Department of Architecture and Built Environment

Heterogeneous Integration of BIM with Low-Cost Indoor Mobile Laser Scanning Method for Building Fabric Maintenance in China

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Abstract

The architecture, engineering and construction (AEC) industry is one of the most energy consuming and waste producing sectors in recent decades. Now it is facing the challenges of technological innovation and structural upgrading due to the increase requirements of sustainable development such as less wastes, lower energy consumption and higher productivity. As the largest AEC market in the world, China is exploring an innovative way based on digitalization and informatization to realize sustainable development of its local AEC industry.

However, the conservative management mechanism of China's AEC industry can no longer fulfill the increased demands and requirements of modern AEC projects from planning phase to operation and maintenance (O&M) stage, which is also the longest and most costly phase of a building project lifecycle. The maintenance, particularly the maintenance of building fabric components, is the key to ensure stable physical and operational performances of a building. As uncertainty caused by labors, natural environments, materials and other impact factors can highly influence the maintenance of building fabric components including costs and durations, it is significant to conduct a study for implementing reliable maintenance cost and schedule planning for building fabric maintenance during the O&M phase in China.

To support such an implementation, emerging digital technologies are adopted in this study. Building Information Modelling (BIM), which is a promising digital technology embraced by global and Chinese governments and organizations to help realize digitalization and innovation of the conservative management mechanism of the AEC industry. Compared with traditional Computer-Aided Design (CAD), BIM brings a N-dimensional concept, which includes the benefits of three-dimensional (3D) visualization, four-dimensional (4D) schedule simulation, five-dimensional (5D) cost estimation and six-dimensional (6D) facility management for improving productivity and minimizing energy consumptions and wastes throughout the project lifecycle. In addition, through technical integration with other heterogeneous digital technologies, such as 3D laser scanning, which is widely used in reality captures from construction environments for quality control purpose, it is applicable to find a low-cost and time-saving method to implement a reliable and efficient economic planning for building fabric maintenance.

Therefore, this study aims to develop a low-cost and efficient mobile laser scanning method that can be integrated with 5D BIM to realize indoor mapping and digital modelling for maintenance cost estimation and planning of building fabric components under the indoor environment of a typical case study in China.

In this study, the low-cost and efficient mobile laser scanning method is developed based on an integration of two common indoor positioning techniques - the Inertial Measurement Unit (IMU) and Ultra-Wide Band (UWB) system with an inexpensive and portable 2D laser scanner. By using developed algorithmic solutions, a motion trajectory provided by the indoor positioning techniques can be combined with 2D scan profiles from the laser scanner to generate a 3D point cloud, which shows reality captures from building fabric components existing in the indoor environment. This developed mobile laser scanning method can make a significant contribution to discovering the real conditions of fabric components for better maintenance planning. In addition, through the empirical investigations of BIM-based workflows for design coordination and impact factors influencing both construction process and maintenance management, a knowledge link between the O&M phase with design and construction phases also has been discovered to help explore solutions for improving the performances and productivities throughout the project lifecycle in the future.

As there are a few studies that focus on the BIM applications in the cost estimation and planning for the maintenance purpose of building fabric components, even there are rare case studies about indoor mapping and digital modelling applied into building fabric maintenance, this PhD study realizes significant achievements to narrow the knowledge gap between the global BIM development and China's local BIM development through the heterogeneous integration of laser scanning with 5D BIM particularly for digitalization of building fabric maintenance in China. Meanwhile it organically establishes a consistent knowledge link between facility O&M phase with design and construction phases to implement a sustainable project lifecycle management. Therefore, the novelty of the study has been guaranteed and its value to relevant research domains including 3D imaging and facility management also has been proved in the thesis. Future improvements and research work based on the outcome of this study also have been discussed.

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Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AACE = Association for the Advancement of Cost Engineering International

AEC = Architectural, Engineering and Construction

AI = Artificial Intelligence

ALS = Aerial Laser Scanning

AOA = Angle of Arrival

ASPE = American Society of Professional Estimators

B/C = Benefit-Cost

BCA = Building and Construction Authority (Singapore)

BIM = Building Information Modelling

BLM = Building Lifecycle Management

CAD = Computer-Aided-Design

CCIA = China Construction Industry Association

CCTV = Close-Circuit Television

CDE = Common Data Environment

CM = Corrective Maintenance

CPUT = Cost Per Unit Time

CSCEC = China State Construction Engineering Corporation

CSV = Comma-Separated Value

DR = Dead-Reckoning

EKF = Extended Kalman Filter

FM = Facility Management

GCS = Government Construction Strategy (UK)

GNSS = Global Navigation Satellite System

GPS = Global Positioning System

GSA = General Services Administration

HTML = Hyper Text Markup Language

HVAC = Heating, Ventilation and Air Conditioning

IAI = International Alliance for Interoperability

ICP = Iterative Closest Point

IFC = Industry Foundation Classes

IMU = Inertial Measurement Unit

INS = Inertial Navigation System

KF = Kalman Filter

LCI = Lean Construction Institute

LIDARS = Light Detection and Ranging

LPS = Last Planner System

MEMS = Micro-electro Mechanical System

MEP = Mechanical, Electrical and Plumbing

MLS = Mobile Laser Scanning

MMS = Mobile Mapping System

MOHURD = Ministry of Housing and Urban-Rural Development (China)

NIBS = National Institute of Building Sciences

NLOS = Non-Line-of-Sight

O&M = Operation and Maintenance

PDR = Pedestrian Dead-Reckoning

PLM = Project Lifecycle Management

PM = Preventive Maintenance

POD = Probability of Detection

PPC = Promises Completed on Time

QS = Quantity Surveying

RFID = Radio-Frequency Identification

RGB = Red, Green and Blue

RICS = Royal Institution of Chartered Surveyors (UK)

RII = Relative Importance Index

RMS = Root Mean Square

RSS = Received Signal Strength

SHS = Step and Heading Systems

SL = Stride Length or Step Length

SLAM = Simultaneous Location and Mapping

SLS = Stationary Laser Scanning

SMEs = Small and Medium-Sized Enterprises

SQL = Structured Query Language

SVG = Scalable Vector Graphics

SZEDA = Shenzhen Exploration & Design Association (China)

TDOA = Time difference of Arrival

TLS = Terrestrial Laser Scanning

TOA = Time of Arrival

UAV = Unmanned Aerial Vehicle

UWB = Ultra-Wide Band

VR = Virtual Reality

WLAN = Wireless Local Area Network

WP = Weight in Percentage

XCM = Xtreme Card Manipulation

ZUPT = Zero Velocity Update

2D = Two-Dimensional

3D = Three-Dimensional

4D = Four-Dimensional

5D = Five-Dimensional

6D = Six-Dimensional

7D = Seven-Dimensional

CHAPTER 1: Introduction

1.1 Research Background

1.1.1 Current Situation of Digitalization in AEC Industry

With the rapid development of the modern society and the dramatic increase of resource and energy consumption, various industries are facing the challenges of low carbon and sustainable development requirements. Particularly as the largest industrial sector in the world, the Architectural, Engineering and Construction (AEC) industry, which consumes nearly 40% of the global energy use every year and results in high resource consumption and 30% of global carbon emission, is trying to mitigate such an issue (Dixit et al., 2010, Gerbert et al., 2016). However, the AEC industry is fragmented due to the separation of professions caused by skill, distance and disciplinary characteristics. Such a fragmentation has resulted in a dispersed knowledge foundation with knowledge gaps occurring between professions (Harrison et al., 2003). These knowledge gaps are used to being filled through manual communications and empirical experiences, which can lead to misinterpretations and inefficient delivery of information across different phases including planning, design, construction, operation and maintenance (O&M) (Bröchner, 1990). Unfortunately, such a situation has severely restricted the development of the AEC industry and this has been proved by flat industrial productivity curve (Winch, 2003). Therefore, the industry is in dire need of efficient and effective improvements to ensure that its productivity can meet the rapidly growing demands caused by urbanization (Lavikka et al., 2018).

Digitalization provides a correct direction for the future development of the AEC industry. It can realize data-driven decision-makings and multi-disciplinary collaborations to support the project management. In addition, with the aid of various digital tools, visualization, simulation, detection and estimation can be easily implemented to serve the AEC project lifecycle for higher productivity and lower wastes (Gerbert et al., 2016). Digitalization can be regarded as a process to maximize the value of information through sharing, exchange and interaction among multi-disciplines and different stakeholders (Schober and Hoff, 2015). Although the implementation of digitalization will make impact on the traditional mechanism of the AEC industry by eliminating original production methods, simplifying personnel and increasing technical investments, it is still inevitable to the future development of the global AEC industry (Lavikka et al., 2018).

1.1.2 Building Information Modelling

Under the background of the global digitalization, lots of new digital technologies have been developed in order to facilitate restructuring and upgrade of the AEC industry. One of the most revolutionary change technologies for this purpose is named Building Information Modelling (BIM). It is expected to create a multi-dimensional digital model that can support visualization, simulation, estimation, collaboration and coordination for the building lifecycle management including planning, design, construction, operation and maintenance (O&M). (Takim et al., 2013). The benefits BIM brings for the AEC project stakeholders include design optimization, clash detection, waste reduction, duration shortening, cost saving, risk decrease and complexity management (Migilinskas et al., 2013). These benefits aim to improve the client satisfaction to time, cost, safety, quality during the project lifecycle and eventually increase the productivity of the AEC industry (Hasan, 2012).

To achieve this aim, an N-dimensional concept of BIM application has been put forward to accelerate the implementation of efficient data management and effective production control of building project lifecycle (Ding et al., 2014, Park and Cai, 2017). This concept emphasizes that based on three-dimensional (3D) modelling, four-dimensional (4D) schedule simulation (4D BIM) and five-dimensional (5D) cost estimation (5D BIM) can convert the traditional project management mechanism into a more digital and smarter one to improve the efficiency and productivity (Jiang, 2017, Jupp, 2017). Particularly the 5D BIM concept has been presented in order to meet the requirements of an effective and efficient workflow for the construction process of the AEC projects (Jiang, 2017) . The 5D BIM combines 3D modelling with schedule simulation and cost estimation, which is based on the calculation of take-off quantities. By using digital tools and software, BIM can provide enormous opportunities for cost planning and management based on Quantity Surveying (QS) (Smith, 2016). This cost planning and management involves not only the cost estimation of take-off quantities during the project design and construction process, but also the maintenance cost at the O&M phase. Furthermore, to deliver all useful building information from the previous phases to O&M phase, a concept of six-dimensional (6D) BIM, which can be defined as digital facility management (FM) based on 5D BIM, also has been proposed to improve the work efficiency of retrofit or maintenance for later period building management purpose (Nical and Wodynski, 2016).

1.1.3 Laser Scanning for Indoor Mapping and Digital Modelling

Laser scanning is an emerging technology for 3D information capture from a real built or natural environment. Terrestrial laser scanning (TLS) is widely used for geodetic surveying and mapping because of its high accuracy and reliability of 3D data collection. But currently its applications for quality control of as-built construction and retrofit of existing building is also drawing lots of concerns (GSA, 2009).

However, due to the site limitation, the high cost, the low portability and the long period of preparations, conventional 3D TLS is not commonly applied to the applications of construction indoor mapping and digital modelling, which aims to generate a geometric 3D model of an unknown indoor environment (Zlatanova et al., 2013). The positions of building components and other obstructions can be detected by using the mobile laser scanning so that information of reality is mapped into the geometric 3D model. This model then can be used for indoor spatial management or virtual navigation services (Huang et al., 2016).

Indoor mapping and digital modelling involves take-off surveying, data structuring, visualization techniques, indoor positioning and so forth. Relevant techniques include photogrammetry, computer graphics, vision analysis, sensor-based capture and so on. Usually the model of indoor mapping is composed of immovable building objects, such as architectural items and structural items (Wang et al., 2018a). Such a model can provide up-to-date spatial information of an indoor environment for many applications like location-based services, disaster rescue, building renovation planning, etc. Laser scanning is regarded as a promising technology to realize indoor mapping and digital modelling (Wang et al., 2018b). The point cloud generated from the scan is the reality capture from the indoor environment for digital modelling purpose.

1.1.4 Challenges to China's AEC Industry

China, which is the largest AEC market all over the world, is facing formidable challenges in the ever-increasing volume of AEC projects under the background of global digitalization (Jin et al., 2017). Although digitalization and informationization of various sectors including the AEC industry has been emphasized in China's "13th Five-Year Plan" for sustainable economic and social development in the future, the current conservative mechanism of China's AEC industry still result in technical and normative barriers to acceleration on the digital development of the industry (Jin and Tang, 2015). An innovative and efficient mechanism is expected to be developed for overcoming the challenges of overload, loss and inconsistency of AEC information (Zhao et al., 2007). The traditional mechanism of AEC project management in China only based on Computer-Aided-Design (CAD) and piles of paperwork can no longer meet the requirements of modern AEC project management due to growing complexities and massive data accumulations (Eastman et al., 2011, Zandieh et al., 2016). Furthermore, decline of productivity and increase of wastes resulting from the outdated mechanism have affected the sustainability of the industry (Zandieh et al., 2016). Therefore, more advanced digital technologies are being embraced to change the current situation and lead the AEC industry to a sustainable development.

