DFD-BASED DESIGN, ASSEMBLY, HIGH-ACCURACY REAL-TIME MONITORING AND LEVELLING CALIBRATION FOR LARGE-SCALE PREFABRICATE STRUCTURE WITH MULTIPLE MEASURING SYSTEMS

XIANG WANG[1] , ZIQI ZHOU[2] , XUEYUAN LV[3] , PHILIP F. YUAN[4] and LEI CHEN[5]
[1,4]*College of Architecture and Urban Planning, Tongji University.*
[2,3,5]*China Construction First Group Corporation Limited.*
[1]*178975753@qq.com*
[5]*18310021@tongji.edu.cn*

Abstract. This article introduces a novel monitoring method for the construction of high-precision prefabricated structures based on multiple sensors and measurement technologies. The proposed method introduces the optical motion capture system and combines it with traditional construction measurement technology to achieve real-time dynamic monitoring of more than hundreds of points within a large construction area more than 18*10m. Tolerance fitting algorithms and the correction methods are developed and testified to provide a global tolerance with ±1mm. Meanwhile a real-time visualization interface is developed to provide the feedback and analysis of the tolerance for each structure components. As demonstrator, such monitoring system is applied in the real construction of a DfD (Design for Disassembly)-based prefabricated steel structure in the "Water Cube" (Chinese National Aquatics Centre) in Beijing. With the demand to control the flatness tolerance within 6mm (within a 25*50m area), a large area monitoring system was applied in the project and finally reduced the construction time within 20 days.

Keywords. Design for Disassembly; Real-time Monitoring; Precise Levelling Calibration; Motion-capture System; Error Fitting Algorithm; SDG 9.

1. Introduction

At present, prefabricated buildings characterized by industrialized construction are being vigorously promoted in China and around the world, and the rapid emergence of new technologies also provides new methods for efficient and recyclable constructions. For example, in the field of industrialization, worldwide researchers have already carried out a lot of practice in many , and DfD is one of such theories. The purpose of DfD (design for disassembly) is to give full play to the performance of the material and to enhance the potential sustainability of a building. In this sense, the disassembly of

POST-CARBON, Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022, Volume 2, 517-526. © 2022 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

the whole life cycle is considered in the design stage, so that the components are easy to disassemble and can be recycled to the maximum extent, effectively improving its green performance (Guy and Ciarimboli, 2008).

In fact, since the birth of modernist architecture, prefabricated buildings, especially variable houses with good adaptability, have attracted a large number of architects to try, and there are also leaders of all ages. Today, as human environmental problems become increasingly prominent, low-carbon measures such as extending the life of buildings and reducing material waste are becoming more and more necessary. How to replace demolition with disassembly in a way of sustainability is a problem worth studying (Figure 1). It is also noticed in the UN's sustainable development goals that decent work/ economic growth as well as the industrial innovation for infrastructure would be some important goals for the future of human beings. Therefore, DfD is a promising concept for such development in the building industry.

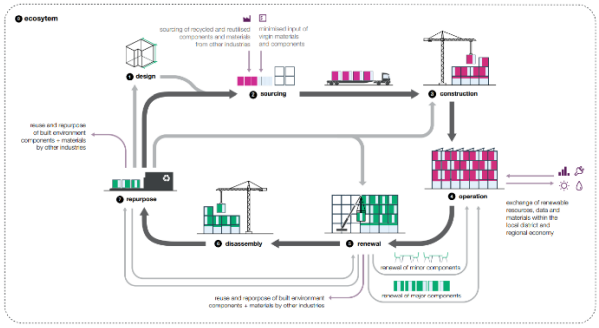


Figure 1. Application of Circular Economy Principles in Construction Industry (Arup, 2021)

Design for disassembly requires both the design process to split building into components system and the construction techniques to assemble the structure. Splitting is the reverse operation of the connection. Tracing the root, the adaptability structure still depends on the component connection method, which belongs to the controllable design content of the architect, and is also the focus of DfD. In the modern prefabricated building structure system, compared to the integrated joints produced by wet work, the DFD system responds to fast installation and damage-free detachment, and clearly puts forward the demand for dry joints. And the object includes structural components and is not limited to enclosure components. The DfD system responds to fast installation and damage-free detachment, and clearly puts forward the demand for dry joints, and the object includes structural members and not only enclosure members.

