigorously assessed for practical applicability and theoretical soundness.

Chapter 8 extends the validation process by applying a comprehensive evaluation framework that incorporates both academic rigor and real-world applicability. The iterative nature of this process follows the "hypothesis-experiment-conclusion" logic, enabling systematic refinement of the SLAP device while addressing the research questions.

5. Contribution to Practice and Theory

The final stage of the DSR process focuses on consolidating the contributions of this research. Chapter 9 discusses the contribution of the research to both knowledge and practical parts. From a knowledge perspective, this study advances the understanding of safety risks in MiC lifting by developing a systematic approach for their identification and ranking. It further contributes to theory through the design of the SLAP and the introduction of a comprehensive validation framework, establishing a structured methodology for evaluating similar technologies. From a practical perspective, the SLAP device addresses critical risks in MiC lifting safety by improving on-site safety, efficiency, and productivity. Its design and lab-based validation, as presented in this research, confirm its feasibility and applicability. Moreover, the systematic design, testing, and validation process provides a foundation for future innovations, including the potential transition to fully automated solutions as the industry builds expertise and confidence.

3.3.4 Experiments

Experiments are a crucial research method in innovative studies, addressing the limitations of traditional approaches by enabling the exploration of new ideas (Sørensen et al., 2010). Traditionally, experiments are conducted in controlled laboratory settings, which are often isolated from real-world environments (Fine & Elsbach, 2000; Gross & Krohn, 2005).

Depending on the level of control researchers have over variables, experiments can be categorized as laboratory, field, or natural experiments, see Figure 3-3 (Sørensen et al., 2010). Laboratory experiments take place in controlled settings, detached from real-world complexities, and are ideal when the experimental process is too uncertain or unstable for real-life conditions. MiC lifting activities, identified as high-risk operations, require strict safety measures during experimental validation. Therefore, laboratory experiments are chosen to ensure environmental control and safety during initial testing. While conducted in a controlled setting, the experiments are carefully designed to simulate real-world conditions and procedures as closely as possible. Once stability and reliability, particularly in terms of safety performance, are demonstrated in the laboratory, the research will progress to field and natural experiments to evaluate the mechanisms in real-world environments.

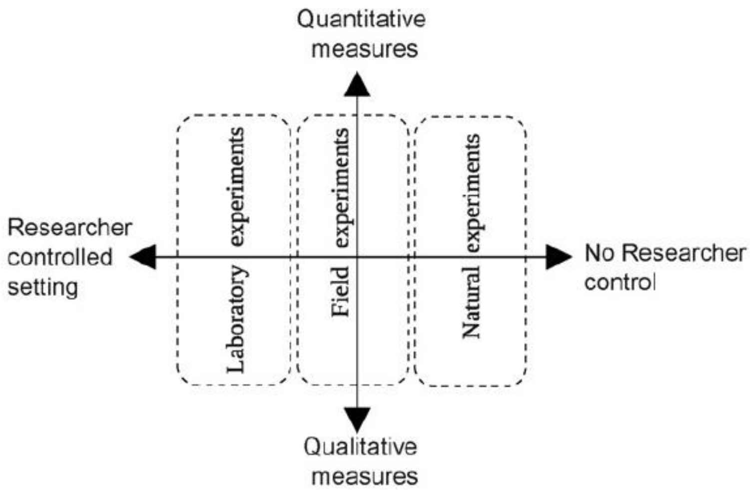


Figure 3-3 Experiment Type Classification (Sørensen et al., 2010)

In this research, after identifying feasible technologies through the mixed-method review (both qualitatively and quantitatively), a platform concept is proposed and designed based on the feasible technology framework, addressing the primary safety considerations on-site. Experiments are employed to further verify the effectiveness and efficiency of the identified platform in MiC scenarios. Unlike traditional construction environments, MiC construction sites feature fewer on-site works but exhibit increased complexity in the transportation and on-site assembly of 3D modules (Bertram et al., 2019). Therefore, the experiments particularly focus on validating the performance of the lifting and assembly processes.

Testing on a real MiC construction site with a 1:1 scale laboratory test would pose potential safety hazards to the project due to uncertainties in the performance and reliability of the technologies. As an alternative, a scaled-down laboratory experiment simulating an on-site situation is proposed. Conducting scaled-down experiments in a laboratory not only enables verification of the platform in a controlled environment, thereby preventing significant losses in the event of experimental failure, but also reduces the initial costs associated with technology verification (Cho et al., 2016). The development and design of the experiment for this study is illustrated in Figure 3-4.

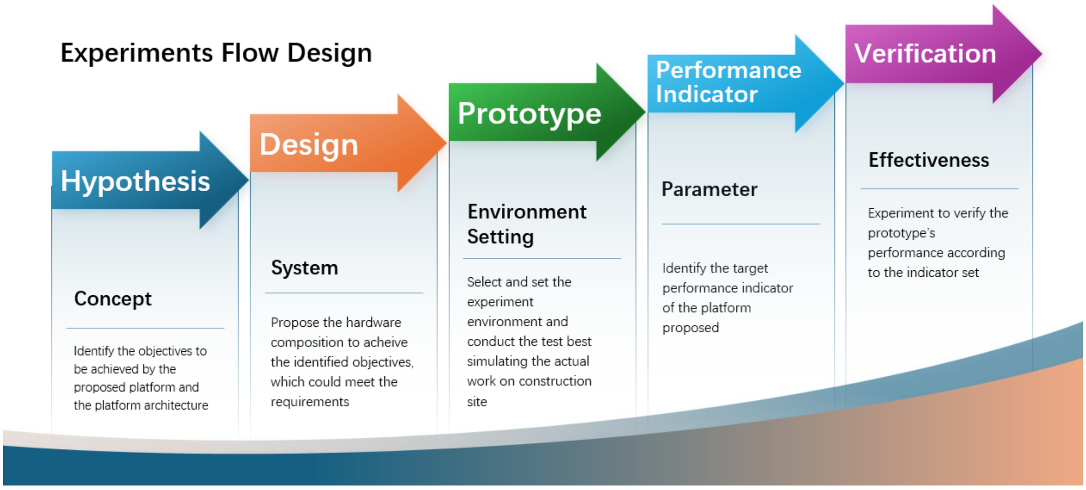


Figure 3-4 SLAP Experiments Flow Design

3.4 Summary of Chapter

This Chapter introduces the methodological framework, outlining the procedures and techniques employed in this study. It begins with a comprehensive overview of research methods, followed by a detailed explanation of the specific approaches used. A mixed-methods review, combining mixed-methods literature reviews, semi-structured interviews, design science research, experimental methods, and empirical validation techniques, was employed, ensuring robust methodological triangulation.

Initially, a mixed-method literature review was conducted to systematically identify potential safety risks associated with crane operations, complemented and validated through semi-structured expert interviews. Following this risk identification phase, an additional mixed-method review was performed to explore suitable technological solutions and design configurations capable of effectively mitigating these safety hazards. Guided by the principles of design science research, an innovative solution concept—the semi-automated MiC lifting platform—was developed. To validate the effectiveness of this proposed concept, a carefully designed and controlled laboratory experiment was conducted, ensuring minimal potential risks during the evaluation stage. Subsequently, empirical validation was conducted following an additional mixed-methods review, thereby establishing and verifying a comprehensive evaluation framework. This framework is designed as a practical and reliable tool for assessing the performance, safety, and productivity of future MiC lifting platforms or similar systems. Finally, the evaluation framework obtained was applied to the developed lab-scale prototype to demonstrate the efficiency, safety, and productivity of the proposed design concept and the effectiveness of evaluation framework, concluding the design science research process.

Chapter 4 Identifying and Ranking the Severity of MiC Lifting Safety Risks

4.1 Introduction

In Chapter 2, this study analyzed real-world safety accidents in the construction industry by reviewing news reports of industry-related incidents. However, it was challenging to identify the primary factors impacting lifting safety solely from these reports, and even more challenging to pinpoint the critical safety risks specific to MiC lifting operations.

This Chapter builds upon the findings from Chapter 2 by expanding the scope of investigation to ensure a more comprehensive and practical analysis of MiC lifting safety risks specifically. Chapter 4.2.1 begins by reviewing the literature on the research domain. It also examines local regulations and industry guidelines to strengthen the contextual grounding of the study.

One of the key goals of this chapter is to evaluate and rank of the identified risks through a systematic combination of qualitative and quantitative methodologies. Semi-structured interviews are first utilized to rank risks based on expert opinions. Subsequently, discussions with expert groups were carried out to confirm and rank the identified risks, ensuring their relevance and suitability for MiC lifting operations. The study then categorizes the risks extracted from real accident cases into different clusters for further quantitative analysis. These clusters are further ranked based on three key criteria: the severity of the consequences of failure, the likelihood of occurrence, and their alignment with existing legislative requirements designed to mitigate such hazards. This comprehensive and multi-dimensional approach allows the study to bridge the gap between theoretical research and real-world applications, addressing potential gaps in the literature and ensuring a more practical understanding of MiC lifting risks.

The Chapter concludes with a detailed breakdown of MiC lifting procedures and an analysis of how the ranked risks identified are distributed across different work stages. By focusing on specific pain points in MiC lifting operations, the study highlights challenges that could be mitigated through automated or semi-automated solutions. This step not only aligns with Research Objective (a) but also lays a solid foundation for developing targeted solutions to address the problem stages by stage, with higher MiC lifting safety risks in subsequent research.

4.2 Identifying Critical Safety Risks in MiC

4.2.1 Semi-structured Interview Design

Building on the methodological framework established in Chapter 3.3.2, this section details the semi-structured interviews conducted to investigate safety risks associated with MiC lifting operations. The primary goal of this section is to transition from the generic safety considerations identified in the literature review (Chapter 2.2.2) to a validated, context-specific understanding of critical risks, their relevance, and their relative severity within MiC scenarios. This approach ensures that the review findings are validated to address the specific safety risks posed by MiC lifting operations.

The interviews were designed with three interrelated aims: first, to verify whether risk categories such as blind lifting, overhead loads, and high payload, are pertinent and distinctly expressed in MiC lifting scenarios; second, to establish a clear hierarchy among these risks based on the practical experience of industry professionals; and third, to use the open-ended nature of the format to uncover any significant, previously undocumented risks specific to MiC lifting operations. To ensure a comprehensive and balanced perspective, participants were drawn from two complementary groups within Hong Kong's construction industry: experienced crane operators, who provide firsthand insight into daily operational challenges and hazards, and crane training instructors from the Hong Kong Institute of Construction, who offer a systematic, normative view grounded in safety standards and pedagogical practice. This dual-perspective approach helps to balance on-the-ground realities with formal safety protocols, reducing individual bias and capturing a more complete picture of risk.

The interview process unfolded in three sequential phases. Initially, participants discussed their professional background and then reviewed a preliminary list of safety risks, commenting on the relevance and completeness of each item within the MiC operation. The second phase focused on comparative ranking through a structured pairwise exercise. Inspired by the NASA-Task Load Index methodology to minimize subjective bias, experts were presented with binary choices between risk factors, yielding quantitative weightings that reflected the relative importance of each hazard. In the final, exploratory phase, open-ended questions encouraged participants to identify any additional concerns, procedural vulnerabilities, or unforeseen hazards associated with MiC lifting that were absent from the original list. This phased structure ensured both structured validation and open discovery.

The qualitative insights from the first and third phases were then integrated with the quantitative rankings from the second phase. This mixed-methods approach allowed the findings to be both measurable and richly contextualized, ensuring that the resulting risk framework was not only statistically informed but also deeply rooted in professional expertise. The validated and prioritized risk profile generated through this process directly supports the subsequent stages of risk clustering and stage-specific analysis, forming a crucial evidence base for the design of the SLAP system in the following Chapters.

4.2.2 Results Analysis

1. Expert Background

To assess the efficiency and effectiveness of knowledge transfer in MiC lifting, the study involved two groups of industry professionals: seasoned crane operators and training instructors from the Hong Kong Institute of Construction (HKIC). Dividing participants into two groups enabled the research to examine potential discrepancies in perspective based on their roles in crane operations.

A total of eight experts participated in the interviews, all of whom are active frontline crane operators or instructors working in Hong Kong’s construction industry. The participants' demographic and professional backgrounds are summarized in

Table 4-1. Notably, all the interviewees were male, reflecting the gender distribution within the industry for both operators and instructors.

By including both groups, the research aimed to ensure a comprehensive understanding of crane operations while also identifying potential gaps or variations in considerations between the two roles. This approach provided valuable insights into the operational challenges faced by crane operators and their instructors in the MiC context.

Table 4-1 Consolidation of Experts' Backgrounds

Type	3< years≤5 Years	5< years≤10	> 10 Years
Number of Experienced Operators	1	1	3
Number of Crane Training Tutors	-	-	3

The interviews were structured to address the distinct roles of operators and tutors, with tailored questions for each group. Participants were encouraged to discuss how the identified safety risks could influence the MiC lifting process.

Among the skilled operators, everyone contributed their insights on the proposed considerations. Four experts highlighted the critical importance of the selected factors in their daily work. One operator noted that the list effectively encompassed most elements relevant to the hoisting phase. Additionally, the operators pointed out other significant issues they believed should be included, such as swing instability during loading, the nature of the loads being lifted, and variations in crane types.

In contrast, the training tutor group offered slightly different insights. Tutors pointed out that operation angles are a crucial consideration during the hoisting process, which is critical to the MiC lifting process and emphasized the importance of maintaining proper crane alignment. They further recommended fostering good practices among crane operators, such as standing by to brake the crane promptly during operations to mitigate potential hazards. Additionally, tutors stressed that effective communication with other workers and the signaler is essential for ensuring safe and efficient MiC lifting.

These insights provided by both groups not only validated the original considerations but also enriched the list by introducing additional factors critical to safe and effective MiC lifting operations.

2. Analysis of Collected Data

To reduce random deviations and mitigate the impact of individual biases, the quantitative data from the interviews underwent initial evaluation using a two-sided Grubbs' test to detect potential outliers (Grubbs, 1949). This method involves calculating the test statistic as follows:

$$G = \frac{\left|Y_i - \underline{Y}\right|}{s} \qquad (4-1)$$

where $\underline{Y}$represents the mean of the sample, while *s* represents the standard deviation

The calculated value of **G** is then compared against the critical threshold:

$$G > \frac{(N-1)}{\sqrt{N}} \sqrt{\frac{t^2_{\frac{\alpha}{2N},N-2}}{N-2+t^2_{\frac{\alpha}{2N},N-2}}} \qquad (4-2)$$

The parameter *t* defines the upper critical value derived from the *t*-distribution. Upon satisfying the associated condition, any statistical outliers in the dataset are identified and subsequently discarded. The Grubbs' test is then reapplied to the refined dataset, and this iterative process continues until the dataset is deemed free of outliers.

In this study, the application of the Grubbs' test revealed no outliers in the expert feedback. This outcome validates the uniformity of expert responses, ensuring the dataset's reliability for further analysis.

4.2.3 Findings

Figure 4-1 illustrates the weightings assigned to the major MiC lifting safety risks that crane operators must account for on-site. These risks are grouped into three categories. Specifically:

"Blind Lifting," "Overhead," and "High Payload" are classified as key factors impacting "Safety."

"Short Path" is identified as a primary factor affecting "Productivity."

"Change Direction" is categorized as a factor influencing operational "Effectiveness."

Figure 4-2 and Figure 4-3 present a detailed breakdown of the weightings assigned to these considerations by the two groups of experts, namely seasoned operators and crane training instructors. These figures highlight the differences and similarities in how each group ranks the considerations.

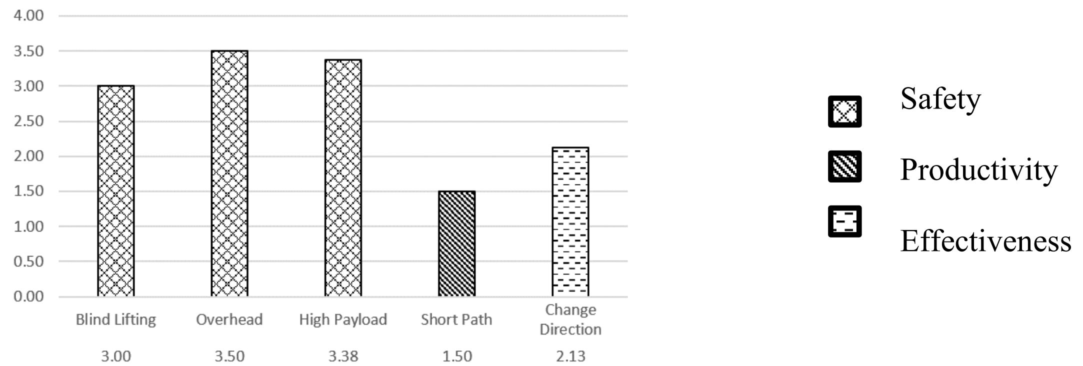


Figure 4-1 MiC Safety Risks Weighting Results (Overall Interviews)

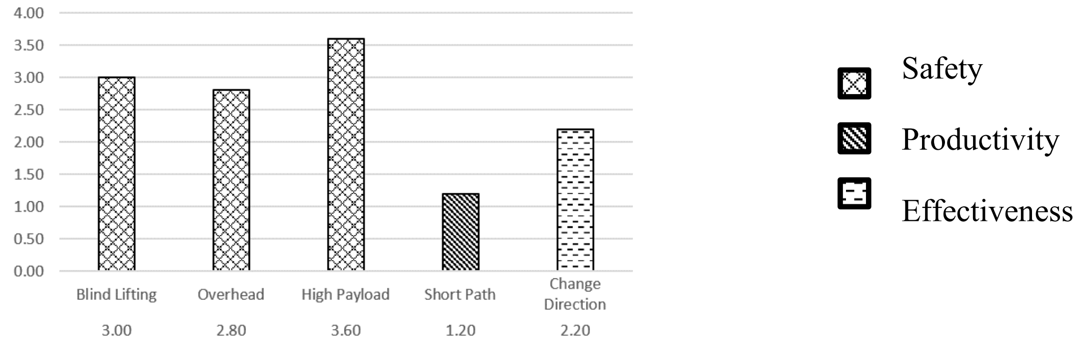


Figure 4-2 MiC Safety Risks Weighting Results (Experienced Operators)

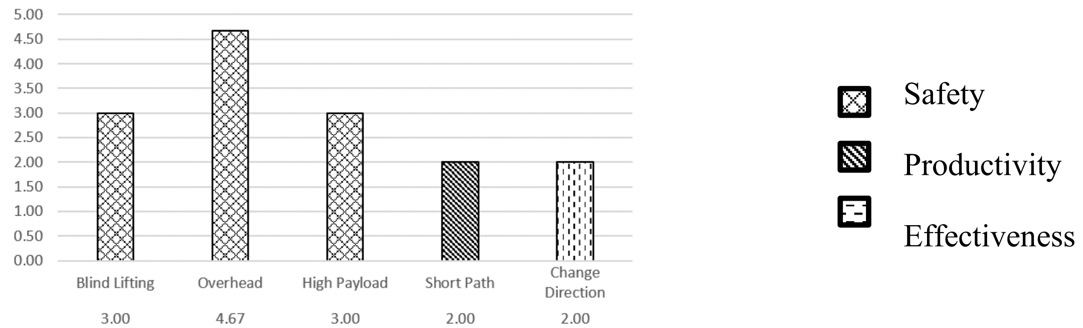


Figure 4-3 MiC Safety Risks Weighting Results (Crane Training Tutors)

Based on the overall verification, four major findings are summarized as follows:

1. Safety as the Top Priority

Among the three categories, the "Safety" emerged as the top priority, receiving the highest average weighting of 3.29. Both groups of experts unanimously emphasized the importance of safety as the primary concern in MiC crane lifting. On the other hand, "Productivity" was given the least emphasis, likely due to the already superior efficiency of MiC module lifting compared to conventional construction methods, making it a secondary consideration. However, the substantial dimensions (as large as 3.1 meters wide and 8.75 meters long) and the significant weighting (ranging from 20 to 30 tons) of MiC modules continue to present unique challenges, safety during lifting becomes a primary concern (BCA, 2017b; Buildings Department, 2018b; Liu et al., 2023).

2. Ranking of Individual Safety Risk

Among all individual safety risks, "Overhead" emerged as the most critical, with the highest weighting of 3.5. "High Payload" ranked second with a weighting of 3.375, although experts noted that modern cranes are equipped with payload monitoring systems to alert operators when the load exceeds safe limits. "Blind Lifting" ranked third with a weighting of 3, significantly higher than "Change Direction" (weighted 2.125) and "Short Path" (weighted 1.5).

The overall priority sequence of the considerations can be summarized as:

Overhead > High Payload > Blind Lifting > Change Direction > Short Path

In MiC module lifting, although workers are rarely positioned directly beneath the lifting path, the modules often move above riggers who guide their direction and placement. The significant dimensions and shadowed areas of the modules heighten the risk of falling hazards, making "Overhead" the most critical factor. Similarly, the substantial weighting of the modules underscores the importance of "High Payload" as a key consideration.

3. Variations in Risk Rankings Between Expert Groups

The prioritization of risks differed slightly between the two expert groups:

Experienced Operators' Ranking:

High Payload > Blind Lifting > Overhead > Change Direction > Short Path

Experienced operators emphasized "High Payload" as the most critical risks, followed by "Blind Lifting." "Overhead" ranked third, trailing "Blind Lifting" by 0.2 points.

Crane Training Tutors' Ranking:

Overhead > High Payload = Blind Lifting > Change Direction = Short Path

Crane training tutors ranked "Overhead" as the highest consideration, with a weighting of 4.67. "Blind Lifting" and "High Payload" were equally rated at 3.5, while "Change Direction" and "Short Path" received the same weighting of 2.

4. Deviations Between Groups and Implications

Notable differences emerged between the two groups in how risks were weighted. Experienced operators assigned an average weighting of 2.56 across all five considerations, compared to the higher average of 2.93 assigned by crane training tutors. This indicates that operators may have a lower level of on-site risk awareness compared to tutors, who focus on preparing future workers. These discrepancies likely arise from the differing priorities and perspectives shaped by instruction versus practical application. For instance:

(a) Tutors may intentionally emphasize safety to instill better habits in trainees.

(b) Practitioners may rank practical matters, such as maximizing payload capacity to increase efficiency or profit, which are most important in MiC lifting.

(c) Alternatively, these differences could be unintentional:

(d) Tutors may not be fully updated on the latest industry developments and operational demands, in particular in MiC lifting conditions.

(e) Practitioners, despite years of experience, may become complacent about safety-related measures.

Another contributing factor to these deviations could be the limited number of experts involved in the study. This limitation could be addressed in future research by conducting more extensive interviews to verify the findings.

4.3 Clustering and Ranking the MiC Lifting Safety Risks

4.3.1 Numerical Analysis Design

The previous section outlined key risks associated with crane operations, derived from an extensive review of research and industry guidelines in Hong Kong. These risks were evaluated through interviews and ranked as follows:

1. Overhead
2. High Payload
3. Blind Lifting
4. Change Direction
5. Short Path

The findings revealed that considerations related to Safety hold the highest priority in complex working environments. Among the remaining categories, Effectiveness had a stronger influence on crane operators' actions than Productivity.

However, these findings largely reflect the opinions of tutors and operators, which, while valuable, are inherently subjective. Although the results provide useful insights tailored to the unique requirements of MiC construction environments—distinct from those of traditional construction sites—objective statistical analysis is necessary to validate and refine these findings. Motivated by this need for greater objectivity, this research extended its scope to analyze crane operation risks across the industry by grouping and prioritizing risks through a rigorous statistical approach. A database of 95 crane-related accident cases that occurred in Hong Kong over the past decade was consolidated and analyzed. This database served as a benchmark to uncover potential risks and validate the findings obtained from the expert interviews and surveys.

The extended study incorporated eight key categorical variables derived from a combination of Human-Machine-Environment (HME) systems thinking and a review of the literature (Chen, 2014; Xu & Wang, 2020; Zhang et al., 2018). These variables formed the foundation for the development of 40 detailed risk categories. The accident database was analyzed to examine the interrelationships among the 40 categories using Multiple Correspondence Analysis (MCA), integrated with fuzzy c-means clustering to uncover latent patterns and associations. (Greenacre & Blasius, 2006; Zadeh, 1973; Zadeh, 1988). To manage the complexity of the data, dimensionality reduction techniques were implemented. These included Cronbach's alpha coefficient to measure reliability, R^2 profiles to evaluate explanatory power, and t-Distributed Stochastic Neighbour Embedding (t-SNE) analysis to visualize the data in lower-dimensional space (Cronbach, 1951; Dhalmahapatra et al., 2019; Van der Maaten & Hinton, 2008). These methods collectively reduced the dimensions from 32 to two, enabling the effective clustering of the 40 categories.

The 40 categories were grouped into eight clusters based on their inter-correlations, as identified through the MCA analysis. While MCA was effective in grouping the risk categories, it was unable to assign priorities to them (Dhalmahapatra et al., 2019; Gerassis et al., 2020; Riviére & Marlair, 2010). Consequently, Failure Mode and Effect Analysis (FMEA) was employed to conduct a more in-depth investigation of the risks and to prioritize them by assigning appropriate weightings to each cluster. (Belu et al., 2019; Bennett et al., 2017; Liu et al., 2017; Wang et al., 2018). The prioritization process involved calculating the Risk Priority Number (RPN) for each category. The RPN was determined by taking into account three key factors: Severity (S), Occurrence (O), and Detection (D). These factors were derived as follows: the Severity factor was evaluated based on the consequences of a failure, the Occurrence factor was determined by the frequency of similar failures in the accident database, and the Detection factor was assessed based on the strength of legislative requirements or procedural safeguards designed to prevent such failures. The RPN was calculated as the product of these three factors, expressed as $RPN = S \times O \times D$.

To ensure the accuracy of the Severity, Occurrence, and Detection factors, the causes of the 95 crane-related accidents in the database were thoroughly reviewed, broken down, and grouped by similar nature. The Severity factor was assigned based on the potential consequences of each failure, such as injuries, fatalities, or property damage. The Occurrence factor was derived from the frequency with which similar causes appeared in the database. Finally, the Detection factor was determined by evaluating the strength of legislative requirements or procedural measures in place to mitigate the risk.

Once the RPN values were calculated for each risk category, a prioritization procedure was applied. If multiple RPN values were associated with a single category, the highest RPN value was adopted for prioritization. This approach reflects the worst-case scenario for each category and ensures that the most severe risks within a category take precedence in the prioritization process.

4.3.2 Results

This study integrated a systematic accident database and introduced an advanced analytical approach integrating factor clustering and prioritization to investigate accidents related to cranes within the construction industry. By analyzing 95 accident cases from Hong Kong, the research extracted key variables using expert insights, literature review, and the HME system framework. The study identified four categorical variables focusing on accident types and primary causes, along with four numerical variables emphasizing accident consequences. These variables collectively contributed to the identification of 40 detailed risk categories.

Using fuzzy coupled MCA, the relationships among variables were analyzed and grouped into clusters based on inter-correlations. The study retained optimal dimensions using Cronbach's alpha coefficient and the R^2 profile, avoiding significant data loss (over 80%) typically observed in conventional MCA methods. This methodological enhancement improved the accuracy of clustering and reliability of the analysis.

The results revealed nine clusters, five of which were identified as critical contributors to crane-related accidents:

1. Poor communication (RPN 526)
2. Operator's nonproficiency (RPN 231)
3. Operator's carelessness (RPN 210)
4. Inadequate site information (RPN 100)
5. Inappropriate use of personal protective equipment (RPN 90)

Additional factors, such as poor visibility (RPN 70), poor weather conditions (RPN 56), operator's fatigue (RPN 45), and tight working schedules (RPN 45), were also identified but ranked lower in priority. The ranking was determined using FMEA, which evaluated risks based on Severity (S), Occurrence (O), and Detection (D). These results highlight poor communication as the most critical factor contributing to crane accidents, followed by operator nonproficiency and carelessness.

4.3.3 Discussions

The findings highlight key safety risks associated with crane operations, with poor communication identified as the most critical factor contributing to accidents. Inadequate coordination between crane operators, riggers, and site managers often leads to miscommunication, delays, or unsafe practices. Addressing this issue through standardized communication protocols, advanced technologies, and enhanced teamwork training is essential to minimize these risks. Similarly, operator nonproficiency and carelessness emphasize the need for stricter certification programs, regular training, and monitoring to ensure operators remain skilled and vigilant during operations. These findings underscore the importance of human factors in crane safety and the need for targeted interventions to address them.

Additionally, environmental and situational factors, such as poor visibility and adverse weather conditions, while ranked lower in priority, still present significant risks. Regarding the MiC lifting, these factors are often amplified due to the large size and weight of prefabricated modules, which demand greater precision and coordination. Mitigation strategies such as improved site lighting, weather monitoring systems, and stricter site inspection protocols are crucial in managing these challenges. Although operator fatigue and tight schedules were ranked lower, their potential to compound other risks, particularly in high-pressure MiC projects, suggests that optimizing work schedules and reducing stress should remain a priority.

The integration of MCA and FMEA in this study provides a robust framework for identifying and prioritizing safety risks, serving as a foundation for developing targeted safety measures. However, addressing these risks in MiC lifting requires innovative solutions that account for the unique demands of modular construction. The complexity of handling large, prefabricated modules introduces distinct safety challenges at each stage of the lifting process. These challenges underscore the importance of systematically breaking down safety risks across the key stages of MiC lifting operations—preparation, hoisting, positioning, and installation etc. Each stage presents specific risk factors that demand tailored solutions to ensure both safety and efficiency. A systematic breakdown will offer deeper insights into how these risks manifest in modular construction in the following section.

4.4 Safety Risks Across MiC Lifting Stages

4.4.1 Breakdown of Lifting Procedures

After conducting an extensive examination of crane operation risks through a combination of literature review, semi-structured interviews, numerical clustering, and prioritization, it is essential to consider the stages where these risks are most likely to manifest. Evaluating operational risks across different stages of the lifting process allows for a deeper understanding of their root causes, enabling the design of precise and effective solutions. To achieve this, this study deconstructs the lifting process of MiC modules at construction sites, dividing it into six distinct stages based on the module's various states in the process: 1) Module Arrival; 2) Hooking the Module; 3) Levelling (Turning Gears); 4) Lifting & Horizontal Steering; 5) Placing Movement; and 6) Positioning & Alignment (Song et al., 2024).

The first stage, Module Arrival, begins when the module is delivered to a designated position and awaits lifting. During this phase, the module is transported by delivery vehicles to a specific location within the site layout, ensuring that it is accessible for the crane's lifting appliance and gears. The focus for the tower crane operator and signalman in this stage is to guide the lifting hook and corresponding lifting frame to the precise position above the module. This must be done efficiently, without obstruction, and with a high degree of precision.

The second stage, Hooking the Module, involves connecting the module to the crane's lifting gear. At this stage, a rigger climbs to the top of the module (on the delivery vehicle) to attach the lifting chain to the module's lifting eye. Following this, the operator adjusts the block and tackle pulley system on the module's top to ensure that the lifting chains are nearly equal in length. This adjustment is critical to prevent overturning and instability during the subsequent lifting stage. Ensuring equal chain lengths is essential for maintaining the module's horizontal position, which is a fundamental objective throughout the lifting and assembly process of MiC.

The third stage, Levelling (Turning Gears), ensures the module is balanced and properly prepared for lifting. This stage is pivotal in maintaining the module's horizontal alignment, which directly impacts the stability and safety of the subsequent lifting process.

The fourth stage, Lifting & Horizontal Steering (Horizontal Steering), is one of the most critical and complex stages of the entire lifting process. This stage involves raising the module from the delivery vehicle (starting point) to a stable position near its target destination. Lifting and orientation adjustment are integrated into this single stage due to the common practice of adjusting the module’s orientation during the final stages of lifting. Additionally, external forces such as wind loads frequently alter the module’s orientation during lifting, necessitating intermittent or continuous adjustments. These adjustments pose several challenges, including potential damage to the service life of lifting gear, safety risks to personnel working beneath the lifting path, and potential impacts on surrounding structures, materials, and machinery. Efficient and stable lifting, with minimal orientation shifts, is crucial for improving both the safety and efficiency of the lifting process. However, achieving this is often complicated by the asymmetry of prefabricated components within the module, which can make it difficult to align the module’s center of gravity with its geometric center. This misalignment increases the risk of overturning and instability even after the tuning stage. As such, maintaining the module’s horizontal position remains a critical focus in this stage. Currently, orientation adjustments rely heavily on manual intervention, with on-site workers manually dragging the module while coordinating with the signalman and crane operator through verbal communication.

Following the lifting and orientation adjustment in the fourth stage, the fifth stage, Placing Movement (Lateral Control, see Figure 4-4), involves positioning the module closer to its destination. This stage focuses on minor positional adjustments and coordinating the crane’s descending movement along the Z-axis. Simultaneously, the module’s position and direction on the horizontal plane are fine-tuned. However, as the module’s position changes, its relative alignment with the lifting hook also shifts, creating a potential for tilting. This remains a significant challenge that current lifting techniques cannot efficiently address.

Figure 4-4 On-site MiC Lifting Placing Movement (Stage 5)

Finally, the sixth stage, Positioning & Alignment, represents the most critical and time-intensive phase of the entire lifting process. This stage begins when the module descends to within one meter of its final designated position. At this point, precise adjustments are made to align the module with the engineered drawings. The riggers manually pull and drag the module, making fine adjustments to its position with precision down to the centimeter or even millimeter level. This meticulous process ensures the module is correctly aligned and securely placed in its final position.

These processes can be further categorized based on the scale of adjustment required into two key stages: a) Gross Adjustment Stage and b) Minor Adjustment Stage. The Gross Adjustment Stage encompasses the initial four processes, starting from module arrival to lifting and rotation. This stage involves large-scale movements and adjustments to transition the module from its delivery position to a stable position near its final destination. On the other hand, the Minor Adjustment Stage includes the placing movement, positioning, and alignment processes, which focus on fine-tuning the module's position to ensure precise placement at its designated location.

These two stages collectively ensure that the module can be accurately and securely placed without errors, facilitating a seamless assembly process. The Gross Adjustment Stage emphasizes major movements and orientation changes, while the Minor Adjustment Stage focuses on smaller, precise adjustments critical to achieving alignment with engineering specifications. A detailed illustration of the MiC lifting and assembly process after the modules arrive at the site is shown in Figure 4-5, which provides a comprehensive visualization of these stages and their respective processes.

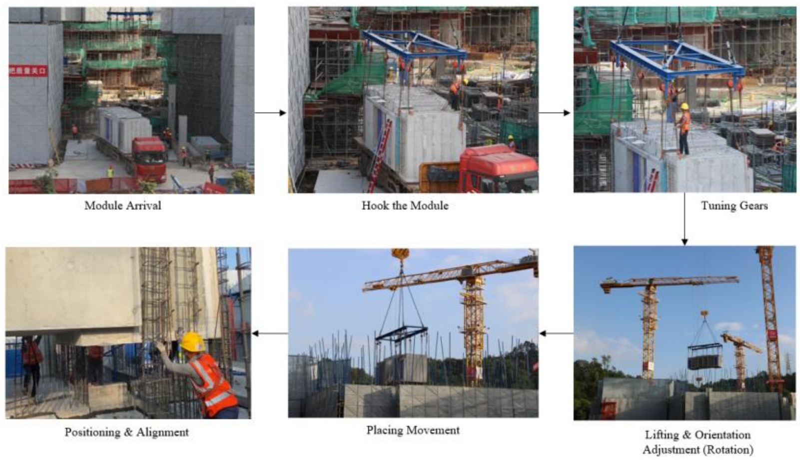


Figure 4-5 On-site MiC Lifting Process

4.4.2 Safety Risks in Different Lifting Stages

In Section 4.3.2, nine major safety concerns in crane operations were identified and ranked as follows:

1. Poor communication

2. Inappropriate use of personal protective equipment

3. Poor weather conditions

4. Operator non-proficiency

5. Inadequate site information

6. Operator carelessness

7. Poor visibility

8. Operator fatigue

9. Tight working schedules

While these concerns represent general safety hazards during normal crane operations, they are equally relevant to MiC lifting activities. However, due to the distinct characteristics of each stage in the MiC lifting process, the emphasis and impact of these nine safety concerns vary across different stages.

To provide a clearer understanding, the key safety concerns encountered at each stage of the MiC lifting process are summarized in the table below. This stage-specific analysis highlights the critical pain points that require greater attention to ensure safety and efficiency during MiC lifting operations.

Table 4-2 illustrates the alignment of these safety concerns with the corresponding stages of the MiC lifting process, serving as a foundation for developing targeted solutions to address these issues effectively.

Table 4-2 Major MiC Lifting Safety Risks at Different Stages

No.	**Stage Description**	**Safety Risks**						
1	Module Arrival;	Inadequate site information						
2	Hook the Module;	Poor weather conditions	Inappropriate use of personal protective equipment (PPE)					
3	Levelling (Turning Gears);	Poor weather conditions	Inappropriate use of PPE	Operator nonproficiency				
4	Lifting & Horizontal Steering (Rotation)	Poor weather conditions	Poor vision	Tight working schedule	Operator nonproficiency	Inappropriate use of PPE	Poor communication between on-site workers	
5	Placing Movement	Poor weather conditions	Operator nonproficiency	Operator carelessness	Poor vision	Operator fatigue	Poor communication between on-site workers	
6	Positioning & Alignment.	Poor weather conditions	Operator nonproficiency	Operator carelessness	Poor vision	Operator fatigue	Poor communication between on-site workers	Tight working schedule

In Stage 1, site conditions play a critical role in ensuring the safe operation of module delivery vehicles. Unstable soil conditions or an insecure foundation beneath the crane and delivery vehicle target locations can pose significant risks, including crane overturns, which threaten both the lifting crane and the delivery vehicles. These risks are further amplified by the large mass and uneven center of gravity of MiC modules, which place additional stress on the equipment. To mitigate these risks, adequate site information must be obtained before beginning the lifting process. This includes ensuring that crane and vehicle target locations are situated on stable, compacted ground or pretreated surfaces capable of supporting the heavy loads involved in MiC lifting. Additionally, precise site information enables effective route planning to avoid obstacles and ensures that the starting location of the modules does not exceed the crane's jib length or lifting radius, which is critical given the large projected area and spatial constraints of MiC modules.

From Stage 2 onward, weather conditions become a critical safety concern, affecting module lifting operations across Stages 2 to 6. In Stages 2 and 3, workers are required to perform tasks at height on top of the modules, making the use of appropriate, secure personal protective equipment (PPE) essential to ensure safety. The challenges posed by MiC modules' large size and high projected area become particularly evident during these stages, as workers are required to perform tasks from heights and operate around multiple lifting points on the module roof. The lifting frame must be positioned directly above the module to ensure smooth vertical lifting during the initial phase. Misalignment at this stage can lead to instability, which is further exacerbated by the uneven center of gravity of MiC modules, thereby increasing safety risks.