1.1.5 Digitalization for Building Maintenance Management

Currently, digitalization is mainly investigated for its application value in the design and construction phase of a building project lifecycle. There are fewer studies about the digitalization for building maintenance management, which is vital to ensure a long-term stable performance of a facility. Current building maintenance management only relies on 2D geometric information from CAD drawings and numerical data stored in spreadsheets or presented on piles of paperwork (Chanter and Swallow, 2008). The perspectives from most facility managers indicate that there is no need to use 3D information for facility management and maintenance phase (Eastman et al., 2011). However, with the growth of building complexity and the increase of facility information, traditional management pattern is facing a growing number of technical challenges such as information loss, lack of coordination, desynchronization and update latency. These issues can directly lead to the increase of time and cost on maintenance management and meanwhile lower the efficiency of maintenance work (Al-Hajj, 1999). Therefore, digital technologies and approaches are desired to help improve the management capacity of massive building information and ensure that the key information related to maintenance can be efficiently utilized to maximize its value in FM.

1.2 Gap and Inconsistency between Global and Local BIM Development

As BIM was earlier applied into the developed countries including the UK, the USA, Japan, Singapore and Norway, etc., its applications in China's local AEC industry started relatively late (Chen et al., 2017; Jin et al., 2017). Although the Chinese government and relevant organizations have made policies and standards to promote the local BIM development, limited to the technical barriers and conservative project management mechanism, the China's local BIM development is too slow to catch up with the pace of the global first-class level of BIM development (Jin et al., 2017). Furthermore, currently there are still gap-in-knowledge existing between underlying theories and real practices to the BIM applications in the global AEC industry, particularly in the area of building maintenance management. Some typical researches highly related to the connection between BIM and building management are listed as shown in Table.1.1. Their research limitations are also identified in bold font.

Commented [CC1]: Explanation of the reason for BIM development inconsistency between global and China's industry.

Table.1.1. Research Topics Highly Related to BIM and Building Management

Authors/Year	**Topic**	**Research Limitation**
Olatunji et al. (2010)	Building Information Modelling and Quantity Surveying Practice	exploration of BIM-based quantity measurement in the project design

		and construction phase, **not considering the later O&M phase**
Mitchell (2012)	5D – Creating Cost Certainty and Better Buildings	application of 5D BIM to **only the design and construction phase** with the goal of delivering better buildings with cost certainty
Frei et al. (2013)	Critical success factors, opportunities and threats of the cost management profession: the case of Australasian quantity surveying firms	combined emerging technologies with factor analysis to achieve efficient cost management for sustained growth and competitiveness of quantity surveying professions, **not specific to the maintenance purpose**
Smith (2016)	Project Cost Management with 5D BIM	investigated the quality and comprehensiveness of 5D BIM model in project cost management for commercial strategy making, **without details of practical applications or case studies for validation**
Lu et al. (2016)	A financial decision making framework for construction projects based on 5D Building Information Modeling (BIM)	estimated 5D BIM-based Cash flow by considering the project and contract types in order to make a better project financing plan for contractors**, less knowledge about technical development of existing BIM tools for maintenance purpose**
Kehily & Underwood (2017)	Embedding Life Cycle Costing in 5D BIM	integrated 5D BIM with Life Cycle Costing functionality by developing a spreadsheet calculation structure based on an existing BIM tool **without extension for detailed maintenance analysis**
Pučko et al. (2017)	Application of 6D Building Information Model (6D BIM) for Business-storage Building in Slovenia	an insight of 6D BIM for execution of maintenance works throughout the building lifecycle, **but only for building system maintenance, not for fabric maintenance**
Lu et al. (2018)	Activity theory-based analysis of BIM implementation in building O&M and first response	provided a comparative analysis based on the activity theory to facilitate the implementation of BIM in building O&M, **however it still stayed on a theoretical model that used data from survey and interview with sample size risk**

From the table, it can be seen that most 5D BIM researches including the above mentioned ones are conducted in foreign countries rather than in China, which means there is an inconsistency of BIM development between the global and the China's local AEC industry. BIM has been mainly investigated for its values in cost estimation of QS and cost management of project lifecycle in recent global researches (Olatunji et al., 2010, Frei et al., 2013, Lu et al., 2016, Smith, 2016, Pučko et al., 2017). 5D BIM is also anticipated to create cost certainty to deliver better performance of the project in the design and construction phase (Mitchell, 2012).

Commented [CC2]: Evidence for the BIM inconsistency.

However, the current issue is how to apply similar 5D BIM and N-D BIM researches from other developed countries into China's local market to eliminate the inconsistency and meanwhile narrow the gap between N-D BIM theory and practice. There is lack of research on a consistent technical link between the use of BIM and the promotion of maintenance work in later O&M phase. Although an activity theory-based study analyzed the BIM implementation in O&M phase through a systematic and dynamic way (Lu et al., 2018), it still stayed on the theoretical level without practical applications. Another case study proposes that the 6D BIM concept can be adopted in FM to provide dynamic information about intervals and costs for execution of maintenance works throughout the building lifecycle (Pučko et al., 2017). It only provides an insight that mainly focuses on the cost estimation of serving building system maintenance. Therefore, the main reason that results in the gap between N-D BIM theory and practice is due to lack of efficient case studies for demonstrating that N-D BIM can bring real economic benefits for current global or local AEC industry.

Commented [CC3]: Knowledge gap between N-D BIM theory and practice.

Furthermore, currently most building maintenance activities are only related to service systems and there is few research that focuses on the maintenance planning of building fabric components. Apparently, there is even no research about the data integration of BIM, or 5D BIM with QS measurement for the cost planning of building fabric maintenance in O&M phase. Limited to the technical barriers, a traditional fabric maintenance workflow usually is only implemented based on owners' experience and piles of documentations. This can lead to underlying risks of information loss, material waste, cost increase and maintenance delay are highly rising with the rapid growth of modern building complexity (Eastman et al., 2011). It is essential to utilize digital technologies to conduct a revolution for the workflow change of traditional fabric maintenance. Particularly for China, the world largest AEC market with millions of buildings, BIM-based efficient maintenance management is vital to it for facilitating a sustainable O&M phase with lower resource consumption and higher productivity in practices. Therefore, according to the results of global BIM researches mentioned in Table.1.1, local case studies that integrate BIM theories with practical digital techniques should be highly encouraged to explore and validate the potential value of BIM in building fabric maintenance and meanwhile to narrow the gap between global BIM applications and China's local applications with higher consistency of BIM development.

1.3 Solution

5D BIM provides the practical applications of integrating 3D digital modelling with schedule simulation and cost estimation to realize intuitive data presentation and decision-making visualization for the building design and construction phases. It also can be extended for the potential application in the O&M phase, particularly for building fabric maintenance. Compared with the traditional mechanism of maintenance management, 5D BIM enables storage, updating, entry and sharing of fabric maintenance information based on a 3D digital model. The uncertainties and potential risks of traditional maintenance management can be reduced and the productivity could be highly improved through digital planning. Therefore, it is available to integrate the 5D BIM and QS measurement with the maintenance cost planning of building fabric components. This integration enables a digital method of cost planning that can be adopted in the management of maintenance activities to predict the input and minimize the uncertainties and potential risks of building fabric failures by computer-based simulation and real-time update. Here the "failures" can be understood as the loss of physical and functional performance due to damage or degradation. In addition, to reduce the discrepancies between the real conditions of the building and its BIM modelling for achieving more reliable cost planning, laser scanning is also applied in order to provide reality capture of geometric information from the building fabric components for comparison with the information from the BIM model. Furthermore, considering the high capital cost and limitations of the traditional TLS, it is essential to develop a low-cost and time saving mobile laser scanning method for the indoor environment.

1.4 Aim and Objectives

This thesis aims to propose a technical heterogeneous integration of 5D BIM with developed indoor mobile laser scanning method for implementing efficient planning of building fabric maintenance, which should be low-cost, time-saving and high-productivity to meet the requirements of sustainable development in China's AEC industry. Such a technical integration not only provides an efficient and low-cost way to apply 5D BIM and mobile laser scanning into the cost estimation of fabric maintenance under the indoor environment, but also links knowledge consistency between building construction phase and its O&M phase through an impact factor investigation to demonstrate the real value of a BIM-based sustainable information flow throughout the AEC project lifecycle in China. In this study, through empirical and experimental investigations, the sustainable information flow also has been proved as a prerequisite for efficient BIM applications in design, construction and facility management.

Commented [CC4]: Modification of study aim.

The objectives of this study include:

I. Review the current situations of global and China's BIM development and investigate potential applications of BIM in different project phases, particularly in O&M phase of China's AEC project lifecycle;
II. Investigate potential impact factors that can result in uncertainties to influence the construction process and even the later maintenance stage, then develop a 5D BIM-based forecast system for predictions of uncertainties caused by these impact factors;
III. Integrate IMU and UWB positioning systems with a low-cost 2D laser scanner to realize a low-cost and time-saving mobile laser scanning for a case study of indoor mapping and digital modelling in China;
IV. Conduct a TLS-based reference experiment to compare the scan results between the developed mobile laser scanning and traditional TLS under the same experimental conditions to ensure the reliability of MLS for further practical applications in building fabric maintenance;
V. Develop an efficient and low-cost method based on the integration of 5D BIM and mobile laser scanning for cost estimation and planning of building fabric maintenance in the case study;
VI. Use the case study to validate the feasibility of the maintenance planning obtained from the low-cost BIM/laser scanning integrated method, then develop a BIM-based panel prototype to implement automated cost planning of building fabric maintenance for practical applications in China.

Commented [CC5]: Revision of study objectives from 10 points to 6 key points.

1.5 Contributions

This study proposes a heterogeneous integration of low-cost and time-saving mobile laser scanning with 5D BIM for estimating the schedule and cost to improve the performance and productivity of building fabric maintenance, which is rarely investigated and explored in traditional building maintenance area due to lack of efficient technologies and limitations of conservative workflows in project lifecycles. Such a BIM-based integration method not only makes a significant contribution to linking efficient fabric maintenance planning with building design and construction management, but also propose an innovative idea to reduce the knowledge inconsistency between BIM development in China's local AEC industry and global BIM development tendency through practical implementations of N-D BIM theory.

Commented [CC6]: Revision of study contributions.

1.6 Achievements

Commented [CC7]: Changing the initial "Contributions" to "Achievements" of this study.

Achievement 1: Development of BIM-based design coordination system and workflows for the China's AEC project lifecycle

The traditional workflow mechanism of AEC project lifecycle management in China has shown its weaknesses in design coordination and collaboration between multi-disciplines and different project phases due to the technical limitations and the conservative management concept (Chen et al., 2017). With the development of BIM, it makes possible to alter the traditional workflow mechanism with innovative characteristics of digitalization to achieve higher efficiency and productivity. This study introduces the development of BIM-based design coordination system and workflows for planning, design and construction phases in the China's AEC project lifecycle, which the BIM theories can be applied into for practical applications.

Achievement 2: Investigation on impact factors that can result in uncertainties during construction process and even maintenance stage

Construction phase is a quite important phase of a building project lifecycle. As it involves multi-disciplines and different resources, the uncertainties and variances that occur during the construction process have become a large risk to the successful completion of an AEC project (Ballard, 2000). Therefore, it is necessary to investigate where the uncertainties and variances result from. A study, which is about what impact factors can result in uncertainties and variances of the construction process and then affect the project management and productivity, is also introduced in this thesis. The impacts of the factors are mainly reflected on the variances of cost, schedule, quality and safety between real construction and original plan (Tatum, 1993). Because these four are the key indicators to judge whether a project is completed successfully (Tatum, 1993, Tatum, 1999). By using online survey and review method, this investigation study aims to determine specific impact factors with rating scales in order to provide an effective data analysis and ranking of potential impact factors. It can help project stakeholders understand the extent of impact each factor can have on the construction process, and meanwhile establish an empirical basis for variance detection on construction process management. Furthermore, it is also found from this study that some of the impact factors related to budget limitation, weather, access to the site, delivery efficiency of materials, tool and equipment can also influence the maintenance activities by resulting in a delay, which is the main reason of why deferred maintenance activities occur in building O&M phase (Arditi and Nawakorawit, 1999; Hamid et al., 2010).

Achievement 3: Development of a forecast system for construction management within 5D BIM

Based on the data collected from the investigation study of potential impact factors, we developed an impact factor forecast system for the predictions of construction process. The predictions can help project managers or planners to make a more reliable and scientific construction plan or adjustments when uncertainties or variances caused by impact factors occur during the construction process in China's AEC projects. This forecast system is developed based on a 5D BIM software platform, which can provide schedule simulation and cost estimation (Fan et al., 2015). Therefore, the variances on original schedule and cost plan compared with predicted schedule and cost can be detected and visualized for a better production control of construction process (Ballard, 2000). This not only provides planners and managers reliable planning of schedule and cost to re-estimate the developing design and construction process, but also gives an innovative idea to link the uncertainty predictions of impact factors in construction phase with their potential effects on maintenance planning in the later O&M phase through similar BIM-based simulations and estimations (Dessouky and Bayer, 2002; Mitchell, 2012).

