INTEGRATING SMART CONSTRUCTION OBJECTS AND AUGMENTED REALITY FOR ONSITE ASSEMBLY OF MODULAR CONSTRUCTION

Yipeng Pan[1], Junjie Chen [1,*], Yonglin Fu[1], and Weisheng Lu[1]

[1]The University of Hong Kong, Hong Kong, China
* Corresponding author: chenjj10@hku.hk

Abstract

Despite the promise of modular construction to transform the construction industry, precise assembly of a large number of modules to their designated positions onsite remains a challenge. The challenge is jointly caused by a lack of technical means to track information about modules (e.g., ID, current position, and position to install) and an absence of visualization tools to communicate the information. By combining three properties (i.e., awareness, autonomy, and communicativeness) of smart construction objects (SCOs) and the visualization capability of augmented reality (AR), this study aims to develop a deployable framework to assist the onsite assembly of modular construction. The framework comprises a smart tracking unit to monitor the condition of each module, a database to aggregate, process then dispatch the module information, also with a pair of AR glasses to intuitively display the information to users. The proposed framework was evaluated with a modular student hostel project in Hong Kong. The case study demonstrates the effectiveness of the framework in soliciting real-time module information, visualizing the moving trajectory of the module, and showing its required install position. The framework is effective to assist onsite assembly of the modular construction.

Introduction

Modular construction is an advanced construction approach where 3D-volumetric building modules are manufactured in the factory environment and then transported to the site for assembly into a complete construction product (Li et al., 2021). It has been widely adopted worldwide due to its higher flexibility, productivity and safety (Gong et al., 2019). Onsite assembly is a risky and complex stage in modular construction, which involves the repetitive process of installing a large number of prefabricated modules (Shan et al., 2019). It inevitably poses huge challenges to site management because of high variability of external environments, fragmented nature of construction organizations, and ambiguous information exchanged (Wu et al., 2022). Therefore, onsite assembly in modular construction (OAMC) requires tracking information about modules (e.g., module ID, current position and position to install) and communicating this information in a timely manner, so as to enable onsite managers to make timely and effective decisions about the modules and their assembly, as well as minimizing the issues related to assembly rework (Wu et al., 2022).

Some cutting-edge technologies to facilitate information sharing and tracking have been adopted in modular construction. Information and Communication Technology (ICT) and the Internet of Things (IoT) are two core technologies for accurate and real-time information sharing, such as Radio Frequency Identification (RFID) and global positioning system (GPS). Based on ICT and IoT, the utilization of smart construction objects (SCOs) (Niu et al., 2016) allows construction information to be embedded into physical components (e.g., RFID tags), potentially increasing the flexibility and independence of construction tasks. Furthermore, Li et al. (2018) proposed an IoT-enabled platform by integrating SCOs and Building Information Modelling (BIM), aiming to support on-site assembly decisions and services in prefabricated construction. Besides, to prompt seamless and flexible information sharing and transmission in OAMC, Zhou et al. (2021) developed an IoT-enabled BIM platform by several tracking and sensing techniques (i.e., SCOs equipped with smart trinity tags and GPS sensors). Despite SCOs providing an intelligent way to track information about modules, there is a lack of methods for communicating this information intuitively and seamlessly for onsite builders in OAMC.

Augmented reality (AR) is helpful for communicating information in a timely and intuitive manner on site. AR is an advanced visualization technology that allows users to view virtual objects superimposed on their view of the physical environment (Wang et al., 2013). AR application in construction has gained growing attention these years. For example, Tavares et al. (2019) proposed a collaborative welding system integrating BIM and AR, which helps an operator tack weld the beam attachments. Kim et al. (2017) developed a vision-based hazard avoidance system for onsite workers to avoid dangers by displaying hazard information on wearable AR devices. little has been known about how AR benefits OAMC. By incorporating SCOs technology, AR can show huge potential to track and communicate information about modules.

