Virtual reality (VR) supported lift planning for modular integrated construction (MiC) of high-rise buildings

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ABSTRACT

Modular integrated construction of high-rise buildings has shown its potential in accelerating the speed of construction, improving safety, safeguarding quality and enhancing productivity. However, due to the disruptive change to the construction process, challenges are identified to effectively plan and handle multiple lifts for hoisting heavy modules. Research on lift planning includes the development of simulation tools. However, the previous tools provided either static simulations or pre-designed animations that did not address the interactions between planners and the tools. Virtual reality (VR) offers an opportunity to build an interactive and navigable 3D environment. This paper aims to develop a user-friendly VR-supported tool for achieving effective lift planning for constructing high-rise modular buildings. First, the module lifting process and tower crane operations were analysed. Second, a VR demonstration was developed using a real-life modular building project. Third, the demonstration was used during interviews with the project team to verify the effectiveness of the developed tool. Results suggest that the tool can help optimise the site layout and lift logistics through the provided functions of collision detection and construction simulation. The findings suggest that VR-supported lift planning will contribute to ensure site safety and enhance the productivity of modular high-rise building construction.

KEYWORDS High-rise modular building; modular integrated construction (MiC); lift planning tools; virtual reality (VR); smart construction
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1. Introduction

The construction industry in Hong Kong is facing severe challenges including shortage of labour, increasing workload and cost escalation with low productivity (Pan et al., 2016). To address these challenges, the Chief Executive of the HKSAR in the 2017 and 2018 Policy Address announced a new policy initiative to promote the use of modular integrated construction (MiC). MiC is the most advanced type of off-site construction that has wide-ranging demonstrated benefits (Gibb, 1999; Lawson et al., 2014). MiC is defined by Pan and Hon (2018) as "a game-changing disruptively-innovative approach to transforming fragmented site-based construction of buildings and facilities into integrated value-driven production and assembly of prefinished modules with the opportunity to realise enhanced quality, productivity, safety and sustainability". High-rise modular buildings have emerged internationally and been demonstrated with the benefits including labour saving, faster on-site construction, decreased waste and cleaner site environment (Pan et al., 2018). However, challenges still exist during the delivery of high-rise modular buildings due to its disruptive changes, compared with conventional construction practice in terms of on-site construction. The major challenge is the installation of multiple heavy modules (Fard et al., 2017; Lawson and Richards, 2010), the predominated activity which affects the construction safety, quality and efficiency. For the development with several blocks, module lifting not only concerns with multiple modules, but also a group of tower cranes. Hence, lift planning should be carried out effectively with an effective planning tool to ensure the successful delivery of high-rise modular buildings.

2. Literature review

Generally, lift planning is carried out by the planner in an iterative and trial-and-error manner until achieving the satisfying layout plan (Varghese et al., 1997). The process still uses 2D drawings to focus on fragmented locations instead of the entire lifting process. This static method may lead to an inappropriate crane operation due to the lack of dynamic information. Even though the tools like 3dMax are adopted for animation, it is tedious of preparing multiple lifting scenarios with manual process, which is proven to be non-productive. To improve the lift planning process, researchers have made great effort to develop systems and algorithms for effective lift planning and optimisation, which can be categorised as (1) crane selection and location optimisation (Al-Hussein et al., 2005; Zavichi et al., 2014); (2) lifting cycle analysis (Tam et al., 2002; Yang et al., 2012); (3) path planning and collision detection (Kang and Miranda, 2008); (4) planning for multiple cranes (Al-Hussein et al., 2005). In order to detect potential crane collisions, the 3D visualisation has been adopted widely to generate virtual construction scenarios (Chi and Kang 2010; Han et al. 2015). Lin et al. (2011) extended the adoption of 3D visualisation with the introduction of a simulation approach for analysing multiple cooperative cranes.

Besides, artificial intelligence (AI) related tools have also been adopted for the lift planning research. For example, Al-Hussein et al. (2005) proposed a searching algorithm for mobile crane selection assisted with 3D animation. Huang et al. (2011) compared various heuristic algorithms, i.e. artificial neural networks (ANN), genetic algorithms (GAs) and mixed-integer linear programming (MILP), so as to optimise crane locations effectively.

