Robotized tower crane: Simulation and high-level action planning system

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Abstract -

Tower cranes are essential in the construction industry and play a critical role in lifting and transporting materials. Despite significant advancements in the construction industry, a comprehensive framework for simulating tower crane operations and an Actions Management Node (AMN) to coordinate these operations effectively are currently lacking. This research presents a comprehensive framework that integrates a full-scale tower crane model with the Robot Operating System (ROS) and simulates its functionalities using a physics-based simulation. The framework not only facilitates operational-level control of a real-scale tower crane, but also incorporates the action management node that abstracts the complexity of crane functionalities. This abstraction enables users to provide a high-level control plan that the action manager executes with precise and efficient sequences of actions to lift and transport materials. The proposed framework, along with the action management node, is evaluated through a physics-based simulation in two different scenarios where construction components are transported from initial positions to designated target locations. The results demonstrate the framework's capability to effectively handle all crane operations, demonstrating its scalability and strong potential for real-world applications in tower crane automation.

Keywords -

Robotic tower crane; Tower crane simulation; Automated transporting system; Action planning; Construction robotics

1 Introduction

Rapid industrialization and urbanization drive a growing demand for housing, factories, and infrastructure as productivity in the construction industry remains stagnant [1, 2]. Tower cranes (TCs) are the most important equipment on construction sites and play a critical role in lifting and transporting structural materials such as steel beams and columns and concrete segments. In addition, TCs are used for the placement of prefabricated elements and heavy equipment, which is important for the assembly of structural frameworks and the installation of machinery. As a result, the overall productivity of construction projects is significantly influenced by the effective planning of crane operations. In addition, in industrial settings such as power plants, TCs are utilized to assemble heavy machinery and shipyards to transport containers and large equipment.

In practical scenarios, operations managers and planners often rely on their experience and subjective judgment to design lift plans, utilizing only 2D drawings or static 3D models [3]. Typically, planners evaluate crane accessibility to material pick-up and placement points and provide approximate estimations of lift task durations. However, these evaluations fail to consider the real movements and dynamics of the crane under operational settings on site [3]. These static planning methods can lead to inefficient and impractical plans for crane operations, compromising the effectiveness of the entire lifting process [4].

Therefore, the efficient operation of TCs on construction and logistics sites plays a critical role in reducing the time required for each load while maintaining safety standards for workers and operators. In this context, the robotization of TC and automation of its operations not only significantly enhance operational efficiency but also improve overall productivity, since the overall productivity of construction projects is heavily affected by the proper planning and operations of a TC [5]. Furthermore, this automation reduces human errors, operational risks, and enables precise load handling. Therefore, the capabilities of TCs make them crucial across various sectors, particularly in the construction industry, to improve productivity and efficiency, and robotization of TCs is an important step toward the envisioned robotized construction site [6].

Numerous studies have explored various aspects of tower cranes in planning, operation, control strategies, and automation techniques. In particular, several research studies investigate various aspects of tower crane controllers, highlighting advancements in control strategies [7–10]. A sliding mode control scheme was developed to enhance the control performance of 5-DOF TCs by precisely driving the trolley, jib, and hook to their target positions while suppressing payload swings caused by unknown payload masses, friction, and wind disturbances, without relying on linearization techniques [10]. Another approach employed data-driven methods to reduce path tracking and positioning errors in automated TCs without permanently integrating additional sensors. This method used a regression model to predict path errors, enabling the computation of a compensatory hook path that ensures the measured trajectory closely aligns with the desired one [1]. Additionally, an offline trajectory planning algorithm was proposed to guide payloads along multiple straight connection lines formed by waypoints, with smooth transitions calculated at their intersections, further enhancing path planning precision [11].