Stage 4 is a major phase of the MiC lifting process, involving the movement of modules from their initial locations on delivery vehicles or storage areas to their target destinations. This stage includes both lifting and steering control, often conducted under tight working schedules, which heightens operational pressures and safety risks. Poor weather conditions and limited visibility during this phase present significant challenges, particularly for longer movement paths. The large mass and high inertia of MiC modules create substantial hazards, as swaying modules over areas with ongoing site activities pose risks not only to workers but also to surrounding equipment. The substantial weight and size of MiC modules make it difficult to stop their movement promptly, requiring highly skilled operators to manage these challenges manually. Additionally, wind and inertia amplify the difficulty of maintaining stability, highlighting the need for advanced control solutions to mitigate these risks. Workers must also be equipped with PPE to reduce exposure to hazards during this phase.

In Stages 5 and 6, which focus on the final descent and precise placement of modules, the challenges shift toward achieving high-precision adjustments. Although horizontal displacement is minimal in these stages, the extended duration required for precision introduces unique risks. The tight placement tolerances of MiC modules, typically requiring ±3 mm horizontal accuracy and ±5° tilt limits (as reported in industry interviews), demand meticulous manual intervention. However, these manual adjustments are time-consuming and often exceed 20 minutes per module, increasing the likelihood of operator fatigue. Inclement weather, poor communication among workers, and operator non-proficiency further compound the risks. In Stage 5, rapid descent speeds caused by fatigue or errors can lead to falling objects, endangering workers in the vicinity.

Stage 6 represents the most critical phase for achieving precise alignment and placement of MiC modules. Current practices rely heavily on manual pulling and visual observations by the assembly crew, which often fail to achieve the sub-centimeter-level precision required for prefabricated elements. The large mass and uneven center of gravity of MiC modules increase the difficulty of achieving accurate placement without sudden positional shifts, which can endanger nearby workers. Additionally, the manual adjustments at this stage are highly time-consuming, often requiring 20–25 minutes per module, according to experienced industrial practitioners. Tight work schedules may pressure operators to rush this process, increasing the likelihood of safety incidents. These challenges underscore the urgent need for advanced, automated solutions that reduce reliance on manual effort, enhance precision, and improve safety and efficiency at this critical stage.

4.4.3 Research Gaps from Risk Analysis

The safety risks encountered during MiC lifting and assembly procedures can be categorized into three primary aspects based on a comprehensive analysis of safety risks identified through interviews and numerical analysis. These categories account for the unique characteristics of MiC modules, including their large mass, high projected area, uneven center of gravity, and tight placement tolerances. These challenges not only highlight critical pain points within the lifting process but also serve as the foundation for formulating the key design objectives of the SLAP device, which is tailored to systematically and effectively address these issues.

Considering the unique on-site challenges and safety risks associated with MiC lifting, the risks can be further grouped into three major categories:

4-3 Categorization of MiC Lifting Safety Risks

MiC Lifting Safety Risks	Risks Categories
1. Poor communication	Reliance on Operator Experience and Attentiveness
2. Operator’s nonproficiency	Reliance on Operator Experience and Attentiveness
3. Operator’s carelessness	Reliance on Operator Experience and Attentiveness
4. Inadequate site information	Poor Working Environment
5. Inappropriate use of personal protective equipment	Poor Working Environment
6. Poor visibility	Poor Working Environment
7. Poor weather conditions	Poor Working Environment
8. Operator’s fatigue	Reliance on Operator Experience and Attentiveness
9.Tight working schedules	Time-Consuming Installations

The three primary aspects are as follows:

1. Poor Working Environment:

The lifting and assembly process requires a significant number of workers (typically 5–7 workers per gang) who are exposed to challenging working conditions, including inclement weather, working at heights, risks of collision, and falling hazards.

2. Reliance on Operator Experience and Attentiveness:

Achieving assembly accuracy heavily depends on the experience and attentiveness of crane operators and ground crews. However, there is a lack of automated solutions that can meet the precision requirements for handling prefabricated elements.

3. Time-Consuming Installations:

The installation of extremely heavy and large components is time-intensive due to challenges related to sway damping, balancing, levelling, precise positioning, and rotation. These issues not only slow down the process but also increase the likelihood of safety hazards.

Building on the identified risk categories, it is important to note that these represent safety challenges rather than the technical problems that need to be solved directly. Each of these categories points to deeper technical gaps in current MiC lifting practices that must be bridged to enhance safety, precision, and efficiency. These gaps underscore the limitations of existing methods and highlight the need for innovative solutions that address the unique demands of MiC operations systematically:

1. Free people from on-site environment
2. Automatically control the module’s roll, pitch, and yaw rotation
3. Automatically control the module’s X/Y movement

Bridging these gaps is essential for improving safety, efficiency, and accuracy during the MiC lifting process. The identified challenges require innovative solutions that reduce human involvement in the on-site environment, automate the control of roll and pitch angular errors, manage yaw-axis rotation, and enable precise X/Y movement of the module. By addressing these gaps, such solutions can streamline the lifting and assembly process, reduce reliance on manual labor, and significantly enhance safety and positioning accuracy. These considerations form the foundation for the development of the SLAP device, as introduced in Chapter 5, which is specifically designed to revolutionize traditional MiC lifting operations into a safer, fully automated, and precision-driven system tailored to the unique demands of modern modular construction.

4.5 Summary of Chapter

This Chapter validates the safety hazards identified in earlier chapters through a combination of qualitative and quantitative methods. Expert interviews and questionnaires modeled on the NASA-Task Load Index format confirmed the ranking of critical safety concerns, with no inconsistencies detected in the data. Key concerns such as "Overhead," "High Payload," and "Blind Lifting" were highlighted as the most significant and directly applicable to MiC lifting operations.

To better understand these risks, the MiC lifting process was deconstructed into six stages: Module Arrival, Hooking the Module, Levelling (Turning Gears), Lifting & Horizontal Steering (Rotation), Placing Movement, and Positioning & Alignment. Each stage was systematically analyzed to identify stage-specific safety challenges unique to MiC lifting. For example, the uneven center of gravity and high inertia of MiC modules exacerbate risks such as sway, instability, and misalignment during critical stages like lifting and placement.

The Chapter concludes by identifying three critical research gaps in MiC lifting operations, emphasizing technical limitations that must be addressed to enhance safety, precision, and efficiency:

1. Free people from on-site environment
2. Automatically control the module's roll, pitch angular error and the yaw axis rotation
3. Automatically control the module's X/Y movement

Addressing these gaps is essential to overcome the unique safety risks of MiC lifting and to improve operational efficiency. The subsequent Chapters will explore the development of a high-precision, efficient lifting platform specifically designed to meet the demands of MiC lifting operations.

Chapter 5 SLAP Design to Mitigate MiC Lifting Safety Risks

5.1 Introduction

Building directly on the findings of Chapter 4, which systematically identified, categorized, and prioritized the critical safety risks inherent in MiC lifting operations, this chapter transitions from problem analysis to solution design. The preceding analysis distilled the complex landscape of stage-specific hazards into three fundamental operational challenges that current manual and crane-dependent practices fail to address adequately: (1) the unavoidable exposure of workers to hazardous on-site environments during fine adjustments, (2) the lack of precise control over a module's angular attitude (roll, pitch, and yaw), and (3) the inability to execute fine-tuned horizontal (X/Y) positioning without relying on labour-intensive manual pulling. These gaps collectively underscore the limitations of existing methodologies in achieving the required precision while ensuring worker safety.

To bridge these gaps, this Chapter introduces the conceptual design of the Semi-automatic Lifting and Assembly Platform (SLAP). SLAP is proposed as an integrated mechatronic system that augments the conventional lifting frame, transforming it from a passive suspension device into an active pose-control platform. The core objective of SLAP is to mitigate the identified risks by enabling precise manipulation of the MiC module's position and orientation with minimal direct human intervention at the hazardous lifting front. This enhancement improves safety performance, optimizes time efficiency, and ensures higher quality outcomes in MiC lifting and assembly process.

5.2 Objectives of SLAP

The design of the SLAP system is fundamentally driven by the need to overcome the specific limitations of current MiC lifting practices, as outlined in Section 4.4.2. In contemporary construction sites, the precise placement of multi-tonne modules relies on an inefficient and risk-prone synergy between crane macro-movements and manual micro-adjustments. This practice manifests three core operational shortcomings that SLAP is engineered to resolve.

First, the unavoidable exposure of workers to hazardous on-site environments is most acute during fine adjustments. This is exemplified by the common practice of manually pulling the suspended module into its final position, which places personnel directly within the dangerous zone of the heavy load to compensate for the inherent imprecision of crane-based positioning. Second, there is a fundamental lack of precise control over the module's angular attitude (roll, pitch, and yaw). Levelling, typically a one-time, pre-lift adjustment via tuning gears, cannot correct tilts that develop in transit or during placement. Simultaneously, adjusting the module's horizontal orientation (yaw) frequently requires workers to physically drag the suspended load, further exacerbating safety risks. Third, the inability to execute fine-tuned horizontal (X/Y) positioning without manual labour involvement. The process relies on a ground signaller visually assessing errors, relaying instructions to the crane operator via radio, and the operator attempting to adjust the massive crane, which is not suitable for the sub-centimeter precision required for final assembly.

The SLAP system is designed to replace these manual, crane-dependent tasks with integrated, semi-automated control. Its primary objectives are therefore defined as follows: to provide precise, closed-loop control of the module's X and Y coordinates relative to its target, eliminating the need for manual pulling; to enable real-time active levelling (control of roll and pitch) throughout the lifting and placement sequence; and to offer accurate, motor-driven steering control (yaw rotation) of the module. By fulfilling these objectives, SLAP reallocates the high-risk adjustment tasks from human workers to a controlled mechanical system, thereby directly addressing the safety gaps identified in Chapter 4. The system maintains a semi-automatic architecture, where operators retain supervisory control and decision-making authority, ensuring adaptability and safety oversight within the dynamic construction environment.

5.3 Working Principles of the Platform

The proposed SLAP system introduces an intelligent enhancement to existing hoisting mechanisms, aiming to increase efficiency while preserving the structural integrity and operational principles of existing tower cranes. This approach ensures flexibility and ease of adoption. By integrating motors into the hoisting system to actively manipulate the cables connected to the crane hook and transforming the conventional single layer lifting frame into a multi-layer hoisting structure with a linear sliding platform concept, the system enables precise control over horizontal movements, height adjustments, and tilt levelling.

The core concept of the SLAP system involves controlling the module's position through the configuration morphing of the hoisting platform, as illustrated in Figure 5-1. Assuming the system is initially in a statically stable state ("State 1" in Figure 5-1), the center of gravity (CoG) of the composite system (comprising the hoisting platform and the MiC module) is maintained directly beneath the crane hook. By adjusting the relative positions of the CoGs of the hoisting platform and the MiC module, a positional shift of the MiC module with respect to the crane hook is achieved, meeting the platform's primary objective. However, as the system returns to static equilibrium, the composite tilts to align the CoG of the system with the crane hook ("State 2" in Figure 5-1). To address this, further adjustments can be made to the relative positions of the crane hook and the composite via the cables, levelling the composite and resulting in "State 3" as shown in Figure 5-1. Additionally, by adjusting the relative position of the crane hook, the system allows for adjustments in the module's height using cables, leading to "State 4" in Figure 5-1.

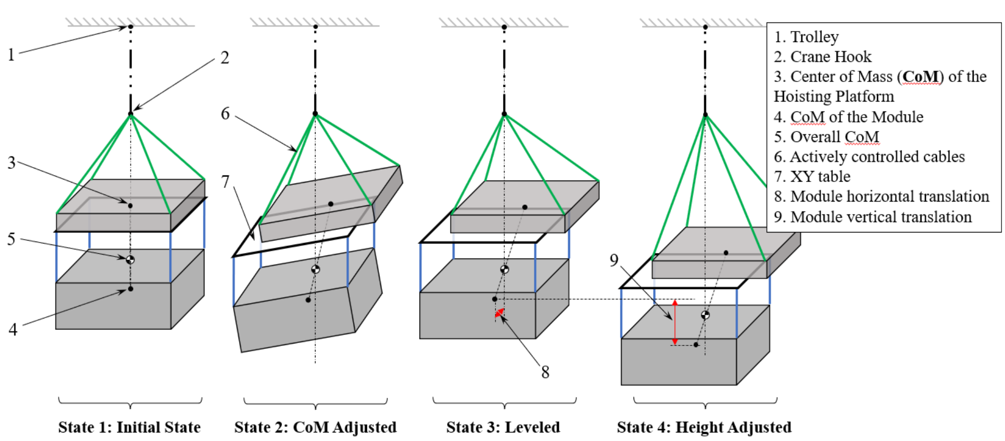


Figure 5-1 Illustration of SLAP's Working Principles

5.4 Platform Architecture

Building on the fundamental working principles outlined in Chapter 5.3, this section details the SLAP system architecture specifically designed for MiC lifting and assembly. The SLAP system combines a mechanical framework, sensors, actuators, and a control mechanism to ensure the MiC module remains statically stable. This is achieved by coordinating several functional modules, including the Horizontal Steering Control Module, the Levelling Control Module, and the Translation Control Module. The system is also designed to allow the operators to monitor and intervene in its operations through both physical and graphical UIs. These interfaces ensure seamless oversight and provide control capabilities when necessary. The monitoring and intervention system will be further discussed in detail in Chapter 6.

5.4.1 Primary Structure

The proposed platform architecture can be divided into three parts: 1) Horizontal Steering Control Module (“HSCM”), 2) Levelling Control Module (“LCM”), 3) Translation Control Module (“TCM”). The workspace-based configuration optimization of the cable-driven mechanism is employed to improve control capability.

The architecture of the SLAP is visually represented in Figure 5-2, which illustrates a conceptual design of the mechanical structure: This includes a steering control module, positioned beneath the crane hook and primarily consisting of a lifting gear system, to enable rotation of the composite (hoisting platform and MiC module) roughly about the vertical axis. Below the steering control module, the hoisting frame, connected via actively controlled hoisting cables, forms the LCM. The lifting gear and hoisting frame are equipped with essential supporting structures, transmission mechanisms, actuators, and sensors to ensure precise operation.

Beneath the hoisting frame, two vertically aligned linear motion frames, stacked together, serve as the primary components of the translation control module. These frames allow horizontal movement and fine positional adjustments. Sensors and the control system are seamlessly integrated into the hoisting frame, using the void spaces left by motors and structural components.

The MiC module is designed to attach under the hoisting frame using either module ropes (can be replaced by rigid connections), as illustrated in Figure 5-2.

In Figure 5-2, the main structural elements are listed on the right side, while the essential functional modules are highlighted on the left, providing a clear overview of the system's design and functionality.

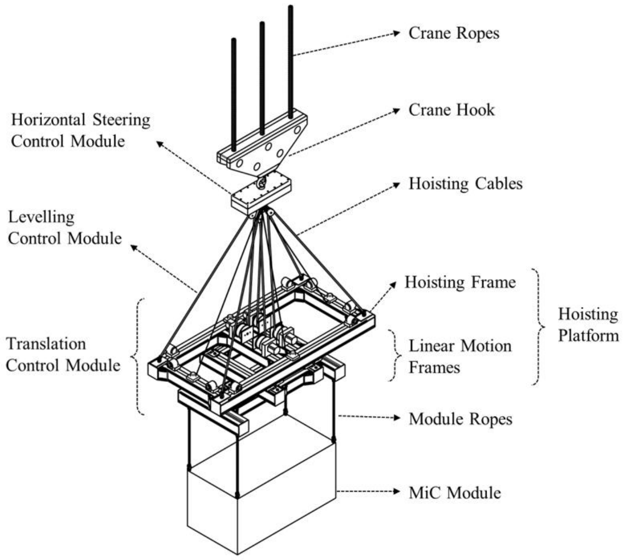


Figure 5-2 SLAP Architecture Design

5.4.2 Horizontal Steering Control Module ("HSCM")

The Horizontal Steering Control Module ("HSCM") is composed of a steering bearing, a servo motor, and a corresponding transmission mechanism. The servo motor controls rotational motion along the gravitational axis, enabling orientation adjustment of the MiC module in the horizontal plane.

As shown in Figure 5-3, the HSCM is directly integrated with the lifting gear (102). The lifting gear includes:

1. Hook (201)

2. Supporting structure (202)

3. Bearing and transmission mechanism (204)

4. Servo motor (205)

5. Rotating shaft (203)

6. Pulleys (206), which are fixed to the rotating shaft

The horizontal steering system operates based on the user's input of a desired steering angle. It controls the servo motor to drive the shaft, and the pulleys are rigidly mounted on it, enabling rotation relative to the supporting structure, which is rigidly connected to the crane hook. Due to the heavy payload, the lifting gear and the tower crane hook are treated as rigidly connected, as are the shaft and the hoisting frame.

This configuration allows the servo motor to control the relative rotation between the hoisting frame and the crane hook along the shaft axis (aligned with the gravitational direction). Since the tower crane provides rotational constraints to the hook along the gravitational axis, the subsystem can achieve the desired horizontal rotation of the hoisting frame (and consequently the MiC module) relative to the ground. This adjustment is achieved without requiring the tower crane to rotate, ensuring precise, localized control of the module's horizontal orientation.

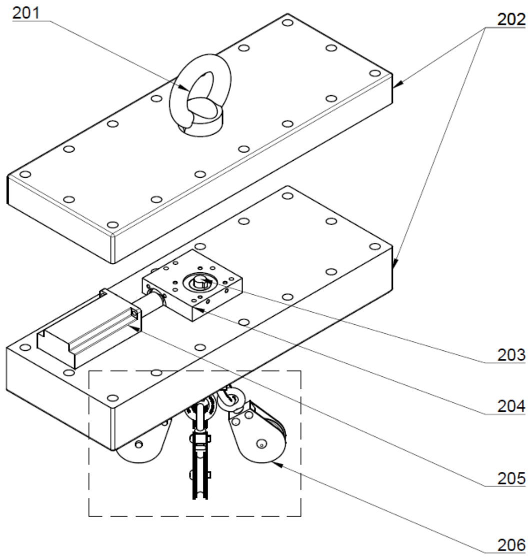


Figure 5-3 HSCM Design Concept

5.4.3 Levelling Control Module ("LCM")

Directly connected underneath the HSCM is the Levelling Control Module ("LCM"). The LCM utilizes four cable actuators, servo motors, and winches to control the cable lengths, enabling the following functionalities:

1. Horizontal Attitude Adjustment (Levelling):

Achieves precise control of the module's attitude relative to the horizontal plane, ensuring proper levelling of the load.

2. Vertical Height Adjustment:

Facilitates short-range vertical height adjustments of the module.

Figure 5-4 illustrates that the LCM is partially integrated into the hoisting frame and connects the HSCM to the hoisting frame via lifting cables (301). The key components are:

(a) Lifting Cables (301): Fixed to a lifting ring (302) on the hoisting frame at one end, the cables pass through pulleys mounted on the HSCM and are ultimately connected to cable actuators (303).

(b) Cable Actuators (303): Each actuator comprises a base frame, a winch, and a servo motor, which work together to adjust the cable lengths.

(c) Inertia Measurement Units (IMUs): Installed on the hoisting frame to measure its attitude and ensure accurate levelling adjustments.

(d) Linear Potentiometers (304): Arranged between the hoisting frame and the HSCM, these sensors measure their relative position, providing data for precise control.

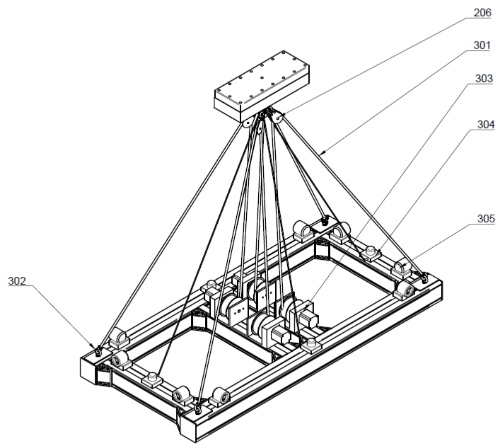


Figure 5-4 LCM Design Concept

The servo motors in the cable actuators control the winches, enabling precise adjustments to cable length. By adjusting the relative lengths of the cables, the LCM can control the horizontal attitude of the hoisting frame and, consequently, the MiC module. Additionally, fine vertical height adjustments are achieved by synchronizing the movement of all four cables. The integration of IMUs and linear potentiometers provides real-time feedback on the position and attitude of the frame, ensuring stability and precise control. This seamless combination of components makes the LCM an essential part of the SLAP system, delivering robust and accurate levelling and height adjustment capabilities.

The main function of the LCM is to adjust both the horizontal attitude and the vertical height of the hoisting frame and the attached module. Since the connections between the hoisting frame and the module—whether cables or rigid—are of equal length, the attitude measured by the IMU on the hoisting frame can accurately represent the module's attitude. The levelling process is achieved by comparing the measured horizontal attitude with the desired one, which is typically completely horizontal. By determining the desired levelling angle, adjustments are calculated based on the measured attitude of the hoisting frame and the relative position of the lifting gear to the hoisting frame, as measured by the linear potentiometers. These calculations are used to determine the required changes to each cable's length, which are converted into servo motor rotation commands and executed.

Similarly, vertical height adjustments are achieved by combining the attitude data from the IMU on the hoisting frame with the relative position data from the lifting gear and hoisting frame provided by the linear potentiometers. By varying the lengths of the cables, the module's height can be precisely adjusted, with the corresponding commands executed by the servo motors.

As illustrated in the working principle in Figure 5-1, the LCM transforms the system through levelling and height adjustments in Stages 3 and 4. Starting from a tilted attitude in Stage 2, the module can achieve a levelled attitude by selectively adjusting the cable lengths. Once the module is levelled, coordinated control of the cable lengths allows the payload's height to be lowered to the desired position, as shown in Stage 4.

5.4.4 Translation Control Module ("TCM")

The Translation Control Module ("TCM") is designed to adjust the position of the load composite's CoG (which includes the hoisting frame, mounted equipment, and the MiC module), relative to the module itself. This is accomplished by using linear guide rails (X-Y Table) driven by servo motors to move different portions of the composite body, effectively shifting the CoG and enabling precise control over the relative positions of each component. The TCM serves two primary functions:

1. Controlled Horizontal Movement: Achieves horizontal movement of the module relative to the ground.

2. Swing Suppression: Reduces oscillations in the load during the lifting process.

As illustrated in Figure 5-5, the TCM is integrated beneath the hoisting frame and consists of the following components:

(a) Lateral (X-axis) Translation Guide (501): Facilitates horizontal movement along one axis.

(b) Lateral (X-axis) Moving Platform with Actuators (502): Enables lateral movement through servo-driven actuators.

(c) Vertical (Y-axis) Translation Guide (503): Provides movement along the vertical axis (Y-axis).

(d) Vertical (Y-axis) Moving Platform with Actuators (504): Drives vertical translation using actuators.

(e) Module Lifting Cables (505): Connect the module to the frame; these cables can also be replaced with rigid connections.

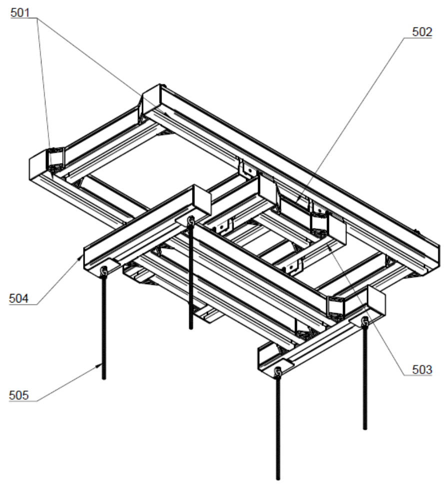


Figure 5-5 TCM Design Concept

The main function of the LCM is to control the lateral position of the module, which is achieved by controlling the relative position between the CoG of the load composite body (hoisting frame and the module) and the module. This process is demonstrated in Figure 5-1, particularly in the transition from Stage 1 to Stage 2. Since the system is in a state of force balance when at rest, the CoG of the composite body (a weighted mean of the hoisting frame's CoG and the module's CoG) must remain directly beneath the stationary tower crane hook. In this condition, the CoG of the load composite body stays fixed relative to the ground target point. By adjusting the relative position between the module's CoG (fixed within the module) and the composite body's CoG, the module's position relative to the ground target can be indirectly modified. In practice, the expected relative translation of the composite body's CoG in relation to the module's CoG can be calculated based on the module's positional difference relative to the ground target point. The detailed mathematical relationship between the composite body's CoG and the module's CoG (and their resulting displacement) is derived in Chapter 6.3.3.

To achieve the desired displacement between the load composite CoG and the module CoG, the TCM calculates the required relative translation distance between the hoisting frame and the module. This calculation considers the masses of the hoisting frame and the module and determines the necessary displacement along two axes. These movements are executed by the two moving platforms, which control the translation along the lateral and vertical axes.

In addition to controlling translational movement, the TCM can also suppress oscillations triggered during the lifting process, especially when the system experiences significant swing. The system calculates the desired acceleration of relative motion between the hoisting frame and the module using data from the IMU, which measures the frame’s speed. By generating a reaction force through this relative motion, the system dissipates the kinetic energy of the frame’s oscillation, effectively stabilizing the load.

5.4.5 Sensing System

The Position and Orientation Sensing System (“POSS”) is a critical subsystem that integrates multiple sensor types to enable precise placement and orientation of the MiC module. The POSS is primarily integrated with the LCM and TCM to provide state feedback for accurate control of the system’s six actively controlled Degrees of Freedom (DoFs). This hybrid actuation approach combines joint motors and cables to maintain system stability near static equilibrium.

This system employs a hybrid actuation approach, combining motor-driven joints and cable actuation to maintain stability and achieve fine control near static equilibrium. A rotation motor directly drives vertical rotation, while linear joints actuate planar motions. Cables are used to accommodate the large workspace required by the cable-driven mechanisms, particularly for resolving significant variations in the relative positions of the crane hook and the hoisting frame.

The POSS incorporates several types of sensors to ensure accurate placement of the MiC module:

(a) IMU Group: Fixed on the hoisting frame to measure attitude.

(b) Linear Potentiometers: Measure relative positions between components.

(c) Computer Vision System: Mounted between the module and the destination to determine the module’s pose relative to the assembly surface.

As shown in Figure 5-6 & Figure 5-7, the POSS integrates these sensors to provide critical feedback for both manual and automatic control of the module's position and orientation. The computer vision system is the most direct and convenient method for determining the crane hook’s position relative to the hoisting frame (Cyganek & Siebert, 2011; Wöhler, 2009).

However, placing cameras on the hoisting frame can lead to potential obstructions in the field of view caused by pulleys and cables, which are also mounted on the frame. Careful consideration is given to camera placement to minimize such obstructions.

In addition, to compensate for these limitations, the system incorporates a combination of linear potentiometers and IMUs, as detailed in Figure 5-6. Four linear potentiometers are fixed between the edges of the hoisting frame and a reference point on the HSCM. By measuring cable lengths, the potentiometers identify the spatial relationship between the reference point and the hoisting frame. Additionally, IMUs mounted on both the HSCM and the hoisting frame provide data on their relative attitudes. This combination of measurements allows the system to compute the relative position of the crane hook by determining the coordinates of the reference point. Furthermore, load cells fixed at the hoisting frame’s cable attachment points measure the forces exerted by the hoisting cables, providing additional state feedback to ensure stability.

As mentioned previously, the POSS also uses vision-based sensors (cameras/Lidar) to determine the relative pose of the module with respect to its target location, such as the assembly surface (He et al., 2021; Li & Allinson, 2008). Cameras and/or Lidar systems are mounted at the corners of the hoisting frame and oriented downward to minimize obstructions caused by other components, such as the TCM. To facilitate accurate alignment, 3D markers or tags can be attached to the module's corners. These markers enable the system to determine the pose of the module and its target relative to the cameras’ reference frame. Within the cameras’ field of view, the position and orientation of each marker can be precisely identified, allowing the control system to align the module with the target location accurately.

The POSS integrates feedback about the crane hook’s position and the forces in the hoisting cables to achieve automatic control of the module. State feedback from the cable-driven mechanism is essential for this process. While the computer vision system provides a direct method for measuring the crane hook’s position, the addition of linear potentiometers and IMUs ensures continuous, reliable measurements even when the field of view is obstructed. The relative positions and attitudes of the hoisting frame and the HSCM, combined with load cell data, contribute to a comprehensive understanding of the system’s status, enabling precise control of the module’s placement and orientation.

The POSS is fundamental to the SLAP system’s ability to manage the semi-automatic operations accurately. By integrating IMUs, linear potentiometers, load cells, and vision-based systems, the POSS ensures precise state feedback for stable system operation.

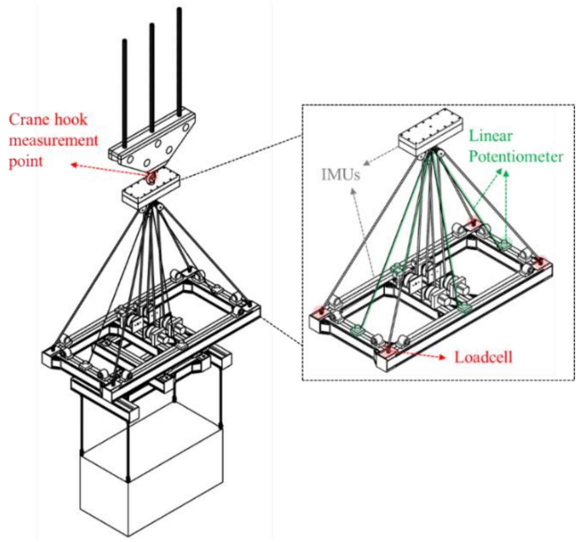


Figure 5-6 LCM Status Measurement

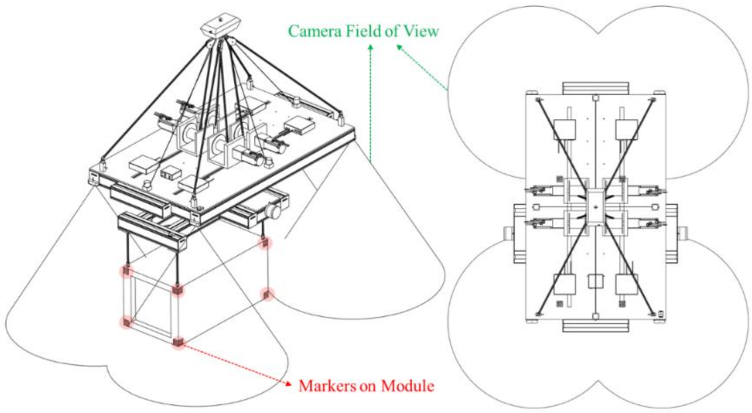


Figure 5-7 POSS Design Concept (Not realized in the prototype)

5.5 Discussions

In modular construction applications, placing a module at a precise location with the desired pose is a fundamental requirement. However, current construction practices rely heavily on manual assistance, which makes achieving this aim challenging. Specifically, the final adjustment of the module's pose—both position and attitude—is performed through the combined efforts of the ground crew and the crane operator. During installation, the crane operator must follow the ground crew's signals to make positional adjustments, often as small as ~15 cm. This level of precision is difficult to achieve with a crane due to its scale, and when the lateral position error is too small for the crane to adjust effectively, ground workers must manually pull the module to refine its position. Additionally, ground workers play a predominant role in attitude adjustments, such as levelling and controlling the steering angle (the module's facing direction). While most levelling requirements can be addressed by adjusting the hoisting cable length during the initial lifting phase, this process is time-consuming. Furthermore, fine adjustments to the levelling and steering angle during the final installation stage rely entirely on the ground crew manually pulling the module laterally. Overall, the current practice of module lifting and installation is labor-intensive, time-consuming, and poses significant safety risks during the MiC lifting process, as workers are required to operate in close proximity to a lifted module.

This Chapter introduces the concept design of the SLAP mechanism to address the limitations of the current manually assisted MiC lifting and assembly process. The SLAP system is designed to solve key challenges, including rotation control of the module, correcting tilting caused by misalignment between the module's CoG and its centroid, and achieving precise micro-positioning during the final stage of the lifting process.

In the SLAP design, the HSCM replaces manual module dragging and guiding by frontline workers with automated rotation. This subsystem enables precise control of the module's rotation angle through encoder feedback control, eliminating the need for manual effort and improving rotational accuracy.

The LCM provides an automated solution to address the current practice of manually adjusting lifting chains and visually verifying the module's levelness by climbing to the top of the module before lifting. The LCM adjusts the cable lengths in real-time to adapt the module to a horizontal position, eliminating the need for workers to intervene manually. This process improves levelling accuracy to within 1° by continuously monitoring and feeding data back from an IMU, enhancing both efficiency and precision.

The TCM resolves the issue of fine end displacement, especially when tower cranes face difficulty making precise adjustments within the final half meter. Using linear slide rails in the XY plane, the TCM facilitates accurate module movement within a defined range. However, this adjustment may cause a slight tilt of the module. To address this, the TCM coordinates with the LCM to ensure that both position and levelling are simultaneously maintained. This integration ensures precise displacement control while preserving the module's levelled position, even during fine adjustments.

The SLAP system incorporates an array of sensing technologies, including encoders, IMUs, potentiometers, load cells, and cameras, to provide comprehensive feedback on the current pose of various SLAP components. These sensors work together to assist the control processor in generating recommendations for module adjustments. Operators, working off-site, review and confirm these recommendations and transmit the approved commands to the controller. This semi-automated approach enhances the reliability and safety of the system while maintaining a level of human involvement/ monitoring.

Despite the SLAP system's capability to adjust the module's pose, the large dimensions and weights of MiC modules (typically 3.3-3.6m × 3m × 5-9m, with weights up to 30 tons) present significant challenges and safety risks (Construction Industry Council, 2022; Lawson et al., 2012). As a result, this study proposes a semi-automatic control approach at the current stage of development instead of the fully automated solution. In this approach, qualified operators or workers remotely confirm critical decisions and retain the ability to take full manual control when necessary. This strategy ensures both safety and reliability, addressing the challenges posed by the scale and complexity of MiC modules. The subsequent Chapter will further explore suitable control logic and strategies for SLAP-based modular lifting.

5.6 Mitigating MiC Lifting Safety Risks Through SLAP

The SLAP system is designed to address the critical safety risks associated with MiC lifting operations by combining semi-automated technologies with human oversight. Through a detailed analysis of MiC-specific risks, the lifting process was broken down into distinct sub-stages. Analysis revealed that the highest concentration of risks occurs in Stages 3 to 6 due to the complex characteristics of MiC modules, such as their large mass, high projection area, uneven center of gravity, and strict placement tolerances. For instance, contractors in Hong Kong require ±3 mm horizontal accuracy and a maximum tilt of ±5°, yet achieving this precision during alignment often takes 20–25 minutes per module, creating significant challenges for both safety and efficiency. Based on this analysis, risks were categorized into three major groups: insufficient design for minimal human intervention, inadequate control over minor adjustments, and rush for lifting and assembly. The SLAP system integrates innovative modules and functionalities to mitigate these risks, as detailed below.

5.6.1 Free People from on-Site Environment

MiC construction sites often require workers to engage in manual operations, such as guiding modules with pulling ropes or physically adjusting their positions during lifting. These tasks expose workers to safety risks, particularly in poor working environments with hazards such as falling objects, poor visibility, and adverse weather conditions. Such conditions are especially concerning during critical stages like lifting adjustment and placing movement, where workers are often in close proximity to heavy modules.

The SLAP system mitigates these risks by introducing automated controls that ensure precise adjustments without requiring significant operator input. The HSCM automates tasks such as the rotation of the hoisting platform and MiC module, eliminating the need for workers to manually guide the module. The LCM automates horizontal attitude and vertical height adjustment. The TCM further enhances safety by automating horizontal movement during the final positioning stage, reducing the need for workers to push or pull the module into place. By automating these operations, SLAP protects workers from risks associated with uneven cable tension, poor visibility, and adverse weather conditions.

Additionally, relocating workers to off-site control stations further minimizes their exposure to unsafe conditions. By reducing physical labor and manual intervention, SLAP significantly improves the working environment, ensuring that safety is maintained even in challenging site conditions.

5.6.2 Automatically control the module's roll, pitch, and yaw rotation

The precision required during MiC module lifting and positioning often relies heavily on the skill and attentiveness of crane operators. Tasks such as levelling the module or correcting angular errors, including roll, pitch, and yaw, are typically performed manually. This dependency introduces instability and inaccuracies, particularly when operators are fatigued, inexperienced, or under stress. Such reliance on human input increases the risk of accidents during critical stages like alignment and final positioning.

The SLAP system addresses these challenges by introducing automated control mechanisms that ensure precise adjustments with minimal operator input. The LCM automates key functions such as roll and pitch angle corrections, enabling the module to remain at a level relative to the horizontal plane. This prevents uneven cable tensions that could lead to instability or even cable failure. Furthermore, the yaw axis rotation is also automated, ensuring precise alignment during positioning. These automated adjustments are particularly advantageous when visibility is limited or when communication between crane operators and ground workers is unclear.

By automating these critical functions, the SLAP system reduces reliance on operator proficiency, minimizes human error, and ensures consistent precision throughout the lifting process. This capability not only improves safety but also increases the overall efficiency of

MiC lifting operations.

5.6.3 Automatically control the module’s X/Y movement

The final stage of MiC lifting, precise positioning of the module along the X and Y axes, is often time-consuming and labor-intensive. Traditional methods require workers to manually push, pull, or drag the module into place, leading to inefficiencies and increased safety risks. These challenges are further exacerbated by tight working schedules, where fatigue and time pressure heighten the likelihood of errors.

The SLAP system eliminates the need for manual adjustments by automating horizontal X/Y movements through the TCM. This automation ensures precise positioning of the module without requiring physical labor, significantly reducing the risks associated with manual handling. By streamlining the installation process, the SLAP system alleviates time pressures faced by workers, enabling them to operate in a safer and more controlled environment. The system balances efficiency and safety, ensuring tight schedules are met without unnecessary risks.

