Digital twinning hoisting process of high-rise MiC components based on 4D point cloud and BIM models

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ABSTRACT

Hoisting is the most crucial phase in the on-site construction of Modular Integrated Construction (MiC) which adopts the concept of "factory assembly followed by on-site installation". The main reason is the hoisting of MiC modules substantially influences the efficiency and safety of on-site installation due to heavy and unbalanced module loads, especially during blind lifting. However, existing monitoring, and planning methods for improving the safety and efficiency of MiC hoisting were confirmed to have limitations, such as underutilization of sensing data or disconnection between simulation and real-time situation of the construction site. This paper aims to introduce a digital twin (DT) method based on 4D point cloud (4DPC) sensing and as-designed BIM to effectively improve the safety and efficiency of the MiC hoisting process. The conceptual framework of DT for MiC hoisting was proposed, and a six-step technical route was specified. The initial test results showed that the movement of MiC can be accurately monitored, based on which further DT simulation will be done in the future.

1. INTRODUCTION

Hoisting is the most critical process of the on-site construction of MiC building, which consists of modules that are manufactured in an off-site prefabrication factory and transported to the site for installation (Zheng et al. 2020). The hoisting process will not only significantly impact the overall project time and efficiency, but is a major source of on-site construction risk (Lei et al. 2013). The unique challenge of lifting modules first comes from their large size, heavy weight, and complex load conditions. Meanwhile, the construction of MiC often happens in constrained urban environments, and thus the complexity of hoisting and positioning these modules will be high. In addition, blind lifting scenarios (where the operator's direct line of sight is obscured) further increase the difficulty of the operation and exacerbate the risk factor. Therefore, the lifting phase requires extra attention from the aspect of work efficiency and safety risk, especially when dealing with heavy, unbalanced module loads and blind lifts (Shapira & Lyachin 2009).

Some monitoring and planning methods were already used to reduce the risks and increase the efficiency of the MiC hoisting process (Zhu et al. 2022; Liu et al. 2021), but they were confirmed insufficient to improve the situation. Specifically, manual supervision and some traditional sensing approaches were used to monitor the hoisting process at construction sites, but few real-time or near-real-time coordination and control analyses were conducted based on sensing results. Therefore, the hoisting efficiency and monitoring cannot benefit a lot from the supervision or monitoring work. Despite some studies focusing on path planning or control of hoisting, most of them mainly conducted the analysis based on pre-designed 3D models or static site reconstruction models. Due to the temporary nature of the construction site, dynamic environmental change must be considered (Sacks et al. 2005). To overcome the existing challenges, some advanced technologies are urgently to be introduced.

DT, a digital replica of a physical system (Tao et al. 2022), has the potential to effectively improve the safety and efficiency of MiC hoisting. DT provides real-time monitoring, updating, simulating, analyzing, controlling, predicting, optimizing, validating, and seamlessly coordinating. By using DT, the hoisting can be real-time monitored and managed alongside the whole process. There is a profound interaction between the physical and digital components through the continual and dynamic data exchange in DT. Therefore, to develop effective DT for MiC hoisting, the most critical thing is to sense and map objects and the environment in the physical world to models in the virtual world for real-time simulation.

However, most existing sensing technologies find it difficult to meet the requirements of sensing and mapping for developing construction DT due to their technical limitations. Specifically, IoT-based and image-based sensors were widely criticized for the vulnerability of signals caused by long distances and obstacles (Zhang et al. 2012) and the lack of depth (Chen et al. 2017), respectively. The emergence of 4DPC, known for its precise spatial and temporal awareness, provides a promising sensing way for developing DT (Silva et al. 2022). 4DPC additionally incorporates temporal information into a traditional 3D point cloud, a collection of three-dimensional data points or coordinates (Xue et al. 2019; Xue et al. 2020; Wu et al. 2024). 4DPC was popular in some dynamic sensing assignments, such as the perception of autonomous driving and monitoring of construction-related activities (Liang et al. 2023) due to its several advantages, such as high resolution, comprehensive spatial-temporal information, and insensitivity to light conditions, (Liang & Xue 2022). The authors proposed a semantic registration method of 4DPC for monitoring crane-related activities in previous research. The proposed method could accurately and near-real-time detect objects from as-designed BIM, which is a digital representation of the physical and functional characteristics of a facility (Chen & Xue 2023; Liang & Xue 2023).