At the same time, due to the highly discretized characteristics of prefabricated building components, the integrity and assembly tolerance have also become an important issue for repetitively disassembled prefabricated buildings. Therefore, many issues, such as the structural design of the assembly system, the application of the building information model of the component system, the installation process planning, and the on-site installation monitoring, have also become important issues in the research of prefabricated structure construction technology based on DfD theory.

This paper discusses mostly the application of the building information models as

well as the IOT (Internet of Things) system to trace the components' information during the assembly and disassembly process of a prefabricated steel structure. At the meantime, a novel highly-precise levelling monitoring system with multiple sensors is also presented as a main characterized technique innovation.

The main case of this article is a DfD-based quick assembly and disassembly steel structure system, which is mainly used for the construction of the competition platform of the Beijing 2022 Winter Olympics curling venues. For the first time in the history of the Olympic Games, the curling venue of the Beijing Winter Olympics has applied a DfD construction system that can be repeatedly disassembled and assembled (figure 2). The main swimming pool of the original 2008 Summer Olympics Swimming Centre- "the Water Cube"- is used for reconstruction, trying to achieve a repeatable "winter and summer" scene change for the different uses. Since the construction time of the structural conversion has greatly affected the daily operations of the venues, the efficiency of the structural conversion has become the core issue of this project. At the same time, because curling has extremely high requirements for the flatness of the venue platform (the vertical height difference of any two points of the venue platform within the entire 50*25m range must be guaranteed within 6mm), the overall stability of the prefabricated structure and the accuracy of the installation also determines the success of the entire project.



Figure 2. Application of a DfD-based fast-built steel structure system in the ice-to-water conversion system for the Olympic curling Hall in the Chinese National Aquatics Centre("Water-Cube")

2. Methodology

Since there is no related project case similar to this project at present, which has realized the full life cycle digital and systematic management of the production-installation-disassembly process as well as the high-precision on-site construction monitoring, therefore, in this study, a process system diagram from design to disassembly to on-site construction monitoring was first built (Figure 3), the key procedure development and key techniques were extracted, and then the technical feasibility analysis and technology research and development were carried out.

The structural design and the component design consider both the possibilities to maintain the integrity of the structure and to make the component small enough for transportation. Based on that, a definition system and its related building information model is built in REVIT. For each component, a customized family is created with several special defined fields to trace its condition, such as the transportation stages, assembly stages as well as the levelling information. To provide a real-time information

for all these fields, several main techniques, such as the IoT-based information gathering and feedback system, the real-time multiple points height monitoring system, and the intelligent auto-levelling system is developed.

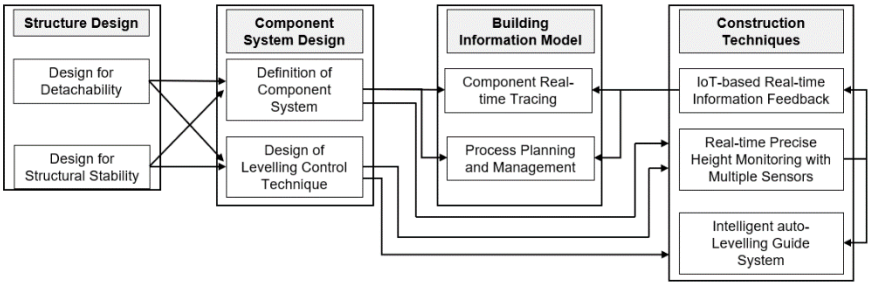


Figure 3. System Framework of the Methodology and Main Processes

As the many aspects of construction information make the system very complex, a simple and hierarchical software system is selected for this project. For the general visualization and data processing of the building information modelling, Autodesk REVIT is selected as the main software platform. With the use of the "Rhino-inside-REVIT" technique, a computational design approach could be achieved by using Grasshopper Platform inside REVIT, and interacting with the same data system. For the sensors and tracing system, extra special plugins are developed inside Grasshopper, including the RFID-based transportation tracing system, the QR-Code-based assembly information tracing system, the signal synchronization of the total station, electronic levelling instruments, as well as the motion-capture system (Figure 4).