In particular, significant research has been achieved in the field of robotic TCs to automate and improve crane operations [5, 12–16]. A motion compensation algorithm was developed for multi-step speed control to achieve the exact displacement based on dynamically optimizing the time duration at each planned velocity [13]. A re-planning module developed constitutes of a Decision Support System (DSS) and a Path Re-planner (PRP) based on a decision-making algorithm to enable near real-time collision-free path optimization [16]. To address operational challenges, an automated lifting path tracking system was developed to eliminate the 'blind spot' issue in tower crane operations [17]. This system incorporated laser devices to assess its feasibility across varying environmental conditions and dynamic payload swinging scenarios. Furthermore, [15] proposed an automated lift path planning method for tower cranes based on point clouds and utilizes an octree-based sampling strategy to generate a roadmap. However, existing planning approaches often do not consider lifting time considerations and face frequent infeasibility in planned paths. To overcome these limitations, [5] introduced a reinforcement learning (RL) algorithm that replicates human decision-making processes by determining actions based on visual inputs. This system employs a lidar sensor to detect surrounding obstacles, thereby preventing collisions and enhancing operational safety, like a human operator. Additionally, [12] developed time-varying linear quadratic regulators (LQR) for trolley and jib control employing a proportional-integral-derivative (PID) method. The proposed controllers were evaluated through the ROS framework and Gazebo simulator. In addition, a robotic truck crane system (RTCS) was developed in a simulation environment and was validated by a small-scale prototype of a truck crane [14].

To enhance productivity in the construction industry, a crucial step is the development of robotized tower cranes capable of transporting objects without the need for expert operators. However, achieving this level of automation requires prior simulation due to the safety risks and costs associated with real-world testing. Therefore, a framework that simulates TCs's operations in realistic scenarios in construction and logistic sites is the first step towards the automation of TCs. This framework should then provide various construction site scenarios and transportation tasks. These can provide better management of TCs and provide precise operation time per load, which can be used for real implementation. The simulation and automation of TCs have the potential to improve efficiency, ensure safer operations, and maximize productivity, especially in construction environments where multiple TCs are in use.

This study presents a comprehensive framework that emphasizes action handling and simplifies the complexities of operational-level commands. It achieves this through the development of an action management node, which translates user-provided high-level plans into precise instructions for the tower crane's controller, enabling the seamless execution of desired motions. The framework, built on the ROS [18], leverages its capabilities for robotic automation and machinery control. ROS provides the best middleware that enables seamless integration of various nodes, allowing for real-time communication between modules and efficient message parsing. To validate the proposed action management node and framework, we integrated them with the Gazebo simulator [19] and conducted simulations using various scenarios involving different objects. The results demonstrate the effectiveness of the framework in simulating tower crane operations with precision and reliability.

The rest of the paper is organized as follows: A detailed description of the tower crane model used in this research is presented in section 2. Following that, Sections 3 and 4 outline the design and implementation of the Action Management Node and the simulation framework, respectively. Section 5 presents the results, demonstrating the effectiveness of the proposed framework. Lastly, Sections 6 and 7 deliver a discussion of the results and conclude the study.

2 Tower Crane Modelling

A tower crane comprises several key components, including the ground base segment, body segment, climbing segment, cabin and motors, apex, counterweight segment, jib base, main and last segments, trolley, cables, and hook, as shown in Figure 1. These components collectively determine the operational workspace of the crane. Adjustments to the working space can be achieved by adding or removing body and jib segments, enabling customization to meet specific site requirements.

Tower cranes, particularly hammerhead tower cranes, are often modeled as five-degree-of-freedom (5-DOF) nonlinear dynamic systems [10]. Three DOFs are actuated—jib rotation, trolley movement, and hoisting cable operation—while two are unactuated, representing radial and tangential swinging. The generalized coordinates for the actuated DOFs are γ (jib rotation), x_t (trolley position), and l_h (hoisting cable length). For the unactuated DOFs, the generalized coordinates are ϕ (tangential swing) and θ (radial swing). Figure 1 provides a schematic representation of a robotized tower crane, highlighting its structural components, jib segments, and trolley-hook assembly, which are responsible for its core functionalities.