Though the planning techniques are becoming smarter, the tools to date cannot offer an interactive way for planners to get involved during the planning process. Thus, it is necessary to conduct further studies in order to improve the lift planning process. Virtual reality (VR), as an emerging technology, is known as its ability for users to navigate in, manipulate and interact with the virtual environment (Bouchlaghem et al., 2005), which happens to provide the chance for planners to be emerged in. VR technology is not new in the construction industry. For example, it has been used for constructability analysis of precast concrete construction (Setareh et al., 2005), construction prototyping (Huang et al., 2007), improving design information integrity for closing building energy performance gap (Niu et al., 2016) and safety training (Sacks et al., 2013). However, little previous research explored how to apply VR in lift planning and optimisation, for modular construction in particular. Thus, this paper aims to develop a VR-supported tool for achieving effective lift planning for high-rise modular buildings.

3. Research methodology

In order to develop a VR-supported tool for an effective lift planning for high-rise modular buildings, this research adopted a mixed approach which was carried out in three steps (Figure 1). First, a comprehensive literature review and a desk study were conducted towards module lifting for high-rise modular buildings, tower cranes analysis and tools of VR application. Second, the VR-supported tool was designed and developed using virtual prototyping techniques. The development started from building the Revit 3D model, then transferred to the environment of Unity 3D – a game engine offering a VR development platform. Relevant programming for crane movements and design for user interface (UI) were conducted accordingly. Third, the developed tool was demonstrated using a real-life MiC project. Module lifting simulation was demonstrated to the project team with the function of collision detection and critical lift analysis, followed by interviews with the project team to verify the effectiveness of the developed tool.

4. Module lifting and tower crane analysis

4.1. Module lifting

Typically, high-rise modular buildings are designed with multiple modules around a central core (Lawson et al., 2012). Hence, site activities mainly include foundation and central core construction, module installation and connection, among which module installation is deemed to be the most critical activity (Lawson et al., 2014). Module lifting dominates the construction process of high-rise modular buildings as it is in the critical path of the construction programme occupying heavy-duty cranes (Olearczyk et al., 2014) which may also concern the site safety to facilitate the mobilisation of multiple heavy modules (Fard et al., 2017). As observed on-site, lifting of a module (Figure 2) includes hooking, hoisting (lift up and rotation) and positioning.

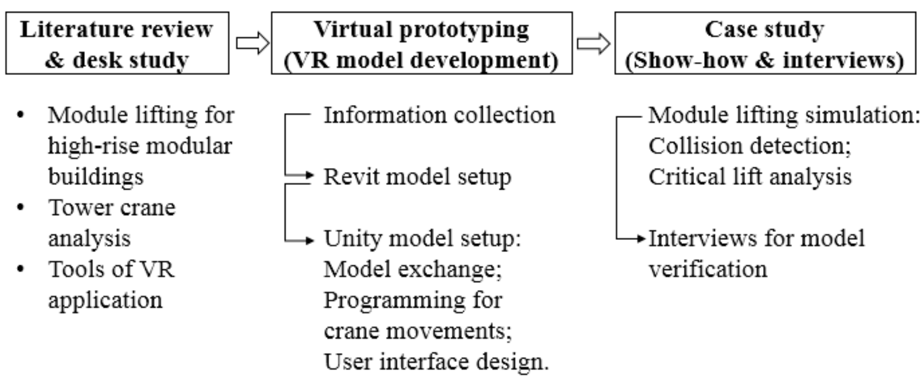

Figure 1. An outline of research methods.

Figure 2. Module lifting process (Photo courtesy: Teambuild).

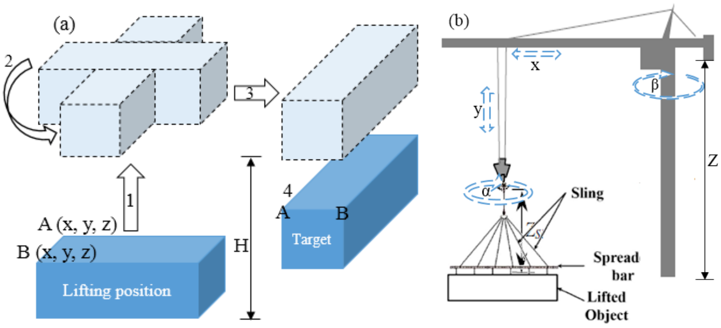

Figure 3. (a) Module lifting process; and (b) DoFs of a tower crane.