Achievement 4: Development of a low-cost mobile laser scanning method for construction indoor mapping and digital modelling

Although terrestrial laser scanning (TLS) and aerial laser scanning (ALS) technologies are suitable approaches for information capture of natural or built environment due to their high accuracy, precision and reliability (Fryskowska et al., 2015, Liang et al., 2016). However, both technologies are widely used for geodetic surveying and outdoor mapping, their applications for construction indoor mapping is still at an exploring stage (Kedzierski and Fryskowska, 2014) in China's AEC market.

Due to the construction indoor mapping is a part of AEC project services for construction quality control, deformation monitoring or existing building retrofit, laser scanning technologies are proposed for these applications (Xu et al., 2017). However, due to some drawbacks such as high cost, long time consuming, site limitation and complex preparation work, TLS and ALS are not the optimal options for construction indoor mapping applications (Abdulrahman, 2013).

Therefore, a more appropriate mobile laser scanning method for indoor mapping and digital modelling is developed in this study to solve the drawbacks of conventional laser scanning technologies mentioned above, and meanwhile give a novel idea for geometric modelling of an unknown indoor environment. Although the accuracy and precision of this mobile laser scanning method cannot reach the same level as the TLS and ALS, its advantages such as high flexibility, low cost and time saving still make it competitive for applications of indoor mapping in the future.

This mobile laser scanning method integrates an inexpensive and high efficient 2D laser scanner with low-cost indoor positioning technologies to realize 3D mapping and modelling. Therefore, it also can be regarded as a contribution to multiple research domains including surveying, data visualization, localization, etc.

Achievement 5: Integration of low-cost mobile laser scanning result with the BIM model for discrepancy check between reality and design

The developed low-cost mobile laser scanning method can generate a 3D point cloud, which comprises of reality captures from a construction indoor environment and the cost is much lower than that of conventional TLS. A 3D BIM design model of the same construction indoor environment can provide position information of building components, geometric information, building materials and other building property information. When the generated 3D point cloud is integrated with the 3D BIM model in a common platform, the discrepancies between the real capture and the design can be identified. The reports of such discrepancies can help provide empirical evidence for some AEC project applications such as quality control of as-built construction or retrofit of building (GSA, 2009).

Achievement 6: Cost planning of building fabric maintenance based on the integration of indoor mobile laser scanning and 5D BIM

With the long-term use of a building, partial deformations of architectural or structural components of the building cannot be avoided. Therefore, an effective operation and maintenance management becomes quite important to maintain a longer lifecycle of the construction. It is possible for us to use the indoor mobile laser scanning mentioned above to capture the real surface conditions of the building fabric components, then compared with the BIM design model, we can detect and determine the discrepancies of geometric dimensions and deformations from the real conditions. Due to 5D BIM, which is extended based on 3D design model, has the specific information about the costs of the take-off quantities of the building fabric components, it can be used to estimate the cost and the time consuming of component repair according to the deformation detections. Therefore, this gives a solution about how to make a reliable and digital plan for long-term building fabric maintenance.

Achievement 7: Development of a BIM-based panel prototype for cost planning of building fabric maintenance

According to the study on the BIM-based building fabric maintenance, a web-based planning panel prototype was preliminarily developed based on a workflow design, which integrates the obtained heterogeneous system data and relevant multi-disciplinary knowledge, in order to help make the maintenance cost planning more accurate, automated, faster and smarter. Regarding the BIM model as the foundation, computer-based programming and specific data transformation format were utilized to make this idea come true and available for further applications in China.

1.7 Beneficiary

The beneficiaries from this study result may include civil engineers, quantity surveyors, project owners, designers, contractors, BIM project manager and software developers from China's AEC industry. This study proposes a low-cost, time saving and portable indoor laser scanning method for civil engineers, surveyors and managers to realize spatial and maintenance management based on indoor mapping and modelling. It also provides innovative workflows for AEC project owners, designers and BIM managers to improve the building design qualities. The forecast system developed in this study also can help contractors and BIM managers to enhance the monitoring and production control of construction process, meanwhile proposes a further development guide for software developers. In addition, quantity surveyors can find a new way from this study to improve their working efficiency and accuracy based on 5D BIM. Furthermore, project owners also will be beneficial from the BIM and laser scanning integrated workflow for their project maintenance phase in both cost saving and quality control.

1.8 Limitations

The limitations of the overall research can be classified into two categories. One is the limitations of experimental site conditions and the other is the limitations of data collection and processing.

For the indoor mobile laser scanning research, all sensors were mounted on a trolley as a mobile platform and the low-cost 2D laser scanner needed to be connected with a power supply by using a wire. However, there are only a few power sockets found in the atrium, where the experimental site is. The length of wire is too short to implement the motion of the trolley from one side to the other. The limitation of wire length can highly affect the flexibility of the mobile laser scanning method. Although a portable power source within the trolley was suggested to solve this problem, due to the connection issue between the portable power source and the laser scanner, this suggestion still needs to be further considered.

In addition, there are some obstacles and thresholds in the atrium, where is the only suitable site for the installation of the localization system, the planned motion trajectory is limited in order to eliminate infeasible path where the trolley cannot pass through due to the obstacles and thresholds. That means part of the scene cannot be captured due to the limitation of site conditions. Although an ideal site condition could be beneficial to the experimental results, it is too difficult to provide such an ideal site that meets all the requirements. On the other hand, the most reliable data still should be from the practical conditions, which reflect the real contexts of applications.

Errors cannot be avoided during the data collection and processing. The error sources could be manual operation, data transfer, data extraction, algorithmic calculation, data integration etc. In this research, limited by low-cost equipment, some automatic operations provided by high-cost and advanced equipment have to be substituted by manual operations, which increase the error probability. Furthermore, algorithms for data processing are developed based on empirical theories and personal experience. Due to the data size in this research is not enormous, the developed algorithms are reliable enough for data processing. However, it still can be improved by using filters or smart programming, which is able to enhance the accuracy and efficiency of data processing, particularly for massive data point clouds. In further studies, Artificial Intelligence (AI) also can be involved to help provide optimal solutions for data processing in various projects such as large-scale indoor mapping and digital modelling of cluttered built environment.

Nevertheless, it is necessary to minimize the effects of limitations on data accuracy and precision. The data not only refer to the experimental results from laser scanning and BIM modelling, but also include the data for later maintenance cost estimation, such as the price of fabric materials, labor costs, inspection costs, etc. They are also named cost parameters. Because there is much uncertainty on these parameters and this could highly affect the final results for decision making, improvement of sensitivity analysis or other advanced tools for reliability analysis should be adopted in order to give a more detailed analysis for the planning of building fabric maintenance.

1.9 Thesis Outline

The thesis is divided into eight chapters. Chapter 1 introduces the research background of this study including the current gap in knowledge, the potential solution, aim and objectives. Chapter 2 is the literature review of the current situations in China's AEC industry and the technologies and techniques that will be referred to in this study. Chapter 3 describes the methodology of this study including the research framework, research methods and research tools. Chapter 4 introduces the empirical surveys and relevant site experiments conducted based on a case study in China for this study purposes. Chapter 5 focuses on the data processing and analysis based on the results from the survey and site experiments. Chapter 6 proposes the integration of 5D BIM and mobile laser scanning for the purpose of building fabric maintenance based on the case study. Chapter 7 introduces the development of a BIM-based panel prototype for cost planning of building fabric maintenance and its commissioning based on the case study. Chapter 8 is the conclusion of this study that includes deliverables, limitations and outlook in the future.

CHAPTER 2: Literature Review

2.1 Uncertainties in Construction Process of China's AEC Project

Construction process can be conceived as a workflow of converting plans and design drawings to completed AEC facilities including buildings and infrastructures (Ballard and Howell, 1997). With the development of digital modelling technologies, production management concepts of construction process are generated based on model conversions (Eastman et al., 2011). However, assumptions and simulations are the key of model-based management, which means under the real conditions, uncertainties existing in the construction process can result in difficult management issues, and these issues can dramatically influence the productivity and efficiency of project construction phase (Hanna and Heale, 1994). Therefore, it is essential to investigate and understand that what uncertainties result in such variances occur between plan and real construction process. Only based on that, contractors and site supervisors can make adjustments according to those variances in order to ensure that the projects can be completed safely, within budget, in time and with satisfied quality (Tatum, 1999). Therefore, to evaluate whether the production control of a construction process is successful or not, schedule, cost, quality and safety are the basic performance criteria (Tatum, 1993). As quality and safety are more difficult to be indicated by using real numerical values compared with schedule and cost, the latter two criteria are more commonly adopted in the performance management techniques in order to evaluate the production control of construction process in China's AEC projects (Chou and Yang, 2012).

The concept of "lean construction" had been developed as an adaption of lean manufacturing principles to the design and construction process of an AEC project by the late 1990s (Abdelhamid et al., 2008). This concept can be regarded as a way to minimize waste of resources and time in order to generate the maximum possible amount of production value during design and construction process (Ballard and Howell, 1994). Due to various project stakeholders and resources involved in design and construction process, the increase of uncertainties leads to variances with the progress of schedule (Howell et al., 1993, Fischer and Tatum, 1997). Therefore, a tool named the "Last Planner System (LPS)" is adopted in the lean construction to make design and construction process more predictable with less uncertainties (Ballard, 2000). The LPS was developed from 1992 and is very different from the "First Planners" concept of traditional construction management (Lauri, 1992). Here the "Last Planners" refer to contractors and site supervisors who are responsible for prerequisites and assignments of construction process (Ballard, 2000). They are also the last people to make and implement production planning on site. The core of LPS is to ensure that all "Last Planners" can fully participate the construction planning and implement effective production controls of their corresponding assignments, in order to guarantee the construction process and the final project can be completed successfully.

LPS consists of four key elements: collaborative workflow, prerequisite activity, production planning and continuous improvement (Ballard, 2000). Collaborative workflow emphasizes that the “First Planners” (including project managers, multidisciplinary designers, etc.) and the “Last Planners” should come to an agreement on the production planning of design and construction process through collaborative work. Prerequisite activity means that all labors, materials, equipment, working space and predecessor work required by an assignment must be prepared before it can start (Damodara, 1999, Kuykendall, 2007). Planners who are responsible for the assignment must ensure all prerequisites are met so that the assignment can be implemented following the plan (Kozlovska et al., 2016). Production planning encourages all “Last Planners” to participate every week’s production planning meeting in order to make a schedule for the next day or next week (Ballard, 2000). Through the collaboration and coordination mentioned above, all planners can acquire more experience and knowledge from practice, meanwhile be able to improve the productivity of construction process.

Studies from the Lean Construction Institute (LCI) indicate that there is a tight correlation between the Percentage of Promises Completed on time (PPC) and the productivity. When the PPC reaches 75 - 90%, the productivity will have a phenomenal growth (Ballard, 2000); if PPC reaches 100%, there will be no delays during the construction process. Before the LPS was adopted for the production control of construction process, only 1/3 assignments could be completed following the plan, which means the PPC was only 33% (Ballard and Howell, 1997). According to the studies, two main issues about the construction process were emphasized in later relevant researches. The first one is what kind of methods or tools can be used by the LPS to improve the production control of construction process, in order to make the PPC higher than 70% (Ballard, 2000). The second one is how the LPS can make the design and construction process more predictable by reducing uncertainties and improving the planning reliability. With the development of the LPS, its aim has been shifted from the initial improvement of productivity to the improvement of plan reliability for construction process.

In addition, it is significant to do predications of construction preparations such as weather, funds, materials in the schedule implementation ahead of time, and make reasonable arrangement of construction processes related to the actual situations (Li et al., 2017). To reduce the uncertainties and make the construction process more predictable, the key is to forecast the uncertainties that may occur during the process and evaluate their potential impacts to the production (Neil and Knack, 1984).

2.2 Building Lifecycle and Maintenance

2.2.1 Necessity of Maintenance in Building Lifecycle

A building lifecycle commonly includes phases of planning, design, construction, O&M and demolition optimization (Ustinovičius et al., 2015). O&M is the phase that requires the most time and cost during the whole lifecycle. Different from planning, design and construction phase, a successful O&M phase management does not focus on how to make a successful delivery of the phase production, but how to maintain the building performance as long as possible and meanwhile reduce the maintenance cost to cut down the total cost of lifecycle (Krstić and Marenjak, 2017). All key information from previous phase deliveries will be used to provide services for the operation of the building and generate scenarios for the maintenance and repair. The aging and deformation of building is an issue that cannot be avoided with a long-term operation. Therefore, a reasonable maintenance and repair scenario is necessary to help mitigate the effects caused by this issue and maintain the building performance as long as possible (Róka-Madarász, 2011). A good maintenance and repair scenario can not only ensure the regular operation of the building, but also help the owner of the building to save the cost during O&M phase.