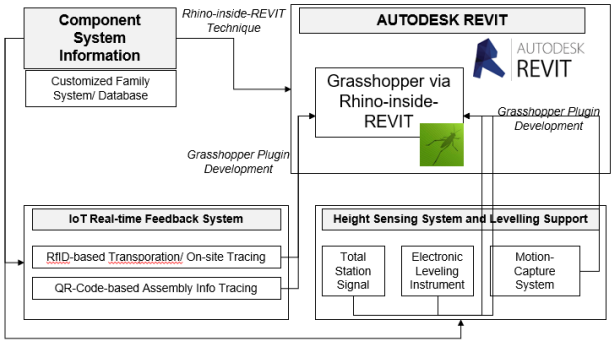


Figure 4. Tool chain and workflow in this research

The construction site has an area of 60*25m, which is far beyond the sensing range of some sensors (such as the resolution range of the infrared cameras of the motion capture system). At the same time, due to the existence of the original swimming pool, the site has a height difference of 3m. Therefore, in the configuration of the hardware system, the relevant sensors are set up by the principle of unilateral arrangement (Figure 5). The RFID chips and QR codes with component information are arranged

on the building components, and the components are stacked in the yard on the opposite side of the site. The construction phase of all components is tracked in real time by means of divisional construction on site.



Figure 5. Construction site and the arrangement of the sensors

3. 3. Design of the prefabricated system

The final construction structure is 56.7m long and 26.7m wide. The supporting frame body is made of prefabricated steel columns and beams, covered with light-weight precast concrete slab to meet the ice-making conditions. The structural beams and column members are all high-frequency welded thin-walled H-section steel. The steel used for the members is Q235B grade steel, and the connection is bolted. The connections used are M16 high-strength structural bolts. The surface layer adopts lightweight concrete prefabricated slabs, the main specification is 1m*1m*1m, the strength grade is L40. Finally, a total of 1,568 prefabricated slabs and a steel structure of 140t are used.

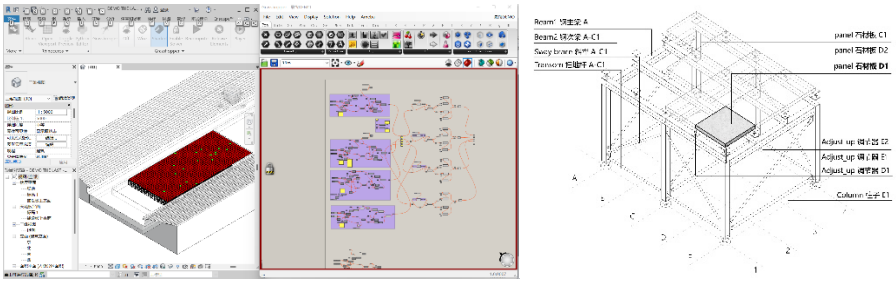


Figure 6. Construction site and the arrangement of the sensors

After the structural design meets the stiffness and stability requirements, its detailed design is completed in REVIT by means of customize family components. All components are defined parametrically through the use of computational design methods in the Grasshopper platform, so the establishment of the component system database and custom modifications can be quickly realized. In terms of the hierarchy of the structural components, in addition to the steel columns, steel main beams, steel secondary beams, and concrete slabs which are necessary for the original structure, steel diagonal braces and steel sweeping poles used for tie-down stabilization structures have been added according to the structural requirements. At the same time, according

to the levelling requirements, a knob-type adjusting device at the bottom of each column and a fine-tuneable knob-type adjusting device for the corner position of each concrete slab are added (Figure 6).