This research aims to develop an implementation framework for tracking and communicating information about modules with SCOs and AR technologies. We first review related works on SCOs and AR technologies in construction industry (Section 2). In section 3, we present a deployable framework to support OAMC, which consists of SCOs to monitor each module, a database to aggregate and process, and dispatch the module information, and AR devices to intuitively visualize the information to onsite man-

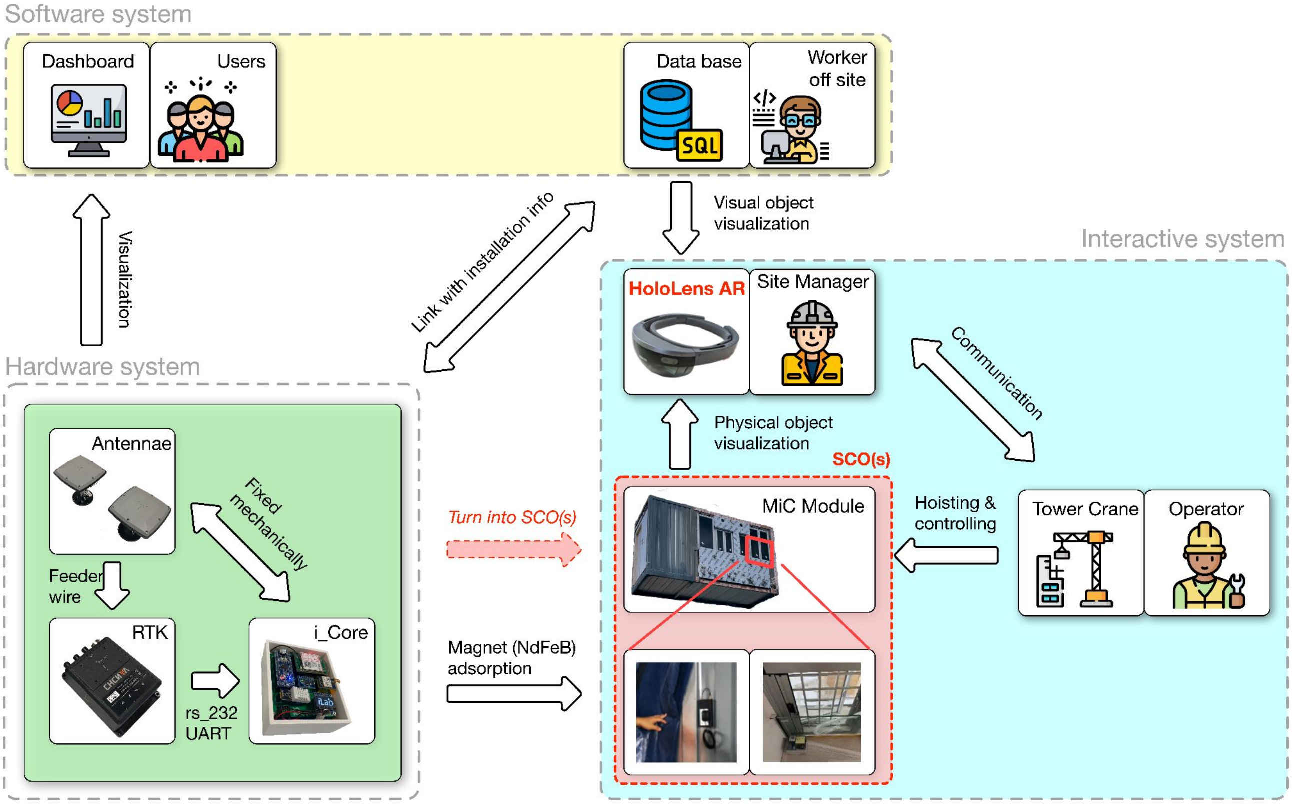

Figure 1: Structure of proposed framework

agers. Section 4 shows a case study to demonstrate the effectiveness of the proposed framework. Finally, Section 5 concludes the paper with an outlook on future work.

Related works

Smart construction object

Smart construction objects (SCOs) are construction resources made smart by augmenting them with capabilities of sensing, processing, computing, networking, and reacting (Niu et al., 2016). They are construction-related specifications and extensions of smart objects that have been previously discussed in the household environment (Beigl et al., 2001) and the manufacturing industry (Zhang et al., 2011). Niu et al. (2016) argued that awareness, communicativeness, and autonomy are three core properties of SCO, and the three core properties may be combined in different manners depending on the needs and requirements of different circumstances. Lu (2018) analysed the underlying reasons that are hindering digital transformation of the construction industry, and advocated SCO as a promising alternative to existing intrusive manners of reengineering conventional construction workflows to emerging robotics and smart technologies.