The FM concept has been recognized as a prospective research discipline since 1990s (Guizzi et al., 2011). It can be defined as a professional guiding and management that focuses on all key building information that can be effectively and efficiently used to serve the building operation and maintenance phase on behalf of asset owners (FMA-Australia, 2012). The implementation of FM requires digital approaches and advanced technologies in order to realize its value for the whole building lifecycle.

According to the explanations of professional industrial guides, FM includes asset commissioning, operation and maintenance. Operation stage involves building relationship management, performance monitoring, contract management, waste management, risk management, etc. Maintenance stage refers to preventative maintenance, risk mitigation, identification of opportunities and maintenance plan (FMA-Australia, 2012).

Building maintenance is defined as a combination of any action carried out to retain every part of a building in an acceptable condition (Mills, 1980). Its objectives include:

- To ensure the buildings and their components are in a safe condition;
- To ensure that the buildings are fit for normal use;
- To ensure that the condition of building meets all requirements of its design purpose;
- To implement maintenance work to retain the value of the physical assets of the building stock;
- To maintain the quality of the building.

In recent years, building maintenance is becoming a productive activity during the operation life of the building. Due to the ageing of existing buildings, more maintenance and renovation work are required to retain the buildings the same equality as long as possible. Therefore, effective and efficient ways are desired to implement this purpose and meanwhile reduce maintenance costs. Because from a long-term prospective, any reduction in costs or resources applied to building maintenance would have a visible and positive effect on the economy.

2.2.2 Current Situation of Building Maintenance

Building maintenance is still a weak area of research and study compared with other lifecycle phases. In recent years, a growing number of concerns on building maintenance are gradually improving its significance in building lifecycle. The purposes of building maintenance work can be classified into several types, including repair, replacement, protection, decoration and cleaning. Repair work aims to maintain that the building condition achieves the required standard. Replacement work is to substitute a component with another new one which can make the same function. Protection and decoration can protect the materials of fabric elements by using covering and specific treatment to enhance the external appearance and internal structure. The purpose of cleaning is to retain the internal appearance of the building (Lee and Phil, 1987).

It can be seen from Fig. 2.1 that the conventional building maintenance can be classified into planned and unplanned type (Jardine and Tsang, 2013). The former one means the maintenance work is predetermined and intended to reduce the probability of failures on building components or facilities. Reversely, the latter one means the maintenance work is carried out after failures occur without any planning.

Planned maintenance consists of condition-based maintenance and preventive maintenance (PM). Condition-based maintenance utilizes the changes in building condition or performance as the main reason to carry out maintenance work (Lee and Phil, 1987). The maintenance work is determined and planned by continuous or scheduled monitoring of the building components or facilities (Al-Khatam, 2003). PM involves a time-based or planned maintenance, which follows a schedule to implement maintenance activities. This maintenance type is usually applied to the external or internal painting and covering work (Marquez, 2007).

Unplanned maintenance is also considered as corrective maintenance (CM), which is the simplest maintenance type (Marquez, 2007). It refers to the replacement or repair of a building element that cannot perform its required function any more. This maintenance can be classified into two types. One type is named immediate corrective maintenance, which is an unplanned maintenance without delay and the cost would be expensive. The other is named deferred corrective maintenance that is delayed to be carried out after a detection of failure. Such deferred maintenance can lead to increased safety hazards, poor building services, inefficient operations, higher O&M costs and eventually result in a decline of the building property value (Hamid et al., 2010; Rostron et al., 2001). Usually, the deferred maintenance requires a long run plan due to the uncertainties of the maintenance date. These uncertainties can result from budget limitations, inclement weather, environmental conditions, access to the site, delivery efficiency of patching materials, the availability of equipment and professional labors (Akinsola et al., 2012; Arditi and Nawakorawit, 1999). Some studies also indicate that budget limitation (or cost limitation) is the main cause of deferred maintenance (Hamid et al., 2010; Talib et al., 2014).

Commented [CC8]: Explanation of a connection between deferred maintenance and its impact factors that can lead to uncertainties in the maintenance.

To deal with failures of building elements, the corrective maintenance is quite important in the whole building maintenance management (BSI, 2010). It also should be noticed that both CM and PM have replacement services included.

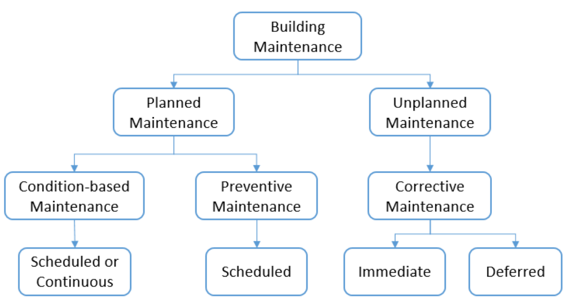

Fig.2.1 Classification of building maintenance types

Nowadays, information is generated in each project phase, maintenance phase is no exception. If we want the building maintenance work to be executed successfully, we need to know relevant key information as much as possible. Current existing tools, which are used by facility managers to assess the maintenance work of a building rely on 2D information that represents geometric space or numerical data stored in a spreadsheet. The perspectives from most facility managers indicate that there is no need to use 3D information for facility management and maintenance phase (Eastman et al., 2011).

However, the potential drawbacks of using traditional 2D-based tools are loss of information and waste of time (Teemu, 2014). The use of BIM 3D model provides a visual and intelligent way to help facility managers or building owners to assess the space or elements that require maintenance work (Becerik-Gerber et al., 2011b). They can also create a database for FM purpose and this can avoid the issue of information loss and meanwhile reduce the time. A relevant case study even indicated that a 98 percent reduction in time has been realized for FM data generation and update by using BIM (Eastman et al., 2011). Furthermore, BIM-based cost estimation also can be applied to the maintenance and repair cost scenarios of an existing building. Due to automatic services provided by BIM, building element materials, take-off quantities and unit costs can be extracted from the digital model. They are the basic information to make a reasonable maintenance and repair cost scenario for asset management.

2.2.3 Digitalization of Building Maintenance in China

Building maintenance in China still depends on empirical knowledge and drawing documents. To realize in-time sharing and permanent storage of building information, digitalization is the inevitable tend for the management of building lifecycle and O&M phase. Therefore, the development of advanced digital technologies is essential to meet the increase of requirements particularly for modern building maintenance management.

Moreover, Chinese government and AEC industry are still exploring the development of systematic regulations of building inspection and maintenance (Wang et al., 2011). Current situation of building maintenance is a large potential challenge to the implementation of sustainability in AEC industry. New manner, which is developed based on the fusion of local conditions, feasible new concepts and emerging technologies, is the key to realize regular and efficient building maintenance (Tan et al., 2014).

Building Information Modelling (BIM) has proven its potential in O&M management for data sharing, updating and storage in some studies from China (Peng et al., 2017) (Lu et al., 2018). It is also suggested to adopt FM in the early phases of building design and construction phases to reduce the efforts and minimize the costs for maintenance during O&M phase (Dessouky and Bayer, 2002; Wang et al., 2013). By using multiple and powerful software tools, BIM can realize a digital information flow throughout different project phases and disciplines of the AEC industry for permanent storage, transformation, sharing and update of project information (Zhao et al., 2007; Eastman et al., 2011). This brings less rework, less wastes, lower consumptions and higher efficiency rather than CAD-based project management workflow to promote the industry towards the direction of sustainable development.

Commented [CC9]: Justification of what benefits BIM-based digital information flow can bring rather than CAD drawings.

However, currently the implementation of BIM in O&M phase is still limited due to lack of practical applications or local case studies to validate the feasibility and reliability in details. Furthermore, there is barely any research about BIM-based digitalization for inspections and maintenance of building structures or fabric components in China due to most relevant studies focus on the maintenance of MEP or other active systems in buildings.

2.2.4 Building Fabric Maintenance

Building maintenance cost is also defined as the cost of any actions carried out to maintain the building in an acceptable condition (Seeley, 1976). It consists of three components: decoration cost, fabric maintenance cost and service maintenance cost. Decoration cost includes building external and internal decoration expenses. Fabric maintenance refers to building external and internal elements, such as walls, windows, floor, roof, columns, glazing, etc. This maintenance cost involves the repair, protection and replacement of the building fabric components, which is actually a combination of corrective maintenance, preventive maintenance and condition-based maintenance. Service maintenance is related to the service systems in the building, such as the cost of cold water and hot water supply, the maintenance of air conditioning and lighting system, the maintenance of lifts or elevators, etc. (Al-Hajj, 1999, Al-Hajj, 1991). This kind of maintenance focuses on the active systems that are opposite to the passive building fabric components, which will be mainly investigated and discussed in this study.

Building fabric components are the most important components to buildings (BPG, 1999, Foster and Greeno, 2013). They are the fundamentals including architectural elements and structural elements of buildings to ensure a long-term and stable physical organization for occupants to stay inside. The analysis of maintenance costs for building fabric components can be used to determine the building areas with a low or high maintenance cost and the level of cost on maintaining each building fabric component. Such an analysis can help managers and owners estimating the maintenance costs and making reliable budget plans for maintenance activities. Here it should be emphasized that most fabric maintenance activities are deferred due to inefficient budget plans with low reliability and accuracy (Hamid et al., 2010). This is why cost estimation is significant to the building fabric maintenance. However, the detailed analysis of maintenance cost usually requires lots of accurate information such as take-off quantity, unit cost, material and texture from building fabric components (Lee and Phil, 1987).

Commented [CC10]: Explanation of why maintenance cost planning can influence the maintenance activities.

Furthermore, building fabric components are usually characterized by materials, take-off quantities, unit rate, manufacturer and other property information. These specific properties are the key information to implement efficient and reliable cost estimations for maintenance activities including repair and replacement work. Therefore, a suitable way to obtain the accurate property information is to utilize the 5D BIM combined with the real captures from the fabric components (Gleason, 2013, Pučko et al., 2017).

2.2.5 Cost of Building Lifecycle and Maintenance Phase

The cost of building lifecycle represents an overall assessment result that includes the cost of the as-built asset and the subsequent costs of its operation, maintenance and disposal phase (Al-Hajj, 1999). It is also proved that the possibilities of cutting down the costs related to O&M phase could increase during the design phase, where if a lifecycle cost analysis is conducted (Sterner, 2000).

The required data for lifecycle cost analysis can be categorized into five classes, including occupancy data, physical data, performance data, quality data and cost data, which are the key information concerned by owners (Krstić and Marenjak, 2017). These data are used for cost modelling of the whole building lifecycle.

The costs of operation and maintenance are also summarized and defined as the running costs of running and maintaining a building asset. In 1976, building maintenance cost was defined as the cost of any actions carried out to maintain the building in an acceptable condition. But it was mentioned that the replacement cost of building materials or components were considered as extra improvements and not included (Seeley, 1976).

After that, the costs of maintenance phase are defined as the expense of maintaining the building asset in a good working condition through periodic inspections and repairs (Al-Hajj, 1999). The yearly costs of individual building maintenance may exceed the initial cost of construction by 10% (Krstić and Marenjak, 2017). In addition, a case study indicates that 30% to 40% of the items contribute to 80% to 90% of the maintenance costs, which means significant costs are focused in a few number of building items (Al-Hajj and Horner, 1998).

Relevant studies also indicate that the building maintenance cost usually is higher than the new construction cost due to the following factors (Thompson, 1994, Chanter and Swallow, 2008):

- Maintenance work is always carried out on a smaller scale rather than that of new construction work and this can lead to diseconomies of scale;
- Maintenance work has to be carried out in a confined or occupied place, where the expenditure is higher than that on an as-built site due to the pause of existing operation work;
- The cost of making satisfying clearing away is disproportionately high;
- Substantial disturbance or extra costs would be incurred during the Q&M phase.

As O&M phase is a high-consumption, high-cost and long-term period, its sustainability is actually more critical than that of construction phase concerned by government and society (Mosly, 2015, Lu et al., 2018). Traditional mechanism of building maintenance management and outdated methods of information representation have shown the weaknesses like information loss, data inconsistency and miscommunication when the building project is in a larger scale or contains massive complex information. This can result in waste of building resources, increase of the overall cost and decrease of performance.

This is why innovative scenarios are desired to help estimate the costs of modern building lifecycle and maintenance management to reduce the uncertainties and improve the value of information particularly under the background of industrial digitalization. In recent years, digital technologies are replacing traditional 2D drawings gradually to provide a new way of building maintenance cost estimation based on generation, utilization and sharing of relevant building information (Bheda et al., 2017). It is expected that the use of the digital technologies can make the maintenance cost estimation more accurate and more reliable to help improve the sustainability of building lifecycle management with reduction of extra costs and resource consumptions (Shen et al., 2013, Ustinovičius et al., 2015).

2.3 Building Information Modelling

2.3.1 BIM Development in Global Scope

It is known that AEC industry is experiencing significant developments in automation and digitalization all over the world (Haas and Kim, 2002). Particularly for those new modern infrastructure and building projects in the U.S. and some developed countries, digital technologies such as BIM is becoming widely used for the planning, design and construction phases of an AEC project lifecycle (McGraw-HillConstruction, 2014). For a traditional AEC project, Computer-aided-design (CAD) currently is still playing a quite important role throughout the project lifecycle (Kalay and Mitchell, 2004). It produces two-dimensional (2D) computer-plotted drawings that are much more accurate and intelligent than manual sketches for building design. However, with the rapid development of digital technologies and practical demands, the limitations and drawbacks of CAD have revealed. Lack of effective visualization, losses of detailed information and conflicts of multi-disciplinary collaboration have seriously affected the project efficiency and industrial productivities in recent years (Eastman et al., 2011).