5.6.4 Discussions on Risk Mitigation by SLAP

The SLAP system effectively mitigates the safety risks associated with MiC lifting operations by addressing the technical problems derived from insufficient design for minimal human intervention, inadequate control over minor adjustments, and the rush for lifting and assembly. The HSCM and TCM reduce the need for physical labor in hazardous areas, thereby improving safety in challenging working environments. This undoubtedly minimizes risks associated with poor weather conditions, limited visibility, and improper use of personal protective equipment (PPE). The LCM and TCM further enhance safety by automating precision adjustments, reducing reliance on operator proficiency and attentiveness. Finally, the TCM optimizes the installation process by eliminating time-consuming manual adjustments and mitigating risks from tight schedules, poor communication among on-site workers, and worker fatigue and carelessness.

Additionally, the SLAP system is designed to meet industry requirements for MiC lifting operations, such as achieving ±3 mm horizontal accuracy and a maximum tilt tolerance of ±5°. These capabilities will be further validated in Chapter 8, where the system’s performance in terms of safety, accuracy, and productivity will be thoroughly assessed. These validations will demonstrate how SLAP meets industry standards, ensuring its practical applicability to real-world MiC projects.

5.7 Summary of Chapter

This Chapter primarily introduces a semi-automatic solution concept for a lifting platform applied to MiC, incorporating various sensor types. The main contribution to the knowledge of this concept design is outlined in the following areas:

1. Position and levelling adjustment achieved through statically stable configuration morphing.

2. Flexibility to enable active sway damping capability.

3. Accurate and robust determination of module pose relative to the target location.

By relocating most on-site workers to off-site, the SLAP could mitigate key safety risks associated with MiC lifting. For example, the HSCM and TCM reduce risks from poor working environments by automating hazardous tasks and minimizing workers' exposure to unsafe conditions, while the LCM and TCM reduce reliance on operator experience and attentiveness by automating precision adjustments. Additionally, the TCM streamlines the installation process, eliminating time-consuming manual adjustments and mitigating risks from tight working schedules. While the system allows for fully automatic lifting, rotating, levelling, and positioning, this design will initially incorporate human involvement in a semi-automatic control setup to ensure stability and reliability at each stage because of the large footprint and weight of MiC modules, alongside the complex and dynamic environmental conditions at construction sites. This approach could also inspire confidence in the system's safety performance, further reducing safety risks during MiC lifting.

This Chapter introduces the hardware design concept of SLAP. However, the control strategy across modules and components, tailored for MiC lifting to monitor construction progress, has not been elaborated in this Chapter. Building on the SLAP design presented in Chapter 5, the next Chapter will focus on developing the control system logic and UI essential for implementing the SLAP mechanism in a construction environment. Furthermore, Chapter 6 will analyze the configuration of the SLAP system by dividing it into controllable and uncontrollable components, studying the relationships between individual components, and deriving mathematical models to describe the motion and displacement of the module. These efforts will lay the foundation for a robust control strategy and an intuitive UI, ensuring the SLAP system can be effectively used in real-world construction scenarios.

Chapter 6 SLAP Control Flow and Principles

6.1 Introduction

When using tower cranes to lift MiC modules, the modules must be transported from their arrival or storage locations (typically on trailers) to a designated position with a specific orientation while minimizing swinging. In current on-site practices, this process is primarily achieved through crane motion, heavily relying on manual assistance from ground crew and workers at the front line.

Given that tower cranes are underactuated systems, capable of constraining motion only along certain DoF, designing and implementing automated mechanisms for precise 6-DoF control presents significant challenges. Existing automated solutions for tower crane operations generally cannot fully address this issue. Specifically, they fail to provide simultaneous control of all six DoFs required to position the load accurately at its target location.

In Chapter 5, a structural concept design was introduced to enable semi-automatic precise pose control of MiC modules, with potential for future development into fully automated control. However, this concept lacked a well-suited control strategy aligned with the current operational logic and procedures of MiC module lifting. The proposed design aims to accomplish comprehensive 6-DoF positioning and orientation control of modules without relying on crane motion or manual pulling. It also seeks to enable operators to quickly adapt to the system, ensuring ease of use, enhanced HMI, improved safety, and overall practicality.

This Chapter is divided into two sections. The first section focuses on the control strategy and UI design, considering the construction sequence and integrating sensor arrangements. The second section revisits the principle of configuration morphing, breaking the system into controllable and uncontrollable components. It involves analyzing pose relationships among individual modules and deriving formulas for the relative mass ratio between the hoisting frame and the module undergoing displacement. This leads to further derivations regarding the module's practical motion range, which theoretically validates the feasibility of the design and lays a solid theoretical foundation for its implementation.

The primary contributions of this Chapter to the body of knowledge are as follows:

1. Achieving six DoF control of MiC modules without requiring modifications to the crane machinery.

2. Aligning the proposed system with current operational practices for MiC module lifting, requiring minimal modifications to existing crane machinery.
3. Ensuring ease of adoption by practitioners and operators due to the system's familiarity with existing workflows.
4. Designing a practical and user-friendly interface that aligns with operator habits while prioritizing safety.
5. Deriving the core relationship between the mass ratio of the hoisting frame, the module, and the lateral displacement enables precise end-point positioning.
6. Determining the maximum lateral displacement for a given module mass based on the relationship above.

This Chapter, therefore, provides a control mechanism by presenting a control logic tailored to the practical details of MiC lifting operations. It also fundamentally examines the theoretical basis of configuration morphing, which underpins the feasibility of implementing this system. By doing so, the Chapter demonstrates the theoretical viability and control logic of the proposed design.

6.2 Control Flow of the SLAP System

6.2.1 Overall Workflow Design

The control strategy presented in this Chapter adopts a top-level design approach, tailored to the unique features of MiC construction sites and the industry's practical operational requirements. This strategy emphasizes the overall control flow and integrates several key aspects: the operational logic of each subsystem under safe conditions, state transitions aligned with construction practices, an intuitive and user-friendly operator interface, and advanced sensing systems incorporated to monitor the module’s current pose and provide feedback to the control actuators.

Central to this approach is the collaboration between human input and automated systems. Two key components, the SLAP Control Panel (SLAP-CP) and the Control System (SLAP-CS), facilitate this interaction. The SLAP-CP acts as the primary interface for human-machine interaction, converting the operator’s inputs into actionable commands. These commands are then relayed to the SLAP-CS, which processes them and coordinates the system’s actuators to execute the corresponding actions. At the same time, the Sensing System, including the Computer Aided Visual System (CAVS), provides real-time feedback, enabling operators to intuitively evaluate the system's performance and make well-informed decisions. Working together, these components create a closed-loop decision-making framework that allows operators to monitor and adjust operations continuously based on dynamic feedback.

1. Overall Control System Design

The overall control system consists of three major components, as shown in Figure 6-1:

(a) SLAP Control Panel (SLAP-CP): The SLAP-CP (concept design is not included in the prototype) acts as the primary interface for operator interaction, providing a set of buttons and knobs that enable intuitive control of the system. Buttons allow operators to initiate critical actions, such as levelling, oscillation damping, or emergency operations, while knobs enable precise adjustments of horizontal position, vertical position, and steering angle. The SLAP-CP translates the operator’s inputs into actionable commands, which are then sent to the SLAP-CS for execution. This interface serves as the essential bridge between human decision-making and automated system control, ensuring that the operator maintains oversight and control of critical operations.

(b) SLAP Control System (SLAP-CS): The SLAP-CS operates as the core processing unit of the system, receiving commands from the SLAP-CP and orchestrating the execution of key functions, including position adjustment, levelling, steering control, and stabilization. It incorporates a task scheduler to rank and coordinate these actions, ensuring smooth and precise operation. The SLAP-CS acts as the central hub, maintaining alignment between operator instructions, system logic, and real-time feedback from the sensing system. Its robust design ensures that all operations are performed accurately and efficiently while adhering to the system’s operational framework.

(c) Sensing System: The CAVS (concept design only in this research) plays a pivotal role in providing real-time feedback and enhancing the operator's situational awareness. It delivers data on the module’s current pose and predicted pose (based on cached commands), enabling operators to monitor system behavior and evaluate performance effectively. The CAVS also communicates the system's readiness status to the SLAP-CP, empowering the operator to make informed decisions. By offering a direct visual representation of the module’s pose, the CAVS ensures that adjustments are made accurately, efficiently, and safely. In addition to the CAVS, as discussed in Chapter 5 on structural design, the system incorporates sensors such as the IMU, linear potentiometers, and force sensors. These sensors continuously monitor and update the latest status of critical structural components, including their angles and positions, and feed this data back to the SLAP-CP. This feedback data further supports the operator in making precise decisions. Moreover, the system continuously monitors this data against predefined safety thresholds. If any parameter exceeds the safety limit, the system will automatically initiate emergency actions, such as halting operations or triggering an emergency lift. These safety mechanisms will be explained in the following sections.

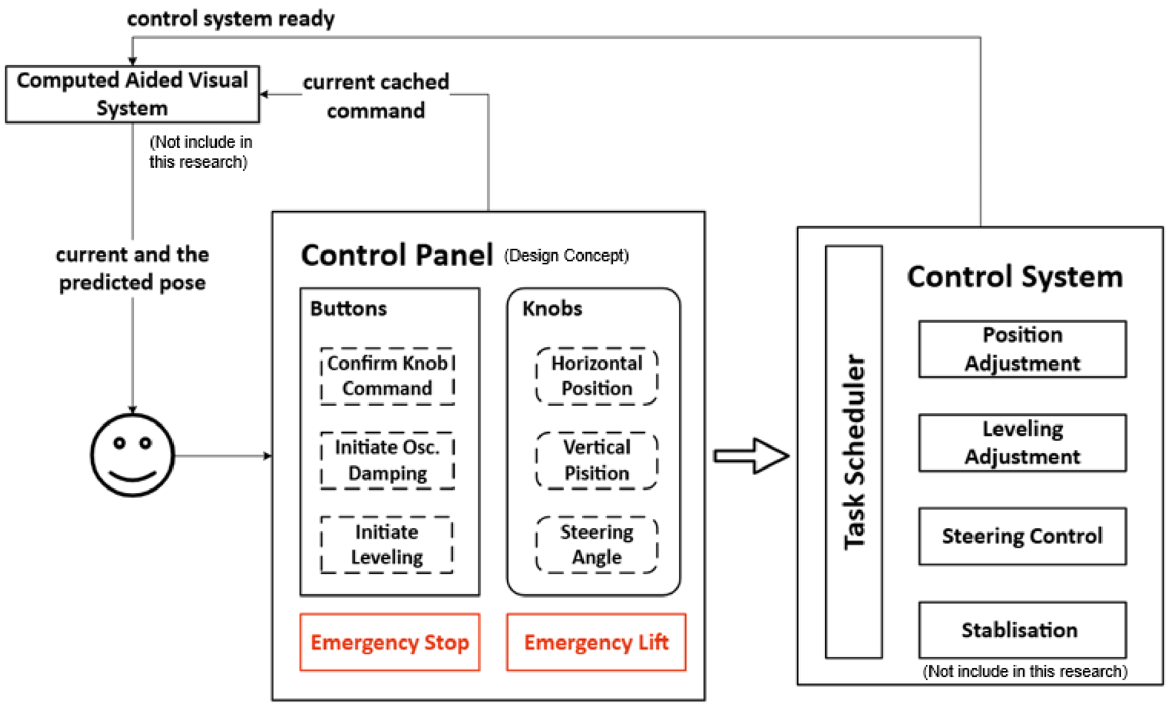


Figure 6-1 Overall Control Strategy for the SLAP (Design Concept)

Together, these components form an integrated control loop to balance human oversight with automation. The operator interacts with the SLAP-CP to provide inputs, which are processed by the SLAP-CS and executed precisely after the operator confirms. Simultaneously, the CAVS supplies real-time feedback to the operator, enabling continuous monitoring and refinement of operations. This cohesive design ensures that the system meets the practical needs of MiC construction by reducing manual effort, improving accuracy, and enhancing safety and efficiency.

2. Operator Workflow and Command Execution

The operator's main responsibility is to assess the module's state using real-time visual feedback from the CAVS and sensor data. Based on this feedback, the operator uses the knobs on the SLAP-CP to make positional or steering adjustments. The SLAP-CS processes these inputs and calculates a suggested module command, which includes adjustments to the steering angle, horizontal position, and vertical position, as well as levelling corrections. This suggested command is cached in the SLAP-CP and visualized in the CAVS, allowing the operator to preview the predicted module pose.

The operator can continue refining the command using the knobs until the predicted pose meets the operational requirements, if manual involvement is preferred. Once satisfied, the operator can confirm the knob command, triggering the SLAP-CS to execute the finalized instructions. After execution, the cached commands in the SLAP-CP are reset to zero, ensuring the system is ready for the next set of inputs.

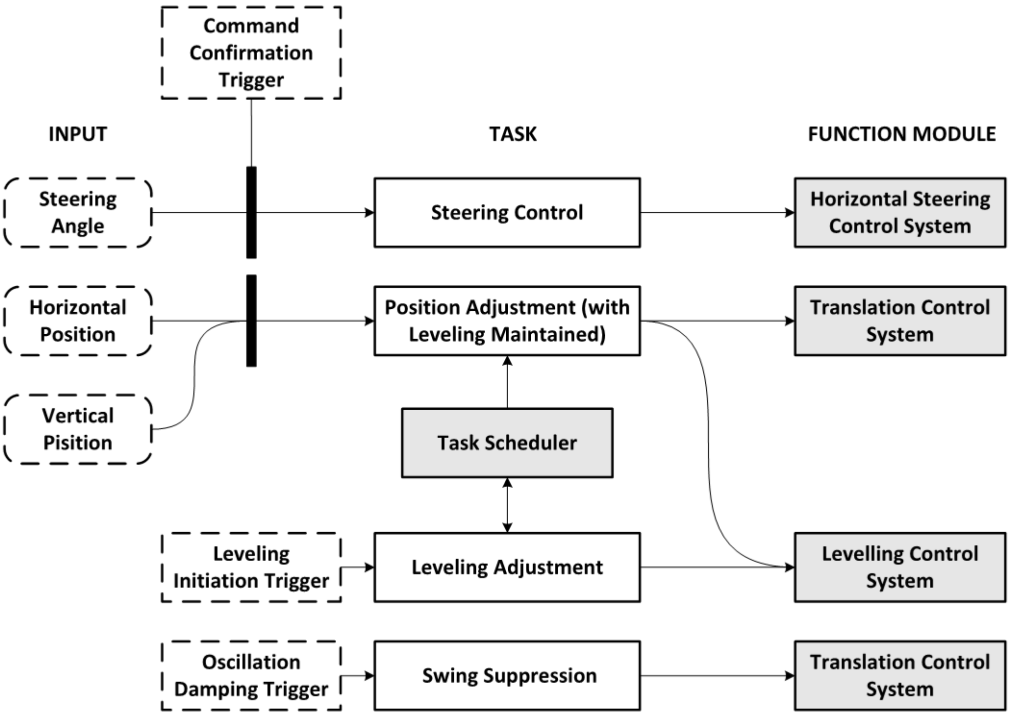


Figure 6-2 Controlled Functional Modules Relationship

Figure 6-2 illustrates the relationship between the operator's inputs, the SLAP-CP, and the functional modules controlled by the SLAP-CS. For example, inputs for steering angle, horizontal position, and vertical position are processed to execute corresponding tasks such as steering control or position adjustment. Similarly, the levelling initiation trigger activates the Levelling Adjustment Module to maintain operational stability.

3. Human-Machine Interaction (HMI) Devices (Design Concept)

Knobs are an important and widely used tool in human-machine interaction (HMI) devices due to their precision and intuitive control (Basu, 2024; Schölkopf et al., 2021; Zhang et al., 2002). In the SLAP-CP, three specialized knobs are provided to adjust specific DoF:

(a) 2-DoF Horizontal Position Knob (HPK): Used for horizontal position adjustments.

(b) DoF Vertical Position Knob (VPK): Used for vertical position adjustments.

(c) DoF Steering Angle Knob (SAK): Used for making rotational adjustments.

The design of these knobs draws from HMI devices used in industries such as remote medical operations, automotive control, and construction machinery. When turned, the knobs incrementally adjust the desired values for their respective DoFs, allowing fine control of the module's pose. For instance, rotating the HPK changes the module's horizontal position, while the SAK adjusts its rotational alignment.

The commands adjusted via the knobs are cached in the SLAP-CP and synchronized with the CAVS, which visualizes the predicted module pose. This real-time visualization helps the operator verify the system's predicted behavior before finalizing the command. Once the operator is satisfied, the finalized instructions will be sent to the SLAP-CS. After executing the command, the cached values are reset to zero, ensuring the system is ready for the next operation.

4. Safety Considerations in the Control System

Safety is critical in construction environments, where risks must be managed carefully to ensure worker well-being and operational reliability. The SLAP-CS also puts safety as a priority and incorporates specific safety features to address these requirements:

(a) Emergency Stop: This function allows the operator to halt all ongoing tasks immediately and freeze all actuators in their current positions to prevent accidents.

(b) Emergency Lift: In emergency situations, the operator can activate this command to raise the module by preset height and maintain all actuators stationary. This feature helps mitigate risks caused by external disturbances or unforeseen hazards.

In addition to emergency responses, the SLAP system addresses common challenges encountered during MiC operations, such as tilted or unbalanced modules and oscillations caused by wind or human interference. To tackle these issues, the SLAP-CP includes dedicated buttons for specific tasks. The Levelling Adjustment Trigger activates modules to correct tilted or unbalanced modules and maintain stability, while the Oscillation Stabilization Trigger initiates slight stabilization measures from the TCM to reduce oscillations and ensure safe operation. By integrating these safety functions, the system enhances operational reliability and minimizes potential risks during MiC assembly.

In summary, the control strategy integrates the SLAP-CP, SLAP-CS, and CAVS into a cohesive framework that balances safety, operational efficiency, and intuitive HMI. Figure 6-2 illustrates how operator inputs via the SLAP-CP are accurately processed by the SLAP-CS and supported by real-time feedback from the CAVS to ensure precise execution. By addressing the unique challenges of MiC construction, the system combines industry-specific requirements with robust safety features, intuitive interfaces, and automation capabilities to deliver high standards of performance, precision, and safety.

6.2.2 Detailed Design for Each Module

This section provides a detailed description of the key components of the SLAP control system, including Sensor Arrangement, Computer-Aided Visual System (CAVS), Task Scheduler, Translation Control System, Steering Control System, and Levelling Control Module.

1. Sensor Arrangement

The SLAP system integrates four sensor types, in addition to the encoders embedded in the servo motors (actuators). These sensors are crucial for ensuring accurate measurements and reliable system functionality:

(a) Inertia Measurement Unit (IMU): Mounted on the Hoisting Platform of the SLAP system, the IMU measures the attitude and moving velocity of the platform. It provides essential data for maintaining module stability and control.

(b) Linear Potentiometer: This sensor measures the length of the cable rolled off the spool, which is fixed on the SLAP's Hoisting Platform. The pulling cable, attached to the bottom of the Steering Control Box, allows the potentiometer to determine its spatial relationship.

(c) Force Sensors: These sensors are installed at the anchor points of the hoisting cables. Each sensor measures the pulling force of its respective cable, ensuring proper load distribution and operational safety.

The combination of these sensors allows the SLAP system to monitor and adjust its operation dynamically, ensuring accurate measurements of module position, orientation, and cable forces.

2. Computer-Aided Visual System (CAVS) (Design Concept)

The CAVS consists of four cameras strategically mounted on the Hoisting Platform, as shown in Figure 6-3. These cameras are positioned to capture a comprehensive view of the module, particularly the bottom area, facilitating precise placement during assembly. The visual feedback provided by the cameras allows operators to detect placement errors and make informed adjustments.

Each camera is integrated with computer vision software capable of identifying key features of both the module and the target location. Using this data, combined with input from the onboard IMU, the system reconstructs and visualizes the module's pose and the target location within a simulated environment (see Figure 6-4). Overlaid markers on the live camera feed enhance clarity by highlighting relevant objects, making it easier for operators to identify critical details.

The simulation-based visualization further displays position and attitude errors intuitively, assisting operators in understanding and addressing discrepancies. Additionally, the system visualizes the predicted module pose, which corresponds to the cached position and steering angle commands stored in the SLAP-CP as instructed by the operator. This feature allows the operator to preview the potential outcome before executing commands, improving safety performance and precision during operations.

However, the CAVS remains a conceptual control design and was not implemented in the subsequent prototype or performance validation.

3. Task Scheduler

As shown in Figure 6-1, the SLAP consists of a Task Scheduler and four functional modules, each designed to perform a specific control function:

(a) Translation Control Module: This module handles translational adjustments based on incoming position commands. It also ensures that the module maintains a levelled attitude throughout these adjustments.

(b) Steering Control Module: This module manages rotational adjustments based on steering commands provided by the SLAP- CP)

(c) Levelling Control Module: This module restores the module to a levelled state if it becomes unbalanced due to external disturbances or control errors.

(d) Stabilization Module: This module reduces oscillations caused by external forces, such as wind or human interference, effectively stabilizing the module. (concept only, not included in the current research scope)

The Task Scheduler coordinates transitions between these functional modules, ensuring smooth and efficient system operation. An example of the state transition logic between the modules is illustrated in Figure 6-3. Additionally, the SLAP-CP can directly activate a specific functional module by sending the corresponding command. Each functional module is supported by a low-level control system responsible for the detailed actuator control loops required for its operation. As shown in Figure 6-2, each functional module operates under the supervision of the Task Scheduler, which ensures precise execution of commands by the corresponding actuators.

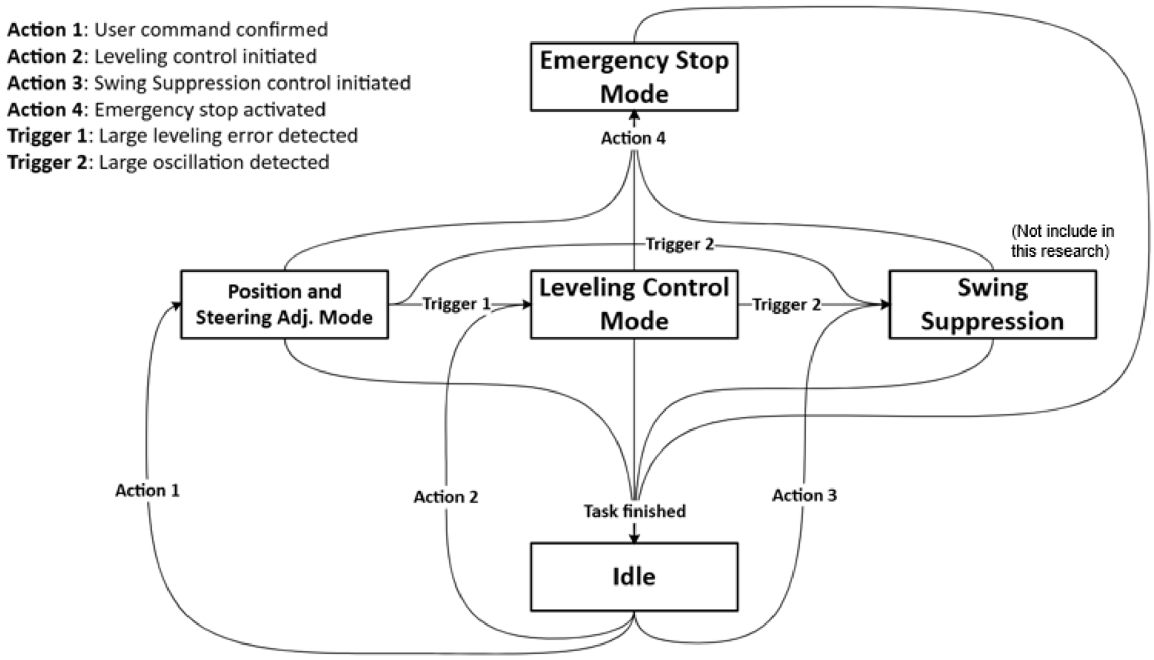


Figure 6-3 State Transition Rules in Task Scheduler

It is worth noting that the "Emergency Lift" function, activated via a dedicated button on the SLAP-CP. Rather than being a separate state, this function is implemented as a combination of a specialized Translation and Steering Adjustment Mode and the Emergency Stop Mode.

The state transition logic of the Task Scheduler is guided by internal safety measures designed to prevent damage caused by module swing or an unlevelled attitude. For instance, when large oscillations are detected, the system terminates the Position and Steering Adjustment Mode and Levelling Control Mode, activating the Stabilization Mode instead (see Figure 6-6). Similarly, if a significant levelling error is detected, the system suspends Position and Steering Adjustment Mode and transitions to Levelling Control Mode. These dynamic transitions ensure the SLAP system operates safely and efficiently under varying conditions, maintaining stability and protecting the system from potential risks.

4. Horizontal Steering Control Module and Translation Control Module

The HSCM and TCM work together to execute position and steering adjustments, as shown in Figure 6-4. Once a desired position change and steering angle change are received, the Motion Planner is activated. Once a desired position change and steering angle change are received, the Motion Planner is activated.

The Motion Planner uses a relative position relationship, detailed in Chapter 6.3.2, along with input from the IMU, displacement sensors, and image recognition by the CAVS to generate a trajectory that transitions the module from its current pose to the desired pose. The planned trajectory not only ensures the module reaches the target position and steering angle but also maintains a levelled attitude throughout.

This is achieved using a mathematical model that dynamically adjusts the module's pose to compensate for disturbances or errors. At each time step, the Motion Planner calculates:

(a) The desired steering joint angle for the Steering Motor Controller.

(b) The desired linear joint positions for the XY-Table Linear Motor Controllers.

(c) The desired hoisting cable lengths for the Cable Length Controllers.

Additionally, the Cable Tension Monitoring Module, in conjunction with force sensors, ensures that all cables remain properly tensioned. If a cable's tension falls below a preset threshold, the module slightly reduces the cable's target length. This ensures balanced load distribution and enhances the reliability of trajectory planning and execution.

Once the planned trajectory is complete, the task automatically exits, and the system transitions back to the Idle State or the next scheduled task.

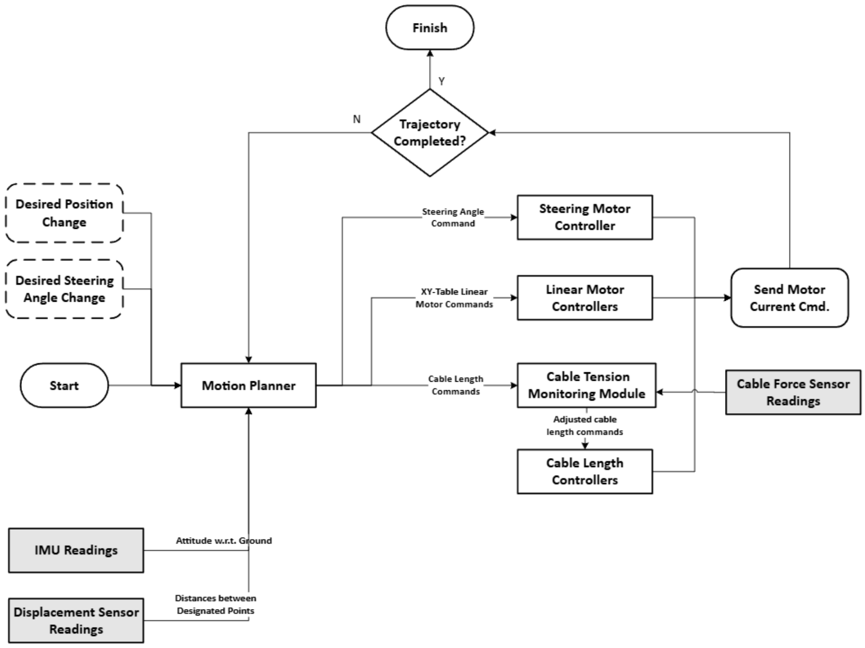


Figure 6-4 Logic Flow of HSCM and TCM

5. Levelling Control Module

The Levelling Control Module, as illustrated in Figure 6-5, shares many structural similarities with the Translation Control Module. It consists of the following components:

(a) Motion Planner: Specialized for levelling tasks, this planner calculates the necessary adjustments to bring the module back to a levelled state.

(b) Cable Tension Monitoring Module: Works to monitor proper tension in all cables, ensuring stable operation.

(c) Cable Length Controllers: Execute the commands to adjust cable lengths.

The workflow of the LCM is nearly identical to that of the TCM, with one key difference: The Motion Planner in the LCM focuses solely on adjusting hoisting cable lengths. The primary objective of this module is to restore the module's levelling attitude to within a preset threshold. By dynamically adjusting cable lengths, the module compensates for disturbances and system errors, ensuring balance and stability.

Once the levelling task is complete, the system automatically transitions back to the Idle State or the next scheduled task.

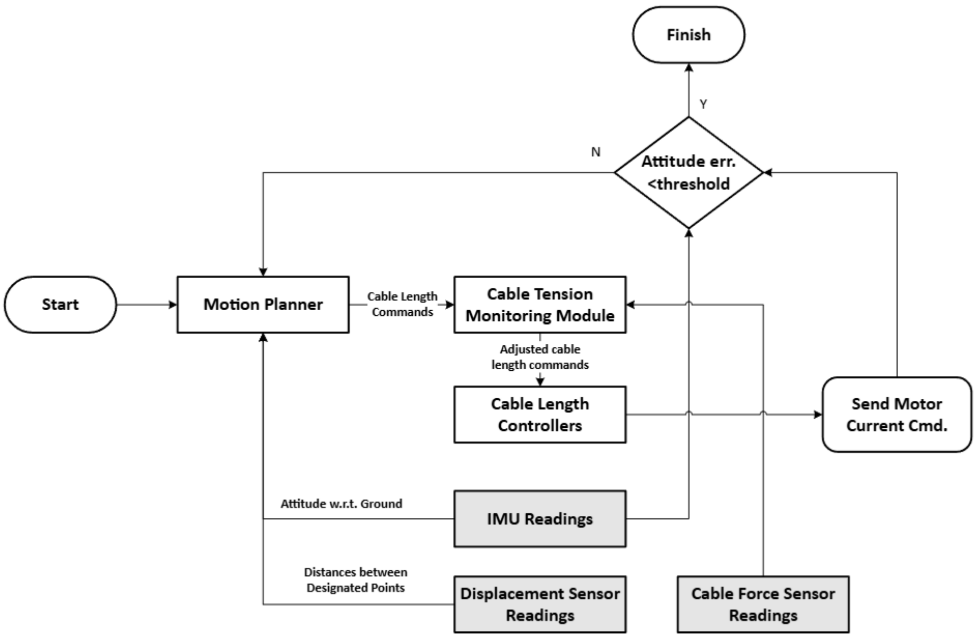


Figure 6-5 Logic Flow of LCM

6.3 Control Principles and Degrees of Freedom (DoF) Analysis

6.3.1 Overview of Control Principles

Section 6.2 primarily focused on the SLAP system's control panel configuration, emphasizing the interconnections between functional modules and their control systems. It examined the control logic governing the system's functional modules, analyzing each module in conjunction with its corresponding low-level control loops and actuators.

In contrast to the focus on control logic and flow in Section 6.2, this section explores the relationships between the SLAP system's hardware components, which serve as the core principles underpinning the SLAP design. These principles treat the hardware components as interconnected rigid bodies, and a mathematical model is developed to describe the relationship between the mass ratio and lateral displacement of the components. This model provides the foundation for lateral position control in the SLAP system, playing a crucial role in simulation-based verification prior to hardware prototyping and experimental validation. The mapping between the structure components and the corresponding frames can be referred to Figure 6-6.

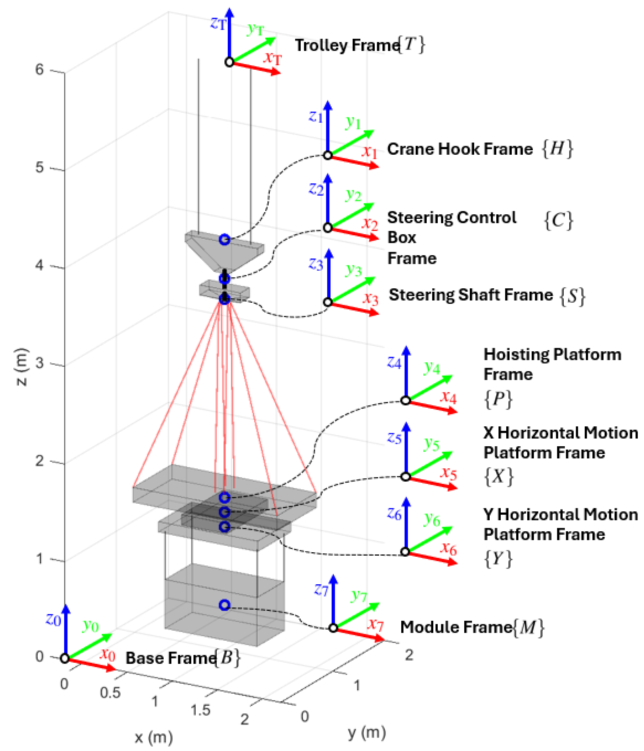


Figure 6-6 Frame Mapping with the Structure Components

The SLAP system is modeled with 23 DoFs, as determined by the joint configurations (see Figure 6-7). However, five independent constraints are imposed by the crane ropes and module ropes that connect the hoisting platform to the module. These constraints do not affect the module's final position, reducing the system's effective DoFs to 18.

The five constraints include:

(a) Two restrictions from the two lifting ropes connecting the trolley and the crane hook (between {T} and {H}).

(b) Three additional constraints from ropes linking the bottom of the hoisting platform to the module ({Y} and {M}).

Among the remaining 18 DoFs, 9 are directly controlled, while the others remain indirectly controlled. The controllable DoFs are distributed as follows:

(a) The spatial joint between {S} and {P} provides 6 controllable DoFs.

(b) The RevoluteZ joint between {H} and {S}, the PrismaticX joint between {P} and {X}, and the PrismaticY joint between {X} and {Y} each contribute 1 controllable DoF.

Although the SLAP system has 9 controlled DoFs and 18 independent DoFs, it is classified as under-actuated. Despite this, the system achieves full control over the module's pose by effectively leveraging the controllable DoFs, ensuring that positional adjustments and operational functionality are implemented successfully.

Through this detailed analysis of joint definitions and the distribution of controlled and uncontrolled DoFs, this section provides a foundational understanding of the SLAP system's positional relationships and dynamic characteristics. The relationship between the in-direct controlled DoFs and the directly controlled DoFs will be further explained in the subsequent sections.

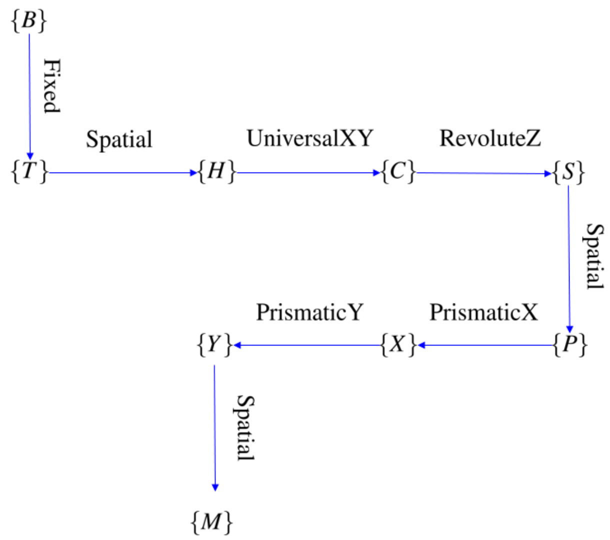


Figure 6-7 23 DoFs Joint Definition of SLAP

Remarks on Joint Definitions

(a) Spatial Joint: A 6-DoF joint allowing unrestricted spatial motion between connected components.

(b) Universal XY Joint: A 2-DoF joint permitting relative rotation along the X-axis of the parent frame and the Y-axis of the child frame.

(c) RevoluteZ Joint: A 1-DoF joint allowing relative rotation along the Z-axis of the parent frame.

(d) PrismaticX Joint: A 1-DoF joint permitting relative translation along the X-axis of the parent frame.

(e) PrismaticY Joint: A 1-DoF joint permitting relative translation along the Y-axis of the parent frame.

6.3.2 Relationship Between Indirectly Controlled DoFs

The 18 independent DoFs in the SLAP system are distributed among various structural components and organized within eight distinct motion frames, as illustrated in Figure 6-6 and Figure 6-7. These motion frames are independent structural entities that are interconnected, with some frames being mutually constrained by their interactions. As explained in the previous sections, out of these 18 DoFs, only 9 are directly controlled, while the remaining 9 are independent but indirectly controlled DoFs. Although the system does not actively manipulate these indirectly controlled DoFs, they remain integral to the overall motion chain and influence the module's pose control through their interactions within the system. Despite their indirect influence on the system, the absence of direct control minimizes the overall impact of their motion on the system's behavior, ensuring that the module's pose remains stable and predictable.

The relationships among these indirectly controlled DoFs can be elaborated as follows:

1. Relative Pose Between the Crane Hook Frame {H} and the Base Frame {B}

When the system reaches a stabilized state, the crane hook remains stationary as long as the crane itself does not move. Therefore, the pose of {H} relative to {B} can be assumed to remain constant and can be determined by the initial pose of the system.

2. Relative UniversalXY Joint Between the Hook {H} and the Steering Control Box Frame {C}

As the SLAP system operates, the UniversalXY joint connecting {H} and {C} adjusts dynamically to help balance the system. This adjustment causes the joint to adopt non-zero relative values, which are determined by the system's dynamic equilibrium. However, these slightly non-zero values have an extremely minimal impact on the module's final pose and can effectively be treated as zero for practical purposes.

3. Relative Pose Between the Module Frame {M} and the Horizontal Motion Platform Frame in Y Direction {Y}

When the system achieves a balanced state with the module levelled, the relative pose between {M} and {Y} remains unchanged. This stability ensures that the module maintains its intended orientation relative to the horizontal motion platform.

These relationships illustrated the role of indirectly controlled DoFs in the overall system dynamics. Although these DoFs are not actively controlled, they are integral to the motion chain of the SLAP system and play an important role in influencing the system's behavior.

Understanding these relationships is essential for accurately modelling and analyzing the SLAP system's performance.

6.3.3 Principles of Controlled DoFs

In the SLAP system, the motion frames containing controlled DoFs are interconnected, forming a complex system of relationships. By analyzing these interdependencies, the desired values for each controlled DoF after actuation can be derived, enabling precise control of the module's pose and motion.

1. Steering Joint Position – RevoluteZ Joint

The rotation of the steering joint, represented as a RevoluteZ joint, is determined by the relative position between {S} (steering shaft frame) and {C} (steering control box frame). When this joint is balanced, meaning its relative displacement is zero, the rotation axis of the steering joint aligns with the Z-axis of the base frame {B}. Under this condition, the desired steering joint angle can be calculated as the sum of the initial steering joint angle and the desired additional steering angle adjustment for the module.