The applications of SCOs have enormous potential to transform the construction industry by solving its long-lasting problems in terms of safety, quality and productivity. For example, Zhu et al. (2021) proposed a component-oriented robot construction approach by integrating SCOs with multiple robots for multi-tasking collaboration of prefabricated housing assembly. To enhance transparency, traceability, and immutability of construction data in supply chain management, Lu et al. (2021) exploited SCOs as blockchain oracles to bridge the on-chain (i.e., blockchain system) and off-chain (i.e., real-life physical project) worlds, and demonstrated that the SCOs-enabled blockchain oracles can effectively guarantee accurate data is retrieved against malicious data. Similar to the above applications, SCOs also have unexplored potential to assist OAMC by taking advantage of their three core properties. Augmenting module units with the smartness to be aware of their installation status (e.g., real-time position, target positions, and velocity) and communicate the information with their vicinity, the site managers can better monitor the assembly process with the help of visualization tools such as AR.

AR in construction

Augmented reality (AR) usually refers to overlaying computer-generated virtual images and objects on real-world scenes to create a mixed-reality world (Jiao et al., 2013). Compared with virtual reality (VR), AR places an emphasis on the precise alignment of real-world scenes with their corresponding virtual world imagery in real time or at the appropriate moment, providing a semi-immersive environment. A great deal of research has been conducted on the application of AR in construction industry (Chi et al., 2013). For example, Hou et al. (2015) demonstrated that AR can reduce worker cognitive load and thus im-