Compared with traditional CAD drawings, international BIM software venders have developed multiple software categories to meet the different requirements of modern AEC projects. According to the industrial disciplines, BIM software can be categorized into architectural design, structural design, MEP (mechanical, electrical and plumbing) design, procurement statistics, construction supervision, etc. (Bheda et al., 2017; Eastman et al., 2011). For categories of functions, BIM software can provide not only 3D models for visualization, but also clash detection, schedule simulation, cost estimation and multi-disciplinary collaboration in order to meet various requirements of project stakeholders (Eastman et al., 2011). The software venders declare that BIM can bring a lot of benefits for the current industrial systems and project workflows. These benefits include duration shortening, cost saving, waste reduction, consumption decline, quality control and complexity management (Migilinskas et al., 2013), which all can be realized through an N-dimensional concept, which is extracted from the BIM practical applications (Ding et al., 2014). Therefore, under the broadcast and declaration of BIM advantages by software venders, a growing number of governments and industrial associations have realized the significance of BIM and its potential benefits for the AEC industrial development in the near future (Bheda et al., 2017; Howell and Batcheler, 2005). Then BIM software are widely adopted to take the place of CAD drawings with a rapid growth of worldwide users (MCGRAW-HILLCONSTRUCTION 2014; Takim et al., 2013). It cannot be denied that this is a great commercial success to the BIM software venders.

Commented [CC11]: Elaboration of how BIM is promoted by its software venders to achieve a commercial success.

According to relevant studies, some developed regions and countries such as the USA, Germany, Finland, Japan, Singapore, Sweden, Denmark, Hong Kong and the UK, have already taken leading positions of BIM development worldwide (Chen et al., 2017; Howell and Batcheler, 2005; Jin et al., 2017). Their governments also have announced BIM related policies and standards to promote its applications in domestic AEC industry. For instance, Danish government has been sponsoring an industrial project named "Digital Construction" since 2003 (Ustinovičius et al., 2015). The U.S. Federal Government has announced a five-year program to encourage BIM adoptions elsewhere and give supports and recommendations on their lessons (Jin and Tang, 2015). The UK Government Construction Strategy (GCS) has required 3D BIM in fully collaborations (all information electronic) as a minimum for all construction projects since April 2016 (Jin and Tang, 2015). Royal Institution of Chartered Surveyors (RICS) has organized annual BIM conference since 2012 to release expertized BIM guidance for infrastructure and building projects (Eadie et al., 2013). The Building and Construction Authority (BCA) of Singapore has announced that BIM would be introduced for architectural submission since 2013 (Jin et al., 2017).

In addition, Graphisoft in Hungary produced the first BIM-based design software and this is recorded as the earliest development of BIM in the world (Takim et al., 2013). Finland is the world leader of BIM implementations where BIM software Tekla and Vico Office were born (Khosrowshahi and Arayici, 2012). Autodesk, which originated from the USA as one of the largest BIM software venders, is providing advanced BIM technical supports for over 150 countries and regions in the world and now the USA has become the biggest producer of BIM software (Wong et al., 2011). These examples indicate that software venders are leading the BIM development in the global scope.

Commented [CC12]: Examples of BIM software venders leading the development of BIM in the global scope.

Fig.2.2, which was created by Mark Bew and Mervyn Richards, who are working for the UK BIM Task Group, shows a maturity model of BIM development (DassaultSystem, 2014). This figure also appeared in the report of the UK Government Construction Client Group (GCCG). It clearly indicates the UK's BIM strategy and the corresponding industry initiatives. In addition, it can be seen that from BIM Level 0 to BIM Level 3, the information formats have upgraded from CAD drawings to transactable and interoperable data under the guidance of BIM relevant standards at different levels. The tools are also converted from traditional paperwork to data files and BIM libraries, and finally to an integrated web-based "BIM Hub". These progresses indicate that as a product of the digital era, BIM not only represents a state-of-the-art technology for the innovation and revolution of the AEC industry, but also leads the industry to a prospective road of development under this background of digitalization and informatization. Currently, the UK has already implemented BIM Level 2 and is moving towards BIM Level 3 (Kemp and Saxon, 2016).

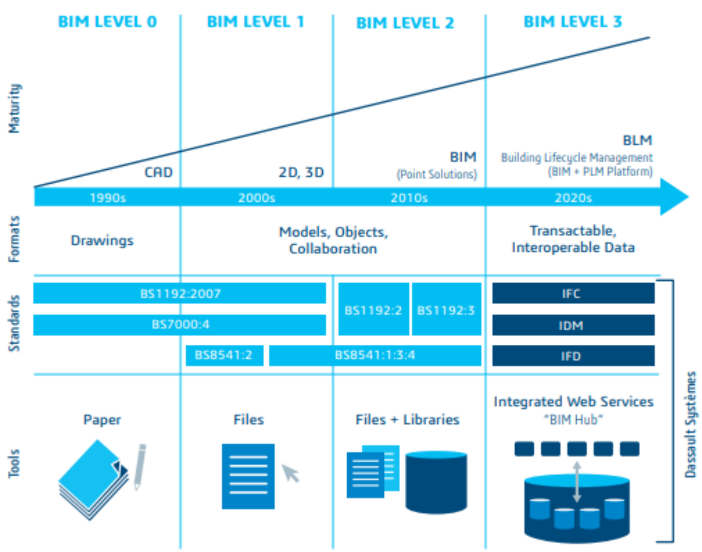

Fig.2.2 Maturity model of BIM development

Although the current BIM development in the global scope shows a positive trend, the software venders are dominating the market because the governments are not involved in the technical aspects of BIM applications. However, the real purpose of BIM applications is to benefit the society and promote the AEC industry to develop in a sustainable and healthy way, but not just for commercial successes of those enterprises. Therefore, more concerns about the BIM benefits to social, economic and environmental aspects should be taken into consideration to help realize the value of BIM for an overall development. Meanwhile more technical researches should be encouraged and supported to narrow the gap between BIM theory and practice in global and local AEC industries. The model representation of BIM Level 3 mentioned above gives a macro research direction of how to apply uniform data formats and integrated services into practice for building lifecycle management based on a digital platform. This is definitely the basic motivation of why such a study about technical integration for lifecycle management is conducted to realize the BIM value in practice.

Commented [CC13]: Critical thinking of current BIM development situation and its real purpose.

Commented [CC14]: The model of BIM Level 3 gives a macro research direction for this study, which can be implemented in practice.

2.3.2 BIM Development in China

As the largest AEC market in the world, China is also undergoing a slow development of BIM applications in its native AEC industry to keep up with the global pace. Compared with those developed countries like the UK, which has formed a mature BIM-based AEC industrial chain, China's BIM development is still at an initial level (Chen et al., 2017). According to a market survey by the China Construction Industry Association (CCIA) in 2012, less than 15% of in total 388 Chinese AEC firms indicated that they have adopted BIM, and even 45% of them stated that they had never heard of BIM (Jin and Tang, 2015). In the same year, another survey from Shenzhen Exploration & Design Association (SZEDA) indicated that over 90% of design firms had heard of BIM, but only 54% of them claimed that BIM application stayed in the experimental stage in small-size projects (Jin et al., 2017). Here it is worth mentioning that Shenzhen is one of the BIM-leading cities in China.

In order to promote the development of BIM application in China's AEC industry, the central government has introduced relevant policies and standards since 2011. The major BIM related policies and standards from the Chinese Ministry of Housing and Urban-Rural Development (MOHURD) during the 12th Five-Year Plan (2011 - 2015) are listed as follows (Jin and Tang, 2015):

- Year 2011—"The 2011-2015 Development Guideline for the Construction Industry Digitalization", which proposed to achieve the digitalization goal by using BIM technology during the 12th Five-Year Plan;

- Year 2012 —"The Announcement of Publishing the 2012 Engineering and Construction Standards", which was the official launch of the Chinese BIM standards;
- Year 2013 —"Request for Proposal on BIM Application in the Construction Industry", which established strategic objectives for BIM applications in public projects;
- Year 2014 —"Proposals on Enhancing the Development and Improvement in the Construction Industry", which aimed to enhance the BIM implementation in multiple phases of project and improve the overall project outcome through BIM usage.

Although in the new 13th Five-Year Plan (2016 - 2020), the significance of BIM in AEC industrial digitalization and structural upgrading is greatly emphasized, the related policies and actions of BIM application are still extensive compared with other developed countries' detailed measures (Jin and Tang, 2015). Therefore, China's AEC industry still has a long way to implement BIM applications in projects successfully.

The reason why Chinese government and industrial organizations show such great interests in BIM is also obvious. Based on powerful BIM software and digital documentation delivery, a growing number of project stakeholders are benefitting from this innovative technology, particularly in production control, efficiency improvement, waste reduction, time and cost saving, etc. (Eastman et al., 2011). The characteristics BIM brings for the AEC industry also are shown in different project phases. For instance, in the design phase, BIM provides more intuitive 3D representations of project information in order to realize earlier collaborations and management of multiple design disciplines, and meanwhile easier verification of design intent consistency compared with traditional design workflow. During the construction phase, BIM realizes automatic clash detection of design before construction, quick reaction to design changes, virtual simulation of construction process, and synchronization of procurement with design and construction. For operation and maintenance phase, BIM supports smarter handover of facility information and integration with operation and management systems (Eastman et al., 2011). For the demands and requirements in different project phases, BIM is implemented by following a multi-dimensional conceptual workflow to improve the overall performance (Ding et al., 2014).

2.3.3 Applications of Multi-Dimensional BIM

BIM is not a tool or software; it provides more ideas rather than that (Eastman et al., 2011). From the planning and design stage, to the construction phase, and finally to the operation and maintenance phase, various resources and multiple disciplines are involved in the lifecycle of an AEC project. Therefore, it gives a tricky issue to the project stakeholders such as the owners and project managers, how to implement a successful management of the project for both productivity and efficiency. BIM shows a multi-dimensional concept, which gives an appropriate solution to this issue. The concept indicates that based on 3D modelling, schedule simulation, cost estimation and facility management can be implemented to convert the traditional construction management process into a more digital and visualized workflow to improve work efficiency and productivity (Jiang, 2017; Jupp, 2017).

3D BIM

According to 2D design drawings, BIM can create a 3D digital model that provides various perspectives for designers to view their initial design and discover errors or omissions. The 3D visualization also improves the clash detection of multiple design disciplines (architectural, structural, mechanical, electrical and plumbing (MEP) designs) in order to reduce wastes and consumptions caused by rework (Eastman et al., 2011). 3D BIM model can reveal massive information for infrastructure and building design details including geometry, dimensions and materials (Gloud and Joyce, 2008). However, in the real projects, only using the information of geometry or other design details is too far away from the construction phase, which highly depends on time and budget (Shou et al., 2015).

Commented [CC15]: Limitation of 3D BIM.

4D BIM

To link the 3D model with time for construction applications, a concept of four-dimensional (4D) BIM is developed and defined as a digital schedule (duration) simulation based on the 3D digital model of a building project (Kymmell, 2008; Shou et al., 2015). It enables a digital link between the 3D model and the schedule planning stage, which provides a timeline to help monitor the execution of activities and the progress of the project in the construction phase (Shou et al., 2018). It brings technical capabilities for the management of infrastructure and building construction process, such as visualization of the time and spatial relationships among construction activities, analysis of the construction plan and node schedule, simulation of construction process and quick response to alterations of construction planning (Jupp, 2017). 4D BIM also can realize the coordination among different stakeholders including designers, civil engineers, contractors and project managers, meanwhile it significantly improves the construction performance and efficiency. Nevertheless, 4D BIM cannot be used to estimate and manage the overall cost of the construction process including quantity take-off, labor, equipment, etc. The cost estimation is quite important to the implementation of construction process and it can highly influence the final productivity of construction phase (Kehily and Underwood, 2017).

Commented [CC16]: Limitation of 4D BIM.

5D BIM

To combine the 4D BIM with cost estimations for construction management, a five-dimensional representation of the 3D physical characteristics with time and cost based on digital modelling of projects is proposed and defined as 5D BIM (Kehily and Underwood, 2017). It is also regarded as a future trend for the integration of multi-disciplinary knowledge and decision making for building design and construction phase based on 3D modelling, schedule simulation (4D) and cost estimation (5D) (Redmond et al., 2012, Jiang, 2017). It enables project stakeholders to visualize the progress of design and construction with related costs over time (Kehily and Underwood, 2017, Park and Cai, 2017).