This paper aims to propose a DT method for the MiC hoisting process to improve efficiency and safety in construction sites. One contribution of the proposed method is integrating the 4DPC sensing method and BIM to bridge the physical world and the virtual environment. The other one is conducting optimal planning and coordination strategy based on the real-time data in the construction site.

2. RELATED WORKS

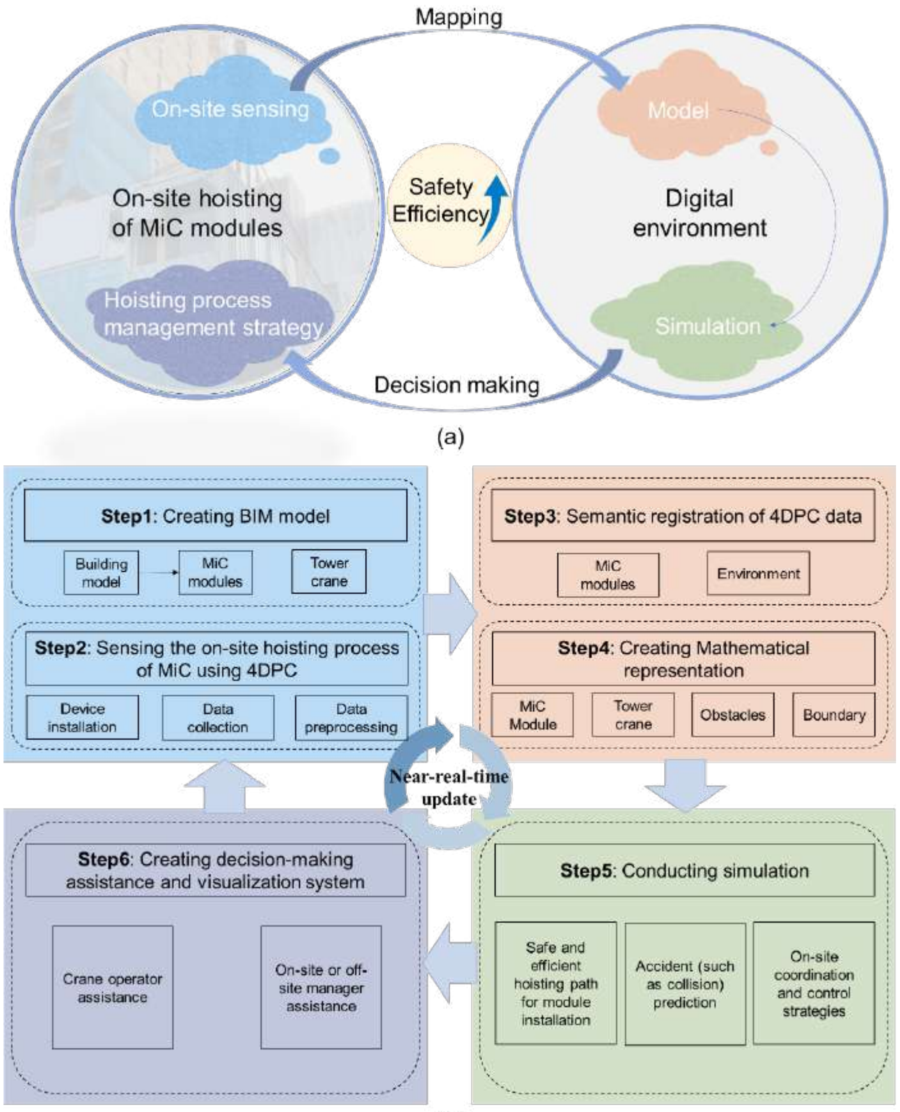
In the last ten years, many studies have focused on monitoring hoisting activities for safety concerns, but less further analysis was conducted based on monitoring results. Fang et al. (2016) developed real-time pro-active safety assistance for mobile crane hoisting operations based on a series of IoT sensors, which require high device and installation costs. In addition, Fang et al. (2018) used the camera to track the crane load sway, but only the 2D location of the load can be identified. Zhou et al. (2019) employed an IoT-based safety monitoring system for blind hoisting, and it was already applied in a practical project. Chian et al. (2022) proposed an image-based deep learning method to detect and track the fall zone of crane load, but it was criticized for overreliance on the quality of the training set.