2. Relative Position Between {P} (Hoisting Platform Frame) and {S} (Steering Shaft Frame):

The desired position of the supporting point "O" of frame {C} relative to {P} is determined by a critical condition: the vector connecting the overall Center of Mass of the composite, denoted as CoMc, to the supporting point "O" must align with the Z-axis of {P} to ensure the platform remains level. Since the CoMc is always directly beneath the supporting point "O," aligned with the gravitational direction, this condition guarantees the levelling of {P}. Furthermore, because the attitude of the module {M} is identical to that of {P}, achieving zero attitude error in {P} also ensures that {M} remains levelled. The attitude of {P} is continuously monitored using an IMU attached to the platform, and any deviations are corrected by adjusting the cable lengths connecting {S} and {P}, thereby maintaining the desired pose of the module.

3. Prismatic Joint Positions – Horizontal Translation of the Module:

The lateral translation of the module can be simplified into a two-dimensional planar problem. Assume the stationary portion of the hoisting platform (the part that does not move with the module) has a mass m_h, with its corresponding CoM denoted as CoMp. The horizontal distance between CoMp and the overall CoM (CoMc) is represented as d_h. Similarly, the module and the moving portion of the hoisting platform have a combined mass m_m, with their

CoM denoted as CoMm, and the horizontal distance between CoMm and CoMc represented as d_m. This relationship is illustrated in Figure 6-8.

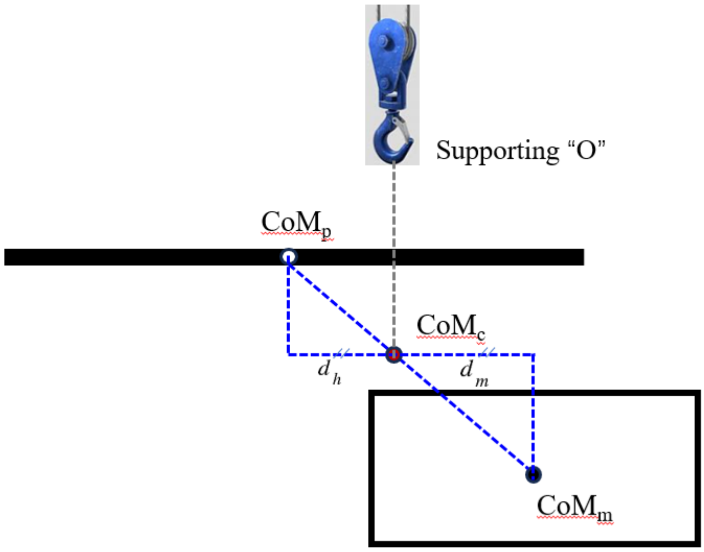


Figure 6-8 Joints Position Relationship

4. Center of Mass (CoM) of Links {C}, {S}, {P}, {X}, {Y}, and {M}:

The overall Center of Mass (CoMc) of the interconnected links {C}, {S}, {P}, {X}, {Y}, and {M} must always remain directly beneath the supporting point "O" of frame {C}. This requirement ensures that the system remains balanced and aligned with the gravitational direction. To achieve lateral translation of the module, the horizontal displacement of the module (CoMm) relative to CoMc must be adjusted. Given that the majority of the system's mass is concentrated in links {P}, {X}, {Y}, and {M}, the overall CoM (CoMc) can be approximated using the CoM of these four links. Assuming the module remains levelled throughout the motion, this horizontal displacement can be achieved through the precise actuation of the linear joints. The exact positions of these linear joints can then be calculated using derived formulas that account for the relationship between the module's CoM, the platform's CoM and the overall CoM, ensuring accurate lateral translation and stability.

5. Prismatic Joint Positions – Mass Calibration

According to static equilibrium, the following equation can be derived:

$$m_h d_h = m_m d_m \tag{6-1}$$

Adding $m_h d_m$ to both sides of the equation:

$$m_h d_h + m_h d_m = m_m d_m + m_h d_m \tag{6-2}$$

Simplifying this equation by factoring out common terms and dividing through $m_h d_m$ to both sides of the equation, the following relationship is obtained:

$$m_h \times (d_h + d_m) = (m_m + m_h) \times d_m \qquad 6-3$$

$$\frac{d_h + d_m}{d_m} = \frac{m_m + m_h}{m_h} \qquad 6-4$$

This equation indicates that the total lateral displacement of the module and platform, relative to the module's lateral displacement alone, is proportional to the ratio of the total mass to the stationary mass. This relationship is critical for calculating the effective stroke of the prismatic joints (in either the X or Y direction), which corresponds to the maximum total lateral displacement of the module and platform. By measuring the relevant masses and the displacement of the module, the maximum stroke can be determined. Alternatively, this equation can be used to calibrate the mass of the stationary portion of the hoisting platform using measured displacements and a calibrated stroke.

6. Relationship Between Module and Stationary Platform Mass Ratios:

A similar derivation can be conducted to establish the relationship between the ratio of total lateral displacement of the module (moving portion) and platform (stationary portion) to the lateral displacement of the stationary portion of the hoisting platform, and the ratio of the total mass to the moving portion of the composite system (m_m). This relationship can be expressed using the following equation:

$$\frac{d_h + d_m}{d_h} = \frac{m_m + m_h}{m_m} \qquad 6-5$$

Similarly, the relationship between the stationary portion and the moving portion can be expressed as:

$$\frac{d_h}{d_m} = \frac{m_m}{m_h} \qquad 6-6$$

From these equations, it becomes evident that the ratio of the module’s mass (moving portion) to the stationary portion of the platform’s mass is equal to the ratio of the distances d_h and d_m:

(a) d_h: Between the CoMp (stationary CoM) and CoMc (overall CoM);

(b) d_m: Between the CoMm (module CoM) and CoMc (overall CoM).

Using these formulas, the SLAP system can achieve precise horizontal motion of the module by manipulating the hoisting platform's stationary portion. By leveraging the known masses of individual components or inversely calibrating the mass ratios using the provided equations, the system can adjust the module's lateral position to achieve the desired module pose.

It is important to note that the module's position change is expressed relative to its levelled frame. The ratio of these position changes depends directly on the ratio of the corresponding moving mass (m_m) to the total system mass. This dependency ensures that the module's motion is accurately controlled while maintaining stability and alignment with the system's overall CoM.

6.4 **Summary of Chapter**

This Chapter focused on the design and implementation of SLAP's control system, including its control interface, consideration of human intervention, and primary control principles. It introduced and implemented three key innovative contributions:

(a) Hierarchical control logic incorporating human-in-the-loop functionality

(b) Statically stable module translation through motion planning

(c) Active module levelling using a cable-driven mechanism

Building upon the hardware design concept of SLAP introduced in the previous Chapter, Chapter 6 first established the overall control logic tailored to SLAP's hardware configuration. This includes the design of the UI (control panel) and control system (logic flow among modules). The control logic was developed with consideration for SLAP's structural and transmission characteristics, operator expectations and preferences, and local safety requirements for on-site operations.

The entire control system is divided into three main parts: SLAP-CP, SLAP-CS, and the sensing system.

(a) SLAP-CS refers to the modules executing the control mechanism, which includes control logic programs and the full set of sensor devices.

(b) SLAP-CP serves as the control panel, providing the UI to the operator.

Within SLAP-CS, the system is further divided into four functional modules: position adjustment, levelling adjustment, steering control, and stabilization. A task scheduler coordinates the actuation, deactivation, and the execution order of these modules. Sensors, as critical components of SLAP-CS, monitor the states of actuators and hardware, feeding real-time data to the task scheduler. In collaboration with CAVS, these sensor readings are used to evaluate system states and execute appropriate control programs when predefined conditions are met.

After defining the overall control system and the higher-level UI, the latter half of this focused on the fundamental principles of the functional modules in SLAP-CS. It begins with an analysis of SLAP's 23 independent DoFs, explaining the relationships between the DoFs with and without actuators. Additionally, to better understand these relationships, key equations are introduced, revealing the relationship between the position displacement ratio (module vs. hoisting platform) and the mass ratio (hoisting platform vs. module). These equations demonstrated the feasibility of achieving high-accuracy lateral position control of the module, with the actual displacement calculated from this relationship.

Ultimately, this Chapter validated the theoretical feasibility of the proposed control mechanisms, laying a solid foundation for the practical implementation and experimental evaluation of SLAP’s advanced control system, which will be explored in detail in Chapter 7 through a scaled-down lab prototype experiment.

Chapter 7 Lab Prototype Experiment of SLAP

7.1 Introduction

The Chapters 5 and 6 of this study introduced the mechanical hardware structure and control system strategy of SLAP, respectively. Chapter 6, in particular, elaborates on the theoretical aspects of SLAP by analyzing its mathematical models. It outlined the control logic and the interaction interface between the system and the operator in semi-automatic scenarios. However, these discussions primarily focused on the system's theoretical feasibility. In practical applications, hardware performance often deviates from theoretical design values, and the effectiveness of SLAP's hardware and control logic is not comprehensively addressed in the previous chapters.

Typically, the validity of a system is first assessed through simulation modelling and then verified with practical experimental testing. In this research, the simulation model of SLAP is developed to control a target module with dimensions and weight similar to those commonly used in local MiC projects. More significantly, the study simplifies the original design concept to construct a scaled-down prototype in the laboratory at the Hong Kong Polytechnic University. This Chapter mainly introduces the prototype aims to closely simulate the working conditions of tower crane operations on MiC sites while maintaining a controlled and safe environment. The primary objective of this experimental setup is to validate the fundamental principles underlying SLAP and assess its real-world practicality.

7.2 Lab Prototype Design

Lab Prototype Design Parameters

As described in Section 5.4, the SLAP concept design consists of three primary functional modules:

(a) Horizontal Steering Control Module (HSCM)

(b) Levelling Control Module (LCM)

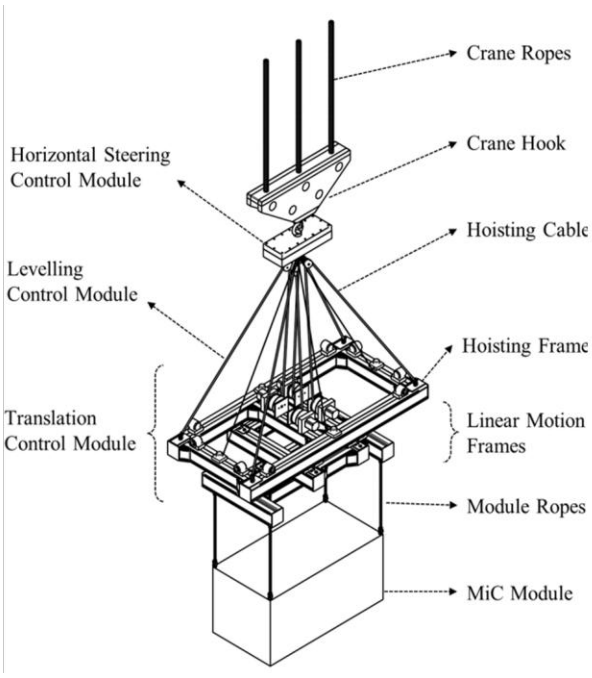
(c) Translation Control Module (TCM)

Each module plays a critical role in ensuring the system operates effectively. The HSCM is responsible for enabling rotation along the gravity axis to achieve precise horizontal alignment. The LCM adjusts the module's attitude relative to the horizontal plane during the final positioning process and allows for minor height adjustments. The TCM ensures the module's horizontal displacement relative to the ground, enabling it to be moved to the designated position. Additionally, the TCM can provide swing suppression functionality when necessary, ensuring the stability of the module during operation.

Although this system is a scaled-down laboratory prototype, all three primary functional modules have been implemented in the hardware design. These modules not only enable testing of individual performance but also coordinate to deliver the critical positioning functionality required for MiC projects, as outlined in Section 6.2. The prototype replicates the three primary functions introduced in Chapter 5. A comparison between the lab prototype and the concept design drawings is provided in Figure 7-1. In addition to the primary functions, compared with the concept design, the system is equipped with a safety belt to prevent the hoisting frame and module from suddenly dropping in the event of motor failure, given the substantial weight of the equipment. This safety feature protects against damage to underlying objects, such as the lab's floor slab in the prototype experiment, ensuring operational safety and reliability.

As illustrated in Figure 7-1, the entire prototype system is mounted on a frame rather than suspended from a crane. Despite the modification, core components of the SLAP system, such as the hoisting cables, steering joint, and prismatic joints, have been preserved. The actuators are managed through a low-level position control loop, with an IMU on the hoisting frame for detecting levelling errors. Additionally, servo motors in the actuators feature encoders for precise position feedback.

As shown in Figure 7-1, the entire prototype system is mounted on a gantry frame rather than being suspended from a crane (which is hardly to be repeated in lab environment). Despite this adjustment, most of the key components of the SLAP system are included, such as the hoisting cables, prismatic joints, and steering joint. The actuators controlling the steering joint, cable drive, and prismatic joints operate through a low-level position control loop. An IMU attached to the hoisting frame measures levelling errors, while servo motors in the actuators utilize encoders to ensure precise control. This configuration allows the prototype to replicate the core functionalities of SLAP while integrating additional safety measures suitable for laboratory use.



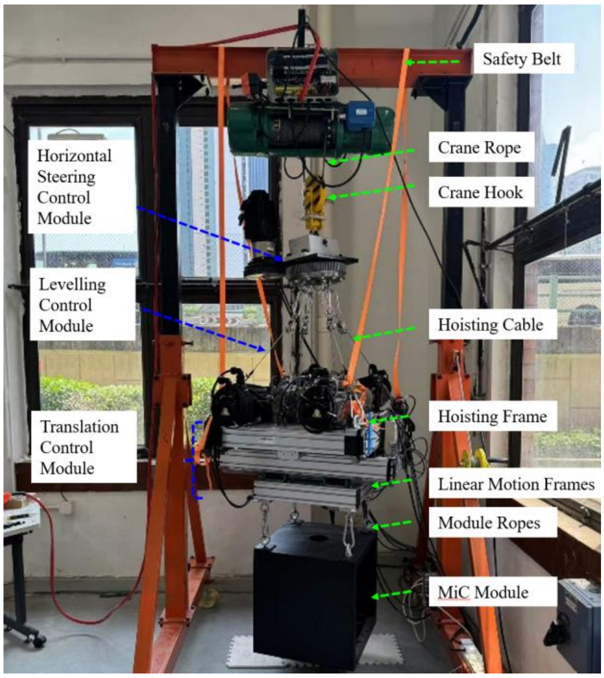


Figure 7-1 SLAP Design Concept vs. Lab Prototype

The prototype's skeleton (frame) is designed based on the parameters listed in Table 7-1 below, which serve as the structural foundation for the scaled-down laboratory prototype. These parameters ensure that the prototype replicates the core operations of SLAP in a controlled environment while meeting the necessary functional and safety requirements. It is important to note that the mechanical assembly process lies outside the research scope of this study.

Table 7-1 Lab Prototype Setting Out Parameters

No.	Size (mm)	Remarks
A	1460	Inner width of the Portal Frame
D	2870	The inner height of the Portal Frame (Top beam exclusive)
I	500	Inner bound of Module

Figure 7-2 Prototype Setting Out Illustration

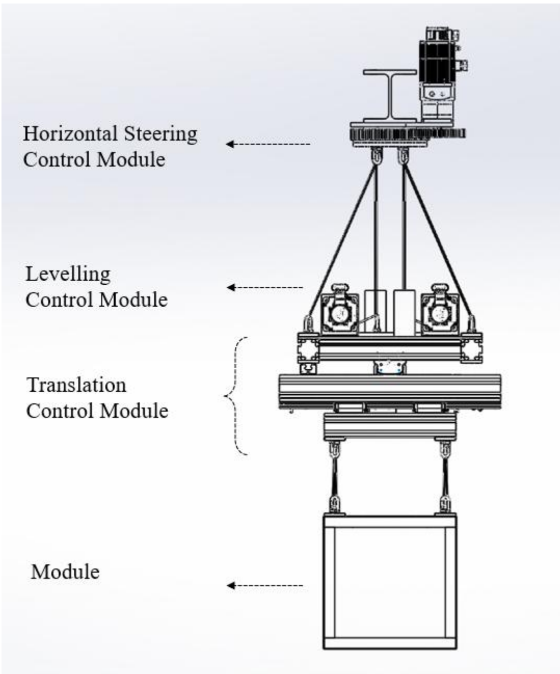


Figure 7-3 Prototype Design Drawing Illustration

1. Horizontal Steering Control Module

The Horizontal Steering Control Module (HSCM) is the only component in the system responsible for effectuating rotation along the gravitational axis. This functionality is achieved using a brushless DC servo motor. While the hardware design of the HSCM lab prototype is largely based on the concept design introduced in Chapter 5, certain modifications were necessary due to the selection of motors and gear configurations.

However, due to design constraints related to the chosen motor and gear system, this integration was not feasible for the prototype. Instead, the steering control box was redesigned with an aluminum-alloy enclosure mounted on a steel plate module. The aluminum enclosure serves as the connection point for attaching the simulated crane hook, while the steel plate supports the motor and gear, forming the steering control frame.

The initial design and setup of the HSCM laboratory prototype are illustrated in Figure 7-4, providing a detailed view of the component integration and assembly process. This design ensures that the HSCM effectively fulfills its role designed in the overall SLAP system, while accommodating the practical constraints of the laboratory environment.

Figure 7-4 HSCM Design Concept

2. Levelling Control Module (LCM)

The Levelling Control Module (LCM) utilizes a cable system driven by four brushless DC servo motors. These motors, along with the cable storage winches, are integrated into the top hoisting platform of the system. At the bottom of the HSCM system plate, a movable pulley assembly is connected. This assembly serves two key functions: it facilitates smooth cable movement and reduces the required pulling force while simultaneously slowing down the motion, thereby improving control precision.

Given the dimensional constraints of the laboratory prototype, the integration of the LCM's major components into the structural platform has been carefully engineered to ensure optimal functionality. Figure 7-5 illustrates the layout and setup of the hoisting platform, showcasing the spatial arrangement of the motors, winches, and other critical components, which are main components comprising the LCM.

Additionally, as shown in Figure 7-1, the LCM serves as the transitional structure that bridges the upper and lower modules, emphasizing the connections between the LCM, HSCM, and TCM. This structural design facilitates seamless interaction and coordination among the modules, enabling the LCM to play a pivotal role in the overall operation of the SLAP system.

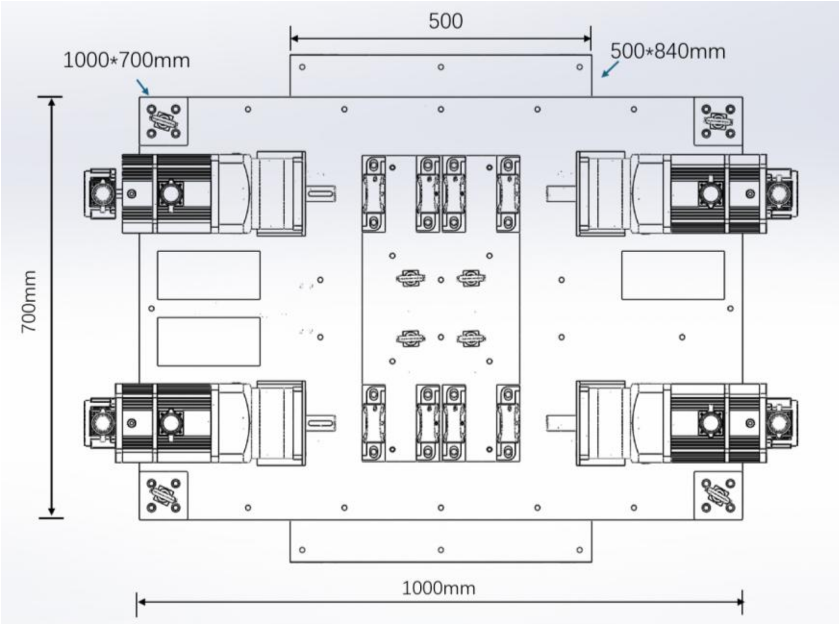


Figure 7-5 Hoisting Platform Design Layout

3. Translation Control Module

The TCM is responsible for the horizontal displacement of the module, achieved through an X-Y guide rail system. This system is composed of:

(a) A shared hoisting platform with the LCM.

(b) The X-direction Guiderail Frame (Prismatic X Joint).

(c) The Y-direction Guiderail Frame, which is perpendicularly connected to the X-direction Guiderail Frame (Prismatic Y Joint).

The travel distances for the guide rail system are as follows:

(a) X-direction: 500 mm.

(b) Y-direction: 350 mm.

The hoisted module is a cube measuring 500 mm on each side, and the Y-direction guiderail frame is designed to accommodate this geometry. This ensures efficient use of materials while enabling the module to be hoisted vertically. The X-direction guiderail frame, however, measures 500 mm × 840 mm. While the X-direction side length matches the Y-frame at 500 mm, the additional length is required to account for:

(a) The 350 mm travel range of the Y-frame.

(b) The 500 mm module width.

(c) The motor length, aluminum frame thickness, and connection plates.

The dimensions of the hoisting platform are 700 mm × 1000 mm, carefully calculated to consolidate all hardware components without overcrowding. These dimensions not only provide sufficient surface area for the integration of the HSCM but also accommodate:

(a) The 500 mm travel range of the X-frame is mounted below.

(b) The 500 mm Y-direction guiderail width.

(c) The accessories and structural components associated with the guide rail system.

After layout planning, all components were successfully integrated onto the platform, as shown in Figure 7-5. This design ensures that the TCM operates efficiently within the confined laboratory setup while maintaining the core functionality required for SLAP's horizontal positioning tasks. Figure 7-6 illustrates the vertical relationship between the directional guiderail frames of the TCM and also highlights its connection with the LCM.

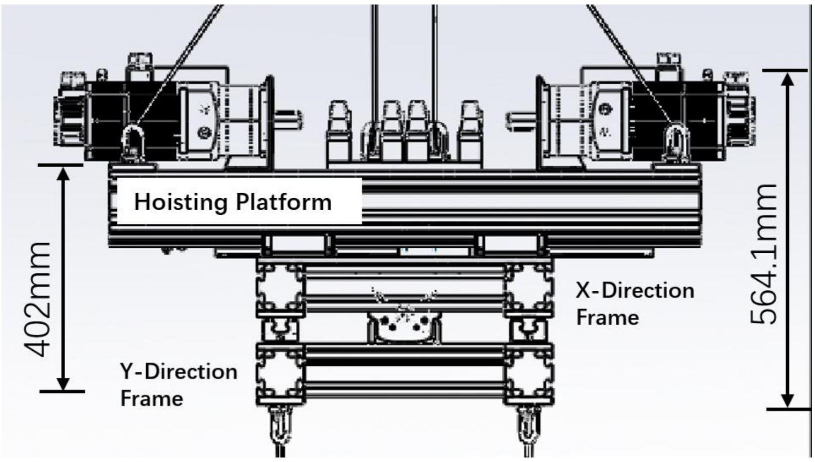


Figure 7-6 TCM Design Elevation

4. Mass of the Key Components of the Prototype

As discussed in Section 6.3, the mass of each system component plays a crucial role in determining the prototype's performance, particularly its horizontal displacement range during MiC end-positioning operations. During the experimental phase, understanding the mass and size of each key component enables precise estimation of the prototype's effective travel stroke, which is critical for simulating the movement of MiC modules.

Controlling the mass ratio between the module and the hoisting frame is especially important for accurately replicating the prototype’s performance relative to real-world MiC construction sites. In actual MiC hoisting scenarios, the mass of the hoisting frame system is typically much smaller than that of the MiC module. For instance, in traditional hoisting operations, the mass ratio of the frame to the module may range from 1:9 to 1:3, depending on the module's size, layout, and any additional equipment mounted on the structure. However, for the laboratory prototype, due to the limited capacity of the servo motors and safety considerations, achieving a real-world mass ratio where the module is significantly heavier than the lifting frame is not feasible. The mass ratio of the prototype is, therefore, approximately 1:1, deviating from the conditions observed in real-world MiC construction.

Therefore, to maintain a reasonable mass ratio between the module and the lifting frame in the prototype, careful control of the weight of individual components is essential. By optimizing the weight distribution, the module's effective travel stroke can still meet the desired range of motion within the controlled laboratory environment.

The gross mass of each key component in the system is detailed in Table 7-2, which provides a comprehensive breakdown of the prototype's structural components and their respective masses. This data is critical for validating the laboratory prototype's performance and ensuring the weight distribution aligns with the design. It is important to note, however, that the listed mass values serve only as an initial reference point for calculating the motion range and control. A more accurate approach involves calibrating the mass ratio through measured travel distances between the components under specific testing conditions. This calibration ensures alignment with the prototype's operational objectives and enhances the overall accuracy of the performance evaluation to be conducted later in the experiment.

Table 7-2 Weight of Prototype Structural Components

Component	**Weight (Gross)**
Hoisting Platform	185.96 kg
PrismaticX Joint (Linear Guiderail X)	42.01 kg
PrismaticY Joint (Linear Guiderail Y)	7.38 kg
Module	169.34 kg

7.3 Verifying Prototype Feasibility

To validate the effectiveness of the SLAP system and ensure alignment with the design objectives outlined in earlier sections, experiments were conducted using a laboratory prototype.

These experiments were designed to analyze the system's operational capabilities, with a focus on translation control, module levelling, and rotation. Among these, rotation is relatively straightforward and requires minimal validation. Thus, the experiments primarily targeted translation and levelling, as these represent the most significant technical challenges. This section provides an overview of the experiment design, the prototype setup, and the results of the validation tests.

7.3.1 Assumptions for Experiment Design

The prototype design is based on several key assumptions to ensure the validity and relevance of the experiments. These assumptions were derived from the geometry and mechanical properties of the SLAP system and are critical for replicating realistic lifting scenarios. Table 7-3 summarizes the key parameters used in the laboratory setup, including distances between the crane hook, the hoisting frame, and the module's center of gravity (CoG).

Table 7-3 Key Assumptions Adopted in Lab Prototype Design

Parameter	**Value**
Vertical distance between the hoisting frame and module CoG (m)	0.768
Vertical distance between the crane hook and hoisting frame CoG (m)	1.09
Crane hook horizontal adjustment range relative to module width	1.024
Crane hook vertical adjustment range relative to module height	0.72
XY platform horizontal adjustment range relative to module width	1.012
XY platform vertical adjustment range relative to module height	0.70

The vertical distance between the hoisting frame and the module's CoG is calculated based on the three-layer hoisting frame's combined CoG, the height of the frame, and the module dimensions. Similarly, the vertical distance between the crane hook and the hoisting frame's CoG accounts for the frame height, the hook's position, and the cable exit point. These parameters ensure that the prototype's mechanical configuration aligns with real-world scenarios. The effective working range of the hoisting platform was determined to be 72 cm, which is sufficient to test the system's ability to meet practical lifting requirements. These parameters underpin experimental design and ensure that the system's operational capabilities can be rigorously evaluated.

7.3.2 Prototype Experiments Set-up

The experiment setup was constructed in the Industrial Center (4F and U006) to simulate MiC lifting operations in a controlled environment. The prototype system consists of the following key components, as indicated in Figure 7-7:

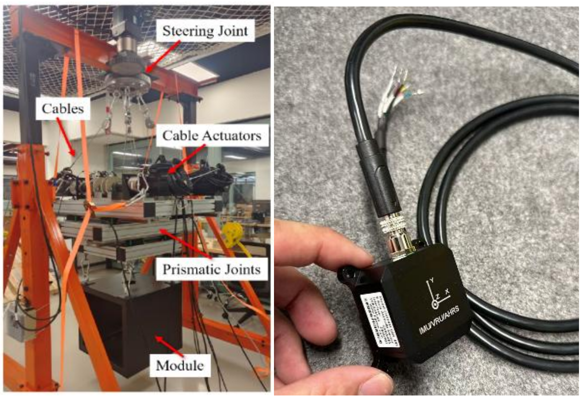


Figure 7-7 Key Components Overview of the Prototype (Left) & IMU (Right)

1. **Hoisting Frame and Module**: The three-layer hoisting frame connects the crane hook to the module via adjustable cables. The module, designed to emulate a typical MiC load, ensures that the system operates under realistic weight and dimension constraints.
2. **Cable Actuators and Steering Joint**: Cable actuators control the tension and length of the cables, enabling precise adjustments during levelling and translation. The steering joint ensures smooth and coordinated cable movement, a critical factor for maintaining stability.
3. **Prismatic Joints**: Prismatic joints allow vertical adjustments of the hoisting platform relative to the module, simulating scenarios where uneven cable lengths or misalignments occur.
4. **IMU**: An IMU was integrated into the module to capture real-time data, including tilt angles, oscillations, and positional changes. These data provide quantitative metrics for evaluating the system’s performance during the experiments.

The experimental environment was carefully controlled to minimize external disturbances, ensuring that the results reflect the system's intrinsic capabilities. The setup was designed to address two primary objectives: (1) to validate the feasibility and correctness of the SLAP design concept and control principles, and (2) to analyze cable length variations and guide rail movement as critical parameters for subsequent experiments.

7.3.3 Validation Experiments

Two experiments were conducted to validate the SLAP system's levelling and positioning capabilities.

(a) Levelling Control Demonstration

The first experiment focused on validating the levelling control function. To simulate an extreme scenario, the prismatic joints were independently moved to their positive limits, causing significant tilting of the hoisting platform. The levelling control system was then activated, and the cable actuators adjusted the cable lengths according to the levelling algorithm. This restored the platform to a level position.

To further test the system, the prismatic joints were moved to their negative limits, creating a more severe tilt. The levelling control system successfully compensated for the tilt in both cases, demonstrating its ability to maintain a stable module position under challenging conditions.

(b) Position Control Demonstration

The second experiment aimed to integrate levelling control with precise positioning. The prismatic joints were moved across three predefined intervals, and at each interval, the levelling algorithm was executed to determine the required cable lengths. Position control was then performed to interpolate the prismatic joint positions and cable lengths, ensuring smooth transitions between the intervals while maintaining levelling.

This experiment demonstrated that the SLAP system could guide the module to a target position based on theoretical calculations, integrating movement and levelling control to achieve precise positioning.

7.3.4 Experiments' Limitation

While the lab prototype successfully demonstrates the three primary functions of SLAP, several simplifications and compromises are made due to the constraints of the lab test environment:

(a) Mass Ratio: The mass ratio between the module and the hoisting frame is smaller than in real-world MiC applications.

(b) Dimensions: The prototype is scaled down to facilitate practical implementation in the lab setting.

(c) Crane Simulation: A gantry system equipped with a winch is used in place of a full tower crane.

(d) Module Center of Gravity: The center of gravity of the module is assumed to coincide with its geometric center.

Additionally, some functionalities from the original concept design (described in Chapter 5) are not fully implemented in the prototype. Features such as swing suppression and control mechanisms for future automation—like the CAVS system and SLAP-CP system (described in Chapter 6) are also excluded in this experiment as the first step of the validation.

7.4 Results and Discussions

As designed in the previous section, the lab prototype’s LCM and TCM functions would be tested as a priority, testing to demonstrate their ability to significantly reduce platform tilting while maintaining precise motion control. This section analyzes and discusses the experimental results, providing quantitative evidence of the SLAP's effectiveness.

1. Levelling Control After Module in Place

The experimental results for the PrismaticX and PrismaticY joints demonstrate the prototype’s ability to compensate for platform tilting caused by prismatic joint motion.

(a) PrismaticX Joint (Figure 7-8)

Initially, the PrismaticX joint moved approximately 15 cm toward its positive limit, causing the hoisting platform to tilt by approximately 2 degrees during the first 30 seconds. At this stage, the levelling control system is activated (from 30 to 40 seconds), adjusting the hoisting cable lengths to minimize the levelling error. Once levelling is completed, the PrismaticX joint is moved an additional 30 cm toward the negative side, creating a more noticeable 4-degree tilt.

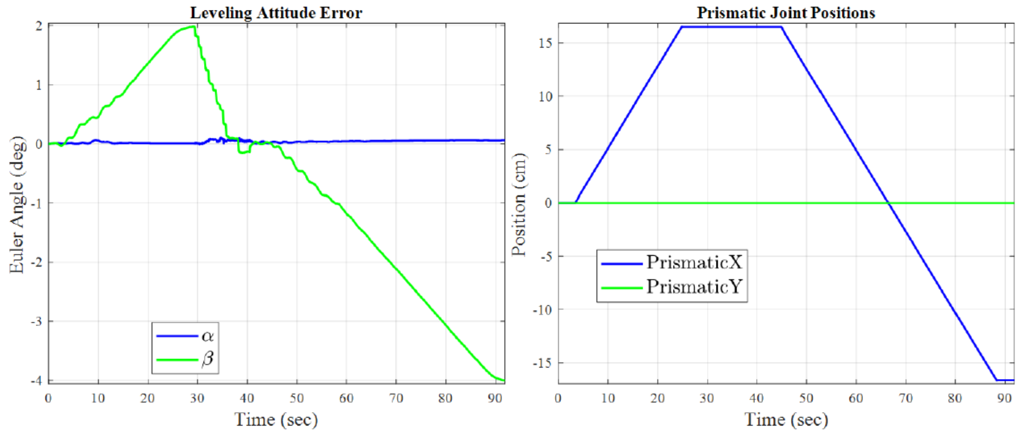


Figure 7-8 LCM X-Axis Motion Followed by Levelling

 # α and β denote the Euler angles corresponding to rotations around the X-axis and Y-axis, respectively

(b) PrismaticY Joint (Figure 7-9)

Similarly, the PrismaticY joint is initially moved 10 cm toward its positive limit, leading to a tilt of approximately 0.7 degrees. The levelling control system is then activated (from 20 to 25 seconds) and successfully corrected the tilt by adjusting the cable lengths. Afterwards, the PrismaticY joint moved an additional 20 cm toward the negative side, resulting in a tilt of over 1.4 degrees.

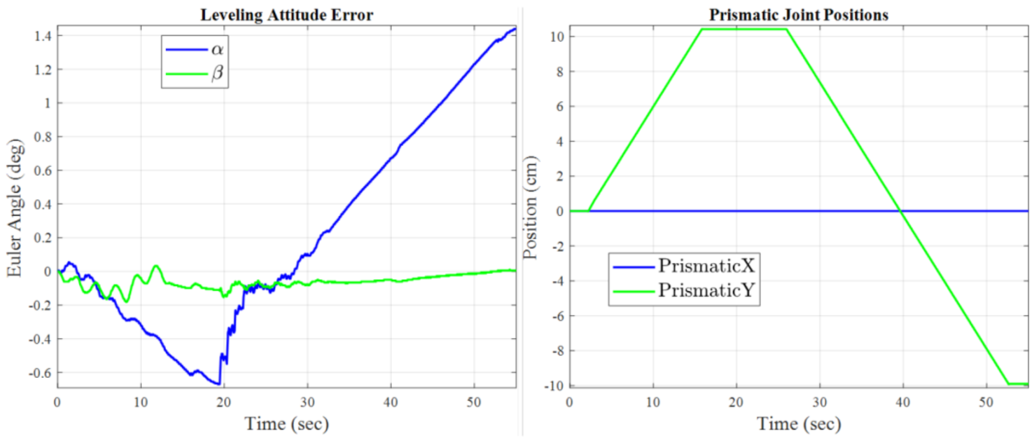


Figure 7-9 LCM Y-Axis Motion Followed by Levelling

 # α and β denote the Euler angles corresponding to rotations around the X-axis and Y-axis, respectively.

The results reveal a clear difference in the tilting behaviour between the PrismaticX and PrismaticY joints. When subjected to the same amount of motion, the PrismaticX joint causes a noticeably larger tilt compared to the PrismaticY joint. This difference can be attributed to the uneven weight distribution of the prototype, where more weight shifts in the X direction than in the Y direction. Specifically, movement in the X direction causes a more pronounced shift in the relative position between the composite structure's CoM and the supporting point. This asymmetry amplifies the tilting effect whenever the PrismaticX joint is adjusted.

Nevertheless, the levelling control system proved to be highly effective in both scenarios. Regardless of the differences in tilt magnitude, the system consistently corrected the tilt and restored the platform to a stable, levelled position, demonstrating its reliability and adaptability to varying conditions.

2. Simultaneous Levelling Control During Module Placement

Figure 7-10 and Figure 7-11 demonstrate the feasibility of the SLAP laboratory prototype in performing precise positioning control with levelling enabled. Both the hoisting cables and the PrismaticX joint were controlled simultaneously, with positions and cable lengths interpolated across three setpoints. The motion of the PrismaticX joint followed a pattern similar to that in Figure 7-8, first moving near the positive limit and then near the negative limit.

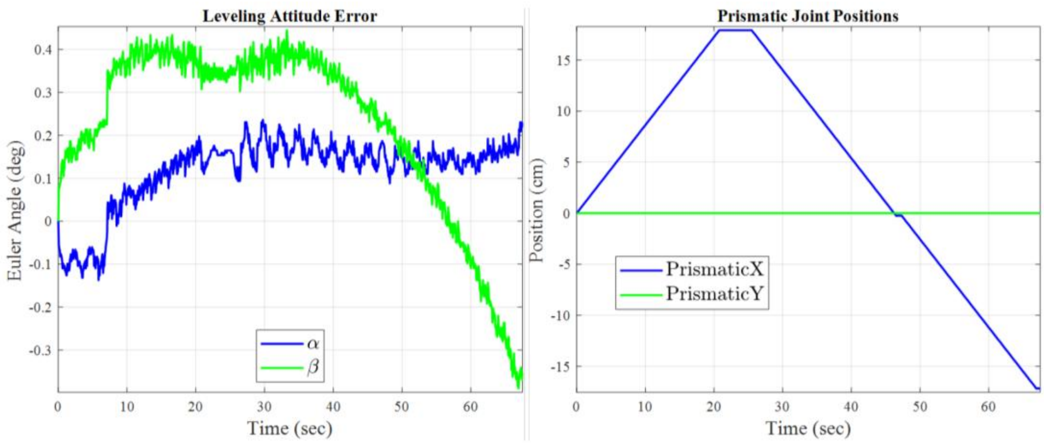


Figure 7-10 LCM X-Axis Motion with Simultaneous Levelling

With the levelling system activated, platform tilting was significantly minimized. During the transition between extreme positions, the PrismaticX joint covered an identical distance as in Figure 7-10. In the absence of levelling (as shown in Figure 7-8), the platform tilt reached approximately 4 degrees, whereas with levelling enabled (Figure 7-10), the tilt was reduced to about 0.8 degrees, representing a tilt reduction of over 80%.