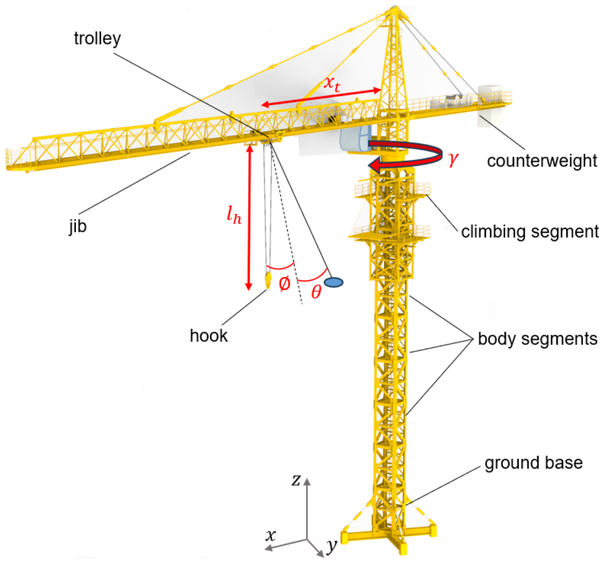

Figure 1. Schematic representation of the tower crane investigated in this study. The red color shows the DOFs of the tower crane.

This study focuses exclusively on the three actuated DOFs, treating the tower crane as a 3-DOF robotic arm. The unactuated DOFs, representing pendulum-like swings, are beyond the scope of this work. The jib, similar to a robotic arm, is mounted on the structural component (known as a mast) and driven by an electric motor coupled with a gear mechanism, allowing rotational motion. The trolley, which moves radially along the jib, is controlled by a cable-driven mechanism powered by a second electric motor. Finally, a pulley system operated by a third electric motor facilitates the vertical hoisting of loads.

The complete action functionalities of the three actuated DOFs are implemented and simulated in this study as part of a robotized tower crane model. This approach underscores the crane's operational capabilities while abstracting complexities related to the unactuated DOFs, ensuring a focused investigation of its robotic aspects.

The initial models of TCs are typically designed in formats such as .prt (Siemens NX) or .SLDPRT (SolidWorks). To integrate these models into robotics frameworks, they must be converted into formats compatible with simulation environments. This process involves modifying CAD files, converting their formats, and generating simulation-supported description files. These description files serve not only to define the crane's geometry but also to provide physical properties, including mass, inertia, joint limits, connections, and kinematics. In addition, modifying CAD files allows for minimizing the computational complexity of the simulation while preserving the operational and behavioral accuracy of the tower crane.

These steps are crucial, as they allow the ROS framework to effectively interpret the connectivity and relative motion of the crane's components, ensuring accurate simulation and control of the robotized tower crane.

3 Action Management Node

The main tower crane operations are gripping the load, lifting, transporting from one location to another, lowering, and releasing [12]. The Action Management Node (AMN) is responsible for handling all these operations by receiving high-level plans from users and converting them to low-level commands that can be used by the TC's planner and controller. The AMN incorporates all the functionalities of a TC within completely separate actions, enabling the transporting of objects from their initial positions to desired target locations. The AMN processes input data such as the object's name and the required sequence of operations, which are then transmitted to the planning and control nodes for the execution.

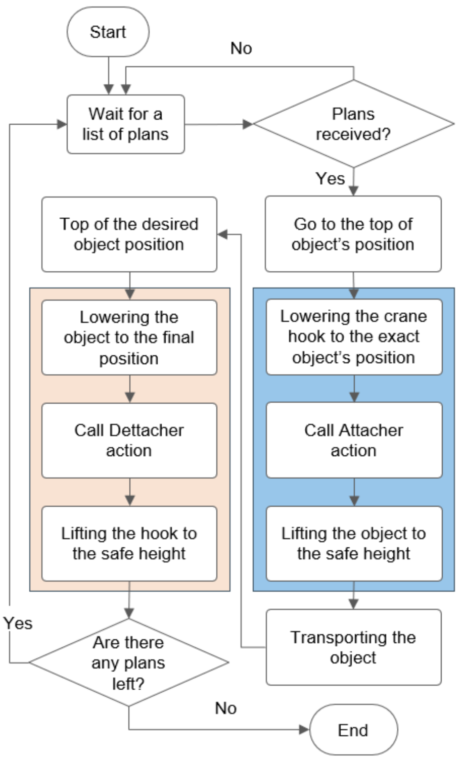

Figure 2. High-level flowchart illustrating the entire process of Action Management Node