4.2. Tower crane analysis

For the development of high-rise modular buildings with several blocks, a group of tower cranes has to be employed to cater for the handling of multiple heavy modules. It seems to be a critical challenge to balance the utilisation of tower cranes and to install the modules smoothly. Hence, it is significant to look into the mechanism of the tower crane which offers the best combination, in terms of height and lifting capacity particularly for high-rise building construction (Lai and Kang, 2009). In this paper, four degree-of-freedoms (DoFs) of a tower crane were categorised in line with the module lifting process (Figure 3):

(1) y: hoisting up and down;
(2) α*: clockwise and counter-clockwise rotation of the hook;
(3) x: trolley back and forth with the cable length fixed; and
(4) β: rotation of the superstructure of the crane.

* The rotation of the hook block is normally pulled by the labour using a rope tied with the module. It is set in the VR model that the hook rotation could be controlled using the keyboard.

5. VR-supported tool development

5.1. Tools for VR application

VR emphasises more on the human-computer interaction as compared with conventional simulation and animation (Wang, 2002), which is mainly used for design and planning in the construction industry currently (Whyte et al., 2000). The VR environment can be experienced with varying tools, such as hardware categorised by degrees of immersion, from desktop immersive (e.g. laptop) to fully immersive (e.g. cave automatic virtual environment). Users can manipulate and interact with the virtual objects by using the keyboard and mouse, or more advanced devices such as wired glove or space mouse (Shiratuddin et al., 2004). Though using laptop as the display offers the minimum sense of immersion, it could not only help to share the VR models easily, but also provide the opportunity for interaction and manipulation by multiple players simultaneously using the keyboard and mouse. Therefore, laptop is selected as the device in this paper for displaying and sharing the developed VR model. For the VR-supported tool development, Unity 3D – a leading game engine which is an open-source platform, is adopted for virtual prototyping.

5.2. System design and tool development

The system architecture of the tool is designed in the Unity 3D platform based on an object-oriented approach (Figure 4). The main components of the model include: (1) the UI for users to interact with the planning objects in a real-time manner to manoeuvre different construction scenarios, and (2) an inference engine for analysing the construction performance with scripting.

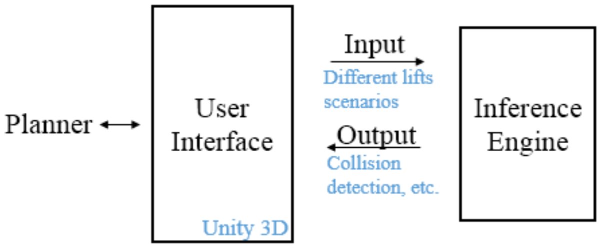

Figure 4. System architecture of the VR-supported planning tool.

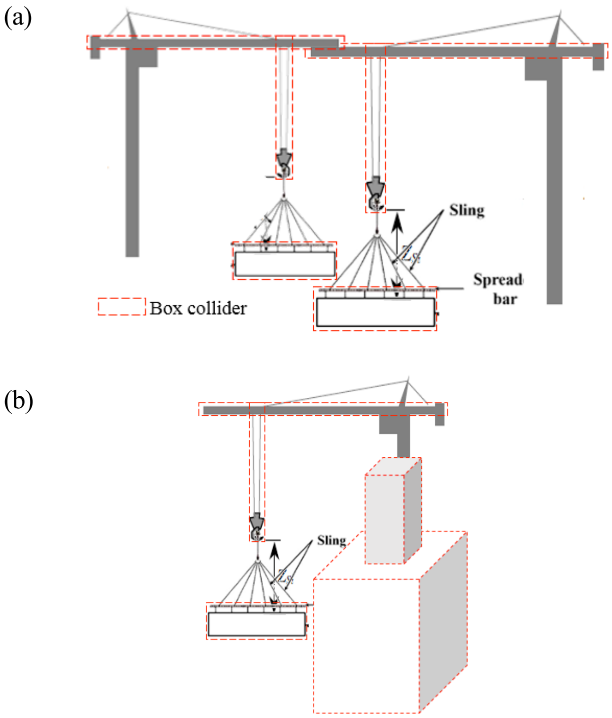

Figure 5. Mechanisms of collision detection. (a) Tower crane to tower crane (T2T); and (b) module to building (M2B).