Likewise, Figure 7-11 presents the results for the PrismaticY joint with levelling control. A comparison between Figure 7-9 (levelling activated after the joint reached its position) and Figure 7-11 (levelling performed in parallel with joint motion) shows that the platform tilt was reduced from 0.7 degrees to around 0.1 degrees, resulting in a tilt reduction of over 85%. These results clearly illustrate the levelling control system's effectiveness in maintaining platform stability during linear motion of the prismatic joints.

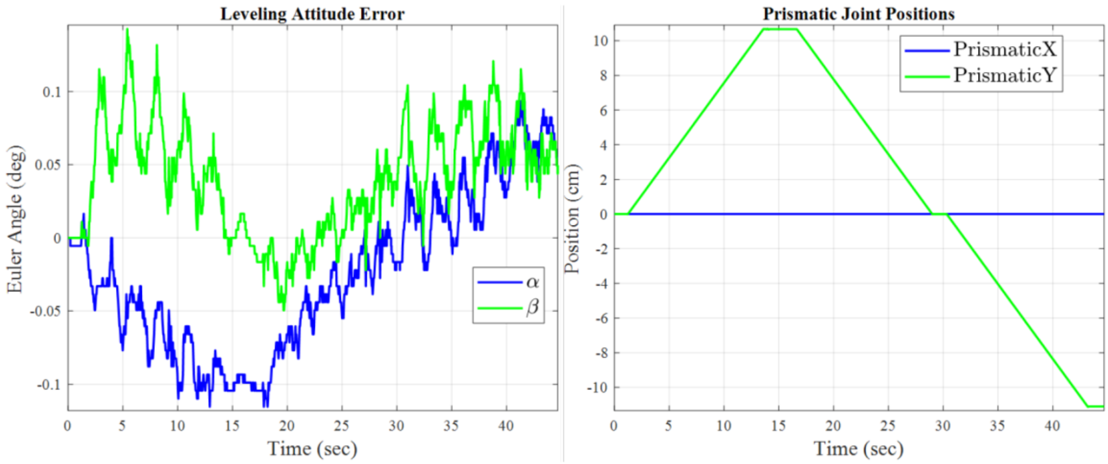


Figure 7-11 LCM Y-Axis Motion with Simultaneous Levelling

Figure 7-12 and Figure 7-13 further showcase a series of photographs capturing the hardware prototype in action, performing motions along the X and Y directions, respectively. These images demonstrate the prototype's ability to integrate the LCM and TCM to achieve precise movement and platform stability.

The photos highlight the practical implementation of the levelling control system and the prototype's ability to maintain stability and accuracy during translational movements. The combined operation of the PrismaticX and PrismaticY joints, along with hoisting cable adjustments, ensures that the prototype can meet the requirements of MiC construction tasks, even in a scaled-down laboratory setting.

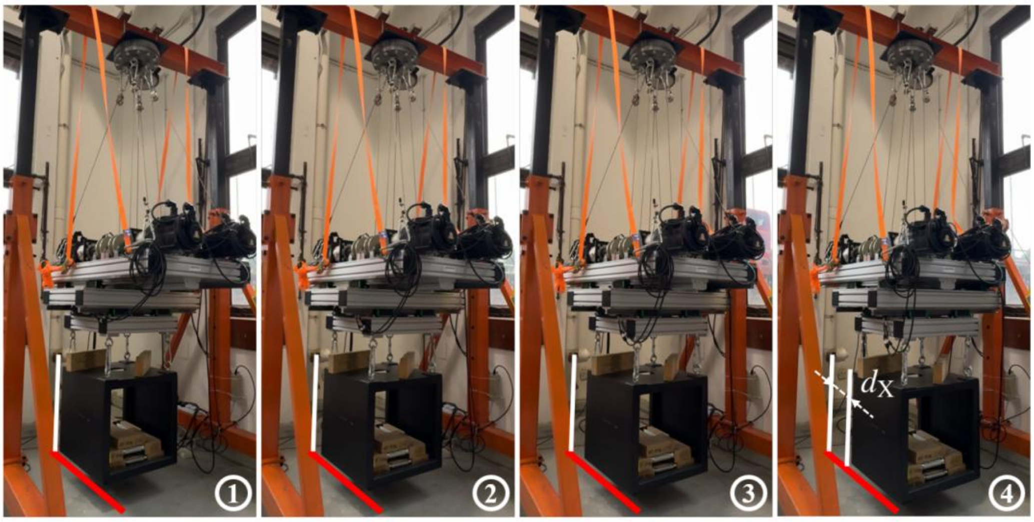


Figure 7-12 Experiment on Linear Motion with Simultaneous Levelling (X-axis)

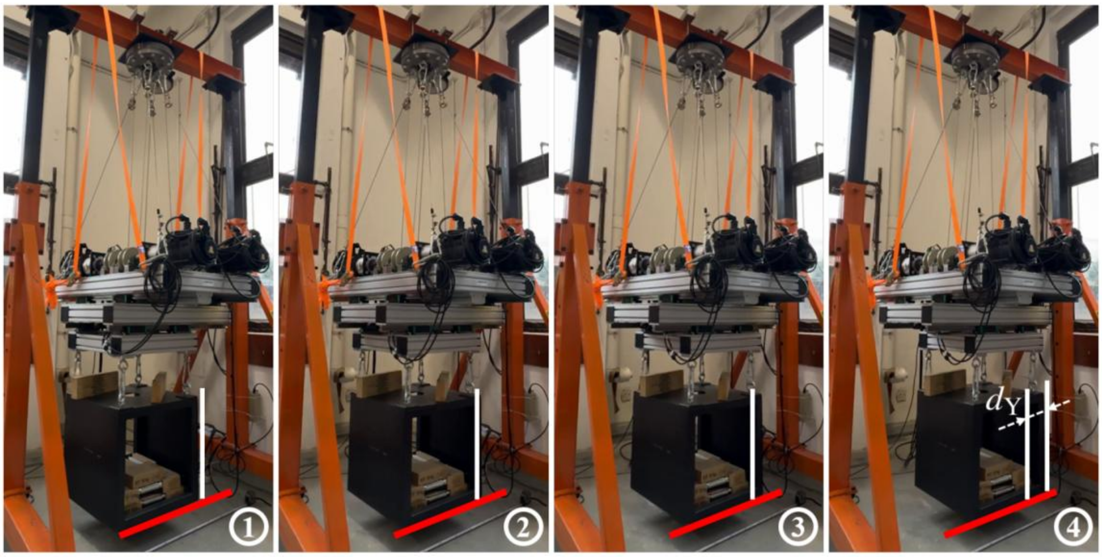


Figure 7-13 Experiment on Linear Motion with Simultaneous Levelling (Y-axis)

7.5 Summary of Chapter

To validate the SLAP design concept and the functionality of its control loops, this Chapter details the design, development, and testing of a laboratory-scale prototype. Although this prototype is a scaled-down and simplified version of the original design, it can also verify the effectiveness of the SLAP design concept via three core functional modules:

(a) Horizontal Steering Control Module (HSCM)

(b) Levelling Control Module (LCM)

(c) Translation Control Module (TCM)

The prototype is equipped with an IMU for real-time measurement of the platform's attitude. To enhance experimental efficiency and ensure accurate validation, modelling, analysis, and basic simulation verifications are conducted before hardware prototyping and testing (though these simulations are not included in this thesis). The simulation results confirmed the feasibility of the design concept in achieving the three primary functions.

The hardware prototype is installed on a gantry structure measuring approximately 1.5 meters wide and 2.9 meters tall. A hoisting mechanism is used as a substitute for the crane system, and electric motors powered the HSCM. The HSCM is connected via 4mm steel cables to an irregular lifting platform assembly with outer dimensions of 840mm x 1000mm. This lifting platform serves as the primary support structure for the LCM and TCM.

Experimental results showed that tilting caused by prismatic joint movements exceeding ±15 cm along the X-axis and ±10 cm along the Y-axis could be corrected within approximately 30 seconds when operating under a "move first, then level" (two system operates one and after) control approach.

Additionally, this Chapter demonstrates the capability of the LCM and TCM modules to operate simultaneously. Experiments show that when the two modules work together, they effectively reduce platform tilting and maintain stability during prismatic joint motion. By activating the levelling control system in parallel with translation position control, significant tilt reductions (exceeding 80%) are achieved while maintaining both accuracy and stability. These results underscore the system’s feasibility for practical applications requiring precise levelling and positioning.

Chapter 8 Performance Validation of the MiC Lifting Platform

8.1 Introduction

Following the feasibility testing and identification of the primary functions designed for SLAP, this Chapter shifts focus to exploring suitable parameters for evaluating the performance of the hoisting robot in MiC projects, of which SLAP is one type. The primary objective of this Chapter is to establish a comprehensive evaluation framework to ensure the robot’s applicability and efficiency in real-world MiC scenarios. To achieve this, reviews of both academic literature and industry guidelines/standards were conducted to identify the most relevant evaluation parameters, encompassing a wide range of factors critical to the prototype's performance.

The study identifies economic indicators and equipment functional performance metrics as the two most suitable categories for evaluating the MiC hoisting robot. Economic indicators are essential for analyzing cost-effectiveness, while performance metrics assess the system’s technical capabilities under operational conditions. Together, these parameters provide a balanced and holistic evaluation framework.

Building on the identification of these parameters and the preliminary quantitative analysis outlined in the previous Chapter, the study further evaluates the SLAP prototype’s operational efficiency. This evaluation serves two purposes. First, it validates the reliability and relevance of the parameters derived from literature when applied to a real MiC lifting platform. Second, it offers a more comprehensive assessment of the SLAP design’s overall effectiveness. This process is integral to determining the system’s practical feasibility and its potential for deployment in large-scale construction projects.

Economic indicators primarily focus on cost-effectiveness, a critical factor in assessing the practicality of the hoisting robot. However, because the SLAP prototype is still in the conceptual validation stage and has not yet reached mass production, cost-benefit analysis is limited to theoretical reviews of potential economic factors. In contrast, Performance Indicators are more directly applicable at the laboratory stage. These metrics are introduced and tested using the prototype to evaluate its functionality and operational reliability. By applying the identified parameters to the prototype in controlled experiments, the study provides a detailed analysis of its performance, offering insights into its suitability for MiC applications.

In summary, this Chapter bridges the gap between theoretical evaluation and practical testing by identifying and applying key evaluation parameters. It refines the framework for assessing MiC lifting platforms and highlights the SLAP prototype's potential for real-world deployment, laying the groundwork for future advancements in construction automation.

8.2 Investigating Performance Parameters

8.2.1 Cost-Benefit Analysis

Cost is a critical factor for industry stakeholders when deciding whether to adopt planned commercial equipment or tools. Typically, cash flow analysis and the comparative method are the two most common approaches for evaluating the cost performance of construction robotics (Sun et al., 2024).

Warszawski (1985) analyzed robotic implementations in construction by examining factors such as initial investment, maintenance, and operation costs through cash flow analysis. Later, Skibniewski (1988) applied similar methods to evaluate the costs of various robotic components in construction. In the post-2000 era, researchers began to emphasize cost comparisons between construction projects that use robots and those that rely on traditional manual methods. One widely used approach is benefit-cost analysis, which assesses the economic efficiency of automated construction technologies (Lee et al., 2013). This method compares the costs of traditional construction with automated alternatives, using a key metric known as the Cost Index (C_I), defined as:

$$C_I = \frac{C_R}{C_T} \qquad 8-1$$

Where:

C_R is the cost of the project using construction robots.

C_T is the cost of the project using traditional construction methods for similar tasks.

To complement the CI, the Benefit Index (BI) is introduced to quantify the advantages of automated construction relative to traditional methods. The BI is calculated as:

$$\Delta BI = W \times S \qquad 8-2$$

Where:

W is the factor weighting matrix derived through the Analytic Hierarchy Process.

S is the score matrix assigned to each sub-technology.

This method has been successfully applied to assess various construction scenarios, including highway interchange construction, construction material tracking, and slab formwork tasks (Jang & Skibniewski, 2009; Shin et al., 2006; Zhou et al., 2008).

Another key metric in this cost-benefit framework is the Performance Index (PI), which evaluates the relative cost-effectiveness of robotic solutions. It is defined as:

$$PI = \frac{BI}{CI} \qquad 8-3$$

This formula captures the benefit difference relative to the cost difference. A PI value greater than 1.0 indicates that the innovative robotic solution is more advantageous than traditional methods, offering financial benefits and cost-effectiveness. In such cases, the robotic approach is deemed financially viable, practical for adoption, and suitable for broader implementation.

These metrics— CI, BI, and PI—clearly highlight the economic benefits of adopting robotics compared to traditional methods. While cost analysis provides critical insights into a robot's economic feasibility, evaluating its functional performance is equally important for determining its operational capabilities and overall efficiency.

8.2.2 Performance Measurement Parameters

In addition to cost-benefit analysis, the functional performance of MiC lifting platforms must be assessed in terms of safety and operational capability. The most critical performance indicators for construction tools like lifting robots are safety performance, efficiency, and accuracy (Smith & John Clarkson, 2005).

(a) Safety Performance – Reliability and Robustness: Safety and reliability are fundamental to evaluating the hoisting robot's performance. Reliability is commonly expressed as the Mean Time Between Failures (MTBF), which measures the average operational time before a failure occurs (Kannan & Parker, 2006):

$$MTBF = \frac{Total\ Operational\ Time}{Number\ of\ Failures} \qquad 8-4$$

Another critical metric is the Mean Time to Repair (MTTR), which reflects the downtime caused by system malfunctions:

$$MTTR = \frac{Total\ Repair\ Time}{Number\ of\ Repairs} \qquad 8-5$$

(b) Efficiency: Efficiency measures the system's ability to maximize resource utilization (Banton, 2024). For robotic systems, task completion time is a widely used parameter. This metric captures the total time required for the robot to complete a given task, from start to finish (Chung et al., 2013).

(c) Accuracy: Efficiency alone is insufficient for evaluating robotic devices. Accuracy is another critical factor, determining whether a robot can achieve widespread industry adoption (Bac et al., 2017). Positioning accuracy is often used to evaluate robotic systems, alongside repeatability, which measures the system's ability to reproduce consistent results in repetitive tasks (Tunstel, 2006). Repeatability is defined as the difference between the tool's initial and final positions when it is moved back and forth between set points.

To ensure robust performance evaluation, it is essential to refer to established industry standards. On the international level, ISO standards provide globally accepted guidelines, such as ISO 9283: Manipulating Industrial Robots – Performance Criteria and Related Test Methods. This standard offers a comprehensive framework for assessing robotic systems, focusing on positioning accuracy, repeatability, and stability in industrial applications (ISO, 1998).

ISO 9283 defines experimental conditions and parameters for evaluating robotic systems, including:

(a) Temperature: 20 ± 2°C

(b) Working Load: 100% (or adjusted based on testing requirements)

(c) Test Velocity: Full velocity override at 100%, with additional tests at 50% and 10%.

The standard specifies a test workspace in the form of a cuboid with diagonal test planes. Performance is evaluated at predefined test points (e.g., intersections along the diagonal plane) to assess the robot's capabilities under various poses. Key metrics include pose characteristics and path characteristics, measured under different loads, velocities, and cycles. Comprehensive testing involves running the robot through five distinct poses (P1–P5) along the workspace diagonal, as illustrated in Figure 8-1, ensuring thorough validation of accuracy and repeatability. A summary of the ISO 9283 testing parameters is provided in Table 8-1, which outlines load conditions, velocity settings, and cycle requirements to standardize evaluations.

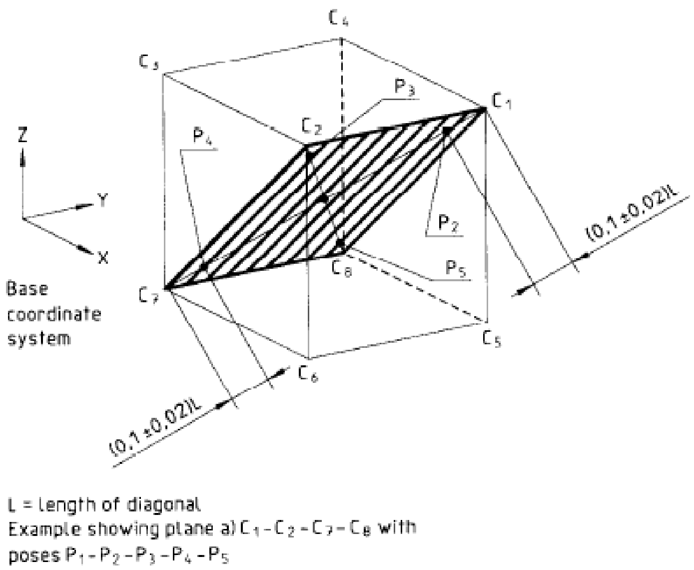


Figure 8-1 Workspace Testing Point Selection Indication (ISO, 1998)

Table 8-1 Summary of Testing Parameters Specified in ISO 9283 (ISO, 1998)

Characteristics to be tested	Load to be use		Test velocities			Number of Cycles
	100% of rated load (M = Mandatory)	The mass of rated load reduced to 10% (O = optional)	100%	50%	10%	
Pose accuracy and repeatability	M	O	M	O		30
Multi-directional pose accuracy variation	M	O	M	O		30
Distance accuracy and distance repeatability	M	-	M	O		30
Position stabilization time	M	O	M	O		3
Position overshoot	M	O	M	O		3
Drift of pose characteristics	M	-	M	-		continuous cycling during 8 hours
Exchangeability	M	O	M	O		30
Path accuracy and path repeatability	M	O	M	M	M	10
Path accuracy on reorientation	M	O	M	M	M	10
Cornering deviations	M	-	M	M	M	3
Path velocity characeteristics	M	O	M	M	M	10
Minimum posing time	M	O	Clause 9 and table 20			3
Static compliance	-	See clause 10	M	M	M	-
Weaving deviations	M	O	M	M	M	3

Pose characteristics
Path characteristics

In Hong Kong, the Factories and Industrial Undertakings (Lifting Appliances and Lifting Gear) Regulations ("CAP 59J") outline the testing and inspection requirements for lifting equipment (Department of Justice, 2006b). These regulations emphasize qualitative assessments of wear, faults, corrosion, and misalignments during inspections. The guidelines also recommend regular, thorough examinations and load tests to ensure the structural integrity of lifting equipment.

Additionally, standards such as BS 5606:2022 – Accuracy and Tolerance in Design and Construction and the Hong Kong Buildings Department Code of Practice for Precast Concrete Construction (2016) set tolerances for construction components. For example, the permitted deviation for precast concrete is ±10mm (ArchSD, 2022; BS 5606, 2022), while the deviation for point alignment is ±15mm (BD, 2016). These tolerances can serve as references for evaluating the positioning accuracy of the lifting robot prototype.

By integrating findings from academic literature, ISO standards, and local industry guidelines, this study identifies comprehensive parameters to evaluate the performance of MiC lifting platforms in both laboratory and practical settings.

8.2.3 Selecting Key Performance Parameters

Based on the literature review of prior academic studies, industry standards for robotic performance measurement, and relevant local regulations, several key performance categories have been identified for the MiC lifting platform. Among these, accuracy stands out as a critical standard for evaluating the quality of the equipment. However, for MiC lifting platforms, safety metrics remain the most critical factors to be assessed. Additionally, robust parameters such as MTBF, and MTTR are also essential for ensuring the device's reliability in real-world applications.

Combining the findings from academic research, industry standards, and guidelines, as well as considering the parameters classification referenced in the literature and standards, the selected testing parameters for the MiC lifting platform include the following:

1. Accuracy

ISO 9283 categorizes accuracy into lateral position accuracy and orientation accuracy, both of which are applicable to the performance evaluation of the MiC lifting platform. The end placement process for MiC involves not only precise positioning but also rotation and levelling (ensuring the horizontal tilt angle approximates zero). Therefore, in MiC lifting platform evaluation, these aspects are measured through lateral position accuracy, orientation accuracy, and levelling accuracy.

2. Safety

For safety performance, CAP 59J provides clear requirements for testing the safe working load, which is one of the most important criteria for the approval of lifting appliances and gears in Hong Kong. Specifically, CAP 59J stipulates that for equipment with a safe working load under 20 tons, the proof load must exceed it by no less than 25%. (Department of Justice, 2006b). This ensures the lifting platform can handle loads safely under standardized testing conditions and meets local regulatory requirements.

In addition to the safe working load, ISO 9283 highlights the importance of testing repeatability. The method involves operating the device between two diagonal points within its working space for 30 cycles. During this process, positional errors at each boundary point are recorded, and the cumulative error after 30 cycles is calculated. These measurements and computations follow the methodology specified by ISO 9283, ensuring consistency and reliability in assessing the device's safety performance.

3. Robustness

For a pre-production robotic device, it is essential to conduct extensive cycle testing and meticulously document key data, such as total operational hours, the number of failures encountered, the time spent on repairs, and the total number of repairs performed. This process ensures the system's ability to maintain its expected performance even when subjected to external disturbances or internal parameter changes. The same principle applies to MiC lifting platforms, where calculating the MTBF and MTTR is critical. These metrics are essential for assessing the reliability and maintainability of the device, as they directly impact its operational efficiency and downtime. By evaluating and refining these parameters during the development, trial operations, and deployment stages, the robustness of the system can be continuously improved, which would improve the safety performance of the device. In construction projects, particularly in lifting operations, safety remains the highest priority, and robustness plays a vital role in ensuring safety. Therefore, subsequent classifications will integrate robustness into the safety category for a more comprehensive evaluation.

4. Productivity

Productivity is a key consideration for the industrial sector, including the MiC lifting field. Measuring the total time required to complete lifting operations provides valuable insight into the device's performance. This data can be compared to the time required for manual lifting methods to evaluate whether the device offers practical and measurable advantages for the project. Additionally, understanding the overall operation time of the lifting platform enables the calculation of the number of modules lifted per hour, a critical metric for construction scheduling and cost estimation.

Based on the review and discussions above, the testing parameters, methods, and thresholds applicable to the Mic lifting platform are summarized in Table 8-2. These parameters have been carefully selected to ensure a comprehensive and accurate evaluation of the device's performance. However, since the SLAP project is currently at the laboratory prototype stage, focused on concept validation and is not yet an industrial production system, certain parameters are not applicable at this phase of testing and are therefore excluded from the experimental study, i.e., the Table 8-2 below.

Table 8-2 Performance Parameters Consolidation from Literature

No.	Category	Performance Indicator	Threshold	Testing Method	Reference	Remarks
1	Quality (Accuracy)	Position	±10mm (ArchSD); ±15mm (BD).	$AP_P = \sqrt{(\bar{x}-x_c)^2+(\bar{y}-y_c)^2+(\bar{z}-z_c)^2}$ $AP_x = (\bar{x}-x_c)$ $AP_y = (\bar{y}-y_c)$ $AP_z = (\bar{z}-z_c)$	(BD, 2016; BS 5606, 2022)	
		Orientation	±1 °	$AP_a = (\bar{a}-a_c)$ $AP_b = (\bar{b}-b_c)$ $AP_c = (\bar{c}-c_c)$	(ISO, 1998)	
		Level	±1 °	$AP_a = (\bar{a}-a_c)$ $AP_b = (\bar{b}-b_c)$ $AP_c = (\bar{c}-c_c)$	(ISO, 1998)	
2	Safety	Payload capability	1.25 x Safe Working Load	Test in factory with witness by the Competent Person.	(Department of Justice, 2006a)	

		Repeatability	30 cycles, within position accuracy	$RP_l = \bar{l} + 3S_l$ $\bar{l}_j = \sqrt{\frac{1}{n}\sum_{j=1}^{n} l_j}$ $l_j = \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2 + (z_j - \bar{z})^2}$ $S_l = \sqrt{\frac{\sum_{j=1}^{n}(l_j - \bar{l})^2}{n-1}}$	(ISO, 1998)	Not included in the SLAP Case Study
		Mean time between failures (Robustness)	Factual Statement	MTBF = Total Operational Time / Number of Failures	(Kannan & Parker, 2006)	Not included in the SLAP Case Study
		Mean time taken to repair (Robustness)	Factual Statement	MTTR = Total Repair Time / Number of Repairs	(Kannan & Parker, 2006)	Not included in the SLAP Case Study
3	Efficiency (Productivity)	Overall time	Factual Statement	Time from task start to complete	(Bac et al., 2017)	

8.3 Validation Using SLAP Prototype

8.3.1 Methodology

Since the SLAP lab prototype focuses on addressing levelling, lateral positioning, and rotation along the Z-axis, the method for evaluating its performance must consider the actual environment in which the prototype is set up. Based on the measurement parameters and methods reviewed and summarized in Section 8.2, the SLAP lab prototype will be used as the experimental sample. As the SLAP prototype remains in the conceptual validation stage and has not yet reached mass production, the cost-benefit analysis is limited to theoretical evaluations of potential economic factors, with lab validation focusing solely on assessing its functional performance. The purpose is to validate the feasibility of the evaluation metrics and provide a quantitative analysis of the SLAP prototype's performance.

The lab prototype experiment was conducted in the ground-floor laboratory of the Industrial Center at the Hong Kong Polytechnic University, where the headroom is more than 5 meters. During the experiment, the pose of each component of the prototype was measured using a motion tracking system.

Motion tracking systems have been widely applied in rehabilitation research since the 1980s. Based on the types of sensors used, these systems can be classified into optical, image-based, mechanical, magnetic, inertial, acoustic, and hybrid systems (Dong et al., 2008). Among these, optical-based systems typically use cameras to detect and improve the accuracy in sensing objects' position. These systems can further be divided into marker-based and marker-free systems depending on the use of markers (Zhou & Hu, 2008).

The Marker-based systems use markers that are attached to the target object, such as by sticking or fixing them in place, to track the movement of the target. The advantage of this approach lies in its high accuracy (errors are typically in the millimeter range). However, a significant drawback is that other objects can easily cover the markers. If the markers are hidden by other objects, the system cannot construct a complete model (Sturman & Zeltzer, 1994). In contrast, marker-free systems rely solely on optical sensors, typically cameras, to track objects. While this eliminates the need for markers, these systems are highly sensitive to noise and highly demand on camera quality and computational performance.

Given the natures of various motion trackers, the selection of the tracking system for this study's performance testing of the SLAP prototype as a MiC lifting platform is based on the following considerations:

(a) As a MiC lifting platform prototype, the result requires relatively high accuracy.

(b) The SLAP lab prototype is small in scale, and the experimental design involves relatively simple movements, meaning the chances of markers being covered are low.

(c) The available computational resources for this study are limited, so a system that ensures accuracy without excessive computational demands is preferred.

Based on these factors, an optical motion tracking system with reflective markers is deemed the most appropriate solution for this experiment. For this experiment, the NOKOV optical 3D motion tracking system was selected. This system comprises 10 cameras with variable focus and adjustable apertures to identify and track the target. Reflective markers were attached to the surface of the SLAP prototype following the rigid body creation rules. Each moving mechanism or component was fitted with at least four non-coplanar reflective markers, commonly 5-6 marks for one rigid body. The purpose of using multiple markers is to minimize the risk of occlusion, which could result in the inability to read marker positions or the loss of rigid body tracking.

8.3.2 Experiment Design

In this experiment, to measure the prismatic joints' maximum travel distances, five evenly spaced points are selected along the Prismatic X and Prismatic Y directions. The relative pose differences between the first and last points of the module (moving part) and the hoisting frame system (stationary part) are recorded, enabling the calculation of the effective travel range. Using this range, the mass ratio between the moving and stationary parts during travel adjustments could be calibrated based on the theoretical analysis in Chapter 6.3.3. This calibration serves as the foundation for subsequent experiments on positioning and levelling accuracy.

Building on the mass ratio calibrated from the travel distance measurement, the next set of experiments evaluates the positioning and levelling accuracy of the SLAP device. For these tests, boundary-level cable-length commands are issued to the SLAP device, while the linear guide rail is moved to the maximum workspace boundary points.

The experiments evaluate two key parameters:

(a) Positional error: The difference between the module's attained and theoretical command positions.

(b) Levelling error: The roll, pitch, and yaw (rpy) angles are compared with the initial after adjustments.

These tests are critical for validating the SLAP device's ability to achieve precise positioning and levelling. The experimental procedures designed to measure these three quality indicators—travel range, positioning accuracy, and levelling accuracy—are summarized in Table 8-3. The table outlines the experimental procedures for quality (accuracy) measurement, serving as a guide for replicating and refining the evaluation process.

Experimental Procedure

The motion tracking experiment is designed to account for the laboratory environment and the features of the SLAP prototype. The experiment is divided into the following six steps:

(a) Camera Placement: Cameras are arranged around the experimental subject to capture 360-degree pose information as comprehensively as possible. See Figure 8-2 for the experimental camera setup.

(b) Software Installation: The motion tracking system software is installed and configured.

(c) Device Calibration: The cameras and system are calibrated to ensure accurate data collection (Figure 8-3 & Figure 8-4).

(d) Rigid Body Creation: Reflective markers are attached to the SLAP prototype components to define rigid bodies for the motion tracking system.

(e) Data Collection: Pose data for the SLAP prototype and its components are recorded during the experiments.

(f) Data Analysis: Collected data are analyzed to evaluate the performance of the SLAP prototype.

This methodology provides a structured approach to accurately capturing the pose data of each SLAP module, ensuring reliable results while meeting the specific requirements of the experimental setup. The designed experiment for measuring quality/accuracy performance of the prototype is listed in Table 8-3.

Figure 8-2 Motion Tracking System Set-up

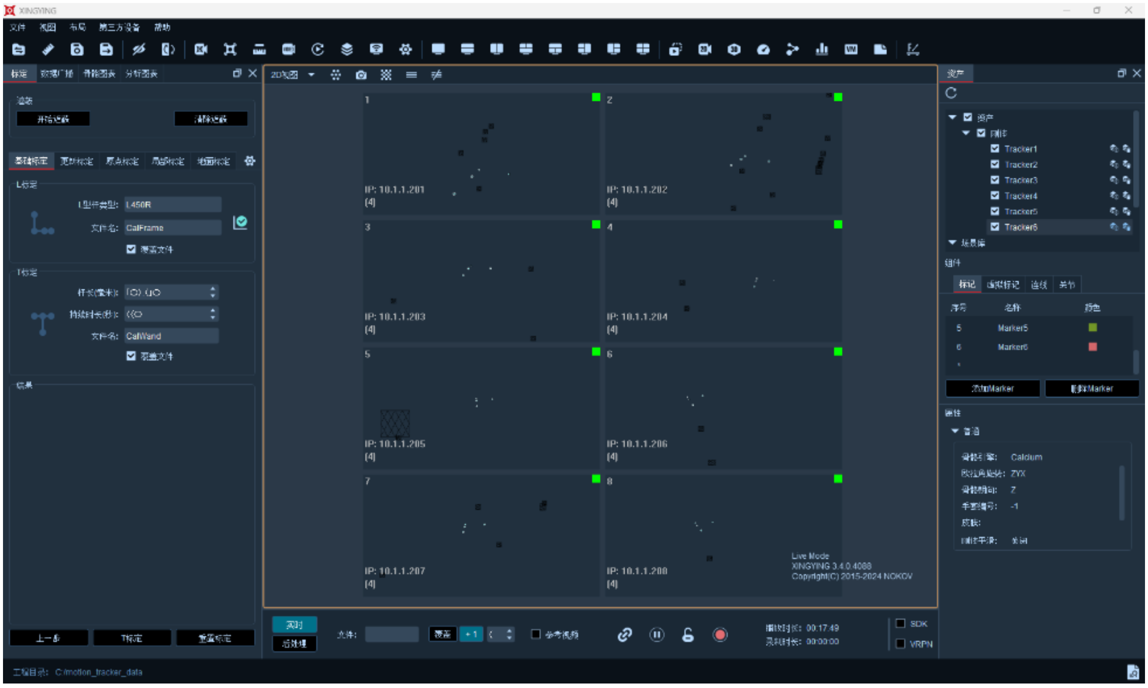


Figure 8-3 L-shaped Rod Calibration for the Motion Tracking System

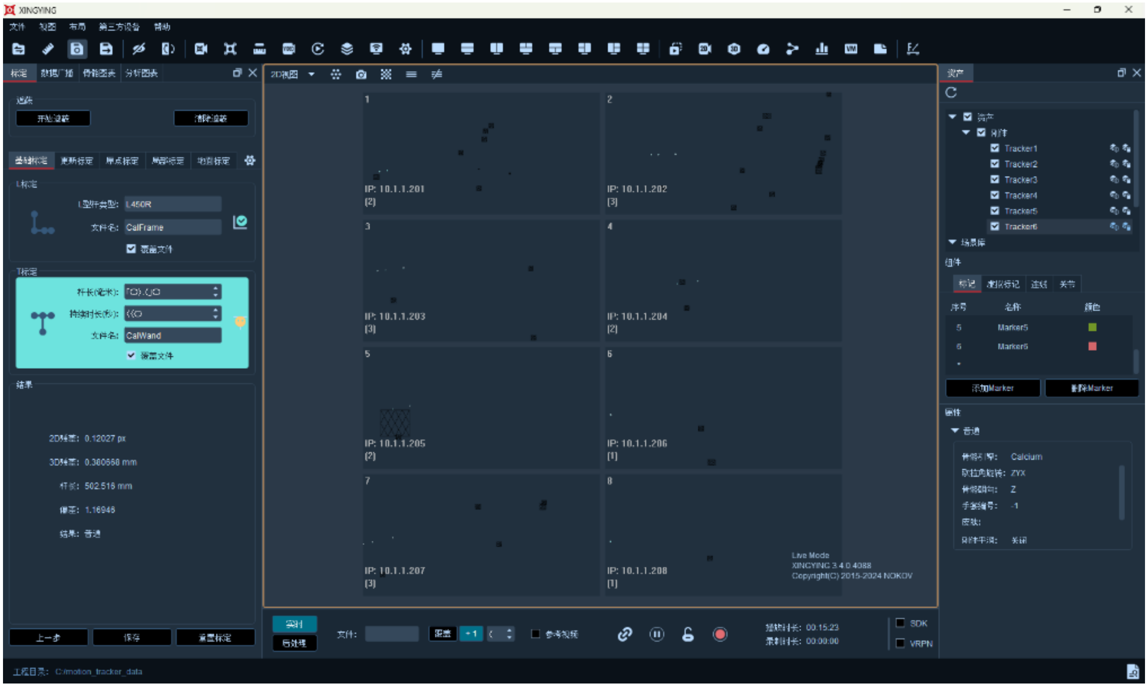


Figure 8-4 T-shaped Rod Calibration for the Motion Tracking System

Transitioning from quality to safety, the SLAP prototype undergoes safety testing in accordance with the requirements set out in CAP 59J Section 7 and its First Schedule. These regulations dictate that a 1.25 proof load must be applied when the safe working load is less than 20 tons. Since the SLAP prototype is designed to handle a safe working load of 600 kg, a proof load of 750 kg (600 kg × 1.25) is applied during the experiments. To ensure the safety of both the SLAP device and the experimental setup, load cells are installed on each cable to monitor real-time cable tension. These load cells play a vital role in detecting any sudden increases in tension that might exceed the maximum load-bearing capacity of a cable, potentially leading to failure. For this experiment, the maximum tension for each cable is set at 2000 N, ensuring that any risk of sudden cable failure is minimized. Addressing these safety requirements in the experiment design ensures that the SLAP prototype meets essential safety standards under operational conditions.

As indicated in Table 8-2, besides quality and safety, productivity is another key performance indicator for lifting platforms, particularly from end-users' perspective. This experiment measures the total time required for the SLAP prototype to complete key tasks, focusing on the time needed to reach and level at workspace boundary points. Since the boundary points represent the maximum time required for such movements, including data recording, the time for movements within the workspace is expected to be shorter. However, it is important to note that the time recorded in these experiments does not directly reflect the efficiency of a full-scale, 1:1 engineering prototype or a future industrial product. Instead, the results provide reference data to evaluate the performance of the SLAP prototype in a controlled laboratory environment. This data helps inform potential improvements and adjustments for future iterations or scaled-up designs.

The sequence of experiments, divided into Quality, Safety, and Productivity, offers a comprehensive and systematic evaluation of the SLAP prototype's performance. By addressing these three critical aspects, the study ensures the validation of the prototype's functionality while providing a detailed analysis of the operational capabilities of both the prototype and the evaluation framework/ parameters.

Table 8-3 Experiment Measurement Methods for Quality (Accuracy)

Experiment	**Measurement Indicator**	**Measurement Method**	**Remarks**
1	Effective lateral translation range module-specific)	1.Setup the motion tracking equipment, calibrate the initial position, and set the global coordinate system origin to zero.	Provides data on the module's effective travel range and mass ratio, forming the foundation for positioning and levelling accuracy tests.
		2.Divide the maximum travel distance along the Prismatic X/Y directions into 6/5 points (respectively).	
		3.Sequentially move the module along the Prismatic X/Y directions by command.	
		4.Level the module and record its pose at each point use motion tracking system.	
		5.Reverse-calibrate the mass ratio between the module (moving part) and the platform (stationary part) based on the absolute distance travelled of the prismatic joints vs. the module's rigid body (in hook coordinate system), for subsequent experiments.	
2	Lateral/ horizontal position accuracy	1.Setup the motion tracking equipment, calibrate the initial position, restart motor power, and set the global coordinate system origin to zero.	Measures the accuracy with which the module reaches its

	(Command vs. Attained)	2.Use the theoretical workspace model to identify boundary points and the initial points (parallelogram boundaries + center = five points).	target position within the workspace.
		3.Calculate the theoretical positions of these five points.	
		4.Sequentially move the module to these points, level it, and record its pose (considering coordinate system transformations to the module's local coordinate system).	
		5.Record the data and analyze the errors.	
3.	Levelling accuracy (Command vs. Attained)	1.Record the roll, pitch, and yaw (RPY) angles of the module at the four boundary points of the workspace (conducted in parallel with Experiment 2).	Conducted alongside Experiment 2 to validate levelling accuracy.
		2. Sequentially move the module to each boundary point, level it, and read the angle data.	

8.3.3 Results

1. Quality

Experiment 1 – Effective Stroke

During motion tracking system setup, Tracker 1 is assigned to the module's rigid body, ensuring accurate tracking of its motion. Table 8-4 and Table 8-5 summarize the module's position at different time intervals, focusing on positions along the X and Y directional paths. Since the X and Y directions move independently during the experiment, the positional data for each direction is extracted and analyzed separately.