The developed node provides continuous feedback to the user, enabling real-time tracking of the crane's status during execution. After completing the operation, the AMN sends a final status result to the user. Notably, the user can interrupt and cancel an operation at any stage of execution, ensuring flexibility and safety.

The workflow for a complete operation, from transporting an object from its initial position to its designated target location, is depicted in Figure 2. This process involves a series of sequential actions organized into three main phases: transportation, lifting (blue box), and placement (orange box). Each phase includes specific actions to ensure the precise and safe handling of materials during crane operations. The lowering action is for operational accuracy, while the lifting is critical for maintaining safety. The AMN incorporates a dedicated action to raise the hook to a predefined safe height, thereby minimizing the risk of collisions during transportation.

Given the assumption of a robotized tower crane, two additional actions, Attacher and Detacher, are introduced to perform tasks traditionally handled by human operators, securing the object to the hook and releasing it at the target location. These actions enable the system to autonomously handle objects, ensuring the same operation. When the tower crane hook reaches the object, the AMN executes the attach plan, securely attaching the object to the hook. At the target location, upon receiving the detach plan, the AMN releases the object. This automated workflow ensures efficient and reliable execution of tasks in an autonomous robotic tower crane system.

4 Simulation Framework

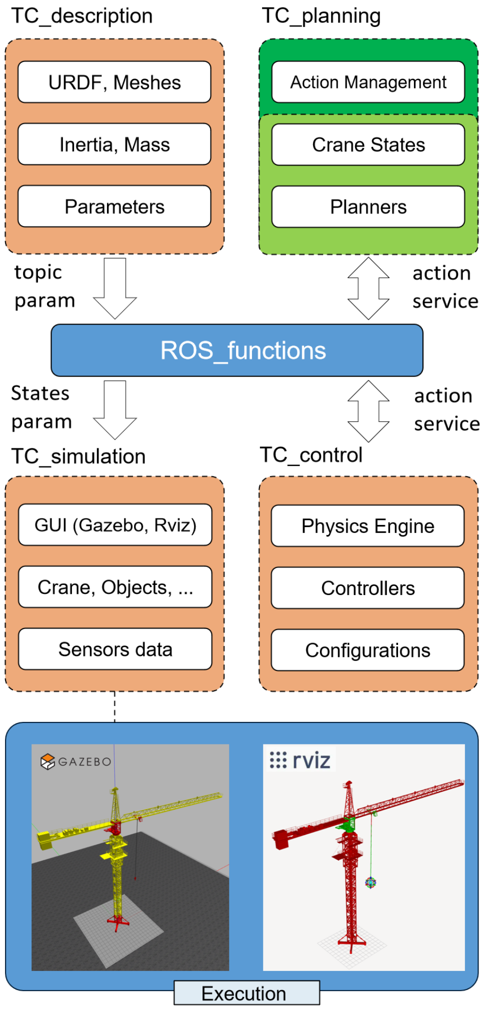

Figure 3. Flow diagram of the simulation framework

To simulate and control the tower crane, several core modules are essential, including the TC modeling, planning, control, and simulation, each composed of multiple sub-modules, as shown in Figure 3. These modules manage the entire process, from crane modeling to executing motion plans within the simulation environment. ROS [18], provides the best middleware that enables seamless integration of various nodes, allowing for real-time communication between modules and efficient message parsing. Furthermore, ROS's modular architecture supports scalability, enabling the addition of new functionalities or modifications to existing modules without disrupting the overall system's integrity. This enables continuous enhancement of the framework, ensuring its adaptability to various operational scenarios and evolving requirements in the construction industry.