In order to realize real-time positioning and tracking and information visualization of the component system, all components in the database are named using unique coding rules. At the same time, in order to realize the collection and processing of information based on IoT theory, a plug-in suitable for reading RFID beacon information has been developed in the relevant Grasshopper platform. Meanwhile, a WECHAT-based Application which is suitable for QR code scanning and information filling has been created. Data crawling and real-time analysis of QR code database information is realized in Grasshopper (Figure 7). Therefore, the repetitively disassembled steel structure system realizes the real-time perception and analysis of the construction information of the whole process at each component level, and is integrated accordingly through the BIM software platform.

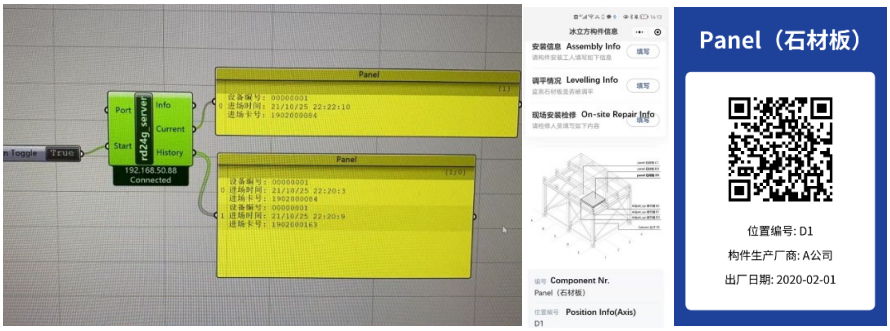


Figure 7. IoT-based Data Collection technique via RFID and QR code techniques

4. Levelling Calibration with multiple sensor systems

The construction of a large-scale DfD system usually have to solve the problem of tolerance that would be caused by the frequent and repeatedly use of the prefabricated components. Therefore, it is also the vital technique problems to ensure the assembly accuracy of the prefabricated structure systems. In the case of this paper, due to the use of the final structure (its top surface would be used as competition curling venues of the Beijing 2022 Winter Olympics), it is of great importance that the flatness of the platform should achieve a very high standard. For the construction, the measuring methods of the top surface of the structure becomes the most challenging task of the whole project.

In traditional construction monitoring, the measurement of surface flatness often relies on traditional measuring instruments, such as the levels, total stations and other equipment. However, due to their operational characteristics, it is often difficult to guarantee the measurement accuracy, measurement speed, and number of measurement target points at the same time. Meanwhile, such traditional construction measurement methods are highly dependent on the operation of the construction personnel on site, so it is difficult to realize real-time construction adjustment of multiple construction sites based on measurement feedback.

It is innovated in this project that a variety of elevation monitoring equipment based on multi-source data was used in collaboration, and for the first time in the construction industry, motion capture system was used as the main height information collection system for the requirements of multi-point (simultaneous monitoring of more than 100 points), real-time (monitoring frequency greater than 100hz), high-precision (repetitive positioning accuracy below 1mm). Due to the problem of unilateral placement of relevant sensors on site, the absolute positioning accuracy of the motion capture system shows a nonlinear error in the depth direction. At the same time, due to the imaging principle of the infrared vision camera, the overall positioning accuracy presents irregular distortions (Eichelberger et al., 2016).

In order to solve this problem, a set of coordinate system compensation and correction algorithm based on ICP (Iterative Closest Points) algorithm was developed in this research, and was finally developed as plugins inside the Grasshopper platform. The basic principle is: after the main beam of the structure is installed, use the midpoint of the structural column top to arrange the positioning beacons applicable to the motion capture (mocap) system, collect the relevant column top coordinate information in the mocap software, and establish a coordinate grid composed of the column points. At the same time, the electronic level and the total station were used as reference data, and the total station was used to collect the horizontal XY coordinates, and the electronic level was used to collect the vertical Z coordinates to generate a second set of real coordinate grids for correcting errors. Finally, the corresponding regions of the two sets of grids were fitted, the error correction translation matrix and the rotation matrix of the different regions were calculated, and they were applied to the error correction prediction process of the points to be measured in the different regions, so as to make the possible global distortion error which would be caused by the motion capture system finally corrected.