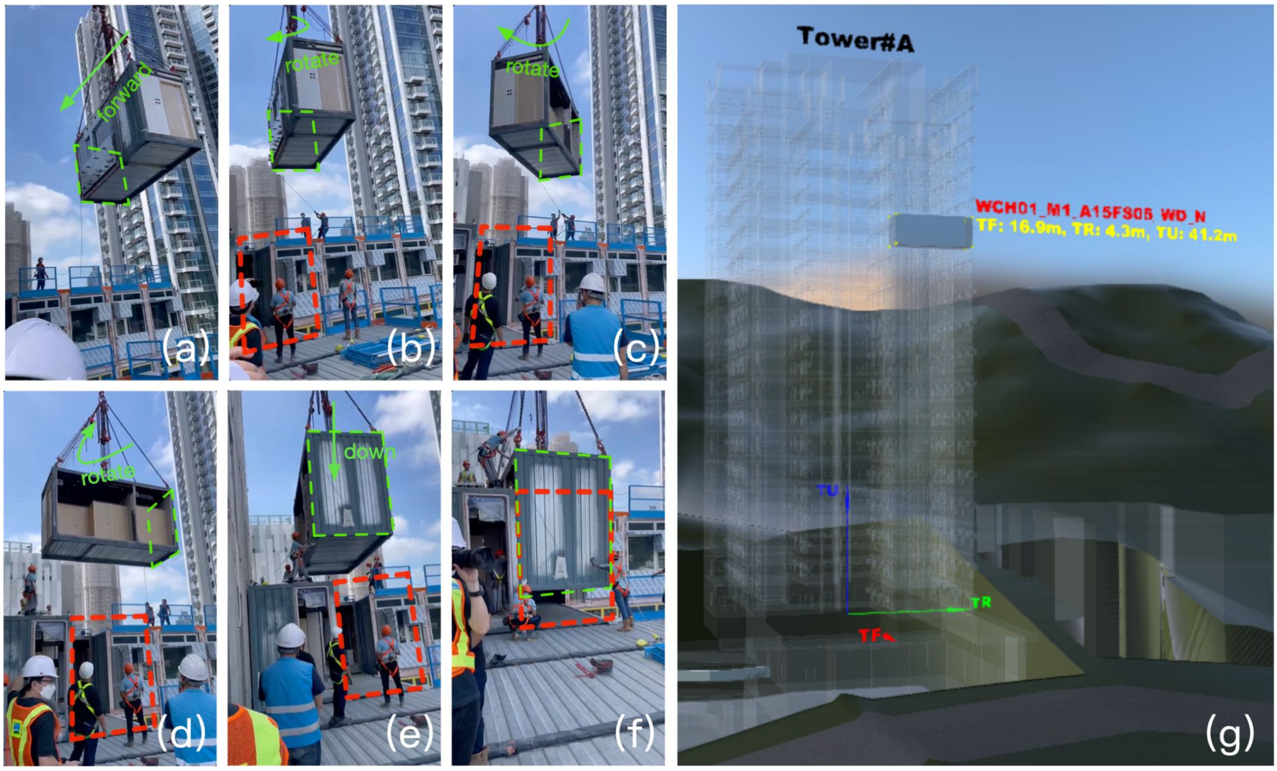

Figure 2: Visualized module assembly process by the integration of SCOs and AR

prove assembly efficiency and performance, as assessed by a prototype scenario of a construction pipeline. It shows that AR can enable effective information acquisition by integrating virtual information into real scenes, which can further benefit assembly tasks as it enhances human perception of the real environment.

Some studies have investigated AR applications in modular construction. Kyjanek et al. (2019) proposed an interactive manufacturing process in which workers with AR devices can collaborate with robots in timber prefabrication. Lin et al. (2019) developed a real-time AR system linking 4D BIM data for modular construction progress monitoring. However, it still remains an unexplored application of AR to assist OAMC. As OAMC requires an intuitive and seamless tool for site managers to access the information about modules in real time, exploring AR applications in OAMC is necessary.

An integrated framework of SCO and AR for OAMC

As shown in Fig.1, a framework integrating SCOs and AR is proposed to assist OAMC. The framework can be divided into three subsystems, i.e., hardware system, software system and interactive system.

Hardware system

The hardware system is a combination smart tracking unit for localization, which was developed to locate the position and orientation of the construction module in real work. The unit has to be attached to a specific position of the construction module, which will turn the module into an SCO.

The i_Core is an integrated smart device developed by HKU in order to track the transportation of construction modules (Lu, 2018) (Lu et al., 2016). An i_Core can collect data from peripheral sensors then assemble and upload them to the database. But the data precision and accuracy of the GPS sensor(u-blox_NEO-M8N) cannot meet the requirement for monitoring the assembly of construction modules. To solve this problem.

RTK(Real-time kinematic) equipment was introduced as an enhanced component to this subsystem. By eliminating the common spatial error between the base station and the mobile station, RTK provides centimeter-scale precision. A pair of high-gain antennae provide an orientation measurement function to RTK. And the RTK equipment provide was in GPRMC format to i_Core through RS-232 Universal Asynchronous Receiver/Transmitter(UART). Next, i_core disassembles the data and extracts strings of longitude, latitude and altitude. Those strings will be assemble together with the unique ID of i_core and uploaded to the database. In that case, our hardware system makes it achievable to visualize the expected accurate position of the construction module through augmented reality glasses.

As for the installation work of equipment, the installation position of antennae and RTK equipment is specific to make sure the orientation and position relationships in the virtual visualization. And NdFeB, a kind of super magnet was utilized for easily installing and removal of the unit