To build up the tool, first, information such as site layout plan, building layout design, module information and tower crane is collected as the input to the VR model. Construction site layout affects the location of tower cranes and temporary storage yard, while building layout determines the final positions of various modules. Module information, e.g. volume and weight, is the key factor for tower crane selection and storage yard arrangement. Once collected the project information, the site information such as site boundary and crane arrangement is presented directly in Unity 3D, while the 3D BIM model of the building is prepared using Revit, followed by the transformation of the Revit model into Unity 3D.

Then, UI is designed to form the space where human-machine interactions occur. This interaction allows humans to operate and control the machine while the machine feeds back simultaneously. Planners could interact with the virtual construction site for any adjustment through the designed UI. Lastly, the inference engine is established to offer the capability for real-time collision detection among tower cranes, modules and buildings.

Functions designed in the developed tool innovatively incorporate the simultaneous control of different virtual objects via the customised programming, and provide the mechanism of collision detection among modules, buildings and tower cranes. During the rehearsal process, for instance, the continuous collision detection using box collider in Unity 3D is called when the moving object collides with static and dynamic geometry (Figure 5).

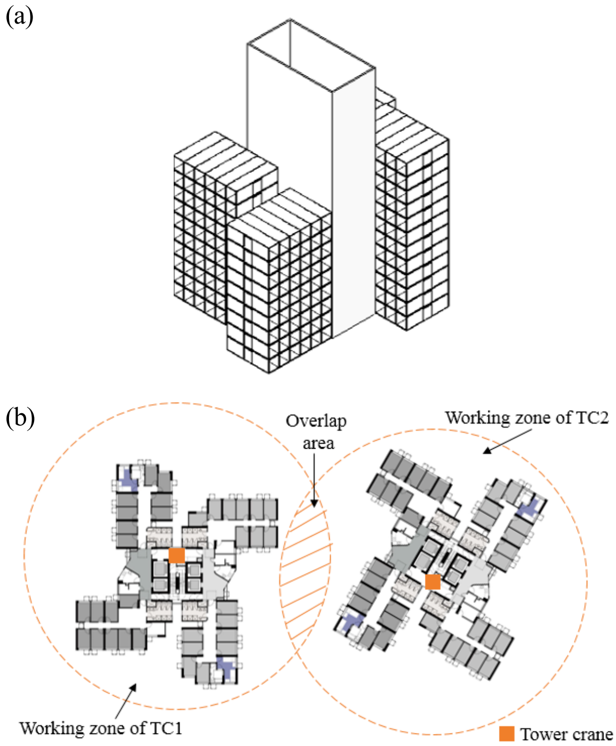

Figure 6. The case building. (a) Revit model; and (b) conceptual construction scenario.

6. Case study

One of the MiC pilot projects in Hong Kong is a student hostel building, and was selected as the case for demonstration. The project consists of two 17-floor towers which could offer around 1,224 student places. Revit model and the possible construction scenarios were built based on the information collected from the project team (Figure 6).

A demonstration (Windows application) towards the selected MiC project was developed in accordance with the procedure described in Section 2.2. The construction information could be virtually displayed which offers the ability of interactions via the keyboard and the designed UI (Figure 7).

Functions of this demonstration could be well realised including (1) real-time module lifting simulation from hooking to final positioning through human-machine interactions (Figure 8); (2) collision detection with the sign "Warning" as shown in the UI in line with the rehearsal of different construction scenarios (Figure 9); and (3) the two tower cranes being controlled simultaneously to simulate various construction scenarios (Figure 10).