Once the crane model is loaded into the system, the state publisher node continuously broadcasts the joint states and transformations of the crane, ensuring that its positions and orientations are consistently updated. This allows other modules, such as motion planning and control, to access up-to-date kinematic data of the crane's current state.

A motion planning node was developed for transportation operations using MoveIt! [20], considering the crane's configurations and properties to ensure accurate and reliable motion planning. This node generates a trajectory consisting of a sequence of joint positions, defining the crane's motion from its initial state to the desired target position. Each joint position in the trajectory is associated with a specific timestamp, defining a time-parameterized trajectory. Once this trajectory is generated, a controller is required to drive the system's joint states to follow the planned positions at the corresponding timestamps.

A controller node was developed by adapting and enhancing existing control libraries originally designed for robotic manipulators. The control node ensures smooth and precise crane movements by implementing acceleration and deceleration profiles, optimizing motion dynamics for efficiency and accuracy. It interfaces with Gazebo

[19], a physics-based simulation environment, to simulate and execute planned trajectories. The controller operates as a closed-loop system, generating control commands for the crane model while continuously receiving real-time feedback to ensure accurate trajectory tracking and execution.

The action management node integrates this iterative feedback mechanism, enabling it to monitor the execution process and send the results to the user. This feedback loop continues until the controller either successfully completes the planned actions or sends an error message for the AMN. By incorporating this functionality, the AMN equips the tower crane with advanced action planning capabilities tailored to various construction scenarios.

5 Results

In this section, the simulation results of the tower crane operations using a physics-based simulation environment are presented. To evaluate the performance and effectiveness of the proposed framework, we utilized Gazebo, a widely-used simulation tool that allows for testing and validation in a virtual environment prior to real deployment. Gazebo simulates the dynamics of the crane, including the effects of gravity, friction, and other physical forces, such as wind and magnetic fields, which are crucial for accurate real-world operation. To validate the proposed framework, two transportation scenarios with different object types and different initial and target positions were evaluated within simplified construction sites. The simulation results presented here demonstrate the framework's ability to accurately replicate tower crane operations, validate motion planning algorithms, and assess the crane's performance in various dynamic conditions.

5.1 Conexes plan

Figure 4 shows the sequential steps involved in transporting conexes from their initial positions to their target locations. The process is systematically divided into six distinct stages for each conex. The detailed breakdown of these stages is as follows:

(a) Action Processing: The Action Management Node (AMN) receives and processes the user-defined plan and initiates the sequence of actions required to execute the operation.

(b) Initial Positioning: The conex is positioned on the ground, prepared for lifting. The AMN starts the plan, beginning with the "Picking" action. This step involves determining the exact initial position of the conex within the workspace.

(c) Object Attachment: The object is attached using the attachment action. To avoid potential collisions with surrounding components in the construction site, this step incorporates a controlled movement in the z-direction.

(d) Object Transportation: The system computes the optimal trajectory for transporting the conex from its initial position to a point directly above the target location, considering TC's working space and controller parameters. This step ensures collision-free movement.

(e) Object Placement: The conex is precisely placed at the target location. To avoid collisions, the AMN