The aim of using 5D BIM is to implement an accurate and reliable cost estimation based on a 3D digital model and eliminates errors caused by manual measurements or estimations (Ustinovičius et al., 2015). In fact, 5D BIM is not only valuable to design and construction phase, but also applicable to the project management throughout the whole building lifecycle including O&M phase. Some relevant researches indicates that 5D BIM can provide existing Quantity Surveying (QS) data for further cost estimation and scenario evaluation in project management (Olatunji et al., 2010, Frei et al., 2013, Smith, 2016). It is also proposed to realize efficient lifecycle costing, which can be integrated with QS cost assessments or bill of quantities based on 5D BIM (Kehily and Underwood, 2017). Therefore, 5D BIM can be tightly linked with take-off QS to deliver better cost management with certainty in the design and construction phase (Olatunji et al., 2010, Frei et al., 2013). Project managers or owners can use 5D BIM to make a dynamic cost plan in real time and acquire feedback information about the variation on the cost estimation. With the extension of deep studies on 5D BIM, it is believed that an emerging framework will be implemented in AEC industry (Wong et al., 2011, Zhou et al., 2012). Moreover, the cost not only occurs in the construction phase, but also in the later O&M and even demolition phases throughout the project lifecycle. Therefore, the current 5D BIM needs to be integrated with facility management knowledge for the extended applications of lifecycle management in the near future (Jiang, 2017; Kehily and Underwood, 2017).

Commented [CC17]: Current limitation of 5D BIM.

6D BIM

When the construction has been built, stakeholders are still concerned about its commissioning and daily operation performance in O&M phase. To meet the demands and requirements of project latter-phase management, six-dimensional (6D) BIM, which integrates 5D BIM with facility management knowledge has been proposed (Pučko et al., 2017). It focuses on a visual representation of the schedule for building maintenance work and daily monitoring of energy consumptions of building systems. Furthermore, it also introduces a sustainable development principle into the investment process, such as the evaluation of solar energy use in the building concept phase (Ustinovičius et al., 2015). This concept is closely related to smart city researches which involve monitoring of building performance, control of resource allocation, forecast of disasters, provision of functional services and the like (Nical and Wodynski, 2016). In addition, based on digital lifecycle management platforms, 6D BIM also can permanently store and use the empirical data recordings, such as impact factors in construction phase, allocations of building resources, timetables and cost statistics, to provide specific references for O&M management in different locations and conditions, although currently there are still some limitations like data security, access permissions, uniform rules and standards on the development of the lifecycle management platforms (Nical and Wodynski, 2016).

Commented [CC18]: Limitation and further application of 6D BIM.

2.3.4 Benefits, Barriers and Challenges of BIM Implementation in China

The implementation of BIM can bring lots of potential benefits in technical, economic and social aspects for AEC projects. Inter-disciplinary collaboration based on BIM technology can achieve the benefits such as reduction of design errors and rework, clash detection, implementation of 3D visualization, shorten of construction period, etc. (Crotty, 2012, Migilinskas et al., 2013). In addition, according to the report of McGraw-Hill Construction in 2014, two-thirds of BIM users had a positive view of the return on their investments in BIM. Contractors also can reduce the cost by using BIM in their AEC projects (Khanzode et al., 2008). Furthermore, the improvement of interoperability of BIM software was also estimated to save up to two-thirds of the annual total cost paid by clients, building users and operators (Furneaux and Kivvits, 2008). Compared with outdated 2D drawings and traditional project mechanism, BIM reduce the unnecessary wastes of both labors and resources, meanwhile enhance the overall working efficiency, which are so important to the development of modern society (Becerik-Gerber and Rice, 2010).

The barriers of implementing BIM can be divided into four main parts: technical barriers, economic barriers, normative barriers and educational barriers. The technical barriers include the learning of complex BIM-based model software and requirement of hardware support. As indicated by Both et al. in their report of 2012 German BIM survey, most respondents who do not use BIM think the complexity of BIM software is too high for them, They are satisfied with the traditional design methods and not willing to accept the new technology even BIM can bring lots of benefits.

Economic barrier is a main barrier due to the high initial cost of BIM investment. For large AEC companies or organizations that have already used BIM, the financial cost may be not a problem. But for those SMEs (small and medium-sized enterprises) who are not using BIM, the high financial investment can be a serious obstacle (Yan and damian, 2008).

Another main obstacle is the normative problem (Both et al., 2012). Unified industrial standards and market regulations of BIM implementation are very essential to ensure each planning stage and project management can be effective, reliable and secure (Smith and Tardif, 2009). Unified standards is also required in order to improve the collaboration among various stakeholders, and furthermore help to keep the consistency throughout the whole project lifecycle.

BIM education could be a challenge if we plan to promote the BIM-based revolution in the AEC industry. Compared with BIM trainings for senior engineers or architects, school BIM education can be more effective to develop BIM relevant talents. Setting BIM courses and BIM-based software practice can help realize students' early accesses to new innovative technologies, so when they are graduated, they have more opportunities to directly enter AEC companies or institutes (Jin and Tang, 2015). In recent years, BIM laboratories have been set up in high institutions in USA, UK, Germany, Singapore and China. They aim not only to provide supports for BIM researches, but also to become cradles of BIM future talents.

2.4 Laser Scanning Technology

2.4.1 Introduction of Laser Scanning Technology

With an increasing demand of 3D visualization for industrial and social applications, various related techniques have been developed in the past few decades. These techniques are able to measure or capture existing conditions in a natural or built environment, and then present them in 3D images for modelling aims. The 3D models created from the data that gathered by these imaging techniques are widely used for urban planning, landscape design, topographic analysis, environmental management, simulation of construction, disaster forecast, etc. (GSA, 2009). Instances of well-known modern 3D imaging techniques are laser scanning technologies [also known as light detection and ranging (LIDAR)], triangulation-based systems (using pattern projectors or lasers) and other systems that use optical interferometry (Csanyi and Toth, 2007). As one of the most widely used 3D imaging techniques, laser scanning technologies are utilized for geospatial mapping and surveying, manufacturing inspection, quality control of building construction, restoration of historical heritage, etc. (GSA, 2009, Kedzierski and Fryskowska, 2014, Fryskowska et al., 2015). Particularly for the applications in construction and built environmental engineering, laser scanning technologies bring a lot of benefits such as increased accuracy, reduced errors and rework, shortened schedule, improved quality control, 3D visualization and spatial analysis (Suveg and Vosselman, 2004, GSA, 2009).

The working principle of 3D laser scanning is not complicated: an RGB (red, green and blue) laser source in the scanner is steered to emit laser beams, which will reflect when its path is obstructed by opaque objects such as walls or other building elements (Gleason, 2013). Then the reflected laser beams will pass through a prism and finally back to a detector in the scanner for distance measurement between the laser source and the object. Then the collected raw data will be registered by using iterative closest point (ICP) method in order to integrate the formed 3D point clouds from different scenes but for the same object (Kedzierski and Fryskowska, 2014). There are two reminders during the scanning process: the first is although laser will reflect when it hits opaque elements, it still can pass through transparent materials such as glass although a scattering effect would occur. That means the users may obtain some wrong 3D results of building objects with lots of windows or curtain walls; secondly, the colors shown in point clouds are not the real ones of the objects, those unreal dark and light colors are formed due to the reflectance of different materials of the objects (GSA, 2009).

Current 3D model generation process via laser scanning technology can be summarized as shown in Fig.2.3 (GSA, 2009, Gleason, 2013). One of the key steps in the process named establishment of triangular mesh, is to use triangulation algorithms which have been proposed directly on the basis of adjacency relation between 3D points due to the scanning results are unstructured and in free forms.

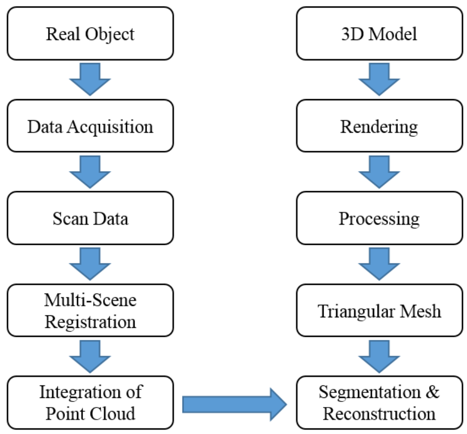

Fig.2.3 Current model generation process via laser scanning

At present, laser scanning technologies can be classified into several categories. According to the spatial locations of the scanners, the technologies can be classified into terrestrial laser scanning (TLS) and aerial laser scanning (ALS). According to the states of the scanners on the ground, it can be classified into stationary laser scanning (SLS, TLS is considered as a type of SLS) and mobile laser scanning (MLS) (Barber et al., 2008, Kedzierski and Fryskowska, 2014, Fryskowska et al., 2015). The details of these laser scanning technologies will be further introduced and discussed.

2.4.2 Terrestrial Laser Scanning (TLS) and Aerial Laser Scanning (ALS)

TLS is one of the most accurate 3D imaging techniques to implement reality captures from contexts. Usually its data accuracy can reach 1-5cm (Liang et al., 2016). For those small-scale outdoor and indoor mapping applications such as building facades, interior landscapes, complicated structures, architectural rooms, etc., the TLS shows an outstanding capability of registering those building elements (Fryskowska et al., 2015, Che and Olsen, 2018). The laser scanner can be mounted on a tripod or a static system to provide a partial or complete field of view. Due to the scanner is located on the ground, the TLS brings some distinct advantages for capturing small irregular and isolated objects from multiple angles and orientations (Xu et al., 2017). In addition, as the 3D models from point clouds only show rich information about the geometry of the target objects, photogrammetry usually is combined with the laser scanning in order to provide imagery of real colors and textures of the target objects for the 3D modelling (Safa et al., 2013). Because photogrammetry is also a common approach to convert 2D images to 3D models. People can take photos of an object in different positions and if the overlaps between each two continuous photos exceed 60%, then an accurate 3D model of the object is able to be generated by integrating the photos of various scenes (Fabris et al., 2009).

However, although the TLS can provide a highly accurate point clouds for 3D modelling, due to the limitations on shapes, sizes and locations of buildings and sites, it is impossible to implement the TLS under some conditions, for instance the narrow corners of a site and the top layers of a building (such as the roofs) (Fryskowska et al., 2015). Therefore, the 3D point clouds of these specific built environments should be acquired by using other methods, such as the ALS.

As TLS cannot be useful at some situations mentioned above, ALS is recommended to complete the data measurement and information capture on the top layers of the buildings in large-scale landscapes (Fryskowska et al., 2015). It can acquire over 40 points per square meter to enable accurate reconstructions of topographic terrains and surfaces in a large-scale area. The scanner for ALS is installed on an aircraft such as a plane, or mounted on an Unmanned Aerial Vehicle (UAV), which can be controlled by users on the ground (Takahashi et al., 2017). ALS is also merged with the photogrammetry to determine the textures of 3D models as well as the TLS. Although ALS enables a high laser scanning performance and fairly uniform locational accuracy in large area, the limitations are also noticeable. It cannot be used to capture 3D information of the building inside, and even on the vertical surfaces. Compared with the TLS, ALS has a much lower accuracy, and shows higher mobilization and costs. Moreover, the aircraft needs a permission to fly due to some specific mapping and surveying sites which are close to an airport (Kedzierski and Fryskowska, 2014).

Neither TLS nor ALS can solely complete the data capture of a complicated environment, the best way to solve this issue is to merge them together. However, the mergence of TLS and ALS also leads to another crucial question of how to integrate the data from two different systems. The data inputs for integration purpose usually include point clouds and photogrammetric imagery from TLS, point clouds and imagery from ALS, 2D maps and vector data. Lots of researches combine these specific inputs for information extraction and 3D modelling of existing buildings and city landscapes (Suveg and Vosselman, 2004, Böhm and Haala, 2005). Point clouds can give accurate coordinate information, but due to the self-occlusion effect, it is difficult to define the boundary lines in the point clouds.

Therefore, the most widely used integration approach is to combine point clouds with aerial imagery (Böhm and Haala, 2005). The basic requirement to implement such a combination is to determine the orientation to a common coordinate system. Some research methods describe how to make relative orientations for acquired point clouds from different systems by transformation (Abdulrahman, 2013). When point clouds of TLS need to be transformed from the local coordinate system into a common coordinate system, which usually is a global coordinate system defined by ALS point clouds. A predefined function which is based on some geo-reference points will be used to recalculate the coordinates of the point sets. These reference points usually are the tie points of imagery or pseudo-homologous points. They can be selected from the natural points that are located at corners, edges or peaks of topographic objects and the target points set by artificial targets or ground marks (Becerik-Gerber et al., 2011a). So the basic issue is how to define and select such reference points from both TLS and ALS data sets with high accuracy. It is quite difficult to identify several exact points which can represent a part of a target object or the entire. Because the initial data sets from TLS and ALS are point clouds that have a great impact on identification and selection of reference points.

To solve this problem, two methods respectively named direct identification and indirect identification are used to define the reference points. The direct method is based on a manual selection of points and the indirect method refers to an automatic or a semi-automatic identification of points. The former is the simplest way to define the coordinates of reference points within point sets through visual interpretation. The latter semi-automatic approach uses filtering based on reflection intensities for edges of object elements to determine the reference points. In addition, specific points and their coordinates also can be identified by using 3D modelling tools, which make the process automatic and convenient. So after the reference points are determined in a common uniform coordinate system, point clouds then can be transformed into it with accurate positions and orientations.