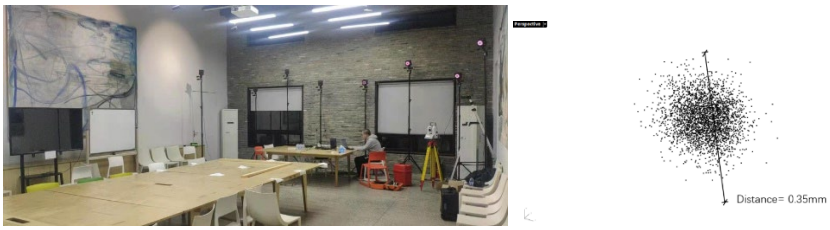


Figure 8. Off-site experiments to test the feasibility of the ICP algorithm

To test this algorithm, a full-scale off-site test was done in a 18m*7m room with the similar configuration (Figure 8). Experiments showed that the repeat positioning accuracy of the motion capture system was high, reaching below 0.4mm (Figure 8), while the global distortion effect was more obvious. The plane error at the farthest point and the total station was more than 3cm, and the level error was more than 1cm. The ICP algorithm test experiment selected a 3m*3m square grid (unified with the steel structure column span) for testing. Two sets of coordinate systems were collected using the grid vertices, and the ICP algorithm was used to estimate the coordinate transformation matrices of different grid areas. 20 arbitrary test points was collected to correct and predict the related errors, and finally are compared with the target results

measured by the electronic level and the total station. Finally, it was shown that among the 20 tested points, the difference between the coordinate results after error correction and the real elevation is small (within -1.67mm-1mm), which could meet the global and local elevation error control of the concrete slab layer (Figure 9).

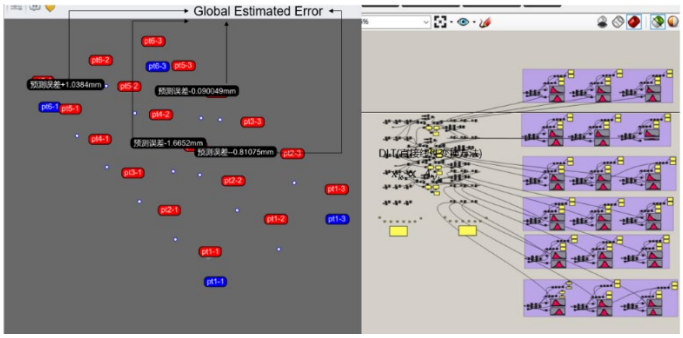


Figure 9. Control grids and the outcome of the levelling calibration tests

5. Feedback System and its on-site Application

Based on related sensor placement principles and error correction algorithms, similar error test experiments were also firstly completed at the construction site. Due to the limitation of the number of lenses of the motion capture system, the overall area of the site construction was divided into four sub-areas. Through the positioning of the total station and the elevation measurement of the electronic level, the four peripheral reference points were first located as the main reference for the determination of the overall elevation. During the construction process, the related algorithm of elevation adjustment was applied twice to the levelling process. Firstly, after the installation of the steel column at the bottom of the structure, the main beam and the secondary beam, the coordinates of the relevant reference points are collected. For this reason, this research has developed a set of height adjustment guide system for this project in the grasshopper platform. By inputting the motion capture measurement elevation of the column apex of the target area to be monitored and the actual elevation measured by the levelling instrument, the relevant error correction and the expected true elevation can be automatically calculated. Then, a large number of beacons of the motion capture system were used to calculate the expected true elevation of their location, and were compared with the theoretical elevation of the point in the BIM system, to give an error alarm when the error was greater than ±3mm. Secondly, after the column and beam system were levelled in the first stage, the concrete slabs would be secondly carefully tuned to meet the final global and local height requirements. At the same time, the system has also developed different display modes for the corner area and central area of the concrete slab. Due to the high degree of discretization of the concrete roof, the four corners where the grid intersects needed to be levelled separately. Therefore, if the system monitored that the measurement points were located at the corners of the slab, the coordinates and prediction errors will be displayed in dots; If it was detected that the measurement point was located in the centre of the slab, its elevation would be displayed as the overall elevation of the entire slab (Figure 10).