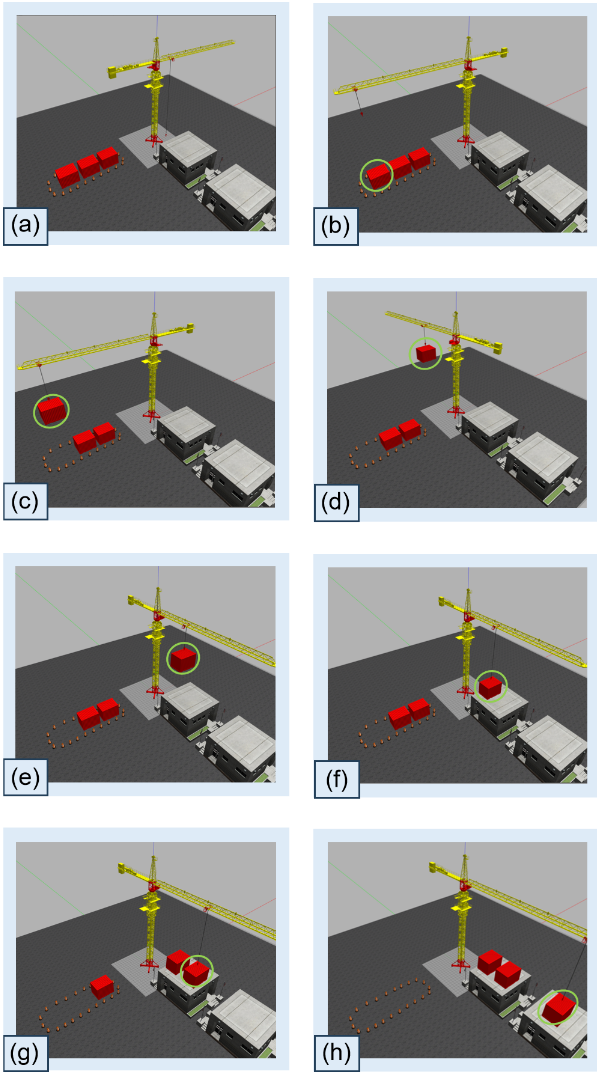

Figure 4. Objects transporting sequences: (a) home position, (b) picking position, (c) attaching the first object, (d) transporting the object, (e) placing position, (f) detaching the first object (g) placing the second object, (h) placing the third object

employs accurate control for object placement in this step.

(f) Object Detachment: Finally, the conex is detached from the hook mechanism. Depending on the operational requirements, the crane either returns to its home state or proceeds with plans for the next objects.

(g) ,(h) Placement of the second and the third objects

This approach highlights the AMN's capability to efficiently manage complex transport scenarios while ensuring precision and safety throughout the operation.

5.2 Beams plan

Figure 5 shows another scenario for transporting construction material—beams, in this case—from source place to the destination. This transportation process includes several crane motions for each beam from precise lifting, transporting, and placing. Figure 5 shows: (a) the initial positioning of beams in the construction site, (b) the transportation phase where the crane is actively maneuvering the elements along trajectories, and (c) the final placement at the designated target positions.

Each stage is illustrated with detailed top-down views. The material source area, highlighted in blue, is located at the rear of the TC where beams are initially placed. These beams must be transported to the target area, highlighted in green, positioned at the top of the building within the construction site. The Action Management Node (AMN) executes the transportation plan sequentially for each beam, continuing the process until the entire plan is successfully completed or an error is encountered.

The evaluation scenarios involving conexes and beams validate the proposed AMN and the framework. These tests demonstrate the framework's ability to achieve precise positioning of materials and enable efficient crane operations. The results show the framework's potential to meet the operational requirements of real-world construction environments.