Meanwhile, computer-aided automated path planning has also been the subject of several research to improve hoisting efficiency and safety. Kayhani et al. (2021) used Dijkstra's method to find the shortest crane-lift path from the starting point to the destination point. Hu and Fang (2020) combined Building Information Modeling (BIM) and the RRT* algorithm to find the optimal crane-lift path. Zhu et al. (2022) integrate metaheuristic optimization and virtual prototyping to optimize the path planning for high-rise MiC modules. However, all of them were only analyzed in the virtual environment without considering the real site condition.

There are few DT-related studies in the construction field. A recent literature study conducted by Boje et al. (2020) discussed the transition route toward a semantic construction DT, which is different from traditional BIM applications in the current practice of the construction industry.

3. METHOD

To improve the efficiency and safety of the MiC hoisting process, the conceptual framework of DT was proposed, as shown in Figure 1(a). There are mainly four parts, i.e., sensing on-site hoisting of MiC, establishing parametric models, conducting the simulation, and making near-real-time hoisting management strategies. Figure 1(b) illustrates six specific steps to develop the proposed DT for MiC hoisting.



(a)

(b)

Figure 1. DT of MiC hoisting: (a) conceptual framework; (b) technical route.

- Step 1: BIM models for construction sites need to be created before hoisting. Herein, BIM models include high-rise MiC buildings (including every single MiC module) and on-site tower cranes. As-designed BIM will play a crucial role in the subsequent parts of the work.

- Step 2: The LiDARs will be installed to collect 4DPC data on the construction site. On-site 4DPC collection is required to cover the potential area of the MiC hoisting process. Meanwhile, the 4DPC data preprocessing, such as data registration from multi-devices and background removal, will be conducted.
- Step 3: The semantic registration will be conducted on preprocessed 4DPC based on as-designed BIM. In specific, the BIM object will be registered into the 4DPC through an optimization process. The detailed semantic registration method can be found in the previous study by authors (Liang et al. 2024).
- Step 4: According to the semantic 4DPC and as-designed BIM, the construction objects and facilities can be mapped into the virtual world. The hoisting-related objects and tower cranes will be represented by mathematical models for the following simulation.
- Step 5: The simulation will be conducted for safety and efficiency improvement. The specific assignment can be optimal path planning or risk prediction.
- Step 6: Based on the simulation result towards the hoisting path, potential risk, and coordination. The assistance and visualization system can be established for crane operators and on-site or off-site managers.

4. EXPERIMENTAL SETUP

In this paper, steps 1, 2, and 3 illustrated in Figure 1(b) were already finished. A novel 4DPC sensing device, as shown in Figure 2(a), was developed in-house (Xue et al. 2024) to collect the high-definition 4D motion data of construction activities. Two 4DPC LiDAR were installed on a temporary platform at the construction site at an angle of one looking down and one looking up, to cover the entire hoisting process of the MiC from the ground to the installation location. The 4DPC LiDAR used in this study was the Livox Mid-70. It is suitable for this high-rise MiC hoisting project due to its great ability, i.e., a 70.4° circular field of view, a maximum detection range of 260 m, and a recommended detection range of 90m (about the 30-story height). The LiDAR scanned 4DPC data with centimeter-level accuracy at a rate of 20 frames per second. However, the target resolution may have been reduced due to the limited scanning duration per frame. In total, the devices collected 1 hour of 4DPC data in lvx format, with a size of 80 MB per minute, from the construction site. In this paper, 15-min 4DPC data including a complete hoisting process was selected to validate the method. To achieve a trade-off between the updating frequency and sufficient resolution of registration, 4DPC data was aggregated every 0.5 seconds, i.e., a frame rate at 2 fps, resulting in a total of 1800 frames.

The proposed method's computational experiment was conducted on a desktop computer equipped with an Intel i7-10700 2.9 GHz CPU, 32 GB of memory, Python 3.8, and Windows 11 64-bit, operating in single-threaded mode. The geometric point-level error for 4DPC points was less than 2cm at a 20m distance. In the registration process, both the BIM objects and input 4DPC utilized voxel grid sizes of 150mm.