X Direction

Table 8-4 Module Positions Along X-Direction Movement (Coordinates)

Time	Tx	Ty	Tz
11.47	365.42	-111.07	-718.28
14.31	400.12	-121.25	-720.51
16.08	448.93	-126.36	-722.77
18.09	501.23	-121.75	-720.67
20.24	536.69	-123.13	-717.55
22.22	603.45	-132.34	-705.89

******Tx, Ty, Tz are all in coordinates of the motion tracker frame (Universal Frame)*

Y Direction

Table 8-5 Module Positions Along Y-Direction Movement (Coordinates)

Time	Tx	Ty	Tz
46.3	485.27	-28.97	-720.22
48.32	485.72	-77.70	-721.74
50.27	485.31	-132.24	-722.97
52.45	488.94	-184.14	-720.48

54.56	490.72	-237.20	-718.47

**Tx, Ty, Tz are all in coordinates of the motion tracker frame (Universal Frame)*

The results show that, after levelling adjustments, the module achieves a maximum effective stroke of 238 mm in the X direction and 208 mm in the Y direction. These measurements clearly indicate the module’s effective travel range in both directions. The independent movement of the X and Y directions ensures that the results accurately reflect the module's capabilities, confirming its performance in meeting the design objectives.

Plotting the points of the module's rigid body, as measured along the travel paths in different directions, reveals potential relationships between these points. For the PrismaticX direction, the data is visualized in Figure 8-5, while Figure 8-6 illustrates the distribution of coordinate points for the PrismaticY direction within the coordinate system. These visualizations offer valuable insights into the module's movement patterns and help to better understand its behaviour in both directions.

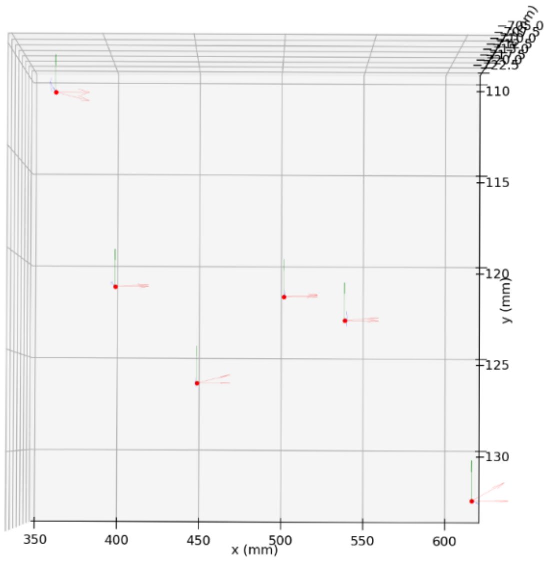


Figure 8-5 Module’s Position Along X-Direction Movement (Plot)

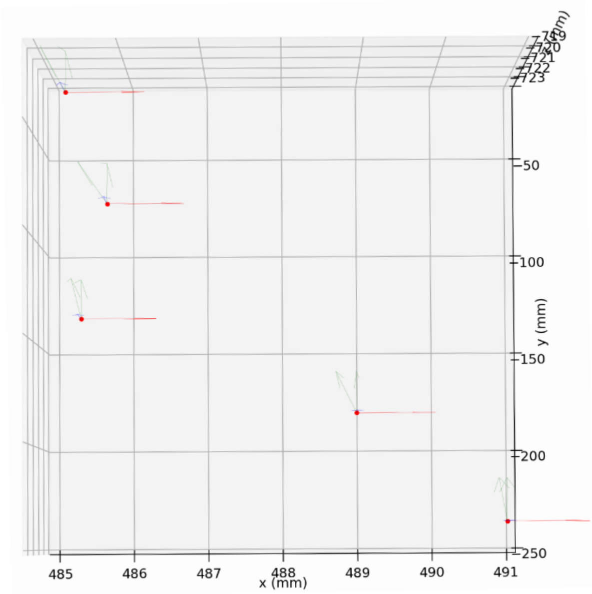


Figure 8-6 Module's Position Along Y-Direction Movement (Plot)

During the experiment, as shown in the travel plot in Figure 8-5 & Figure 8-6, it can be observed that when the SLAP system moves in one fixed axis direction, the coordinates of the other axis exhibit some fluctuations within the range of 15mm to 20mm. Considering the hardware setup and the experimental procedure, several possible causes for these fluctuations can be identified:

(a) At extreme boundary points, the platform's tilt angle is relatively large, and the initial motor commands for levelling may be more forceful, leading to slight oscillations.

(b) Minor fluctuations might also result from asynchronous tensioning and releasing of the cables during the levelling process, causing slight tilting of the platform.

These factors are likely to contribute to the observed fluctuations in the experimental data.

Figure 8-5 and Figure 8-6 reveal that the points in each direction exhibit an approximately linear relationship. To further validate this observation, the experiment evaluates the linearity of the travel stroke. For this purpose, the Pearson correlation coefficient is selected as the evaluation metric, as it serves as a widely recognized and essential tool for assessing the linear correlation between continuous variables. This metric provides a quantitative measure to confirm the linearity observed in the experimental data.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad 8-6$$

In the calculation process, Xi represents the X-coordinate value of the i-th point, $\bar{x}$ denotes the mean value of the X-coordinates, and n is the total number of coordinate points included in the analysis. The same definitions apply to the Y-series values, maintaining consistency in the analysis across both directions.

The results of these calculations show a Pearson correlation coefficient of 0.9997 for the X direction and 0.9973 for the Y direction. According to the definition of the Pearson correlation coefficient, when the value of r approaches 1, regardless of its sign, it indicates a strong linear trend among the data points, with the points distributed closely around a straight line. These results clearly confirm the high linearity of the module's travel stroke in both the X and Y directions, validating the precision of the system's movements.

In addition to evaluating linearity, this experiment also aims to calibrate the mass ratio between the moving and stationary parts of the system when the module is in motion. To achieve this, the positions of both the module and the platform are transformed into the hook coordinate system. The differences in their X and Y directions are then used to calculate the mass ratios for each direction. Through reverse calibration, the mass ratio for this experimental prototype is determined to be 1.124 in the X direction (moving to the stationary parts) and 0.7017 in the Y direction (moving to the stationary parts). These calibrated mass ratios are subsequently applied in the later workspace experiments. Using calibrated values improves the accuracy of the experimental results.

Experiment 2 – Workspace (Accuracy)

Table 8-6 presents the control results from the workspace tests of the SLAP laboratory prototype, detailing the attained pose of the module as it moves sequentially from the central starting point to four limit positions of the Prismatic X Joint and Prismatic Y Joint. The motion begins with the module traveling from the central point to the (-) Prismatic X Joint limit and the (-) Prismatic Y Joint limit. Once this position is reached, the (-) Prismatic X Joint remains stationary while the (+) Prismatic Y Joint moves approximately 184 mm to its positive range limit. The sequence then continues with the (+) Prismatic Y Joint held stationary while the (+) Prismatic X Joint moves approximately 224 mm to its positive range limit. Finally, the motion concludes as the (+) Prismatic X Joint remains stationary while the (-) Prismatic Y Joint moves back to its negative range limit. This systematic movement sequence comprehensively evaluates the module's accuracy across its workspace, ensuring that both joints are assessed under various boundary conditions.

To maintain consistency in data analysis, this study addresses the discrepancy between the coordinate origins of the theoretical model and the motion-tracking system by using displacement as the evaluation metric. Displacement is calculated as the difference between the final and starting positions, enabling a direct comparison between the command and attained poses. This approach serves as a robust and reliable method for evaluating accuracy across the SLAP's workspace, ensuring that the results are both consistent and meaningful.

Throughout this series of movements, the most significant error based on the theoretical control inputs for the command positions without levelling occurs at the Prismatic X negative limit and the Prismatic Y positive limit, where the error in the X direction reaches approximately 15.5 mm. The second-largest error is observed when both the Prismatic X and Y Joints reach their positive limits, resulting in an X-direction error of roughly 13 mm. For all other points, the errors remain within 10 mm (millimeter scale). Notably, the Prismatic Y Joint demonstrates better accuracy compared to the Prismatic X Joint, with all points except the first stay within 5 mm. This highlights the Y Joint's superior precision under the same experimental conditions.

The sources of these errors can be attributed to a combination of factors. Beyond control-related inaccuracies, the primary contributors include simplifications in the theoretical modeling process, manual measurements during the system setup, and unavoidable systematic errors in hardware fabrication. These factors collectively influence the accuracy of the system and are further elaborated in the Discussion Section to provide a deeper understanding of their impact.

Table 8-6 Comparison Between Commanded and Attained Positions (without Levelling)

Boundary Point No.	**No Levelling After Reaching Boundary**					
	Command position (mm)		Attained position (mm)		Error (mm)	
	x	y	x	y	x	y
1	-112.100	-92.632	-120.348	-83.592	8.248	-9.040
2	-112.100	92.632	-96.560	95.591	-15.540	-2.959
3	112.100	92.632	125.352	96.411	-13.252	-3.779
4	112.100	-92.632	106.134	-90.920	5.966	-1.712

This experiment incorporates local feedback control to address low-precision issues caused by non-negligible discrepancies in the model and pose measurements during open-loop motion planning, as shown in Table 8-6. To improve accuracy, the experiment first measures the roll-pitch-yaw (RPY) angular errors after the module reaches the attained position. Subsequently, a levelling procedure is performed to correct these errors. Once the levelling is complete, position data is recorded and analyzed to evaluate the error reduction, as presented in Table 8-7. The results in Table 8-7 show that, after the levelling procedure, the errors for both the Prismatic X Joint and Prismatic Y Joint (except at Point 1) are reduced to within 10 mm. Furthermore, the Prismatic Y Joint achieves remarkable accuracy, with most errors reduced to below 2 mm. This demonstrates a clear improvement in precision, particularly in the Y direction.

The results demonstrate the effectiveness of combining local feedback control with the levelling procedure to enhance motion execution accuracy. By addressing the limitations of open-loop control systems, this experiment incorporates closed-loop feedback mechanisms to improve both the accuracy and reliability of the SLAP prototype. These findings showcase the potential for such mechanisms to optimize performance and ensure consistent results in future applications.

Table 8-7 Comparison Between Commanded and Attained Positions (with Levelling)

Point No.	**Levelling After Reaching Boundary**					
	Command position (mm)		Attained position (mm)		Error (mm)	
	x	y	x	y	x	y
1	-112.100	-92.632	-127.692	-86.413	15.592	-6.219
2	-112.100	92.632	-105.607	93.836	-6.493	-1.204
3	112.100	92.632	120.653	91.281	-8.553	1.351
4	112.100	-92.632	104.268	-94.585	7.832	1.953

If zero displacement is set as the origin of a new reference frame, i.e., (0, 0), the displacements of both the command and attained positions (displacement compared with the initial position) can be represented within this coordinate frame. This approach enables a clear geometric comparison between the theoretical and actual motion outcomes. The geometric relationship between the SLAP command positions and attained positions, under direct command without feedback control, is illustrated in Figure 8-7. In contrast, the geometric relationship for the four displacements after levelling is presented in Figure 8-8. These figures visually represent how the SLAP system performs under different control conditions.

In both figures, the plane enclosed by the four extreme coordinate points represents the workspace of the SLAP system under the prototype parameter conditions. By comparing the actual workspace boundary—determined from attained positions—with the theoretical workspace boundary—calculated from command positions—the workspace error range can be identified. This comparison offers a more comprehensive evaluation of the overall workspace variation compared to analyzing the error of each individual point separately. It highlights the system's ability to execute precise motions across its entire operational range, providing insights into the alignment between theoretical and actual performance.

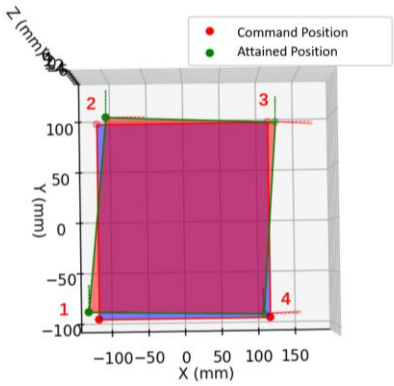


Figure 8-7 Motion Range under Command and Attained Pose (without Levelling)

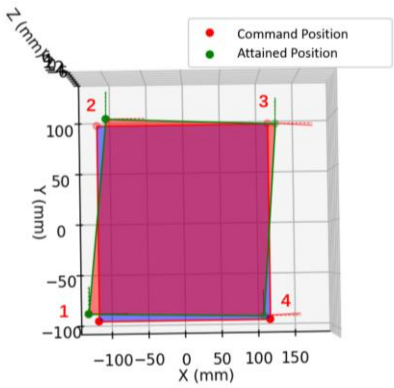


Figure 8-8 Motion Range under Command and Attained Pose (With Levelling)

Table 8-8 presents the lengths of the theoretical and actual workspace range, along with the corresponding errors observed during the experiment. The results show that the workspace remains highly stable under experimental conditions, with all errors staying within 5 mm. This stability indicates a strong alignment between the theoretical and actual workspace range, even without additional adjustments.

After applying feedback control and performing manual levelling, as shown in

Table 8-9, most edge length errors are further reduced. Specifically, the errors for three of the edges are brought within 3 mm, while the error for Edge 4-3 is minimized to just 1.3 mm. This reduction demonstrates the effectiveness of these corrective measures in enhancing precision.

Although there is an increase in error for Edge 1-4 (7.9 mm), this may be attributed to residual system inaccuracies or minor adjustments introduced during the levelling process. Nevertheless, the overall improvement in workspace edge precision highlights the critical role of feedback control and levelling procedures in improving the accuracy of the SLAP prototype's positioning function.

Table 8-8 Motion Range Comparisons (without Feedback Control)

No Levelling After Reaching Boundary			
Workspace Edge	**Theoretical length of a side (mm)**	**Actual length of a side (mm)**	**Error (mm)**
2-1	185.264	180.755	-4.509
3-2	224.199	221.913	-2.286
4-3	185.264	188.313	3.049
1-4	224.199	226.600	2.401

Table 8-9 Motion Range Comparisons (with Feedback Control)

Levelling After Reaching Boundary			
Workspace Edge	**Theoretical length of a side (mm)**	**Actual length of a side (mm)**	**Error (mm)**
2-1	185.264	181.597	-3.667
3-2	224.199	226.275	2.075
4-3	185.264	186.587	1.323
1-4	224.199	232.104	7.905

Experiment 3 – RPY Levelling Angle Error (Accuracy)

Since Experiment 3 is an independent process from Experiment 2 and can be carried out immediately after each step of Experiment 2, it is possible to conduct both experiments concurrently to improve overall experimental efficiency. This experiment records the RPY angles (Roll, Pitch, Yaw) at the center point (initial) and the four extreme boundary points using a motion tracker and IMU. To establish a consistent reference, the RPY angles at the center point are set as the benchmark.

Table 8-10 presents the RPY angle differences between the boundary points (upon reaching the command positions) and the origin. The results show that the roll angles (R, around the X-axis) at all four points are less than 1 degree, while the pitch angles (P, around the Y-axis) are approximately 1 degree. These values indicate a reasonable level of accuracy in the initial positioning. To further improve precision, the system executes a feedback levelling procedure based on the detected angle differences. As shown in

Table 8-11, the levelling process achieves significant reductions in angle errors. Specifically, the roll angle (R) errors at Point 2 and Point 3 are reduced to less than 0.1 degrees, and the pitch angle (P) errors across all points are brought within 1 degree. These results demonstrate the effectiveness of the levelling procedure in optimizing the SLAP system's angular accuracy.

However, the levelling command in this procedure is specifically designed to adjust angles relative to the X-Y plane (horizontal surface). Consequently, the yaw angle (Y, around the Z-axis) remains largely unchanged before and after levelling, staying stable within a range of 1-2 degrees. While the results confirm the SLAP device’s strong levelling capability for roll and pitch angles, the consistent yaw angle error suggests the current levelling strategy could be further investigated. This highlights the need for additional consideration or for the development of a separate control approach to address potential Z-axis adjustments, if required.

Table 8-10 Angular Discrepancies Among Different Boundary Points (without Levelling)

Point No.	No Levelling After Reaching Boundary		
	Error (degree)		
	r	**p**	**y**
1	0.006	-1.162	-0.906

2	-0.813	-0.794	-1.655
3	-0.389	0.748	2.364
4	0.286	1.292	2.067

Table 8-11 Angular Discrepancies Among Different Boundary Points (with Levelling)

Point No.	Levelling After Reaching Boundary		
	Error (degree)		
	r	**p**	**y**
1	0.140	-0.551	-1.801
2	-0.037	0.438	-2.943
3	0.043	0.420	1.394
4	0.296	0.966	1.059

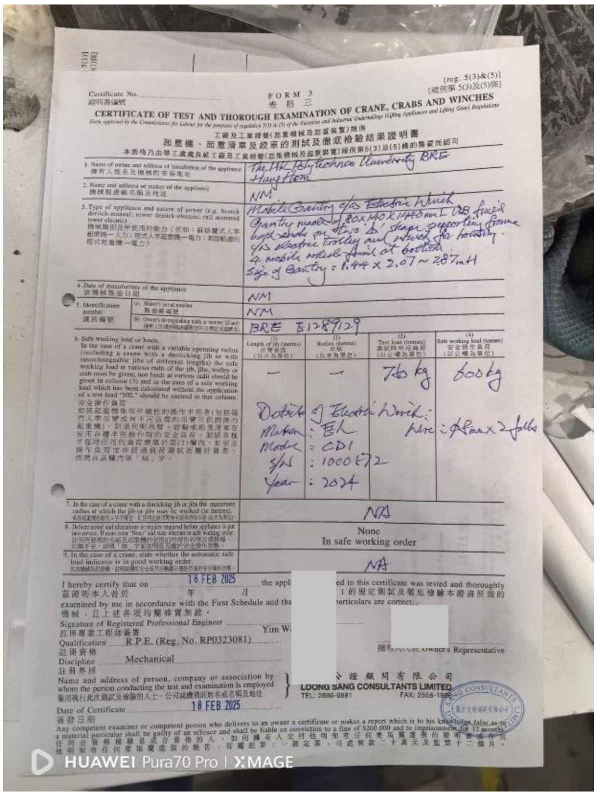
2. Safety

According to CAP 59J regulations, when the safe working load is less than 20 tons, the proof load must reach 1.25 times the safe working load. For this prototype, the safe working load is 600 kg, which sets the required test load to 750 kg. To meet this requirement, 30 bags of cement, each with a nominal weight of 25 kg, are selected as the payload. The total weight is verified and certified by an independent notary's office to ensure accuracy and compliance.

During the static load test, the payload is hoisted and held stationary for three minutes. Throughout the test, the structure sustains the load without any signs of damage, deformation, or instability. This result validates the device's ability to handle its designated safe working load and ensures that it meets the necessary safety standards for experimental use. In addition to the static load test, dynamic load tests are conducted to simulate real-world operational conditions and further confirm the safety and stability of the prototype in parallel. With the same 750 kg payload, the device undergoes controlled vertical and horizontal movements, including upward, downward, leftward, and rightward directions. These motions are executed reliably, and the structure maintains its stability without any deformation, cracking, or structural failure.

The successful completion of both static and dynamic load tests demonstrates that the prototype meets the safety requirements of CAP 59J. Furthermore, the results confirm the device's operational reliability and stability under various loading conditions, providing confidence in its safety and performance during real-world applications.

Figure 8-9 Static Load Testing (750kg)



[reg. 5(3)&(5)]
[規例第 5(3)及(5)條]

Certificate No. ....

FORM 3
表格三

CERTIFICATE OF TEST AND THOROUGH EXAMINATION OF CRANE, CRABS AND WINCHES

起重機、起重滑車及絞車的測試及徹底檢驗結果證明書

1. Name of owner and address of installation of the appliance	The HK Polytechnic University BRE Hung Hom
2. Name and address of maker of the appliance	NM
3. Type of appliance and nature of power (e.g. Scotch derrick-manual; tower derrick-electric; rail mounted tower-electric)	Mobile Gantry c/w Electric Winch ... 4 mobile wheels fixed at bottom. Size of Gantry: 1.44 x 2.07 ~ 2.87m H
4. Date of manufacture of the appliance	NM
5. Identification number (a) Maker's serial number	NM
(b) Owner's distinguishing mark or number (if any)	BRE E1289129

6. Safe working load or loads	(1) Length of jib (metres)	(2) Radius (metres)	(3) Test load (tonnes)	(4) Safe working load (tonnes)
	—	—	750 kg	600 kg

Details of Electric Winch:
Maker: 巨人
Model: CD1
S/N: 1000E72
Year: 2024

7. In the case of a crane with a derricking jib or jibs the maximum radius at which the jib or jibs may be worked (in metres).	NA
8. Defects noted and alterations or repairs required before appliance is put into service. If none enter 'None' and state whether in safe working order.	None In safe working order
9. In the case of a crane, state whether the automatic safe load indicator is in good working order.	NA

I hereby certify that on 18 FEB 2025 the appli... ed in this certificate was tested and thoroughly examined by me in accordance with the First Schedule and tha... particulars are correct.

Signature of Registered Professional Engineer .... Yim W...

Qualification R.P.E. (Reg. No. RP0323081)

Discipline Mechanical

Owner's Representative

Name and address of person, company or association by whom the person conducting the test and examination is employed: LOONG SANG CONSULTANTS LIMITED TEL: 2896-8881 FAX: 2558-1996

Date of Certificate 18 FEB 2025

Any competent examiner or competent person who delivers to an owner a certificate or makes a report which is to his knowledge false as to a material particular shall be guilty of an offence and shall be liable on conviction to a fine of $200,000 and to imprisonment for 12 months.

HUAWEI Pura70 Pro | XMAGE

Figure 8-10 Certificate - Test and Thorough Examination of Crane, Crabs and Winches

3. Productivity

The productivity test of the SLAP system, as designed, is conducted in conjunction with Experiments 2 and 3 to optimize experimental efficiency. The primary objective of this test is to evaluate the system's total time consumption during transitions from the initial point to the four boundary points of the workspace. To address system errors that arise during motion planning and execution, a feedback compensation mechanism is applied upon reaching each target position. This comprehensive test includes necessary actions to achieve precise positioning, such as post-levelling error compensation, ensuring a thorough assessment of the system's performance.

To maintain consistency and eliminate potential discrepancies caused by variations in individual trials, the total time recorded for the productivity test is based on a single-cycle experiment. This cycle involves sequentially moving from the initial (center) point to each of the four boundary points. In Experiment 2, the total time required to complete this process, including levelling at each boundary point, is recorded as 20 minutes. This indicates that the system requires approximately 5 minutes to transition to and stabilize at target boundary point. The recorded time encompasses multiple components: the time for the SLAP prismatic joints to drive the module to the designated position, the time for the cable-driven system to perform levelling adjustments, the stabilization period after reaching the target position, and the manually recorded data collection time.

Stabilization of the module is determined by monitoring the roll (R) and pitch (P) angle readings from the IMU, see Figure 8-11. The module is considered stable when the rate of change for both angles falls below 0.12 deg/s (the minimum data IMU could record). At this point, data recording begins to ensure accurate measurements. By integrating motion planning, feedback-based levelling, and stabilization processes, the SLAP system demonstrates reliable performance within an efficient time frame. These results highlight the system's ability to achieve high productivity in workspace operations while maintaining precision and consistency.

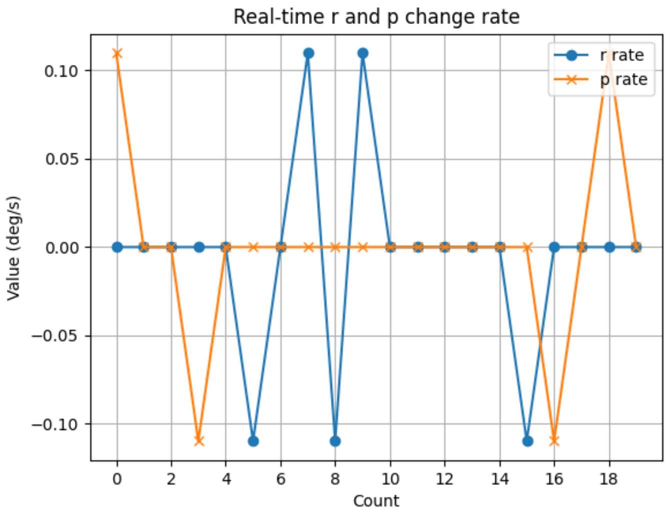


Figure 8-11 Angular Changing Rate Monitoring in Stabilization Process

8.3.4 Discussions

To comprehensively assess the SLAP system, this section evaluates its performance across three key aspects: Quality, Safety, and Efficiency. The findings in each area are summarized below.

1. Quality

The experiments first measure the effective stroke of the Prismatic X and Prismatic Y directions based on design specifications and experimental data. The results reveal that the effective travel range for the module is 238mm in the X direction and 208mm in the Y direction. These distances ensure that the module can travel more than 200mm in both directions, facilitating precise positioning within this range. For a module with a 500mm x 500mm projection designed in the SLAP lab prototype, the travel distance in the X direction accounts for 47.6% of the module's size, while the Y direction accounts for 41.6%. In practical construction applications, the travel range ratio is expected to be lower than these laboratory results, depending on factors such as the mass ratio between the hoisting system and the module, as well as the size of the hoisting frame. However, this travel range remains comparable to the manual movement required for module positioning during MiC installations, including during practical application.

After reverse-calibrating the mass ratio, the prototype's effective workspace boundaries are further refined. The boundaries in the Prismatic X and Y directions are measured precisely at 224.3mm and 184.5mm, respectively. The error between the theoretical command and actual attained positions is reduced to less than 5mm. After employing closed-loop feedback levelling, the error at most points is further minimized to within 3mm, except for one outlier caused by motor error, which resulted in a 7.9mm deviation. These results meet the accuracy requirements for MiC installations in the local construction market.

The SLAP prototype also achieves excellent levelling performance after lifting objects. With open-loop control commands, the module's roll (r) and pitch (p) angles are maintained at approximately ±1°. When closed-loop feedback control is applied, these angles are further reduced, consistently staying within ±1°, some even below 0.1°. This performance meets the levelling accuracy required for practical construction applications.

2. Safety

To ensure hardware safety, the SLAP prototype undergoes both dynamic and static load testing in accordance with Hong Kong’s statutory requirements. Specifically, the tests adhere to CAP 59J Section 7 and the First Schedule, which mandate that the proof load exceeds the safe working load by at least 25%. The SLAP prototype, therefore, undergoes rigorous load testing to validate its compliance with these safety standards.

To further enhance safety during testing, load cells are installed on each cable to monitor real-time cable tension. These load cells prevent sudden tension spikes that could exceed the cable’s maximum load capacity of 2000N, thereby mitigating the risk of cable failure.

Beyond laboratory testing, the SLAP prototype significantly reduces risks associated with working at height and the manual effort required to position MiC modules. This improvement is particularly critical during the final stages of MiC positioning and installation, where heavy loads and large-scale operations pose substantial safety challenges. By minimizing these risks, the SLAP system contributes to safer construction workflows.

3. Efficiency

Efficiency is a critical performance indicator for lifting platforms in practical applications. Currently, the average time required for lifting and positioning a MiC module is approximately 30 minutes. In laboratory tests, the SLAP prototype demonstrates the ability to accurately position and level a module at a workspace boundary point within 5 minutes.

Although this result reflects the performance of a laboratory-scale prototype rather than a full-scale industrial device, it provides valuable insights into the potential efficiency of the SLAP system. The 5-minute duration includes all manual operations that may not be included in practical construction, such as issuing commands, monitoring vibrations, and recording data. Despite these additional steps, the prototype achieves precise positioning within this timeframe. For future industrial prototypes, automating data collection and vibration monitoring processes could further reduce the positioning and levelling time to under 3 minutes, offering even greater efficiency.

4. Limitations and Future Work

While the SLAP system demonstrates promising performance, this study acknowledges certain limitations that could be addressed in future iterations of the prototype and its industrial-scale counterparts.

One significant consideration is the presence of errors in the system. Since the SLAP prototype is currently semi-automated, human involvement introduces operational errors. Additionally, the manual measurements and assembly processes used in constructing the laboratory prototype result in systematic errors that are challenging to eliminate. While many of these errors are mitigated during experiments through adjustments and compensations, their root causes provide valuable insights for future research and development.

A comprehensive summary of potential experimental errors and corresponding mitigation strategies is presented in Table 8-12. These findings lay the groundwork for addressing challenges in future prototypes, ensuring continued improvements in the SLAP system's design, accuracy, and performance.

Table 8-12 Analysis of Potential Errors in Experiments

	Error Source	**Cause Analysis**	**Mitigation Strategy**
1	Measurement errors in tape measure readings of cable lengths and hook lengths	The tape measure has inherent errors, especially when measuring cables inside the system, where obstructions may affect accuracy.	Design the cable-driven workspace to be larger than the Linear Guiderail workspace, ensuring full utilization of the guide rail's stroke and reducing dependency on manual measurements.

2	Calibration inaccuracies due to misalignment of the L-shaped rod to the platform	1. The L-shaped rod cannot be perfectly aligned with the platform due to placement issues, and the platform itself may have slight installation discrepancy. 2. The L-shaped rod lacks a reference point to the platform, making it difficult to ensure alignment with the Prismatic Joint direction.	Use a spirit level to calibrate the platform before positioning the L-shaped rod to ensure proper alignment and minimize installation discrepancies.
3	The CoMs of the X/Y axis guiderail and module might not align with their geometric centers	Manufacturing tolerances, counterweight placement, and installation errors may cause slight mismatches between the geometric center and the actual CoM.	Ensure precise assembly and alignment during installation to minimize mismatches between the geometric center and the CoM.
4	Discrepancies between theoretical and actual models	Theoretical models are simplified (e.g., using straight lines), but real-world systems include additional elements such as pulleys, which introduce deviations from the ideal model.	Use the IMU to measure real-time inclination and apply corrections to compensate for discrepancies between the theoretical and actual models
5	Prismatic joints may rotate slightly along the Z-axis during movement	Movement introduces vibrations, and external factors like environmental vibrations or wind may cause the whole system slightly rotate along Z axis.	Project the coordinates into a unified coordinate system during calculations to mitigate the effects of rotational discrepancies along the Z-axis.

In addition to the systematic errors analyzed above, several limitations in the hardware and control design of this first-generation laboratory prototype are identified. As this prototype represents an initial attempt to validate the hardware design, certain imperfections in its structure and control system are expected. These limitations highlight areas for improvement in future research and subsequent iterations of the prototype.

The structural and control design shortcomings contribute to deviations observed in multiple experiments. For instance, during the Y-axis effective stroke experiment, the maximum fluctuation is approximately 20mm. However, in the workspace range tests, the error is reduced to 10mm or less. These discrepancies are primarily attributed to two factors. First, the weight of the Z-axis motor cannot be neglected, which causes slight rotation of the system during module movement, introducing positional inaccuracies. Second, the mass ratio used in the effective stroke experiment is based on manual measurements, which inherently include errors. To address this, the mass ratio is reverse calibrated using the measured travel distances from the effective stroke experiment. This calibrated mass ratio is then applied in the workspace experiments, reducing errors and improving overall accuracy.

As mentioned above, one of the most critical factors contributing to errors is the weight of the Z-axis rotation motor. This issue is particularly evident in the effective stroke and workspace range experiments. For example, as illustrated in Figure 8-7 and Figure 8-8, the scattered data points in the bottom-left corner of the attained positions are directly caused by the motor's weight. Additionally, the absence of a feedback loop in the Z-axis rotation mechanism exacerbates the problem. This design limitation results in more pronounced yaw (Y) errors than roll (R) and pitch (P) errors. After levelling, the yaw angle error reaches a maximum of -2.9°, underscoring the need for feedback control in future iterations to mitigate rotational inaccuracies.

Another significant challenge encountered during the experiments is the time required for vibration damping after the module moves. Currently, stability detection and data capture are performed manually. Stability is determined by monitoring the IMU readings and ensuring the angular velocity remains below 0.12 degree/s (with the IMU’s minimum detectable change being 0.006°). These manual processes are time-consuming and introduce variability due to human involvement. To address this issue, future iterations of the prototype will incorporate automation for stability detection and data capture. Eliminating manual intervention will significantly reduce the time required for positioning, levelling, and stability detection. While the current process takes approximately 5 minutes, with automation, this duration could be reduced to less than 3 minutes or even faster.

In summary, the SLAP laboratory prototype successfully validates the proposed measurement methods and performance indicators, demonstrating its ability to meet the quality, safety, and efficiency requirements for MiC installations. However, it is important to acknowledge that the results are still at the laboratory stage. Key differences exist between the lab prototype and real-world applications, such as the mass ratio between the platform and the module and the absence of external disturbances like lateral wind forces. Addressing these challenges, including incorporating enhanced sway damping in future works and ensuring mechanical accuracy, calibration precision, and high-frequency control, is crucial for future on-site applications. Despite these limitations, the findings provide valuable insights for further refinement and optimization of the system, laying a strong foundation for future research and industrial implementation.

8.4 Summary of Chapter

This Chapter first presents a comprehensive evaluation framework for the MiC lifting platform, integrating a detailed review of the academic literature, international ISO standards, and Hong Kong local regulations and guidelines. The objective is to identify suitable parameters for assessing MiC lifting platforms. Based on this analysis, four major evaluation categories—Quality, Safety, Productivity, and Robustness (Robustness is included in Safety in the later experiment)—were identified, along with eight detailed indices. These evaluation metrics are carefully aligned with the conclusions from the literature review and expert interviews conducted in Chapter 4, forming a robust theoretical framework and methodological foundation for the subsequent experimental investigations.

Building on this foundation, a meticulously designed laboratory prototype validation was conducted to validate both the proposed evaluation method and the overall performance of the SLAP system. The experimental setup was tailored to closely simulate real-world operating conditions and evaluate the system's capabilities in terms of quality (accuracy), safety, and productivity. In anticipation of potential system errors, particular attention was given to incorporating feedback compensation mechanisms, ensuring that discrepancies during motion planning and execution were addressed effectively. This proactive design approach enhanced the reliability of the experimental results.

The results of the experiment are then presented and critically analyzed. The findings demonstrate the SLAP system's effectiveness in achieving precise positioning, validating its performance across multiple metrics. Additionally, the analysis identifies areas for improvement, including the Z-axis motor weight and the need for yaw angle compensation. These limitations are acknowledged as opportunities for refinement rather than fundamental flaws, reinforcing the potential for further optimization. The discussions also highlight the crucial role of feedback compensation mechanisms, particularly in correcting post-levelling errors, which significantly contribute to the system's overall precision and reliability.

In conclusion, this Chapter achieves two key objectives. First, it develops and validates a customized evaluation framework for assessing MiC lifting platforms, integrating insights from academic literature, industry standards, and local regulations. This framework, consisting of tailored measurement methods and performance indicators, provides a robust theoretical basis for evaluating MiC lifting systems in terms of quality, safety, productivity, and robustness. Second, the framework is successfully applied to assess the SLAP system through experimental testing, demonstrating its effectiveness as a reliable and precise mechanism for MiC lifting tasks. The experimental results highlight the system's advantages in quality, safety, and efficiency, while identifying minor limitations, such as Z-axis motor weight and yaw angle compensation, which can be addressed through future refinements.

Together, the evaluation framework for MiC lifting platforms and its successful application to the SLAP laboratory prototype lay a solid foundation for advancing semi-automated solutions, and eventually fully automated solutions, in the MiC lifting domain. The promising experimental results underscore the SLAP system's potential for broader applications in MiC lifting tasks, paving the way for future innovations in this field.

Chapter 9 Conclusions

9.1 Summary of Findings

This research systematically addressed the critical scientific problem of improving safety performance in MiC lifting operations. By tackling four closely related research questions, this study identified safety risks, proposed innovative semi-automated solutions, and validated their feasibility through a combination of theoretical and experimental approaches. The findings, derived from the analyses and solutions presented in Chapters 4 to 8, are summarized below and reflect the key contributions of this research.

Objective (a): To identify and analyze the key safety risks in MiC lifting operations across different stages, and to determine specific, measurable gaps that can be addressed through technological solutions.

Q1. What are the critical safety risks in MiC lifting operations, and how can they be systematically identified and prioritized?

Chapter 4 employed a structured methodology combining both qualitative and quantitative analyses to identify and prioritize safety risks in MiC lifting operations. First, a semi-structured interview approach was adopted, engaging two groups of experts with experience in MiC and crane operations. These interviews were supported by NASA-TLX-based questionnaires to elicit structured feedback on safety risks and their relative importance. This qualitative approach ensured a detailed understanding of expert perspectives on key safety concerns. To enhance data reliability, a two-sided Grubbs test was performed to identify and exclude outliers, thereby strengthening the credibility of the findings.

Building on the qualitative insights, quantitative methods were employed to validate and rank the identified safety risks. MCA and FMEA were applied to a dataset comprising 95 crane-related accident cases in Hong Kong. These methods provided a systematic, data-driven means of determining the most critical risks based on their relative likelihood and impact. Through this rigorous mixed-methods approach, the study identified nine major safety risks, including poor communication, operator non-proficiency, inadequate site information, and adverse weather conditions. By grounding the findings in both expert input and real-world accident data, this Chapter ensured that the identified risks were not only comprehensive but also prioritized effectively for practical application in addressing safety challenges in MiC lifting operations.

Q2. How do safety risks vary across different operational stages of MiC lifting, and how can they be broken down into actionable problems?

A major finding of Chapter 4 was the breakdown of the MiC lifting process into six operational stages: module arrival, hooking, levelling, lifting, placing, and alignment. This stage-specific analysis revealed how crane-related safety risks vary and interact across different phases, providing a deeper understanding of safety challenges in MiC lifting operations. For instance, manual involvement during module hooking and alignment was found to increase fall hazards and alignment errors, whereas poor visibility and adverse weather conditions during lifting amplified the risk of accidents.

After detailing the risks within each stage and analyzing their operational features, the study categorized these risks into three broad groups:

1. Reliance on human attentiveness: Key tasks, such as hooking, alignment, and placement, rely heavily on operator skill and concentration, increasing the likelihood of errors and safety hazards.
2. Poor working environments: External factors, such as inadequate visibility, adverse weather, and tight working spaces, intensify safety risks and operational difficulties.
3. Time-consuming tasks: Precision-intensive processes, including module positioning and final alignment, remain labor-intensive and inefficient, leading to delays and increased pressure on workers.

However, not all risks in these categories can be directly addressed through technological solutions. To develop actionable and practical interventions, these risks were further analyzed and abstracted into specific, technology-solvable problems. This process involved isolating the core operational challenges within each risk category and translating them into measurable and addressable issues.

By abstracting these risks into solvable technological problems, the study proposed the following actionable items to guide the development of solutions:

1. Free people from on-site environments: Technologies should reduce or eliminate the need for workers to physically operate in hazardous areas during MiC lifting operations.