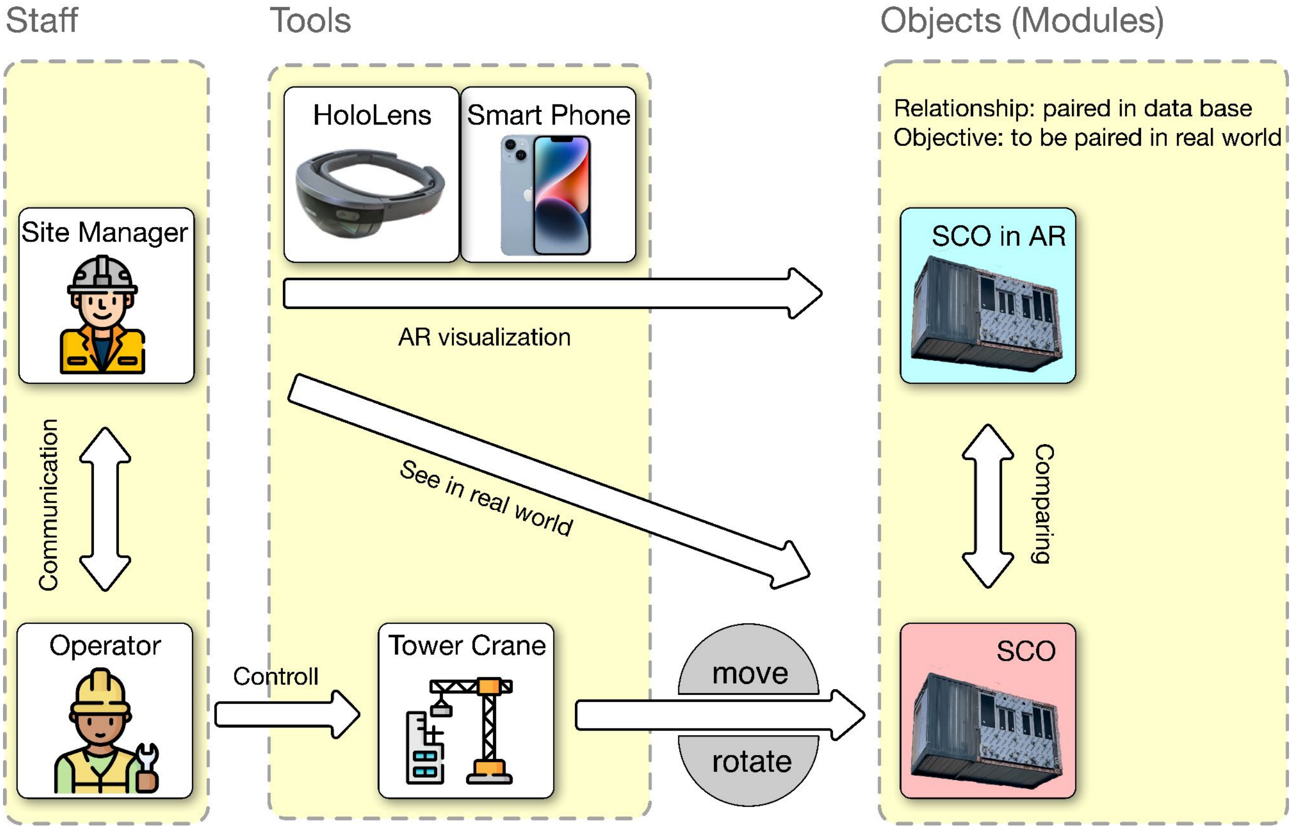

Figure 3: A re-engineered workflow using the proposed framework for onsite assembly

from the construction module.

Software system

Each construction module was given a unique ID for distinction. Lou et al. proposed a nomenclature for construction (Lou et al., 2022), which was implemented to nominate each construction module in the system we proposed. But it is barely practicable to applicate this nomenclature for the nominating of i_cores. Because not always one specific i_core is paired to one specific module. To address this problem, the pairing stage is deployed on a central database. And the accurate assembly position of each module is also stored and managed on this database. The off-site management reduces the assembly accident rate on site.

Another part of the software system is a dashboard for process visualization. The dashboard is also linked to a web-BIM website to display the project in a more humanistic way.

Interactive system

During the field investigation, we found the construction process especially the module assembly stage was quite disorderly. That is the crucial factor that we introduce a new interactive system with AR technology. In general, workers on site mainly take responsibility for the work related to construction. So, it is inappropriate to leave them in charge of instructing the tower crane operator to hoist and install modules. Because they cannot easily get the installing requirements of a module from its ID. There are also real related cases of installing modules in the wrong position by mistake.

The system we proposed decouples this work. What the worker on site has to do is attach the paired i_core with RTK on the module. The module ID to pair is managed on the central database and will display on the screen of i_core. Then the site manager can visualize the visual module and the physical module through AR glasses, and conduct the operator to control a tower crane to install it. The work to make sure the installing position of each module would be taken the responsibility of workers off-site. In that case, the site manager can shorten the time cost on site, which is a great merit. Thus tower cranes are managed based on demand, urgency, and prioritized work tasks that must be performed within a set period of time in the field (Al-Hussein et al., 2006).