Figure 10. On-site application of the tuneable structures with the mocap beacon and the levelling support system

At the construction site of this project, the BIM control system and related levelling support system were connected to the central control screen, and the construction personnel were assisted to fine-tune the relevant structure through real-time playback. This construction method greatly saved the time required for on-site installation, especially the levelling process, and provided a large amount of data support for the construction planning. Compared with the previous structural conversion construction using traditional level measurement, it is in the first construction that only a final concrete slab elevation measurement was once applied, and that the measurement point only included the centre point of each concrete slab. The overall construction time was more than 40 days. In the second construction test that combined all new technologies, the structure realized two elevation adjustments in different stages, and realized real-time elevation adjustment and feedback of multiple points in the construction area. For the elevation control of the final concrete slab, the second construction experiment realized the coordinate feedback and adjustment of the four corner points and both the centre point of each concrete slab. At the same time, because of the existence of digital technology and real-time feedback technology, the entire construction process has been improved and optimized, and the entire process of installation and levelling of the entire steel structure has been completed within 20 days.

In the second construction, a part of the construction area that did not use levelling monitoring was reserved as a comparison verification area in all areas. It was tested via scanning with the laser tracing instrument to test all the slab centre coordinates. The results showed that the area with levelling monitoring basically meet the requirements of the project for global and local elevation errors, and the overall accuracy was controlled between -1.5mm-1.5mm (Figure 11). Compared with the levelling monitoring area, the unmonitored area had a larger elevation error, and it was related to the experience of the construction personnel. A large number of measurement points in the area were lower than the global elevation, and the error was in the range of -2 to -10 mm. (Normally, the construction personnel would firstly control the concrete slab at a lower height, and then fine-tune its height upwards by adjusting bolts).

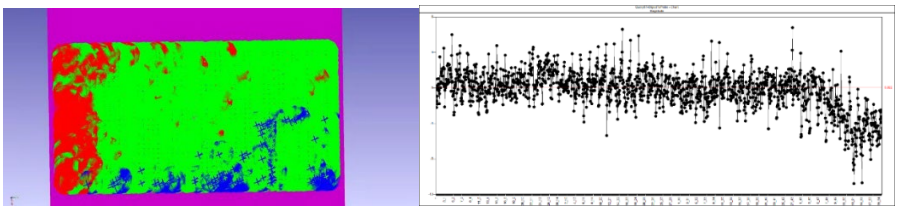


Figure 11. Final levelling check with laser tracing instrument of centre point of each concrete slab

6. Conclusion

This research demonstrates a systematic and integrated design-build-monitoring workflow for rapid disassembly and assembly of steel structures based on DfD theory, integrating related BIM technology and construction monitoring technology, and developed on the REVIT and Grasshopper platforms related software systems. The research successfully helped the China National Aquatics Centre in the rapid and repeatable scene transition from the 2008 summer swimming venue to the 2022 winter curling venue, effectively reducing the required structural construction time and ensuring the structure itself the high standard of elevation control requirements. In the current era of pursuing digitalization and sustainability of the construction industry, it is expected that the relevant design and construction methods proposed in this study can contribute to the intelligent reform of the construction technology in the future. At the same time, the related research on related sensor applications and algorithms in this study is still experimental in nature, and the related equipment is relatively expensive and the installation cost is relatively high. In future research, it is also expected that more advanced and cost-effective sensors can be added, and more environments in the construction process can be assisted and optimized.

Acknowledgements

This paper is supported by the National Key R&D Program of China (2020YFF0304303).

References

Arup. (2021, December 20). *The Circular Economy in The Built Environment.* Retrieved December 20, from https://www.arup.com/perspectives/publications/research/section/circular-economy-in-the-built- environment.

Eichelberger, Patric, et al. Analysis of accuracy in optical motion capture–A protocol for laboratory setup evaluation. *Journal of biomechanics.* 49.(10), 2085-2088.

Guy B, Ciarimboli N.(2008). *DfD: Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building*. Hamer Centre.