2. Automatically control the module's roll, pitch angular error, and yaw axis rotation: Automation should handle angular adjustments with precision, minimize manual interventions, and ensure a safer, more accurate module alignment.
3. Automatically control the module's X/Y movement: Systems should enable precise automatic control of horizontal movements, improving both efficiency and positioning accuracy.

By categorizing risks, identifying critical gaps, and translating them into actionable items, this chapter established a strong foundation for the development of semi-automated solutions to enhance the safety, precision, and efficiency of MiC lifting operations.

Objective (b): To design, develop, and validate a Semi-automated Lifting Adjustment Platform (SLAP) capable of mitigating the identified risks and improving the safety, efficiency, and accuracy of MiC lifting operations.

Q3. What innovative semi-automated or automated solutions can be developed to mitigate actional problems identified from the safety risks in MiC lifting?

Chapters 5 through 7 addressed the research gaps identified in Chapter 4 by proposing, designing, and validating the SLAP system. This integrated platform comprises three core modules:

1. HSCM (Horizontal Steering Control Module): Automates module rotation and horizontal steering, eliminating manual rope pulling in poor visibility or adverse weather, reducing physical risks, and enhancing operational safety.
2. TCM (Translation Control Module): Enables automated horizontal movement and precise alignment, preventing workers from manually pushing modules, reducing collision risks, and significantly improving positioning accuracy.
3. LCM (Levelling Control Module): Automates both gross and fine levelling adjustments, maintaining module stability by addressing uneven cable tension to avoid cable breakdown.

Chapter 5 focused on the conceptual design of the SLAP system, detailing how its modular framework addresses the safety risks identified in Chapter 4. By integrating sensor-driven automation and control mechanisms, the SLAP system significantly reduces human involvement in hazardous tasks, such as module alignment and placement, while enhancing operational precision.

Chapter 6 developed the control mechanisms, logic, and user interface for the SLAP system, ensuring seamless integration with existing crane machinery. The control design emphasized achieving precise 6-DoF control for module movement without requiring significant modifications to traditional lifting equipment. Additionally, configuration morphing was introduced to provide the foundation of the whole system.

Chapter 7 implemented the SLAP system as a scaled prototype, measuring 2.8m in height and 1.4m in width, and conducted validation experiments in a controlled lab environment. The prototype demonstrated significant improvements in safety and precision, including:

- Levelling adjustments within 20 seconds for prismatic joint movements of ±15 cm (X-axis) and ±10 cm (Y-axis).
- Over 80% reduction in tilt through the combined operation of the LCM and TCM.
- Millimeter-level positioning accuracy was attained, validating the feasibility of deploying the system in real-world scenarios.

These findings validated the system's ability to address key research gaps, demonstrating its potential for precise levelling and positioning in modular construction, and laid the groundwork for evaluating its real-world performance in Chapter 8.

Having developed and implemented these innovative solutions, the study proceeded to Research Question (d), which established a framework for assessing the performance of automated MiC lifting systems and adopted it to evaluate the effectiveness of the lab prototype. This evaluation was crucial to validating the proposed solutions and ensuring their applicability in real-world MiC lifting scenarios.

Objective (c): To assess the practical performance of the SLAP system using a systematic evaluation framework based on industry practices and measurable parameters for safety, efficiency, and productivity

Q4. How can the performance of the proposed solutions be systematically validated to ensure their effectiveness and performance in MiC lifting scenarios?

Chapter 8 successfully developed and applied a comprehensive validation framework to evaluate the performance of the SLAP system in real-world MiC lifting scenarios. The evaluation assessed critical parameters such as safety, accuracy, and productivity, providing quantifiable evidence of the system's effectiveness. While the results from the lab prototype cannot be directly compared to industry requirements due to differences in testing conditions and reference standards, the findings provide valuable insights and demonstrate the potential of the SLAP system to address on-site challenges effectively. Key findings as:

• Safety: The SLAP system complied with statutory load requirements, with dynamic and static load tests exceeding the safe working load by 25%. Real-time monitoring of cable tensions further ensured operational safety by detecting and preventing potential failures. These features, combined with a completely hands-off operation for the operator, significantly enhance safety by removing personnel from hazardous lifting zones.

• Accuracy: The SLAP system demonstrated remarkable precision. Even without visual assistance for closed-loop feedback, horizontal positioning accuracy consistently reached ±3 mm, comparable to industry requirements. For tilt correction, the system adjusted roll angles from within 5° to under ±0.1° and pitch angles to under ±1°, achieving stability and precision that meet industry standards. The system's effective workspace travel ranges of 238 mm in the X direction and 208 mm in the Y direction covered 47.6% and 41.6% of the module's size, respectively, demonstrating its adaptability to typical MiC module dimensions.

• Efficiency: The SLAP system streamlined the lifting process, reducing the time for moving, positioning, and levelling a module to less than 5 minutes. This is a significant improvement compared to manual methods, where levelling alone typically takes 20–25 minutes. By automating the process, the system not only saves time but also eliminates the need for operators to physically handle the module or lifting frame, further enhancing safety and efficiency.

Although these are laboratory results, similar performance can be achieved in industry practice by addressing key factors: incorporating sway damping mechanisms to counteract environmental disturbances such as lateral wind forces in future work, and implementing strict calibration protocols and high-frequency control systems to ensure precise and stable operation under dynamic on-site conditions.

These findings demonstrate the SLAP system's ability to address the critical scientific problem of how a novel semi-automatic solution can be developed and validated to systematically resolve the intertwined safety and practical applicability challenges in MiC lifting operations. Although the lab results are not directly comparable to industry requirements, they provide a strong foundation for refining the system for on-site use. The research findings highlight the SLAP system's contribution to closing the gap between theoretical advancements and real-world implementation, showcasing its potential to transform MiC lifting practices. The validation framework further establishes a robust tool for evaluating and improving future automated lifting technologies, ensuring continued advancements in safety, precision, and operational performance.

9.2 Contributions

This research contributes to both academic understanding and practical advances in MiC lifting technologies, addressing safety, efficiency, and quality challenges in MiC lifting operations.

9.2.1 Contributions to Knowledge

This research advances the theoretical framework by introducing new insights and perspectives through systematically identifying and prioritizing safety risks in MiC lifting operations, design, development, and validation of the semi-automated solution to mitigate the MiC lifting risks. The SLAP system itself addresses critical knowledge gaps by providing an innovative, integrated solution to long-standing challenges in MiC lifting, including safety hazards, operational inefficiencies, and precision bottlenecks.

1. Systematic Identification of Safety Risks in MiC Lifting Operations

A key theoretical contribution of this research lies in addressing the lack of a structured and systematic approach to identifying and categorizing safety risks in MiC lifting operations. While existing studies on MiC safety are abundant, they are often fragmented or limited to individual case studies. This research begins with a thorough literature review, is validated by experienced operators, and culminates in a quantitative analysis of 95 local cases in Hong Kong. These efforts systematically identify and classify stage-specific safety risks across the six operational phases of MiC lifting, filling a critical gap in the understanding of safety challenges in the field.

2. Proposing the SLAP System as a Novel Methodology

The SLAP system represents a groundbreaking contribution to the knowledge base by introducing a structured methodology to mitigate the identified risks and improve MiC lifting performance. Unlike existing manual or semi-automated systems, which often rely on fragmented or ad hoc solutions, the SLAP system delivers a holistic approach by integrating multiple advanced functionalities, including the HSCM, TCM, and LCM. These modules are designed to automate critical lifting tasks, such as module rotation, horizontal positioning, and levelling adjustments, thereby addressing specific risks identified in the study.

The SLAP system's design is rooted in rigorous theoretical principles, incorporating state-of-the-art sensor fusion algorithms, real-time feedback mechanisms, and advanced control strategies to ensure precision and stability. This research answers a critical scientific question: "How can a novel semi-automatic solution be developed and validated to systematically resolve the intertwined safety and practical applicability challenges in MiC lifting operations?" By developing and proposing the SLAP system, this study not only fills a gap in the existing knowledge system but also establishes a new benchmark for MiC lifting automated technologies.

3. Bridging the Gap Between Theory and Application Through Validation

The third theoretical contribution lies in the validation of the SLAP system's practical feasibility through a systematic evaluation framework. This framework, designed to assess safety, efficiency, and productivity, incorporates measurable parameters such as positioning accuracy (errors of 3mm or less), roll/pitch angles (controlled within ±1°), and alignment time (reduced from 30 minutes to 5 minutes). The validation process bridges the gap between theory and practice by rigorously evaluating the SLAP system under industry-relevant conditions and parameters. The systematic evaluation framework contributes to the theoretical understanding of how automated systems can be assessed in realistic construction scenarios, offering a replicable model for future studies.

4. Advancing the MiC Lifting Knowledge System

The SLAP system goes beyond incremental improvements for human behaviors, offering a paradigm shift in how MiC lifting risks are mitigated and performance is enhanced. This research contributes to the broader knowledge system by demonstrating how a well-designed, semi-automated solution can simultaneously address safety risks during the lifting together with other challenges, such as inefficiency and inaccuracy. The SLAP system and its validation framework serve as a foundation for future advancements in automation development and digitalization of construction processes, inspiring further exploration of AI-driven and fully autonomous solutions.

9.2.2 Contributions to Practice

The study also delivers practical contributions that address pressing challenges in the construction industry, particularly in the context of MiC lifting operations:

1. Enhanced Safety Performance

The SLAP system provides a practical solution to improve MiC lifting operation safety. The prototype significantly reduces risks associated with manual lifting tasks, such as work-at-height accidents and uncontrolled load movement, ensuring safer working conditions on construction sites.

2. Reduction in Manual Labor and Fatigue

The SLAP system demonstrates how semi-automation can alleviate the physical demands on workers by reducing the need for manual involvement during module positioning and levelling. This improves operational efficiency and reduces worker fatigue, especially for tasks requiring sustained precision and effort, such as large-scale MiC module installations, which currently rely heavily on extensive physical work.

3. Improved Efficiency in Lifting Operations

The SLAP prototype significantly enhances productivity by reducing the time required to position and level MiC modules. The 5-minute positioning time demonstrated in laboratory tests represents a sixfold improvement compared to traditional methods, providing a clear advantage for contractors working under tight project schedules. This improvement in efficiency directly translates to cost savings and faster project delivery.

4. Foundation for Future Industry Innovation

The SLAP system, the validation framework and experimental findings establish a strong foundation for advancing innovation in MiC lifting technologies.

The design and the prototype of the SLAP system provide a blueprint for developing next-generation automated lifting platforms. With the integration of advanced technologies such as real-time feedback, AI decision-making, and Simultaneous localization and mapping (SLAM), future systems can autonomously achieve millimeter-level positioning accuracy while reducing module positioning times to just a few minutes. These advancements will set new benchmarks for safety, efficiency, and precision, driving broader adoption of fully automated solutions in the construction industry.

The evaluation framework offers a replicable model for evaluating emerging automated solutions, particularly the MiC lifting area, enabling industry practitioners to assess safety, accuracy, productivity, and cost-effectiveness before deployment. This ensures that new technologies meet rigorous standards, reducing risks and enhancing adoption rates.

9.3 Limitations of the Research

As a novel research concept, the SLAP system shows significant potential for enhancing MiC lifting performance. However, several limitations remain that need further refinement to improve its practicality and effectiveness. These limitations encompass the UI design, constraints in the control system, hardware limitations, as well as the simplifications and assumptions made to facilitate laboratory validation. Addressing these limitations will not only improve the system but also establish a foundation for subsequent advancements.

Need for the Feedback Mechanism

The SLAP system currently operates under an open-loop control framework. Without a feedback mechanism, the system cannot dynamically adjust for positional deviations or environmental disturbances during operations. For instance, the absence of a feedback control loop in the Z-axis prevents the timely correction of yaw angle errors caused by motor weight-induced rotation. The open-loop design also limits the system's ability to adapt to real-time changes, such as module misalignments caused by wind or system vibrations.

This limitation, however, provides an opportunity to implement closed-loop control strategies in future iterations. The closed-loop control algorithms, capable of real-time adjustments based on sensor feedback, can enhance the system's ability to manage dynamic CoM shifts and environmental disturbances. Furthermore, the current prototype does not include the Computer-Aided Visual System (CAVS), which is conceptually critical for providing real-time visual feedback and guidance during module positioning. The absence of CAVS limits the system's ability to dynamically adapt to misalignments or unexpected conditions. Integrating IMUs and CAVS for real-time pose tracking and error correction would not only improve system accuracy and reliability but also enable the system to address real-world challenges more effectively. These developments would pave the way for a more robust, precise system that, in the future, could contribute to the development of autonomous SLAP systems.

Hardware and Testing Constraints

Due to the limitations of available equipment and experimental conditions, several limitations have impacted on the SLAP system's performance, which could be further improved in future iterations. For instance, measurement errors occur when using tape measures to manually record cable and hook lengths, which causes inaccuracies due to obstructions within the system. Additionally, calibration inaccuracies, such as the misalignment of the L-shaped rod to the platform, further reduce the system's overall precision. These issues could be mitigated through the use of enhanced experimental equipment and design, such as integrating higher-precision measurement systems and refining the manufacturing and assembly process to ensure more accurate alignment between components.

Additionally, the SLAP system has only been tested in a controlled laboratory environment, which does not replicate the complexities of real-world MiC construction projects. Factors such as load variability and environmental disturbances (e.g., wind, temperature changes) have not yet been evaluated. Conducting full-scale industrial trials with partners in the construction sector will be essential to validate the system's performance under these conditions. Such testing would also help identify further improvements needed for weather resilience and scalability.

UI Design and Automation Limitations

The current prototype lacks a functional UI, relying on manual commands for operation. A functional UI, incorporating features such as real-time pose visualization, augmented reality feedback, and error notifications, would greatly enhance operability and reduce human error during module positioning. Moreover, the SLAP system has yet to fully leverage recent market developments, such as AI-driven path planning and SLAM-based navigation systems. By gradually increasing automation modes, the system would transition from semi-automatic to fully autonomous operations.

Lack of Economic Evaluation

As the SLAP system remains in its prototype stage, a comprehensive cost-benefit analysis, including the economic parameters outlined in Chapter 8, has not yet been conducted. Future iterations of the system, particularly as it approaches a production-ready stage, should include detailed economic modeling to assess its cost-effectiveness for industry adoption. This should encompass lifecycle costs, operational savings, and return on investment to provide a clearer picture of its industrial viability.

Nevertheless, the SLAP system’s current limitations underscore key areas for future improvement, including the transition from open-loop to closed-loop control, the development of a user-friendly UI with enhanced autonomy, the mitigation of hardware constraints, and the need for real-world testing to validate performance under practical conditions. Additionally, conducting comprehensive economic assessments will be essential to evaluate its cost-effectiveness and industrial viability. Addressing these challenges will enable the SLAP system to evolve into a more precise, reliable, and scalable solution for advancing MiC practices.

9.4 Future Directions

Building on its current findings, the SLAP system offers significant opportunities for further development to address the identified limitations. One critical area is the implementation of a user-friendly UI, as outlined in Chapter 6. The absence of a functional UI in the current prototype limits operational ease and user-friendliness, which are essential for practical on-site applications. Future research should prioritize developing a well-designed UI to enhance operational efficiency, allowing operators to remotely manage the system and monitor its performance, especially from safer, non-frontline positions. This would significantly improve usability and practicality for real-world construction scenarios.

Another priority is the integration of a Computer-Aided Visual System (CAVS) to provide real-time visual feedback and guidance during module positioning and levelling. CAVS would enhance precision by dynamically adapting to misalignments or environmental disturbances. As an extension, incorporating SLAM technology into the CAVS design would enable the SLAP system to sense its environment, autonomously localize itself, and adjust to dynamic construction conditions. These enhancements would improve the system's accuracy, autonomy, and adaptability, making it more robust for practical applications.

Future iterations should also address hardware constraints by refining the design and assembly process to mitigate issues such as calibration inaccuracies and measurement errors. Higher precision measurement systems and improved alignment methods would enhance overall performance.

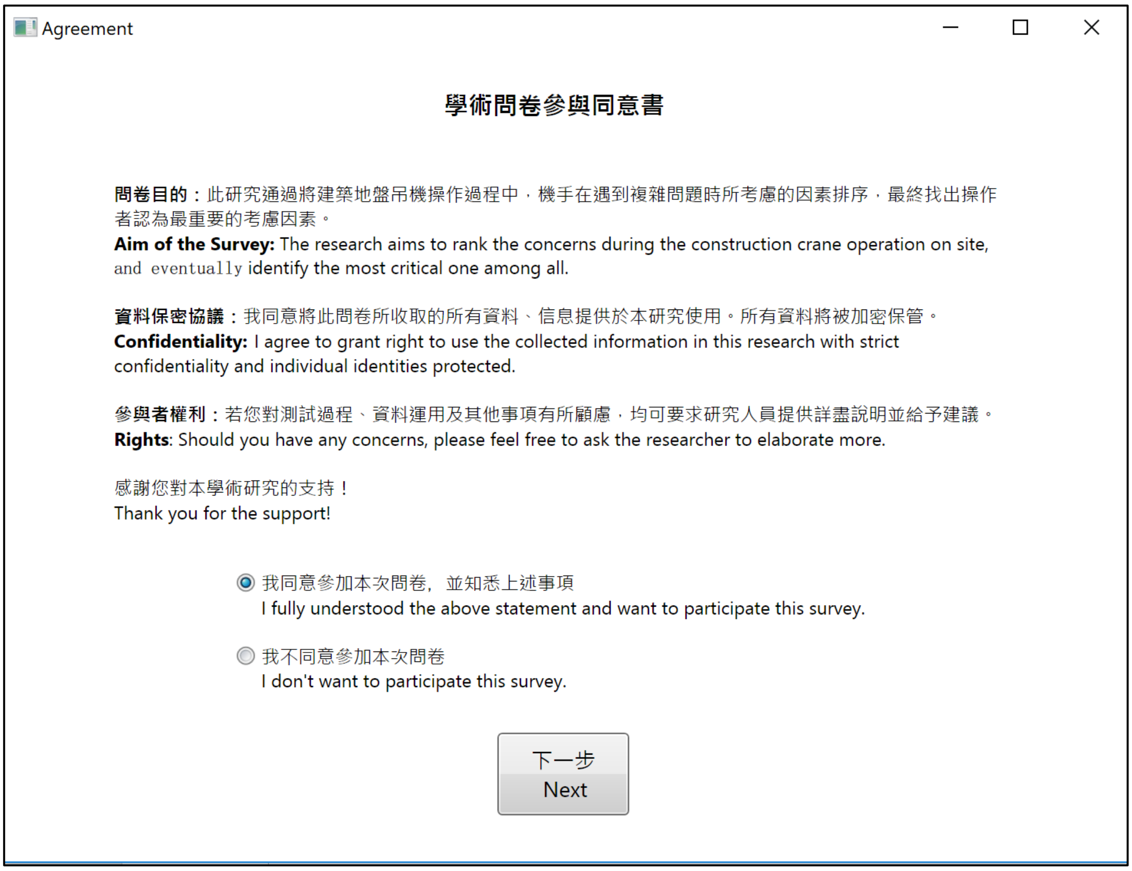
In addition, the SLAP system must be tested and validated in real-world MiC projects to fully assess its readiness for industry adoption. Extensive field trials under practical conditions, including exposure to environmental factors such as wind, rain, and sunlight, are essential for evaluating the system's reliability, scalability, and effectiveness. These real-world applications would provide valuable insights, ensuring the system's functionality is robust enough for mass adoption in the construction industry.

As the SLAP system progresses beyond the prototype stage, a comprehensive cost-benefit analysis should be conducted to assess its industrial viability. This analysis will not only provide a clear understanding of the system's economic value for the adoption of the industry, ensuring alignment with the practical and financial needs of construction projects, but also evaluate its sustainability performance. Future work should include assessing SLAP's environmental impact, including energy consumption and potential reductions in material waste, to ensure that the system contributes to sustainable construction practices while meeting economic and operational demands.

The SLAP system can evolve into a fully autonomous, intelligent, and adaptable lifting solution by addressing these limitations and pursuing these research directions. These advancements will establish the system as a benchmark for precision, efficiency, and practicality in the MiC industry, ultimately driving broader adoption of automation technologies in construction.

Appendices

1. Semi-Structure Interview Questionnaire



Agreement

學術問卷參與同意書

問卷目的：此研究通過將建築地盤吊機操作過程中，機手在遇到複雜問題時所考慮的因素排序，最終找出操作者認為最重要的考慮因素。
Aim of the Survey: The research aims to rank the concerns during the construction crane operation on site, and eventually identify the most critical one among all.

資料保密協議：我同意將此問卷所收取的所有資料、信息提供於本研究使用。所有資料將被加密保管。
Confidentiality: I agree to grant right to use the collected information in this research with strict confidentiality and individual identities protected.

參與者權利：若您對測試過程、資料運用及其他事項有所顧慮，均可要求研究人員提供詳盡說明並給予建議。
Rights: Should you have any concerns, please feel free to ask the researcher to elaborate more.

感謝您對本學術研究的支持！
Thank you for the support!

◉ 我同意參加本次問卷，並知悉上述事項
I fully understood the above statement and want to participate this survey.

○ 我不同意參加本次問卷
I don't want to participate this survey.

下一步
Next

PersonalData

基本資料

年齡 Age:

性別 Gender: ○ 男 Male ○ 女 Female

擁有吊車執照年數 How many years have you been holding a crane license:

○ 無 None ○ <1年 ○ 1-3年 ○ 3-5年 ○ 5-10年 ○ >10 年

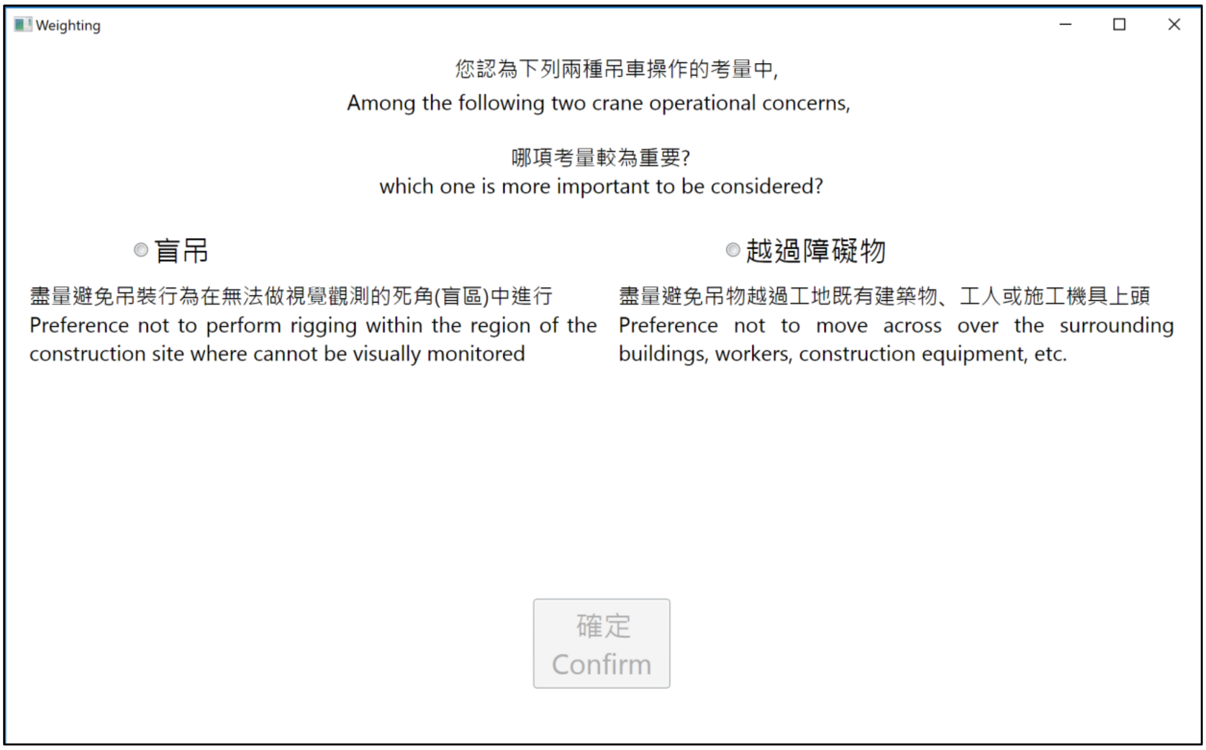
平均每天駕駛時數 Average hours in crane operation everyday:

○ 無 None ○ <1h ○ 1h – 5h ○ 5h – 9h ○ >9h

是否擁有其他駕照（複選）Do you process other driving licenses (Multiple selections):

☐ 普通機車 Motorcycle (<250c.c) ☐ 重型機車Motorcycle (>250c.c)
☐ 小客車 Private car ≤7 seaters ☐ 大客車 Coach >7 seaters
☐ 貨車 Lorry ☐ 拖頭 Trailer

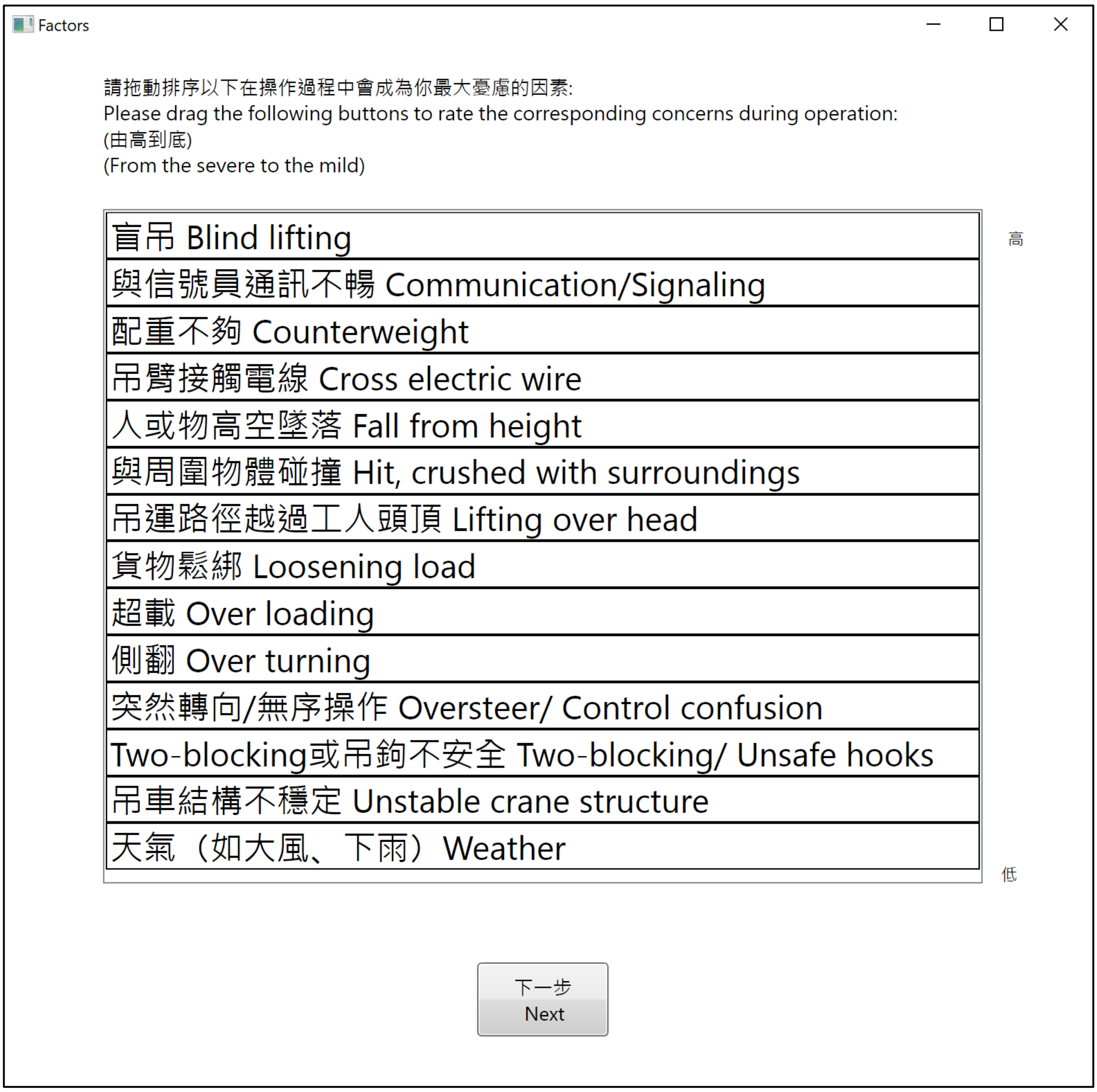
下一步
Next


Weighting
您認為下列兩種吊車操作的考量中,
Among the following two crane operational concerns,
哪項考量較為重要?
which one is more important to be considered?
盲吊
盡量避免吊裝行為在無法做視覺觀測的死角(盲區)中進行
Preference not to perform rigging within the region of the construction site where cannot be visually monitored
越過障礙物
盡量避免吊物越過工地既有建築物、工人或施工機具上頭
Preference not to move across over the surrounding buildings, workers, construction equipment, etc.
確定
Confirm

請比較下列各項考量的重要性，進行排序：

類別Category	**考量Concern**	**描述Description**
安全 **Safety**	盲吊 Blind lifting	盡量避免吊裝行為在無法做視覺觀測的死角(盲區)中進行 Preference not to perform rigging within the region of the construction site where cannot be visually monitored
	高空作業 Rigging at a high elevation	盡量避免將吊物吊在高空中搬運 Preference not to maintain rigging activities at high elevations
	高負載 Full loading	盡量避免吊裝行為進入高負載(吊物力矩最大)的情況 Preference not to operate rigging activities across the zones with maximum loading capacity required (maximum rigging moment)
	越過障礙物 Overhead	盡量避免吊物越過工地既有建築物、工人或施工機具上頭 Preference not to move across over the surrounding buildings, workers, construction equipment, etc.
效率 **Efficiency**	最短路徑 Shortest path	盡量使用最短的搬運距離完成吊裝作業 Preference to move the lifting object along with the lifting trajectory with minimized distance to the destination
有效 **Effectiveness**	吊裝方向調整 Changes of lifting direction	盡量不做過多的吊裝方向調整 Preference not to change the direction of rigging too many time (frequently)

Open-ended Question for Supplementary




Feedbacks
上述因素中是否有非常不重要的考慮因素，若有請填寫：
Please write down the concern(s) from the above that is (are) considered trivial during operation, if any：
請填寫你認為本問卷中遺漏的考慮因素（如有）：
Please supplement other important concerns (If any)：
上一步
Previous
提交
Submit

2. SLAP Experiment Code

```
import serial
import serial.tools.list_ports
import numpy as np
import pandas as pd
from HyPA_driver import HyPA_driver
import keyboard
import time
import os

my_hypa = HyPA_driver()
motor_1_f, motor_2_f, motor_3_f = 0, 0, 0
motor_4_f, motor_5_f, motor_6_f, motor_7_f = 0, 0, 0, 0

# The current position.
motor1_t = my_hypa.position_check(1)
if motor1_t >= 3500000000:
    motor1_t = motor1_t - 4294967295
motor2_t = my_hypa.position_check(2)
if motor2_t >= 3500000000:
    motor2_t = motor2_t - 4294967295
motor3_t = my_hypa.position_check(3)
if motor3_t >= 3500000000:
    motor3_t = motor3_t - 4294967295
motor4_t = my_hypa.position_check(4)
if motor4_t >= 3500000000:
    motor4_t = motor4_t - 4294967295
motor5_t = my_hypa.position_check(5)
if motor5_t >= 3500000000:
    motor5_t = motor5_t - 4294967295
motor6_t = my_hypa.position_check(6)
if motor6_t >= 4000000000:
    motor6_t = motor6_t - 4294967295
motor7_t = my_hypa.position_check(7)
if motor7_t >= 4000000000:
    motor7_t = motor7_t - 4294967295

# print(motor1_t, motor2_t, motor3_t, motor4_t, motor5_t, motor6_t, motor7_t)

# x/y table length
x_length = 0.465
y_length = 0.338

current_dir = os.getcwd()
print(f"当前工作目录：{current_dir}")
file = '1_05_0_68'

initial_cable_length_file = os.path.join(
    current_dir, '0_72\cable_and_table_length_'+file+'\cable_length_vec_0_0_-1_-1.txt')
initial_cable_length_vec = np.loadtxt(initial_cable_length_file, delimiter=',')

initial_x_table_length_file, initial_y_table_length_file = os.path.join(
    current_dir, '0_72\\cable_and_table_length_'+file+'\\x_trajectory_0_0_-1_-1.txt'), \
os.path.join(current_dir, '0_72\\cable_and_table_length_'+file+'\\y_trajectory_0_0_-1_-1.txt')

initial_x_table_length, initial_y_table_length = np.loadtxt(initial_x_table_length_file),
np.loadtxt(initial_y_table_length_file)
# 组合成完整路径
```

```
initial_cable_length_1 = initial_cable_length_vec[0, 3]
initial_cable_length_2 = initial_cable_length_vec[0, 0]
initial_cable_length_3 = initial_cable_length_vec[0, 1]
initial_cable_length_4 = initial_cable_length_vec[0, 2]

initial_x_table = initial_x_table_length[0]
initial_y_table = initial_y_table_length[0]

initial_cable_winch_encoder_tick_1_offset = 30162
initial_cable_winch_encoder_tick_2_offset = -30283
initial_cable_winch_encoder_tick_3_offset = 29922
initial_cable_winch_encoder_tick_4_offset = -29857
initial_table_x = 0
initial_table_y = 0


position = '4'
if position == '1':
    cable_length_relative_path = '0_72\cable_and_table_length_'+file+'\cable_length_vec_0_0_-1_-1.txt'
    x_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\x_trajectory_0_0_-1_-1.txt'
    y_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\y_trajectory_0_0_-1_-1.txt'

elif position == '2':
    cable_length_relative_path = '0_72\cable_and_table_length_'+file+'\cable_length_vec_-1_-1_-1_1.txt'
    x_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\x_trajectory_-1_-1_-1_1.txt'
    y_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\y_trajectory_-1_-1_-1_1.txt'

elif position == '3':
    cable_length_relative_path = '0_72\cable_and_table_length_'+file+'\cable_length_vec_-1_1_1_1.txt'
    x_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\x_trajectory_-1_1_1_1.txt'
    y_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\y_trajectory_-1_1_1_1.txt'

elif position == '4':
    cable_length_relative_path = '0_72\cable_and_table_length_'+file+'\cable_length_vec_1_1_1_-1.txt'
    x_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\x_trajectory_1_1_1_-1.txt'
    y_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\y_trajectory_1_1_1_-1.txt'

elif position == '5':
    cable_length_relative_path = '0_72\cable_and_table_length_'+file+'\cable_length_vec_1_-1_0_0.txt'
    x_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\x_trajectory_1_-1_0_0.txt'
    y_table_relative_path = '0_72\\cable_and_table_length_'+file+'\\y_trajectory_1_-1_0_0.txt'

cable_length_file_path = os.path.join(current_dir, cable_length_relative_path)
cable_length_vec = np.loadtxt(cable_length_file_path, delimiter=',')
x_table_file_path = os.path.join(current_dir, x_table_relative_path)
x_table_trajectory_vec = np.loadtxt(x_table_file_path)
y_table_file_path = os.path.join(current_dir, y_table_relative_path)
y_table_trajectory_vec = np.loadtxt(y_table_file_path)
step_threshold = len(cable_length_vec)

print(x_table_trajectory_vec[-1]-initial_x_table)
print(y_table_trajectory_vec[-1]-initial_y_table)


r, p, y = my_hypa.gyro_read()
print("r_before: ", r)
print("p_before: ", p)
print("y_before: ", y)
i = 0
rpy_array = []
```

```
while True:
    # Position check
    motor1_dis = my_hypa.position_check(1)
    if motor1_dis >= 3500000000:
        motor1_dis = motor1_dis - 4294967295
    motor2_dis = my_hypa.position_check(2)
    if motor2_dis >= 3500000000:
        motor2_dis = motor2_dis - 4294967295
    motor3_dis = my_hypa.position_check(3)
    if motor3_dis >= 3500000000:
        motor3_dis = motor3_dis - 4294967295
    motor4_dis = my_hypa.position_check(4)
    if motor4_dis >= 3500000000:
        motor4_dis = motor4_dis - 4294967295
    motor5_dis = my_hypa.position_check(5)
    if motor5_dis >= 3500000000:
        motor5_dis = motor5_dis - 4294967295
    motor6_dis = my_hypa.position_check(6)
    if motor6_dis >= 4000000000:
        motor6_dis = motor6_dis - 4294967295
    motor7_dis = my_hypa.position_check(7)
    if motor7_dis >= 4000000000:
        motor7_dis = motor7_dis - 4294967295

    r, p, y = my_hypa.gyro_read()

    rpy_array.append([r, p, y])

    # my_hypa.control_motors(0, initial_cable_winch_encoder_tick_1_offset-1*(cable_length_vec[i, 3]-
initial_cable_length_1)/0.3770*(10000*35), \
    #                   initial_cable_winch_encoder_tick_2_offset+1*(cable_length_vec[i, 0]-
initial_cable_length_2)/0.3770*(10000*35), \
    #                   initial_cable_winch_encoder_tick_3_offset-1*(cable_length_vec[i, 1]-
initial_cable_length_3)/0.3770*(10000*35), \
    #                   initial_cable_winch_encoder_tick_4_offset+1*(cable_length_vec[i, 2]-
initial_cable_length_4)/0.3770*(10000*35), \
    #                   initial_table_x-1*(x_table_trajectory_vec[i]-initial_x_table)/x_length*6077530, \
    #                   initial_table_y-1*(y_table_trajectory_vec[i]-initial_y_table)/y_length*4437960)


    my_hypa.control_motors(0, 0-(cable_length_vec[i, 3]-initial_cable_length_1)/0.3770*(10000*35), \
                        0+(cable_length_vec[i, 0]-initial_cable_length_2)/0.3770*(10000*35), \
                        0-(cable_length_vec[i, 1]-initial_cable_length_3)/0.3770*(10000*35), \
                        0+(cable_length_vec[i, 2]-initial_cable_length_4)/0.3770*(10000*35), \
                        0-(x_table_trajectory_vec[i]-initial_x_table)/x_length*6077530, \
                        0-(y_table_trajectory_vec[i]-initial_y_table)/y_length*4437960)

    my_hypa.clear_error(6)
    my_hypa.clear_error(7)

    i = i + 1
    print(i)

    if keyboard.is_pressed('q') or i >= step_threshold:
        #监听停止条件 - 按下键盘 q 或者 变量 i 达到 step_threshold 时，触发停止逻辑
        print("Stop")
        print("Current position: ", motor1_dis, motor2_dis, motor3_dis,
              motor4_dis, motor5_dis, motor6_dis, motor7_dis)
        #打印当前电机位置，输出当前 7 个电机的位置，显示它们的状态。
        motor_1_f, motor_2_f, motor_3_f, motor_4_f, motor_5_f, motor_6_f, motor_7_f \
```

```
          = my_hypa.control_motors(motor1_dis, motor2_dis, motor3_dis, motor4_dis, motor5_dis, motor6_dis,
motor7_dis)
      while motor_1_f or motor_2_f or motor_3_f or motor_4_f or motor_5_f or motor_6_f or motor_7_f:
          # Position check， 进入循环，持续监测电机位置
          motor1_dis = my_hypa.position_check(1)
          # 读取电机位置，并进行溢出修正, 读取 7 个电机的位置，如果数值超过 3,500,000,000，说明可能
发生了 溢出（因为 32 位无符号整数最大值是 4294967295），需要进行修正
          if motor1_dis >= 3500000000:
             motor1_dis = motor1_dis - 4294967295
          motor2_dis = my_hypa.position_check(2)
          if motor2_dis >= 3500000000:
             motor2_dis = motor2_dis - 4294967295
          motor3_dis = my_hypa.position_check(3)
          if motor3_dis >= 3500000000:
             motor3_dis = motor3_dis - 4294967295
          motor4_dis = my_hypa.position_check(4)
          if motor4_dis >= 3500000000:
             motor4_dis = motor4_dis - 4294967295
          motor5_dis = my_hypa.position_check(5)
          if motor5_dis >= 3500000000:
             motor5_dis = motor5_dis - 4294967295
          motor6_dis = my_hypa.position_check(6)
          if motor6_dis >= 4000000000:
             motor6_dis = motor6_dis - 4294967295
          motor7_dis = my_hypa.position_check(7)
          if motor7_dis >= 4000000000:
             motor7_dis = motor7_dis - 4294967295
          motor_1_f, motor_2_f, motor_3_f, motor_4_f, motor_5_f, motor_6_f, motor_7_f =
my_hypa.control_motors(
             motor1_dis, motor2_dis, motor3_dis, motor4_dis, motor5_dis,
             motor6_dis, motor7_dis)
      break
r, p, y = my_hypa.gyro_read()
print("r_after: ", r)
print("p_after: ", p)
print("y_after: ", y)
#读取 陀螺仪数据（roll、pitch、yaw），可能用于检测系统的最终状态。

np.savetxt(file+"_experiment_2_trial_1_" + position + ".txt", rpy_array)
```

References

Aflakian, A., Safaryazdi, A., Masouleh, M. T., & Kalhor, A. (2018). Experimental study on the kinematic control of a cable suspended parallel robot for object tracking purpose. *Mechatronics*, *50*, 160-176.