Case study

Due to the benefit of high prefabrication, modular construction has promoted the world around rapidly. In Hong Kong, modular construction development is only at an initial stage. Cooperating with the HKU Estates Office and Paul Y. Engineering, we conducted a pilot study in Lau Fau Shan, Yuen Long District, and finally tested our system on the HKU Student Residence at Wong Chuk Hang.

The HKU Student Residence at Wong Chuk Hang is a typical modular construction project in Hong Kong (Zhang et al., 2021), selected as one of the two pilot projects for adopting modular integrated construction in Hong Kong by the Development Bureau. This project will provide two 17-floor towers for around 1224 student places as well as living accommodations for management staff and support facilities. The project is expected to assemble 6 types of components, a total of 884 modules. The transfer floor of the platform structure and the core wall will be built with poured reinforced concrete structure, and the "assembly and synthesis" technology will be applied to the construction of dormitory units above the transfer floor of the platform structure. All fixed furniture components will be well-installed in each module in the workshop.

Fig.3 shows the relationship and interaction between site staff, tools and SCO during the assembly stage. And Fig.2 are several photos from the point of view of the site manager, illustrating how to conduct the assembly stage of construction modules on site with the help of the system we proposed. Before hoisting, the smart tracking unit should be installed on the construction module, turning the module into an SCO. Firstly, in Fig.2 (a), the site manager on site noticed that the SCO has not arrived at the predefined location in AR devices (e.g., AR glasses, smart phones). So, he told the operator to hang the SCO forward with the tower crane until it was just suspended over the predetermined position in AR. Then, in Fig.2 (b)-(d), the SCO reached its right location in AR but its orientation was incorrect. The site manager asked the operator to rotate the SCO clockwise with the tower crane. Finally, in Fig.2 (e) (f), the site manager found that the SCO was over the predefined position in AR and at the correct predefined orientation in AR. He instructed the operator of the tower crane to release the SCO. And with the help of workers on site, the module was well-installed and can be visualized through Web-BIM as displayed in Fig.2 (g).

The system we proposed made it clear to divide the work in the module assembly stage and helps the site manager to set rational and better labor assignments during the onsite assembly stage. During its application in HKU Student Residence at Wong Chuk Hang assembly stage, no mistaking case did occur in the first stage of module assembly.

Conclusions

Onsite assembly is a critical stage in modular construction, which aims to install hundreds of separate modules into their designated positions within the required tolerance of error. However, the practice of onsite assembly is challenged by a lack of means to collect and vividly display information about the modules to site managers for effective quality control. This study proposes to integrate smart construction objects with augmented reality to assist onsite assembly of modular construction. A deployable framework was proposed by combining the awareness, autonomy, and communicativeness of SCOs and the visualization capability of AR. The framework was evaluated with a modular student hostel project in Hong Kong, which demonstrates the effectiveness of the framework in collecting real-time module information, visualizing moving trajectory of the module, and showing its required install position.

Prospects for this system lie on two sides. As for the hardware part, we hope the size of the hardware system which is strictly restricted by the size of RTK antennae can be more compact and portable for rapid deployment and recycling. PCB(Printed Circuit Board) and MEMES(Micro-Electro-Mechanical System) is promising for redesigning the hardware system to achieve the same functions in a smaller size, referring to our new generations of i_core.

As for the software part, which hopes to be reconstituted in the future not only for incorporating more AR devices for better cooperation but also for adapting various BIM models for better adaptability and flexibility.

References

Al-Hussein, M., Niaz, M. A., Yu, H., and Kim, H. (2006). Integrating 3d visualization and simulation for tower crane operations on construction sites. Automation in construction, 15(5):554–562.

Beigl, M., Gellersen, H.-W., and Schmidt, A. (2001). Mediacups: experience with design and use of computer-augmented everyday artefacts. Computer Networks, 35(4):401–409.

Chi, H.-L., Kang, S.-C., and Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. Automation in construction, 33:116–122.

Gong, P., Teng, Y., Li, X., and Luo, L. (2019). Modeling constraints for the on-site assembly process of prefabrication housing production: a social network analysis. Sustainability, 11(5):1387.