The developed lift planning tool (demonstration) was shown to the client of the hostel building project and opinions were collected after the demonstration. The demonstration was perceived as an effective tool which is apt at training for crane operators with the function of interactions and useful for the demonstration to stakeholders with a 3D environment. In addition, the demonstration could serve as a decision-making tool given that more detailed information is available, e.g. accurate site layout, building layout, module type and dataset of cranes. More installation uncertainties could be identified through such an interactive platform to enhance site safety and construction productivity. Nevertheless, suggestions were given in terms of the level of details, universality and dynamism, which mean that more details should be incorporated into the platform. The platform should better incorporate comprehensive database to make it more generic and timeline should be added to show the construction progress, and the dynamic simulation like truck flow on-site is supposed to be looked into.

7. Discussion

This research has proposed a VR-supported lift planning tool to assist the optimisation of module lifting logistics for high-rise modular buildings. Radical changes of MiC to the site layout plan and construction process due to the transformation from fragmented construction into integrated assembly with multiple and heavy modules, determine the significance of planning for module

Figure 7. UI and keyboard controller.

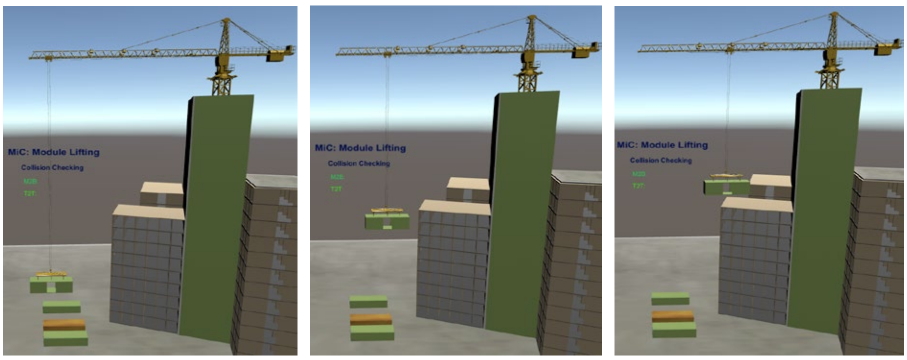

Figure 8. Module installation process simulation in Unity 3D.

installation in a safe and efficient manner. Additionally, MiC is an innovative construction technology and is relatively new to the construction industry in Hong Kong which puts forward requirements on innovative and effective planning tool/method. The characteristics mentioned above distinguish the tool from those developed for conventional construction and the traditional simulation and animation tools for lift planning.

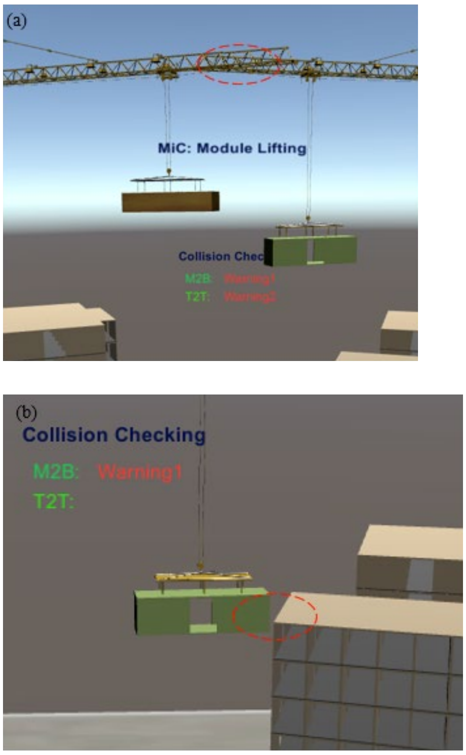

Figure 9. Collision detection in Unity 3D. (a) T2T; and (b) M2B.

First, lifting studies towards traditional building construction are generally conducted without considering the volume of the lifting components (Tam and Fung, 2011; Younes and Marzouk, 2018), which is different from modular construction with heavy modules. The model established in this paper reflects the features of modules in terms of volume and weight which is closely related to construction safety and lifting efficiency. For instance, one more DoF of the tower crane, rotation of the hook block, is added into the VR model in the view of the rotation of heavy modules, which is correlated with the frequency of collision detection between modules and the building.