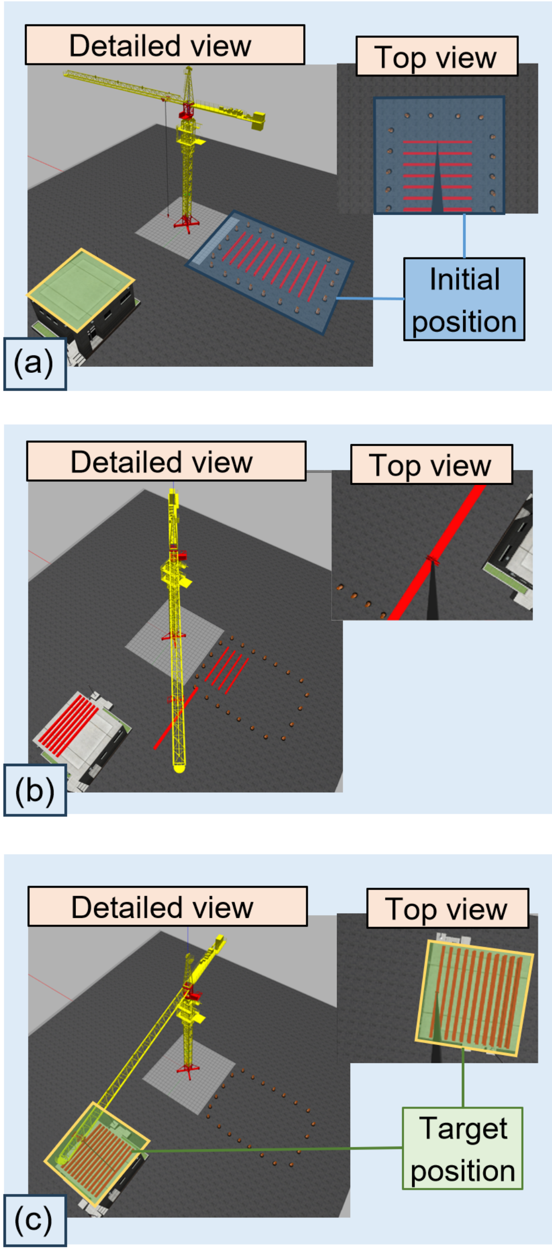

Figure 5. Beams transporting sequences: (a) initial state, (b) in process, (c) final state

6 Discussion

This study introduces and evaluates a comprehensive framework for automating tower crane operations using robotic frameworks. The proposed system integrates TC functionalities within a physics-based simulation environment, supporting both operational-level control and high-level plans. By abstracting the complexities of crane operation, the framework allows users to control the TC without the need for an expert operator. In addition, the action management node demonstrated its effectiveness in two different scenarios, confirming its feasibility and robustness toward automation planning.

This study focused on controlling the actuated joints of the tower crane within a realistic simulation environment, excluding radial and tangential swings from its scope. The assumption is ideal, but the hoisting could experience swing and rotation due to wind or inertia of mass during object transportation. These dynamics are external to TC functionalities and are typically compensated through control strategies and algorithms. It is also important to note that robotic simulators, such as Gazebo, rely on rigid body dynamics and do not natively support flexible or non-rigid structures. However, the flexibility of TC components, such as ropes, can be approximated by modeling them as chains of rigid links. While this approach closely replicates real-world dynamics, it significantly increases computational load on physics simulation.

Future research will address cable swings and tower crane structural deformation by integrating advanced mathematical models or sensor-based feedback control methods to enhance the accuracy and realism of the framework. Furthermore, we plan to deploy our framework to a scaled-down version of a tower crane in the future.

The modular and scalable nature of the framework allows for its extension to other crane types by providing their unique configurations, characteristics, and operational requirements. Additionally, the framework is built on the Robot Operating System (ROS), which facilitates seamless integration of distributed nodes through robust communication protocols and acts as a layer of abstraction on top of robotic hardware (actors and sensors) or simulation engines, such as Gazebo. Although the current implementation is optimized for Gazebo, the framework can be adapted to interface with other physics engines. However, this would necessitate additional development efforts to address differences in communication protocols and simulation interfaces.

Finally, this framework holds the potential to interface with real-world tower cranes in future applications, provided the cranes are equipped with suitable drivers to enable external connections. However, limitations and specific requirements should be considered when transitioning the framework to real-world operations to ensure reliability and accuracy in practical scenarios. These limitations include safety and compliance issues, as implementing a fully or semi-autonomous robotic crane in construction environments requires compliance with strict safety regulations and industry standards, which may impose additional design and operational constraints. Furthermore, sensor and localization challenges must be addressed, as precise localization of the crane and its load depends on sensor accuracy. External disturbances, and calibration errors could degrade performance, particularly in outdoor construction sites. Additionally, due to the increased communication between the framework and sensors, high-performance computing resources are required to handle real-time data processing and motion planning efficiently.

7 Conclusion

This research presents a simulation framework and action management node for planning and control of the jib, trolley, and hoisting using high-level information from the user and translating them to sequences of actions for the tower crane operations. The developed framework is validated on the physics-based simulator with a real-scaled tower crane model. The developed framework is scalable to a real TC as far as the desired data types are provided to the ROS framework.

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