Antonelli, G., Chiaverini, S., & Fusco, G. (2000). Kinematic Control of Redundant Manipulators with On-Line End-Effector Path Tracking Capability Under Velocity and Acceleration Constraints. *IFAC Proceedings Volumes*, *33*(27), 183-188. https://doi.org/10.1016/s1474-6670(17)37926-0

ArchSD. (2022). *General Specication for Building*. https://www.archsd.gov.hk/media/publications-publicity/general-specification-for-building/GS_2022-01.pdf

Asai, K., Hashiba, H., Tagawa, H., Sakurai, H., Fujii, Y., Fukumoto, T., Nagashima, Y., & Nanase, F. (1993). *Assembling method of segment for rectangular shield of large section* (Japan Patent No. JPH06330693A). https://patents.google.com/patent/JPH06330693A/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Austin, E. K. (1981). *Guidelines for the development of continuing education offerings for nurses*. Appleton-Century-Crofts.

Babaghasabha, R., Khosravi, M. A., & Taghirad, H. D. (2016). Adaptive robust control of fully constrained cable robots: singular perturbation approach. *Nonlinear Dynamics*, *85*(1), 607-620. https://doi.org/10.1007/s11071-016-2710-8

Bac, C. W., Hemming, J., Van Tuijl, B., Barth, R., Wais, E., & van Henten, E. J. (2017). Performance evaluation of a harvesting robot for sweet pepper. *Journal of Field Robotics*, *34*(6), 1123-1139.

Bailey, D., & Garralda, M. (1987). The use of the social stress and support interview in families with deviant children: methodological issues. *Social psychiatry*, *22*, 209-215.

Banton. (2024). *Efficiency: What It Means in Economics, the Formula To Measure It*. https://www.investopedia.com/terms/e/efficiency.asp

Baskerville, R. L., Kaul, M., & Storey, V. C. (2015). Genres of inquiry in design-science research. *MIS quarterly*, *39*(3), 541-564.

Basu, S. (2024). *Plant Intelligent Automation and Digital Transformation Volume II: MIS and HW-SW Implementation*. Elsevier.

BCA. (2017a). *Design for Manufacturing and Assembly (DFMA) PPVC. Crystal Engineering Corp, 1–26.*

BCA. (2017b). *Prefabricated Prefinished Volumetric Construction (PPVC) Guidebook*.

BD. (2016). *Code of Practice for Precast Concrete Construction*. https://www.bd.gov.hk/doc/en/resources/codes-and-references/code-and-design-manuals/cppcc2016e.pdf

Belu, N., Ionescu, L., & Rachieru, N. (2019). Risk-cost model for FMEA approach through Genetic algorithms–A case study in automotive industry. IOP Conference Series: Materials Science and Engineering,

Bennett, M., McDermott, R., & Beauregard, M. (2017). The Basics of FMEA.

Berler, M. (2019). *Maintaining Equilibrium: Finding Our Way Therapeutically in a Digitally Disrupted Marketplace*. Pace University.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, *1*(1), 1-34.

Bock, T., & Linner, T. (2016a). *Construction robots: Elementary technologies and single-task construction robots*. Cambridge University Press.

Bock, T., & Linner, T. (2016b). *Site automation*. Cambridge University Press.

Bramberger (2021). *Cable robot* (United States Patent No. US20210347614A1). https://patents.google.com/patent/US20210347614A1/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot.

Bramberger, R. (2021). Cable robot. In: Google Patents.

Briand, L., El Emam, K., & Morasca, S. (1995). Theoretical and empirical validation of software product measures. *International Software Engineering Research Network, Technical Report ISERN-95-03*, 31-46.

BS 5606. (2022). *Accuracy and tolerance in design and construction. Guide*. https://standardsdevelopment.bsigroup.com/projects/2018-03537

Buildings Department. (2016). *Circular Letter - Use of Off-site Prefabricated Steel Reinforcing Bar Products*. bd.gov.hk.

Buildings Department. (2018a). *Modular Integrated Construction (MiC)*. https://www.bd.gov.hk/en/resources/codes-and-references/modular-integrated-construction/index.html.

Buildings Department. (2018b). *Steel MiC Systems*. https://www.bd.gov.hk/en/resources/codes-and-references/modular-integrated-construction/mic_steelList.html.

Buildings Department. (2023). *Steel MiC Systems*. https://www.bd.gov.hk/en/resources/codes-and-references/modular-integrated-construction/mic_steelList.html.

Cai, S., Ma, Z., Skibniewski, M., Guo, J., & Yun, L. (2018). Application of automation and robotics technology in high-rise building construction: An overview. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Carlos, B., Mohamed, A., Carlos, B., & Mohamed, A. (2008). Trends in robotics and automation in Construction. In *Robotics and Automation in Construction*. InTech.

Cavell, G. (2017). *National Association of Broadcasters Engineering Handbook*. Taylor & Francis.

Caverly, R. J., Forbes, J. R., & Mohammadshahi, D. (2015). Dynamic Modeling and Passivity-Based Control of a Single Degree of Freedom Cable-Actuated System. *IEEE Transactions on Control Systems Technology*, *23*(3), 898-909. https://doi.org/10.1109/tcst.2014.2347807

Chen, W. (2014). A quantitative Fuzzy Causal Model for hazard analysis of man–machine-environment system. *Safety science*, *62*, 475-482.

Chintada, A., & V, U. (2022). Improvement of productivity by implementing occupational ergonomics. *Journal of Industrial and Production Engineering*, *39*(1), 59-72.

Cho, J.-H., Jung, J.-H., Kim, S.-Y., & Yook, J.-G. (2016). A scaled down laboratory experiment of cross-borehole pulse radar signatures for detection of a terminated tunnel. *Measurement Science and Technology*, *27*(9), 095008.

Choi (2004). *Transfer Method of Ceiling Crane for Coil Transfer* (South Korea Patent No. KR20060031143A). https://patents.google.com/patent/KR20060031143A/en?oq=KR20060031143.

Chung, C.-S., Wang, H., & Cooper, R. A. (2013). Functional assessment and performance evaluation for assistive robotic manipulators: Literature review. *The journal of spinal cord medicine*, *36*(4), 273-289.

CIC. (2023). *MiC Resources Center*. https://mic.cic.hk/en/ProjectsInHongKong/18

CIC. (2023a). *Projects In Hong Kong: Married Quarters for the Fire Services Department at Pak Shing Kok in Tseung Kwan O*. https://mic.cic.hk/en/ProjectsInHongKong/2.

CIC. (2023b). *Projects In Hong Kong: InnoCell*. https://mic.cic.hk/en/ProjectsInHongKong/1.

CIC. (2023c). *Projects In Hong Kong: Hong Kong Infection Control Center, North Lantau Hospital*. https://mic.cic.hk/en/ProjectsInHongKong/21.

Construction Industry Council. (2022). *Heavy Lifting Operation for MiC Projects*. https://www.cic.hk/files/page/51/20221220%20Heavy%20Lifting%20Operation%20for%20MiC%20Projects.pdf

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *psychometrika*, *16*(3), 297-334.

Cyganek, B., & Siebert, J. P. (2011). *An introduction to 3D computer vision techniques and algorithms*. John Wiley & Sons.

Factories and Industrial Undertakings (Lifting Appliances and Lifting Gear) Regulations, (2006a). https://www.elegislation.gov.hk/hk/cap59J!en

Department of Justice. (2006b). *Factories and Industrial Undertakings (Lifting Appliances and*

Lifting Gear) Regulations.

Department of Justice. (2006a). *Cap. 59I Construction Sites (Safety) Regulations*.

Department of Justice. (2006b). *Cap. 59J Factories and Industrial Undertakings (Lifting Appliances and Lifting Gear) Regulations*.

DEVB. (2016). *Microsoft Word - TCW 1-2016 QA for Off-site Prefabricated Rebar Products.docx*. devb.gov.hk.

Dhalmahapatra, K., Shingade, R., Mahajan, H., Verma, A., & Maiti, J. (2019). Decision support system for safety improvement: An approach using multiple correspondence analysis, t-SNE algorithm and K-means clustering. *Computers & Industrial Engineering*, *128*, 277-289.

Dong, W., Lim, K. Y., Goh, Y. K., Nguyen, K. D., Chen, I.-M., Yeo, S. H., & Duh, B.-L. (2008). A low-cost motion tracker and its error analysis. 2008 IEEE International Conference on Robotics and Automation,

Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M., & Buchli, J. (2016). Mobile robotic brickwork: automation of a discrete robotic fabrication process using an autonomous mobile robot. *Robotic fabrication in architecture, art and design 2016*, 204-217.

Du, Q., Chi, H. L., Li, X., & Shen, G. Q. (2020). Prioritizing operational considerations of crane operator training for modular integrated construction. Construction Research Congress 2020,

Enshassi, M. S., Walbridge, S., West, J. S., & Haas, C. T. (2019). Integrated risk management framework for tolerance-based mitigation strategy decision support in modular construction projects. *Journal of Management in Engineering*, *35*(4), 05019004.

Ergonomic Partners. (2024). *Hydraulic or Pneumatic Industrial Manipulator Arms and Vertical Lifters*. Retrieved 2024.05.17 from https://www.ergonomicpartners.com/manipulator-arms

Eric Bramwell Britcher, Jeffrey Allen Moore, & Samuels, J. A. (2012). *Solar panel field array support system and apparatus and method for construction use* (United States Patent

No. US10696451B2). https://patents.google.com/patent/US10696451B2/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot

Fine, G. A., & Elsbach, K. D. (2000). Ethnography and experiment in social psychological theory building: Tactics for integrating qualitative field data with quantitative lab data. *Journal of Experimental Social Psychology*, *36*(1), 51-76.

Flood, I., & Issa, R. R. (2010). Empirical modeling methodologies for construction. *Journal of construction engineering and management*, *136*(1), 36-48.

Forcael, E., Mata, R., González, B., Opazo-Vega, A., García-Alvarado, R., González, M., Núñez, E., & Padilla, J. (2025). Enhanced robotic cross-laminated timber panel assembly process. *Developments in the Built Environment*, 100667.

Frohm, J., Lindström, V., Stahre, J., & Winroth, M. (2008). Levels of automation in manufacturing. *Ergonomia-an International journal of ergonomics and human factors*, *30*(3).

FU, L., Hua FENG, Xuequan ZHOU, Qing MAO, Zhangquan QANG, & Hai TU (2022). *Workpiece assembling method, assembling piece installing system and engineering machinery assembly line* (China Patent No. CN202210305965.6A).

Fukase, Y., & Kurita, H. (1994). *Crane* (Japan Patent No. JPH07237884A). https://patents.google.com/patent/JPH07237884A/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Galletta, A., & Cross, W. E. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication* (Vol. 18). NYU press.

Gangloff, J., Weber, X., & Cuvillon, L. (2020). Modal Control for Active Vibration Damping of Cable-Driven Parallel Robots. *Journal of Mechanisms and Robotics*, *12*(5). https://doi.org/10.1115/1.4046434

Gerassis, S., Saavedra, A., Taboada, J., Alonso, E., & Bastante, F. G. (2020). Differentiating between fatal and non-fatal mining accidents using artificial intelligence techniques. *International Journal of Mining, Reclamation and Environment*, *34*(10), 687-699.

Gharbia, M., Chang-Richards, A., Lu, Y., Zhong, R. Y., & Li, H. (2020). Robotic technologies for on-site building construction: A systematic review. *Journal of Building Engineering*, *32*, 101584.

Gov. (2023a). *Housing project moves for reuse*. https://www.news.gov.hk/eng/2023/02/20230218/20230218_133023_022.html.

Gov. (2023b). *Tai Po transitional housing reuses the modules of the Nanchang project*. https://www.news.gov.hk/chi/2023/07/20230706/20230706_144039_886.html.

Greenacre, M., & Blasius, J. (2006). *Multiple correspondence analysis and related methods*. Chapman and Hall/CRC.

Greene, J. C., Caracelli, V. J., & Graham, W. F. (1989). Toward a conceptual framework for mixed-method evaluation designs. *Educational evaluation and policy analysis*, *11*(3), 255-274.

Gregor, S., & Jones, D. (2007). The anatomy of a design theory.

Groover, M. P. (2016). *Automation, production systems, and computer-integrated manufacturing*. Pearson Education India.

Gross, M., & Krohn, W. (2005). Society as experiment: Sociological foundations for a self-experimental society. *History of the Human Sciences*, *18*(2), 63-86.

Grubbs, F. E. (1949). *Sample criteria for testing outlying observations*. University of Michigan.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology* (Vol. 52, pp. 139-183). Elsevier.

Hayakawa, S., Wan, W., Koyama, K., & Harada, K. (2022). A Dual-Arm Robot That Manipulates Heavy Plates With the Support of a Vacuum Lifter. *IEEE Transactions on Automation Science and Engineering*. https://doi.org/10.1109/TASE.2022.3199355

He, W., Jiang, Z., Ming, W., Zhang, G., Yuan, J., & Yin, L. (2021). A critical review for machining positioning based on computer vision. *Measurement*, *184*, 109973. https://doi.org/10.1016/j.measurement.2021.109973

Hesse-Biber, S. N. (2010). *Mixed methods research: Merging theory with practice*. Guilford Press.

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS quarterly*, 75-105.

Hirohiko, G., Tan, M., Zhang, E., Shigeki, O., Shinya, K., & Zeng, M. (2016). *Substrate conveyance robot and lining treatment system* (China Patent No. https://patents.google.com/patent/CN108028218A/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot

HKHA. (2019). *Microsoft Word - BC 7-2019 (QH 1-2019) (Eng).docx*. housingauthority.gov.hk.

Ho, T., Tasaki, R., Miyoshi, T., & Terashima, K. (2018). Optimal Control of Payload's Skew Rotation in Crane Systems with State and Control Input Constraints. 2018 IEEE Conference on Control Technology and Applications (CCTA),

Ho, T. D., & Terashima, K. (2018). Robust control designs of payload's skew rotation in a boom crane system. *IEEE Transactions on Control Systems Technology*, *27*(4), 1608-1621. https://doi.org/10.1109/TCST.2018.2834879

Hong Kong Housing Authority. (2020a). *Housing in Figures*.

Hong Kong Housing Authority. (2024). *Safety Alert: Lorry-mounted crane toppled in Wong Chuk Hang*. Retrieved from https://www.housingauthority.gov.hk/mini-site/site-safety/common/resources/alerts/2024/SH-2024-04e-CIC.pdf.

HWArobotics. (2024). *Semi-Automated vs. Fully Automated Warehouse System: What Do You Need to Know?* https://www.hwarobotics.com/about/semi-automated-vs-fully-automated-warehouse-system-what-do-you-need-to-know/

Inel, F., Medjbouri, A., & Carbone, G. (2021). A Non-Linear Continuous-Time Generalized Predictive Control for a Planar Cable-Driven Parallel Robot. *Actuators*, *10*(5). https://doi.org/10.3390/act10050097

Info government. (2018). *Housing Authority increases use of precast concrete components and mechanised construction (with photos)*. info.gov.hk.

Inoue, F., Wiuanabe, K., Ikeda, Y., Wakisaka, T., Wakabayashi, A., & Nekomoto, Y. (1998). A practical development of the suspender device that controls load rotation by gyroscopic moments. Proceedings of the International Symposium on Automation and Robotics in Construction (IAARC),

Ishihara, S., & Ohtsuka, T. (2023). Automated loading of a hydraulic excavator using nonlinear model predictive control with preference-based calibration. *SICE Journal of Control, Measurement, and System Integration*, *16*(1), 247-256.

ISO. (1998). *Manipulating industrial robots-Performance criteria and related test methods*.

ISO. (2024). *Practical solutions for real-world problems*. https://www.iso.org/about.

Jabbari Asl, H., & Janabi-Sharifi, F. (2017). Adaptive neural network control of cable-driven parallel robots with input saturation. *Engineering Applications of Artificial Intelligence*, *65*, 252-260. https://doi.org/10.1016/j.engappai.2017.05.011

Jamshidifar, H., Khosravani, S., Fidan, B., & Khajepour, A. (2018). Vibration Decoupled Modeling and Robust Control of Redundant Cable-Driven Parallel Robots. *IEEE/ASME Transactions on Mechatronics*, *23*(2), 690-701. https://doi.org/10.1109/tmech.2018.2793578

Jamshidifar, H., Rushton, M., & Khajepour, A. (2021). A Reaction-Based Stabilizer for Nonmodel-Based Vibration Control of Cable-Driven Parallel Robots. *IEEE Transactions on Robotics*, *37*(2), 667-674. https://doi.org/10.1109/tro.2020.3031269

Jang, W.-S., & Skibniewski, M. J. (2009). Cost-benefit analysis of embedded sensor system for construction materials tracking. *Journal of Construction Engineering and Management*, *135*(5), 378-386.

Jia, H., Shang, W., Xie, F., Zhang, B., & Cong, S. (2019). Second-order sliding-mode-based synchronization control of cable-driven parallel robots. *IEEE/ASME Transactions on Mechatronics*, *25*(1), 383-394.

Jiwen, P., Long, X., Jianqi, S., & Yuan, S. (2020). *Brick laying robot*. https://patents.google.com/patent/CN111219069A/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot.

Jong-man, S., Seong-ho, L., Ji-hwan, J., Young-woon, J., Jun-won, P., Ki-young, L., & Cheolyoung, K. (2021). *Ceiling construction robot* CN113146645A). https://patents.google.com/patent/CN113146645A/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot

Jun, X., Geng, C., Guoxin, X., Chong, G., Jun, Y., & Yuewu, Y. (2021). *Bricklaying equipment and building system* (China Patent No. CN113187238A). https://patents.google.com/patent/CN113187238A/en?q=(construction+Lifting+robot)&num=25&oq=construction+Lifting+robot.

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of advanced nursing*, *72*(12), 2954-2965.

Kannan, B., & Parker, L. E. (2006). Fault-tolerance based metrics for evaluating system performance in multi-robot teams. *PERFORMANCEMETRICS*, *1062*, 54.

Karatsareas, P. (2022). Semi-structured interviews. *Research methods in language attitudes*, 99-113.

Kato, S. (1992). *Working Robot* (Japan Patent No. JPH05340107A). https://patents.google.com/patent/JPH05340107A/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Kayhani, N., Taghaddos, H., Mousaei, A., Behzadipour, S., & Hermann, U. (2021). Heavy mobile crane lift path planning in congested modular industrial plants using a robotics approach. *Automation in Construction*, *122*, 103508.

Khosravi, M. A., & Taghirad, H. D. (2014). Robust PID control of fully-constrained cable driven parallel robots. *Mechatronics*, *24*(2), 87-97. https://doi.org/10.1016/j.mechatronics.2013.12.001

Knight, M. (2025). *Semi-Automated vs Fully Automated: Which one is right for your manufacturing process?* https://www.rnaautomation.com/insight/semi-automated-vs-fully-automated-which-one-is-right-for-your-manufacturing-process/

Knox, S., & Burkard, A. W. (2014). Qualitative research interviews: An update. In *Quantitative* *and qualitative methods in psychotherapy research* (pp. 342-354). Routledge.

Labour Department. (2017a). *Code of Practice for Safe Use of Mobile Cranes*.

Labour Department. (2017b). *Code of Practice for Safe Use of Tower Cranes*.

Labour Department. (2019). *Code of Practice in Times of Typhoons and Rainstorms*.

Labour Department. (2024). *Labour Department highly concerned about fatal work accident that happened in Yau Ma Tei yesterday*. Retrieved from https://www.info.gov.hk/gia/general/202412/29/P2024122900268.htm.

Lawson, R. M., Ogden, R. G., & Bergin, R. (2012). Application of modular construction in high-rise buildings. *Journal of architectural engineering*, *18*(2), 148-154.

Lee, M.-k., & Park, G.-w. (2003). *Heavy weight handling apparatus* (Korea Patent No. KR100553695B1). https://patents.google.com/patent/KR100553695B1/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Lee, U.-K., Yoo, W. S., An, S.-H., Doh, N., Cho, H., Jun, C., Kim, T., & Lee, Y. H. (2013). Performance assessment model for robot-based automated construction systems. *Journal of the Korea Institute of Building Construction*, *13*(4), 416-423.

Li, J., & Allinson, N. M. (2008). A comprehensive review of current local features for computer vision. *Neurocomputing*, *71*(10-12), 1771-1787.

Li, J., Gao, C., Feng, T., & Jing, W. (2018). Novel Moving Mass Flight Vehicle and Its Equivalent Experiment. *Journal of Dynamic Systems, Measurement, and Control*, *140*(11). https://doi.org/10.1115/1.4040326

Li, J., Gao, C., Li, C., & Jing, W. (2018). A survey on moving mass control technology. *Aerospace Science and Technology*, *82-83*, 594-606. https://doi.org/https://doi.org/10.1016/j.ast.2018.09.033

Li, S., Hu, J., Cui, Y., & Hu, J. (2018). DeepPatent: patent classification with convolutional neural networks and word embedding. *Scientometrics*, *117*(2), 721-744. https://doi.org/10.1007/s11192-018-2905-5

Liang, C.-J., Kang, S.-C., & Lee, M.-H. (2017). RAS: a robotic assembly system for steel structure erection and assembly. *International Journal of Intelligent Robotics and Applications*, *1*, 459-476.

Ling. (2023). Workplace Tragedies Persist: At Least 42 Workers Lost Their Lives, 2 Killed in Austin Road Incident. *hk01*. https://www.hk01.com/article/974857?utm_source=01articlecopy&utm_medium=referral

Liu, H.-C., Li, Z., Song, W., & Su, Q. (2017). Failure mode and effect analysis using cloud model theory and PROMETHEE method. *IEEE Transactions on Reliability*, *66*(4), 1058-1072.

Liu, Z., Hwang, B.-G., & Lim, J. M. (2023). Prefabricated and prefinished volumetric construction: Assessing implementation status, perceived benefits, and critical risk factors in the Singapore built environment sector. *Journal of Management in Engineering*, *39*(6), 04023045.

Lu, M.-L., Dufour, J. S., Weston, E. B., & Marras, W. S. (2018). Effectiveness of a vacuum lifting system in reducing spinal load during airline baggage handling. *Applied ergonomics*, *70*, 247-252. https://doi.org/10.1016/j.apergo.2018.03.006

Melenbrink, N., Werfel, J., & Menges, A. (2020). On-site autonomous construction robots: Towards unsupervised building. *Automation in Construction*, *119*, 103312.

Mercedes-Benz. (2020, September 02, 2020). *Factory 56* https://group.mercedes-benz.com/innovation/digitalisation/industry-4-0/opening-factory-56.html

Meziane, R., Cardou, P., & Otis, M. J.-D. (2019). Cable interference control in physical interaction for cable-driven parallel mechanisms. *Mechanism and Machine Theory*, *132*, 30-47.

Ming, C., Renyuan, D., Shichuan, T., & Daqiang, Z. (2019). *Multi-mechanical-arm traveling crane system and control method and fault processing method thereof (Same system with item 24 below) focus on multiple mechanical arm and switching different effectors design* (China Patent No. CN110054084B). https://patents.google.com/patent/CN110054084B/en?q=(construction+hoisting+robot

)&num=25&oq=construction+hoisting+robot

Misiti, A. (2020). *A History of Industrial Robots*. https://www.wevolver.com/article/a-history-of-industrial-robots

Moo-rim, K., Yu, H.-y., & Kim, J.-k. (2012). *Apparatus and method for building refractory in converter* (Korea Patent No. KR101359968B1). https://patents.google.com/patent/KR101359968B1/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Mulrow, C. D. (1994). Systematic reviews: rationale for systematic reviews. *Bmj*, *309*(6954), 597-599.

Nowak, S. (2012). *Understanding and Prediction: Essays in the Methodology of Social and Behavioural Theories* (Vol. 94). Springer Science & Business Media.

Oberoi, H. S., Nelson, B. P., Draper, A. S., Hu, C. Y., Matthewson, R., & Sarh, B. (2015). Automated assembly of panelized aircraft fuselages. In: Google Patents.

on.cc. (2017a). *Fatality Caused by the Breakage of Tower Crane Cable in Munsang College*. <https://hk.on.cc> (Nov. 28, 2017). (In Chinese)

on.cc. (2017b). *Construction Fataility to the Crane Driver During Inspection*. <https://hk.on.cc> (Jan. 21, 2017). (In Chinese)

Pandilov, Z., & Dukovski, V. (2014). Comparison of the Characteristics Between Serial and Parallel Robots. *Acta Technica Corviniensis-Bulletin of Engineering*, *7*(1).

Pearson Jr, K. D. (2021). Portable robotic construction system. In: Google Patents.

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of management information systems*, *24*(3), 45-77.

Petticrew, M., & Roberts, H. (2008). *Systematic reviews in the social sciences: A practical guide*. John Wiley & Sons.

Picard, E., Tahoumi, E., Plestan, F., Caro, S., & Claveau, F. (2020). A new control scheme of cable-driven parallel robot balancing between sliding mode and linear feedback. *IFAC-*

PapersOnLine, *53*(2), 9936-9943.

Policy Address. (2017). *The Chief Executive's 2017 Policy Address*. [Online] Available: https://www.policyaddress.gov.hk/2017/eng/pdf/Agenda.pdf.

Pott, T. B. A. (2013). *Cable-Driven Parallel Robots*. https://doi.org/10.1007/978-3-642-31988-4

Qian, S., Zi, B., Shang, W.-W., & Xu, Q.-S. (2018). A Review on Cable-driven Parallel Robots. *Chinese Journal of Mechanical Engineering*, *31*(1). https://doi.org/10.1186/s10033-018-0267-9

Qiang, Q., Shichuan, T., Renyuan, D., Jiawei, Z., & Wenxin, A. (2019). *Building construction system and construction method therefor* (China Patent No. https://patents.google.com/patent/WO2020155600A1/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Rauscher, F., & Sawodny, O. (2020). Modeling and control of tower cranes with elastic structure. *IEEE Transactions on Control Systems Technology*, *29*(1), 64-79.

Riviére, C., & Marlair, G. (2010). The use of multiple correspondence analysis and hierarchical clustering to identify incident typologies pertaining to the biofuel industry. *Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy*, *4*(1), 53-65.

Rogers, J., & Costello, M. (2008). Control authority of a projectile equipped with a controllable internal translating mass. *Journal of Guidance, Control, and Dynamics*, *31*(5), 1323-1333. https://doi.org/10.2514/1.33961

Schneidewind, N. F. (1992). Methodology for validating software metrics.

Schöberl, M., Huber, A., Kreppold, S., Dirnaichner, J., Kessler, S., & Fottner, J. (2023). Cobot uptake in construction: embedding collaborative robots in digital construction processes. *Construction Robotics*, *7*(1), 89-103.

Schölkopf, L., Lorenz, M., Stamer, M., Albrecht, L., Klimant, P., Hammer, N., & Tümler, J. (2021). Haptic feedback is more important than VR experience for the user experience assessment of in-car human machine interfaces. *Procedia CIRP*, *100*, 601-606.

Shapiro, H. I., Shapiro, J. P., & Shapiro, L. K. (2011). Cranes and derricks. *(No Title)*.

Shin, Y.-S., Choi, H.-B., Lee, U.-K., An, S.-H., & Kang, K.-I. (2006). A study on selection of slab form work system for high-rise building construction. *Journal of the Architectural Institute of Korea*, *22*(2), 147-154.

Siu. (2023). The Third Serious Industrial Accident in 4 Days: 4 Workers Injured by Steel Bars. *Wenweipo*. https://www.wenweipo.com/a/202311/12/AP65502283e4b0fdf828a65e03.html

Skibniewski, M. J. (1988). Framework for decision-making on implementing robotics in construction. *Journal of Computing in Civil Engineering*, *2*(2), 188-201.

Smith, H. W. (1975). Strategies of social research: The methodological imagination. *(No Title)*.

Smith, J., & John Clarkson, P. (2005). A method for assessing the robustness of mechanical designs. *Journal of Engineering Design*, *16*(5), 493-509.

Smith, L. (1992). Ethical issues in interviewing. *Journal of advanced nursing*, *17*(1), 98-103.

So-Ryeok, O., & Agrawal, S. K. (2005). Cable suspended planar robots with redundant cables: controllers with positive tensions. *IEEE Transactions on Robotics*, *21*(3), 457-465. https://doi.org/10.1109/tro.2004.838029

Song, C., Li, X., Du, Q., Jiang, R., & Shen, Q. (2024). Hybrid pose adjustment (HyPA) robot design for prefabricated module control in modular construction assembly. *Automation in Construction*, *168*, 105798.

Sørensen, F., Mattsson, J., & Sundbo, J. (2010). Experimental methods in innovation research. *Research policy*, *39*(3), 313-322.

Sorensen, K. L., Singhose, W., & Dickerson, S. (2007). A controller enabling precise positioning and sway reduction in bridge and gantry cranes. *Control Engineering Practice*, *15*(7), 825-837.

South China Morning Post. (2024). *Flying debris after crane collapses injures 5 workers at construction site in Hong Kong*. Retrieved from https://www.scmp.com/news/hong-kong/law-and-crime/article/3277952/falling-objects-crane-injures-5-workers-construction-site-hong-kong.

Sturman, D. J., & Zeltzer, D. (1994). A survey of glove-based input. *IEEE Computer graphics and Applications*, *14*(1), 30-39.

Sueyoshi, S. (2014). Robot system. In: Google Patents.

Sun, B., Mao, C., Wang, T., & Li, Z. (2024). Cost Assessment Framework for Construction Robots: Comparative Study of Robotic and Traditional Construction. *Journal of Management in Engineering*, *40*(5), 05024009.

Takahashi, H., Farrage, A., Terauchi, K., Sasai, S., Sakurai, H., Okubo, M., & Uchiyama, N. (2022). Sensor-less and time-optimal control for load-sway and boom-twist suppression using boom horizontal motion of large cranes. *Automation in Construction*, *134*, 104086.

Tang et al. (2016). *Multi-mechanical-arm traveling crane system and control method and fault processing method thereof* (China Patent No. CN110054084B). https://patents.google.com/patent/CN110054084B/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot.

Tang, X., & Shao, Z. (2013). Trajectory generation and tracking control of a multi-level hybrid support manipulator in FAST. *Mechatronics*, *23*(8), 1113-1122. https://doi.org/10.1016/j.mechatronics.2013.09.002

The Standard. (2023). *Driver killed by falling concrete slab*. Retrieved from https://www.thestandard.com.hk/section-news/section/4/256360/Driver-killed-by-falling-concrete-slab.

Tian, S., Qu, Q., Chen, M., Xie, Z., Du, R., & Zhang, J. (2019). *Multi-row hoisting system and operation control method thereof (focus on crane trolley working path control)* (China Patent No. CN110092301B). https://patents.google.com/patent/CN110092301B/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Tunstel, E. (2006). Performance metrics for operational mars rovers. Performance Metrics for Intelligent Systems Workshop,

Uchimura, Y., & Hirose, M. (1993). *Positioning device for heavy objects by the cooperation of* *the lifting machine and the robot* (Japan Patent No. JP2638415B2). https://patents.google.com/patent/JP2638415B2/en?q=(construction+hoisting+robot)&num=25&oq=construction+hoisting+robot

Van der Maaten, L., & Hinton, G. (2008). Visualizing data using t-SNE. *Journal of machine learning research*, *9*(11).

Vom Brocke, J., Hevner, A., & Maedche, A. (2020). Introduction to design science research. *Design science research. Cases*, 1-13.

Wang, W., Liu, X., Qin, Y., & Fu, Y. (2018). A risk evaluation and prioritization method for FMEA with prospect theory and Choquet integral. *Safety science*, *110*, 152-163.

Warszawski, A. (1985). Economic implications of robotics in building. *Building and Environment*, *20*(2), 73-81.

Wieringa, R. (2014a). *Design science methodology for information systems and software engineering*. Springer.

Wieringa, R. (2014b). Empirical research methods for technology validation: Scaling up to practice. *Journal of systems and software*, *95*, 19-31.

William, E. (1994). Crane Hazards and Their Prevention. *Professional Safety*, *39*(3), 53.

WIPO. (2023). *Guide to the International Patent Classification*. WIPO. https://doi.org/https://doi.org/10.34667/tind.48084

Wöhler, C. (2009). *3D computer vision: efficient methods and applications*. Springer Science & Business Media.

WSP. (2020). *Temporary Quarantine Facilities constructed using fast-track Modular Integrated Construction (MiC) technology*. https://www.wsp.com/en-kr/projects/temporary-quarantine-facilities-constructed-using-modular-integrated-construction-technology.

Xiaoyang, L., Changwu, Q., & Shouhong, M. (2019). *Automatic wall building workstation of robot* (China Patent No. CN211037884U). https://patents.google.com/patent/CN211037884U/en?q=(construction+hoisting+robot

)&num=25&oq=construction+hoisting+robot

Xu, W., Furie, D., Mahabhaleshwar, M., Suresh, B., & Chouhan, H. (2019). Applications of an interaction, process, integration and intelligence (IPII) design approach for ergonomics solutions. *Ergonomics*.

Xu, W., & Wang, T.-K. (2020). Dynamic safety prewarning mechanism of human–machine–environment using computer vision. *Engineering, Construction and Architectural Management*, *27*(8), 1813-1833.

Yeung, & Wong. (2017). Accident During Lifting Triangle Support Bracket. *hk01*.

Yue, H., Sun, Y., Zeng, N., Chen, S., Tan, Y., & Wang, Q. (2025). Legged Robots for Construction Management: Applications and Challenges. *Journal of construction engineering and management*, *151*(8), 03125006.

Zadeh, L. A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Transactions on systems, Man, and Cybernetics*(1), 28-44.

Zadeh, L. A. (1988). Fuzzy logic. *Computer*, *21*(4), 83-93.

Zake, Z., Chaumette, F., Pedemonte, N., & Caro, S. (2020). Robust 2½D Visual Servoing of A Cable-Driven Parallel Robot Thanks to Trajectory Tracking. *IEEE Robotics and Automation Letters*, *5*(2), 660-667. https://doi.org/10.1109/lra.2020.2965033

Zarei, M., Aflakian, A., Kalhor, A., & Masouleh, M. T. (2018). Oscillation damping of nonlinear control systems based on the phase trajectory length concept: An experimental case study on a cable-driven parallel robot. *Mechanism and Machine Theory*, *126*, 377-396.

Zhang, J., Tan, R.-H., Cao, G., & Sun, J.-G. (2018). Application of standard solution to human-machine-environment coupling effect. Automated Invention for Smart Industries: 18th International TRIZ Future Conference, TFC 2018, Strasbourg, France, October 29–31, 2018, Proceedings,

Zhang, S., Wang, D., Zhang, Y., Wang, Y., Wang, Y., & Ma, X. (2002). The human machine interface implementation for the robot assisted endoscopic surgery system. Proceedings. 11th IEEE International Workshop on Robot and Human Interactive Communication, Zhou, H., & Hu, H. (2008). Human motion tracking for rehabilitation—A survey. *Biomedical signal processing and control*, *3*(1), 1-18.

Zhou, H., Williams, K. M., & Farah, W. (2008). Methodology to evaluate the effects of access control near freeway interchange areas. *Journal of transportation engineering*, *134*(12), 504-511.

Zhou, M., Yu, Q., Huang, K., Mahov, S., Eslami, A., Maier, M., Lohmann, C. P., Navab, N., Zapp, D., & Knoll, A. (2019). Towards robotic-assisted subretinal injection: A hybrid parallel–serial robot system design and preliminary evaluation. *IEEE Transactions on Industrial Electronics*, *67*(8), 6617-6628.

Zhu, Q., Zhou, T., & Du, J. (2022). Haptics-based force balance controller for tower crane payload sway controls. *Automation in Construction*, *144*, 104597.

Zi, B., Duan, B. Y., Du, J. L., & Bao, H. (2008). Dynamic modeling and active control of a cable-suspended parallel robot. *Mechatronics*, *18*(1), 1-12. https://doi.org/https://doi.org/10.1016/j.mechatronics.2007.09.004