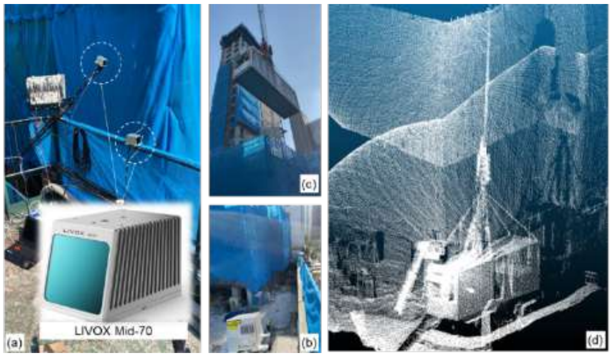
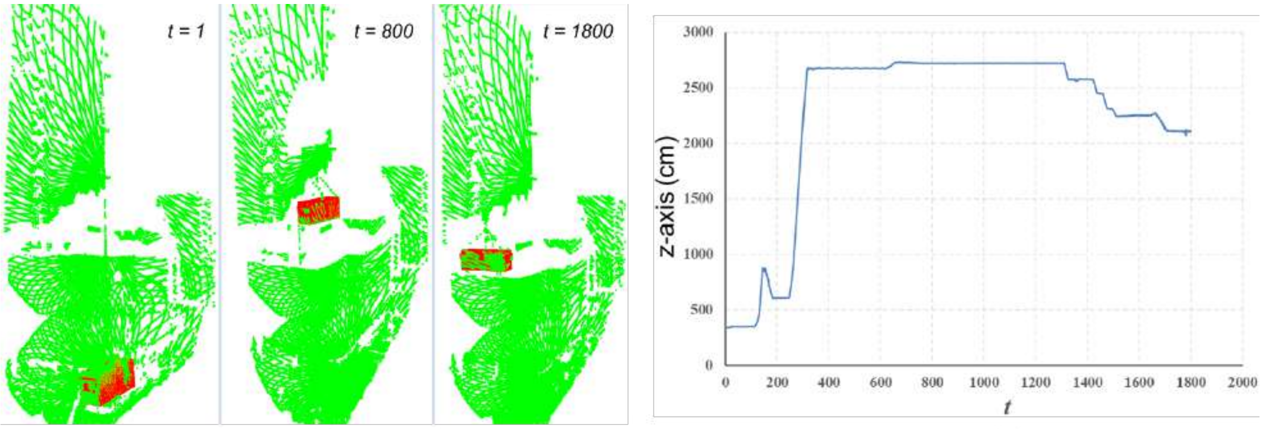


Figure 2. (a) On-site installation of the device; (b) Example of 4DPC data frame

5. INITIAL RESULT AND DISCUSSION

The initial result will be discussed in this section. Figure 3(a) illustrates the accurate registration result in the start (t=1), process (t=800), and end (t=1800). From the registration result, the 3D location and direction information can be extracted. For illustration purposes, figure 3(b) shows the movement of the MiC module in the z-axis direction. In specific, the center of the MiC module rose from a height of around 350 cm to 870 cm and then went down to about 600cm. After temporary adjustment, the MiC module was hoisted to the height of 2670 cm and finally stopped at the installation location (nearly 2110 cm).

Further DT analysis will be conducted based on the registration result of 4DPC and as-designed BIM.



(a) (b)

Figure 3. Registration result: (a) 3D illustration of 4DPC; (b) Decomposed movement in z-axis direction.

6. CONCLUSION AND FUTURE WORK

The hoisting process significantly impacts the efficiency and safety of on-site MiC construction due to heavy and unbalanced module loads, particularly during blind hoisting.

However, the traditional monitoring or planning methods are difficult to effectively reduce the risk and improve the efficiency of MiC hoisting due to technical limitations.

This paper tries to improve the safety and efficiency of the MiC hoisting process by introducing Digital Twin (DT) which is based on the 4DPC sensing and BIM. The conceptual framework was proposed, and the 6-step technical route was determined. The initial results presented that the spatial-temporal information of the MiC module can be accurately obtained. Based on the sensing results, further work will focus on establishing mathematical representation (modeling) and DT simulation for different purposes in the future.

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