Furthermore, planners normally carry out lift planning in an empirical way through 2D drawings and sometimes with 3D animations (Bosche et al., 2006; Hermann et al., 2015) to investigate the possible construction scenarios. However, some detailed uncertainties could not be identified for the innovative modular construction based on their experience. The proposed tool supported with VR technology is shown to be useful for module lift planning by means of (1) function of interactions which allows the planners to manoeuvre the lifting components as many times as necessary and control the tower cranes simultaneously; (2) navigable 3D environment which help identify the detailed construction risks from different views; (3) real-time simulation of different construction scenarios to analyse the performance of the designed site layout and lifting logistics; and (4) allowing users to get familiar with the environment and work before actual implementation on-site.

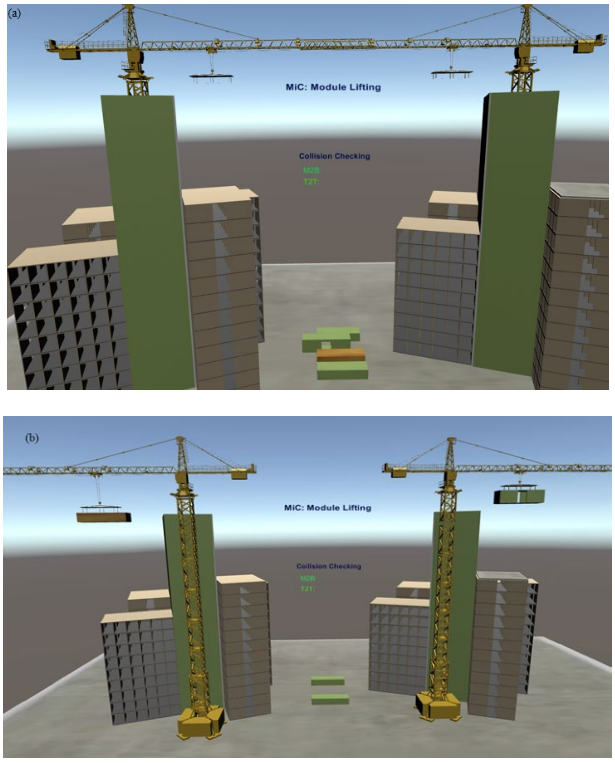

Figure 10. Construction scenarios with two tower cranes working simultaneously. (a) (Scenario 1) Tower cranes are located in the central service core, and the temporary storage yard is located in the middle of the two blocks; and (b) (Scenario 2) tower cranes are beside the central service core, and two temporary storage yards located on the sides of the two blocks separately.

Assisted with the superiorities of the VR technology, the tool may be able to deal with construction planning in a more dynamic and systematic manner provided that a generic platform could be developed with more detailed and accurate information embedded in. In future, the tool is supposed to be smarter connected with intelligent algorithms, which could effectively contribute to decision-making for mega projects.

8. Conclusions

This paper has developed a VR-supported lift planning tool for supporting MiC of high-rise buildings. First, a literature review and a desk study were conducted to analyse the module lifting process and mechanism of the tower crane. Then, a VR-supported planning demonstration was developed in the Unity 3D platform. Lastly, the demonstration was displayed and discussed with the project team of a real-life high-rise modular building project in Hong Kong.

The results reveal that the developed tool can be executed in most personal computers and enable users to simulate construction processes virtually before real construction. It is found that the developed tool could help optimise the construction layout and module installation sequence through the provided functions of collision detection and simulation of different module installation scenarios. These findings prove that the VR-supported lift planning tool can contribute to ensure site safety and enhance productivity of MiC for high-rise buildings in an interactive manner. The tool developed thus will help de-risk the adoption of innovative modular construction technologies in difficult sites of built urban areas, and will have significant contributions to the successful implementation of MiC policy in Hong Kong.

The research reported in this paper also identifies the need for further study. There is a lack of comprehensive database on the types of cranes and limited performance data displayed in the UI on the construction progress, which may hinder the practical application of the VR-supported tool. Future research could further develop the tool to be more systematic and dynamic to suit different types of modular building construction.

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Notes on Contributors

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