Hou, L., Wang, X., and Truijens, M. (2015). Using augmented reality to facilitate piping assembly: an experiment-based evaluation. Journal of Computing in Civil Engineering, 29(1):05014007.

Jiao, Y., Zhang, S., Li, Y., Wang, Y., and Yang, B. (2013). Towards cloud augmented reality for construction application by bim and sns integration. Automation in construction, 33:37–47.

Kim, K., Kim, H., and Kim, H. (2017). Image-based construction hazard avoidance system using augmented reality in wearable device. Automation in construction, 83:390–403.

Kyjanek, O., Al Bahar, B., Vasey, L., Wannemacher, B., and Menges, A. (2019). Implementation of an augmented reality ar workflow for human robot collaboration in timber prefabrication. In Proceedings of the 36th international symposium on automation and robotics in construction, ISARC, pages 1223–1230. International Association for Automation and Robotics in Construction (IAARC ….

Li, C. Z., Xue, F., Li, X., Hong, J., and Shen, G. Q. (2018). An internet of things-enabled bim platform for on-site assembly services in prefabricated construction. Automation in construction, 89:146–161.

Li, X., Wu, L., Zhao, R., Lu, W., and Xue, F. (2021). Two-layer adaptive blockchain-based supervision model for off-site modular housing production. Computers in Industry, 128:103437.

Lin, Z., Petzold, F., and Ma, Z. (2019). A real-time 4d augmented reality system for modular construction progress monitoring. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, volume 36, pages 743–748. IAARC Publications.

Lou, J., Lu, W., Xu, J., Li, X., and Wang, J. (2022). Nomenclature for offsite construction. Building Research & Information, 50(8):894–908.

Lu, W. (2018). Smart construction objects (scos): An alternative way to smart construction. Building Journal.

Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., and Yeh, A. G. (2021). Exploring smart construction objects as blockchain oracles in construction supply chain management. Automation in construction, 129:103816.

Lu, W., Niu, Y., Liu, D., Chen, K., and Ye, M. (2016). i-core: Towards a customisable smart construction system for hong kong. Innovation in Construction.

Niu, Y., Lu, W., Chen, K., Huang, G. G., and Anumba, C. (2016). Smart construction objects. Journal of Computing in Civil Engineering, 30(4):04015070.

Shan, S., Looi, D., Cai, Y., Ma, P., Chen, M.-T., Su, R., Young, B., and Pan, W. (2019). Engineering modular integrated construction for high-rise building: a case study in hong kong. In Proceedings of the Institution of Civil Engineers-Civil Engineering, volume 172, pages 51–57. Thomas Telford Ltd.

Tavares, P., Costa, C. M., Rocha, L., Malaca, P., Costa, P., Moreira, A. P., Sousa, A., and Veiga, G. (2019). Collaborative welding system using bim for robotic reprogramming and spatial augmented reality. Automation in Construction, 106:102825.

Wang, X., Love, P. E., Kim, M. J., Park, C.-S., Sing, C.-P., and Hou, L. (2013). A conceptual framework for integrating building information modeling with augmented reality. Automation in construction, 34:37–44.

Wu, L., Lu, W., Zhao, R., Xu, J., Li, X., and Xue, F. (2022). Using blockchain to improve information sharing accuracy in the onsite assembly of modular construction. Journal of Management in Engineering, 38(3):04022014.

Zhang, S., Rong, X., Bakhtawar, B., Tariq, S., and Zayed, T. (2021). Assessment of feasibility, challenges, and critical success factors of mic projects in hong kong. Journal of Architectural Engineering, 27(1):04020047.

Zhang, Y., Huang, G. Q., Qu, T., Ho, O., and Sun, S. (2011). Agent-based smart objects management system for real-time ubiquitous manufacturing. Robotics and Computer-Integrated Manufacturing, 27(3):538–549.

Zhou, J. X., Shen, G. Q., Yoon, S. H., and Jin, X. (2021). Customization of on-site assembly services by integrating the internet of things and bim technologies in modular integrated construction. Automation in Construction, 126:103663.

Zhu, A., Pauwels, P., and De Vries, B. (2021). Smart component-oriented method of construction robot coordination for prefabricated housing. Automation in Construction, 129:103778.