2.4.3 Applications of Terrestrial Laser Scanning

TLS is also known as a type of SLS due to the scanner is mounted on a non-mobile platform. It is also the most widely used SLS approach to capture the existing scene for 3D modelling purpose. Usually a terrestrial laser scanner is fixed on a tripod or a static base to provide a rapid and reliable data capture in a 360^{o} scanning field of view. The maximum measurement range even can reach hundreds of meters and the measurement errors can be controlled within several centimeters. Moreover, the scanning result is a 3D point cloud which contains millions of points with fairly high accuracy.

As the laser scanner is stationary during the scanning process, it has to be moved from one fixed position to the next in order to make sure that scans are taken in various views. To guarantee the scan results from different positions finally can be integrated to a complete point cloud, targets are used to link the scans from different views. Usually, at least three targets are needed and the scan from each position should contain these targets in the result (Becerik-Gerber et al., 2011a).

Currently, the most accurate terrestrial laser scanner in our department is a Leica HDS7000 3D laser scanner (shown in Fig.2.4), which can provide a 360º scanning field in horizontal view and a 320º field in vertical view. Its maximum measurement range is 187m and the minimum is 0.3m (LeicaGeosystemsAG, 2012). The linearity error is controlled less than 1mm and the highest scan rate can reach over 1 million points per second. In addition, Leica has its own bundled software named Cyclone that is used to register and process the collected point sets from laser scanning. This makes the data processing more automatic and saves time. Currently, this terrestrial laser scanner is mainly used for two applications, which are related to 3D modelling of buildings. The first application is quality control of as-built constructions, and the other one is repair and restoration of existing or historical buildings.

Fig.2.4 Leica HDS7000 3D laser scanner

Application 1: Quality Control of As-built Constructions

A common issue which almost occurs in every AEC project is that the as-built constructions usually vary from their initial design models particularly in structural aspect (Randall, 2011). Therefore, quality control method is required in order to calculate the discrepancies between the as-built construction and the design model, which is an essential step for the acceptance work of construction phase. The traditional measurement ways for dimensional (surface) quality control include tapes, calipers, optical ranging devices, etc. However, these physical manual measurement ways usually bring lots of problems such as long measuring time, great labor consumption, measurement error accumulation and less accuracy. Therefore, more advanced automatic and semi-automatic technologies such as TLS and total station have been adopted to collect the 3D information of building interior and exterior.

Compared with the traditional physical manual measurement, TLS provides a better solution to implement geospatial data measurement with higher accuracy and efficiency (GSA, 2009). Furthermore, physical manual measurement has certain limitations on unmeasurable locations such as the beams of constructions or irregular building elements, but this is not a problem to the TLS. With the assistance of bundled software, reality capture from the scanner can be registered and processed to generate a 3D point cloud, as shown in Fig.2.5 from a case study of a carpark in China, which then can be imported into modelling software to realize an implementation of “point-to-line-to-plane” for the final 3D as-built model (Abdulrahman, 2013). This model then will be compared with the initial design model in a common reference system such as CloudCompare software, in which the design model is considered as a benchmark without errors. Therefore, through this method, the discrepancies between as-built constructions and design models are easily found out and the performance of quality control is highly improved.

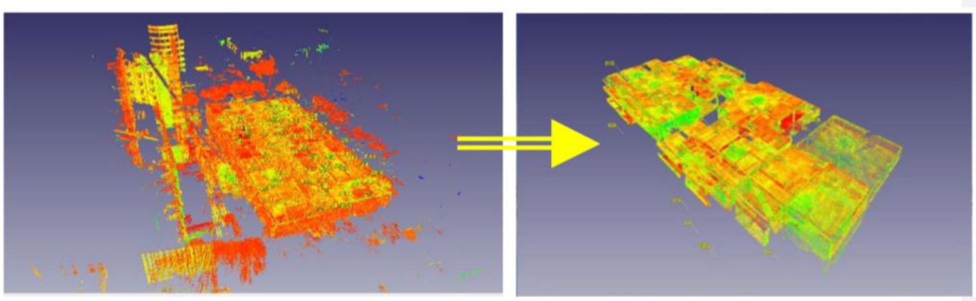

Fig.2.5 Registered and processed point clouds of a carpark case study in Cyclone

Application 2: Repair and restoration of existing building

The aging of structure can lead to damage even collapse of constructions, particularly to some long-standing buildings. To inspect the current conditions of existing or historical buildings, laser scanning is considered as a feasible and efficient approach to capture geospatial information about facades and section profiles of existing buildings (Barazzetti et al., 2015). Then 3D models will be created based on the registered point clouds that is generated from the TLS reality capture. Furthermore, to make the 3D model present more realistically, imagery from photogrammetry also can be combined with the laser scanning results to show the real colors and textures of existing building materials. Therefore, planners and civil engineers can use such highly simulated 3D models to make appropriate repair and restoration plans for existing buildings, particularly for historical ones.

2.4.4 Benefits and Limitations of Terrestrial Laser Scanning

In these applications, the whole process of data handling is called “scan-to-model” (Hichri et al., 2013). A key technical point of this process is how to create an interface for data transfer from laser scanning results to modelling tools. Currently, a software named Recap which is developed by Autodesk, Inc. gives an appropriate solution. It is able to convert registered point clouds from Cyclone to 3D mesh results according to customized settings for visual optimization. Then the optimized results are seamlessly delivered into modelling tools. Benefiting from the rapid scanning rate, large measurement range and fairly high accuracy of TLS, users can greatly save the field time and stay within budget by preventing rework due to errors from manual measurement. Furthermore, the versatility of TLS in different scanner types and measurement contexts also allows users to implement various applications particularly for building constructions (Randall, 2011). Therefore, the integration of laser scanning with BIM is becoming an emerging approach for construction management in AEC industry all over the world. This integration achieves the transformation of real on-site data to scan point clouds, and then the scan outputs are converted to set up start points for 3D modelling by BIM tools (Gleason, 2013). To those stakeholders of building projects, the integration of scan with BIM not only realizes 3D visualization of existing conditions in a real environment, but also proposes a digital solution to implement the data synchronization between real buildings and design models.

However, currently there are still some technical and economic limitations that constrain the seamless integration of scan with BIM (Hichri et al., 2013). From the technical aspect, firstly the pre-work of TLS such as target assignments and stationary position settings can influence the scanning results (Becerik-Gerber et al., 2011a). This indicates that the operation of stationary scan is lack of flexibility. Secondly, even though the scan process of TLS is automatic, users still have to manually register and process the collected point cloud datasets, which means manual errors will occur during the data registration and processing if the professionals are not trained to a certain level. Moreover, technical gaps are still existing between laser scanning bundled software and BIM tools so that the interoperability between heterogeneous systems is a key issue to the integration (Gleason, 2013). From the economic aspect, the capital of advanced SLS technology is too high to implement the extension of applications. This capital includes the costs of laser scanner, bundled software, fixed targets and the like.

2.4.5 Mobile Laser Scanning (MLS)

To solve the inconvenience caused by TLS, mobile mapping system (MMS) concept was announced in the late 1980s and early 1990s (Abdulrahman, 2013). For the initial applications, the laser scanner was mounted on a vehicle to rapidly capture 3D data from existing natural or built environment. Compared with stationary systems, mobile systems are more cost effective and time saving. Even though the accuracy of MLS is lower than that of TLS due to the physical movement, it also has been significantly improved with advances of MLS technology in recent years (Jung et al., 2015). According to study reports of Riegl Inc. in 2011, they had developed a typical laser scanner with a range measurement accuracy of around 8mm. This high accuracy really makes a great contribution to mapping and surveying applications by using MLS (RIEGL, 2007).

However, the crucial difference between SLS and MLS is the way of positioning. Both laser scanning technologies make use of GNSS (Global Navigation Satellite System) for positioning but the details are different (Barber et al., 2008). For example of a laser scanner mounted on a tripod as a stationary system, the positioning components include GPS (Global Positioning System) -base station, antenna for GPS-base station and radio link to GPS rover; for a laser scanner mounted on a vehicle as a mobile system, a common positioning way is to combine IMU with GPS. Usually a vehicle-based MLS system consists of a laser scanner mounted on a rigid structure, a digital camera, GPS antennas of rover, radio link antennas to GPS base station and IMU components (Itzik and Filin, 2011)

2.5 Indoor Positioning Methods

2.5.1 Review of Indoor Positioning

The positioning (or named localization) is a scientific process to find out the position of a person or an object according to one or more reference points which already have known positions. From ancient age to current modern age, the positioning means and methods have also kept changing with the dramatic development of research technologies, initially starting with smoke signals, through sailing with magnetic compass, until today's satellite-based GPS, which is a great success in both theoretical and practical domains. This system uses receivers to acquire signals sent by satellite to calculate and provide the accurate global coordinates of the receiver in open air. Nowadays, due to the stable and reliable positioning performance, GPS technology is widely used for various applications, such as vehicle tracking, mobile asset management, field adventure, emergency search and rescue, etc. (Groves, 2013).

However, each technology has its own drawbacks and limitations. As a battery powered system, GPS has a high energy consumption which does not conform the concept of sustainable development, also to those devices with limited battery power, this can be a problem for long term positioning. In addition, the GPS can only provide high precision in outdoors and is not applicable for indoor positioning. Because the signals can be interrupted by building fabric elements such as walls or other obstacles (Lee et al., 2015). Therefore, other localization technologies are proposed in order to solve the problem of signal interruption for indoor positioning. They are categorized into three mainstreams: Beacon-based positioning, Dead-Reckoning (DR) and device free (Basiri et al., 2017). In addition, some technologies also merge into another to form multisensory positioning systems, which can highly improve the accuracy and reliability of positioning.

For Beacon-based positioning, GNSS is the most widely used technology despite it is only for outdoor applications. Actually GNSS has the technological possibility to be applied to indoor positioning by using ground-based PseudoLites (Groves, 2013). However, due to the high costs, it is not a competitive solution for indoor positioning. Wireless Local Area Network (WLAN) is one of the most popular positioning technology based on the radio frequency signal, it uses lots of Wi-Fi access points for fingerprinting solutions (Conrad, 2014). An Radio-frequency identification (RFID) system consists of RFID readers and active tags, it is used as a proximity localization system (Jin et al., 2006). Bluetooth is another wireless technology for short distance positioning through several tags or beacons (Bahillo et al., 2014). Ultra-Wide Band (UWB) can provide consistent positioning results over a period and both its advantages and disadvantages will be discussed later.

For DR positioning, Inertial Navigation System (INS) is the best known technology for tracking by using inertial sensors. Currently, smartphones that have Micro-electro Mechanical System (MEMS) INS are allowed to become devices for Pedestrian Dead-Reckoning (PDR) (Ruiz, 2017). MEMS INS provides a relatively reliable orientation measurement of the object motion, although there are lots of negative effects (Li and Wang, 2014). Another DR positioning technology is Step and Heading Systems (SHS), which use peak-detection, zero crossing and other approaches to realize the estimations of step length and heading. In general, DR positioning technologies are not able to provide high measurement accuracies.

Tactile sensors and CCTV cameras can be used for device-free positioning purpose. Tactile positioning is based on the direct physical contact between sensors and a surface or an obstruction, which offers a relatively straightforward and accurate estimation of the location; CCTV cameras can detect the object under a network covering environment and use visual odometry to track the object by comparing patterns in continuous images.

Table.2.1 shows some mainstream indoor positioning technologies in recent years (Belakbir et al., 2014). They are compared according to different aspects including measure range, accuracy, signal type and cost. Each of them has their own advantages and disadvantages.

Table.2.1. Comparisons of Mainstream Indoor Positioning Technologies

System	Range	Accuracy	Signal	Cost
GPS	outdoor	1 – 5m	RF	high
WLAN	20m	1 – 10m	RF	moderate
Active Badge	5m	7cm	IR(infrared radiation)	moderate
Active Bat	50m	9cm	US(ultrasound)	moderate
UWB	15m	10cm	RF	moderate
INS/RFID	indoor	2m	RF	moderate
Landmarc	50m	1 – 2m	RF	moderate
Cricket	10m	2cm	US	low
Cellular Network	indoor	50 – 300m	RF	low

In this study, the positioning methods are used for the implementation of indoor mobile laser scanning, which is not only lower-cost, more portable and more convenient than traditional TLS, but also applicable to help locate the accurate positions of the building components that require particularly deferred maintenance. Because deferred maintenance can take a long duration even throughout the construction and maintenance process (Ofori et al., 2015). With the long-run process, it would be difficult to find out the components that require maintenance due to the change of indoor construction environment or clutter on site. The integration of laser scanning with indoor positioning methods can highly improve the scan efficiency of building fabric components with high localization accuracy and meanwhile provide a solution of real-time inspection with high mobility. This is another advantage that the indoor mobile laser scanning have for the fabric maintenance in this study.

Commented [CC19]: Another advantage of indoor mobile laser scanning method for fabric maintenance purpose in this study.

A commonly-used, low-cost and convenient measurement sensor for indoor positioning is the Inertial Measurement Unit (IMU), which can estimate positions and orientations of target by measurement integration. In addition, compared with some navigation and tracking technologies, such as Simultaneous Location and Mapping (SLAM) that uses high sensitive sensors to generate the map of an unknown place, the inertial sensors have no requirements for the environment (Jung et al., 2015). That means IMU can still be reliable even operating conditions are unfavorable. In addition, SLAM usually requires a looping trajectory from the pedestrian, but there is no trajectory requirement for IMU applications (Mazumdar et al., 2014). However, IMU can only provide stance estimations on a short time scale due to the accumulation of drift will seriously affect the accuracy in a long term. Therefore, IMU usually is integrated with other systems like GPS and UWB, in order to provide much more accurate position and orientation estimates (Godha and Lachapelle, 2008). Recent studies have introduced some promising approaches for pedestrian indoor scenarios by using platforms based on UWB, Wi-Fi and RFID. In the later chapters, UWB system and its integration with IMU will be introduced in details and they will be utilized to provide positioning services for the development of the indoor mobile laser scanning in this study.

2.5.2 Inertial Navigation System (INS) and Inertial Measurement Unit (IMU)

Pedestrian INS is based on navigation sensors to acquire the altitude and velocity of mobile objects at a high update rate (Dorobantu, 1999). Compared with other positioning technologies, it has advantages of lower cost, better manufacturing and easier calibration. For indoor applications, INS also can provide reliable navigation information to fill the vacancy of GPS signal outages (Mahmoud et al., 2017). The key component of INS is the IMU, which consists of 3-axial accelerometers, 3-axial gyroscopes and magnetometers. The accelerometer is used to measure the accelerations of the object caused by motion and gravity in the navigation coordinate system and the gyroscope is used to measure the angular rate (the rate of turn) of the object in the system (Nilsson et al., 2012). By integrating the acquired accelerations, it is able to obtain the velocity of IMU and integrating the velocity again, the displacement of the object is acquired. Also integrating the angular rates of the IMU produces the relative orientation of the object (Jekeli, 2001). Therefore, both displacement and orientation on a short time scale are known so that the position and attitude of the object in 3D space then can be determined. In addition, the magnetometer is used to prevent the orientation errors by utilizing the magnetic north as a reference (Foy et al., 2006).

Currently, there are two types of INS: strap-down INS and INS with stabilized platform. The strap-down INS is based on a non-stabilized platform, which means the sensors are simply strapped to the vehicle or human body (Ruiz, 2017). When IMU is strapped to the human body such as the foot, angular rate signals from gyroscopes are integrated to keep track of the attitude of body and specific force in start position is transformed to force in displaced position by using the attitude and accelerations from accelerometers. Then gravity is eliminated to the accelerations and the obtained values are used to calculate the position by double integrations. The advantages of this strap-down system include low cost, increased reliability by eliminating some moving parts and there is no need for calibrations in some steps. However, high update rate (about 2000 Hz) usually is required to ensure that the angular rate can be accurately integrated into an attitude (Weed et al., 2004).

INS also can be fixed on a stabilized platform, like a three-gimbal frame (Ruiz, 2017). This system can keep the gyroscope signals to zeros by using motors so that the attitude of the object can be directly obtained by measurement readings. Then the accelerations from accelerometers only need to be corrected for gravity and then transformed to position by double integrations. An issue which should be noticed is the gimbal lock in the system. That means when two of the three gimbal axes are driven into a parallel direction, in other words, one gimbal axis coincides with the other axis and then two gimbals rotate around the same axis. Hence there will be no gimbal available to adjust the rotation along one axis, which also means there will be a loss of degrees of freedom along one direction. In addition, due to the gimbal system consists of some expensive precision mechanical moving parts, its cost is much higher than strap-down system and sometimes frequent use can lead to wear-out failure of the system.

The working principle of 3-axial measurements of IMU is not complicated. The measurement vector from the three uniaxial accelerometers need to be transformed to the navigation coordinate system in order to obtain the acceleration in the navigation coordinate system (Jekeli, 2001). The gravity acceleration component has been subtracted from it and this can be made by using a 3-axial (X,Y and Z axis) gyroscope, which can measure or maintain the orientation according to the conservation of angular momentum (when rotating, the orientation of axis is unaffected by tilting or rotation of the mounting) (Fischer et al., 2013). Therefore, it can measure the rotational rate of the system, and based on which the relative orientation of the IMU can be determined by integration. Additionally, it should be noted that both accelerometers and gyroscopes suffer from slowly time-varying biases (Hol et al., 2009).

Although the IMU is low-cost, small size and low power consumption, its accuracy is critical due to the fast accumulation of drift errors (or error growth) over time (Mahmoud et al., 2017). So it is not reliable on long-term run and only suitable for positioning in a quite short duration which is only a few seconds. In order to address this problem, a Kalman Filter (KF) is proposed to eliminate noises and improve the measurement accuracy with an optimal linear estimation. It is developed based on statistical theories in order to combine measurements with prior knowledge to minimize errors (Kalman, 1960). However, due to the errors of IMU are non-linear, an Extended Kalman Filter (EKF) is used to solve this issue. Because a low-cost IMU is used in this research and its errors are assumed to be linearly propagated due to the time interval between measurement updates is quite short. The EKF is able to linearize the system state model and measurement model with this assumption to improve the trajectory estimation and reduce the effect of sensor drift (Mahmoud et al., 2017).

Therefore, a zero-velocity detector and a robust EKF, which comprises of error states including navigation errors, sensor errors and gravity uncertainty for estimation, can be used to fuse data from both IMU and GPS system to constrain the error growth and improve the accuracy and reliability of estimated trajectory (Placer and Kovacic, 2013). This enhanced system is named zero-velocity-update-aided INS, which can be simply mounted on the foot for tracking measurement and will be introduced in more details later (Bahillo et al., 2014). The reason of choosing foot as a mounting point is because that the filter improves the accuracy by using properties of the walking motion, which produces regularly reoccurring stationary periods. It was reported that such a foot-mounted INS showed a position errors of $\pm$ 0.2-1% for short distances (<100m) (Nilsson et al., 2012).

In addition, effective integration of vision and inertial sensors also can solve the problem of inertial divergence over time. This integration has been approved under indoor environments by using calibration approaches. Currently there are two calibration approaches, one is calibrated estimation for intrinsic properties of vision sensors (cameras) and the other is determination of the unique transformation between camera and INS measurements (Randeniya et al., 2008).

2.5.3 Ultra Wide-Band (UWB)

UWB is an emerging wireless positioning technology for real time location and progress tracking. It can realize low-energy consumption for short-range, large- bandwidth communications over a large portion of the radio frequency spectrum. Compared with the GPS signal, the UWB signal is any signal that has a bandwidth larger than 500MHz or a fractional bandwidth greater than 0.20 (Purushothaman and Abraham, 2007). The large bandwidth leads to wonderful time resolution (range resolution) which proposes an applicable method for indoor ranging and positioning. In addition, because the UWB signal provides high bandwidth at a lower center frequency, which is beneficial to the penetration of materials and operation in shadowed environments. Resolvable multipath and penetration enable UWB applications in complex indoor wireless local area network (Belakbir et al., 2014). Furthermore, compared with other positioning and tracking technologies, UWB has the following advantages (Shahi et al., 2012):

- Very low power makes it appropriate for specific indoor environments which are sensitive to radio frequencies such as hospitals or health care facilities;
- It has longer read ranges than laser scanning and vision-based detection and tracking systems (up to 1000m);
- There is no requirements for base station connections so that it is more flexible and convenient;
- Low frequency allows the UWB signal to penetrate through a lot of materials and keep immunity to interference.

A typical commercially available UWB system is comprised of a network of synchronized UWB receivers that can track battery-powered and inexpensive UWB transmitters (Yan, 2010). The transmission of radio signal between transmitters and receivers is realized by the use of UWB antennas. For UWB positioning, there are several algorithms based on different measurements (Alarifi et al., 2016):

- Time of arrival (TOA) – for measurements of multiple UWB transmitters, errors often occur due to multipath;
- Angle of arrival (AOA) – for measurements of multiple antennas, errors often occur due to multipath;
- Received signal strength (RSS) – for RFID and WLAN systems, usually sensitive to multipath effect;
- Time difference of arrival (TDOA) – for measurements of three or more UWB receivers, elimination of most errors.

Stationary UWB receivers can provide very precise TOA measurements of the signals from UWB transmitters. However, there is a challenge of how to detect and mitigate positioning errors caused by Non-line-of-sight (NLOS) conditions and multipath channel degradation that can result in poor positioning performance (Yan, 2010). NLOS occurs due to the direct line –of-sight signal is obstructed and only a reflected signal is received, which leads to the increase of the length of signal. Multipath interference means both the direct line-of-sight signal and reflected signal are received, which distorts the correlation peak in the correlation process and results in errors. Therefore, UWB is combined with a 2D laser scanner to provide a new approach for precise positioning (Tappero et al., 2009). This approach requires the measurements of AOA and TDOA. The TDOA is widely used to determine the distance between the reference point and the target, its enhanced results (E-TDOA) can be used as an input of accurate positioning measurement (Bocquet et al., 2005). Here the scan data is only used as reference to monitor UWB performance, and is never directly used to compute positioning. In addition, the laser scanning data can be employed to construct a database of NLOS error measurements which are used to provide positioning correction information that improves UWB measurements under NLOS conditions (Tappero et al., 2009).

Due to the advantages of UWB technology in indoor positioning applications, it has been considered as an effective real-time tracking and monitoring method for the controls of construction projects, such as construction material tracking and on-site activity progress tracking (Motamedi and Hammad, 2009). It also can substitute RFID technology, which has been widely used as a material tracking means for the construction industry, to provide more accurate and convenient 3D location estimations due to the latter needs to be integrated with GPS or other tracking technologies (Razavi et al., 2009).

However, the performance of UWB system still could be affected by the following conditions when it is implemented for indoor construction projects (Shahi et al., 2012):

- Construction-related materials of the indoor environment may have an impact on the performance. It has been proved that metal surfaces can lead to obstruction and the strongly affect the performance by the presence of occlusions;
- Although the mean of UWB system errors can be compensated by location-based error corrections, the standard deviation or error variance cannot be compensated;
- With the construction progress and the increase of construction-related stuffs in the indoor environment, the line-of-sight from one or more receivers may be occluded and NLOS conditions would occur. When the occlusions reach 100%, the performance of UWB system will be deteriorated substantially.

In addition, the error magnitude and variability of UWB system is also related to the layout design of receivers and site-specific error characterization. Therefore, the site installation layout should be optimized in order to reduce NLOS conditions.

CHAPTER 3: Research Methodology

3.1 Research Framework

This study aims to achieve ten research objectives as stated in Chapter 1. These ten objectives are the solutions to find out the answers of ten research questions that are highly related to this study as shown in Table.3.1, which presents the overall research framework of this study. To implement these solutions, corresponding research methods for achieving each objective are also proposed in the table. In addition, the overall research workflow has been divided into eight steps, which are also shown in Table.3.1. The methodology of this study is developed and elaborated based on this research framework.

Table.3.1. Research Framework

Research Question	Research Objective	Research Method
What are the challenges in the current China’s AEC industry?	Review the current situation of China’s AEC industry and its digitalization development	Literature Review
How can BIM be applied into various phases of China’s AEC project lifecycle?	Review the current situations of global and China’s BIM development and investigate the applications of BIM/5D BIM in various phases of China’s AEC project lifecycle.	Literature Review; Comparative Study; Grounded Theory
What is the gap-in-knowledge between underlying BIM-based theories and current practices in O&M phase of project lifecycle?	Investigate potential impact factors that can affect the construction process and develop a 5D BIM-based forecast system to predict uncertainties in construction phase	Literature Review; Online Survey; Interview; Likert Scale; Quantitative Statistical Method;
How can 5D BIM improve the productivity of construction process?	Review the current situation of O&M phase (particularly the building maintenance) and determine the gap-in-knowledge between BIM theories and practices for building maintenance in China	Literature Review;
Why is the laser scanning chosen for this study of building maintenance?	Review the development of laser scanning and propose a mobile laser scanning idea for potential applications in building maintenance	Literature Review
What techniques can be used to realize mobile laser scanning under the indoor environment?	Integrate IMU and UWB systems with a low-cost 2D laser scanner to realize a low-cost and time-saving mobile laser scanning for indoor mapping and digital modelling in a Chinese case study	Pedestrian Dead-Reckoning (IMU); Coordinate Frame Transformation (UWB); On-Site Experiment; MATLAB-based Algorithm for Data Processing & Integration
What advantages does the mobile laser scanning have over the traditional TLS for indoor applications?	Compare the mobile laser scanning with traditional TLS by experiment under the same conditions	On-Site Experiment; Cloud Compare
How can the integration of 5D BIM with mobile laser scanning be realized to fill the gap-in-knowledge of building fabric maintenance in China?	Develop an efficient low-cost method based on the integration of 5D BIM and mobile laser scanning for cost estimation and planning of building fabric maintenance in the case study in China	Framework Design; Cloud Compare; Cost Estimation Theory; Weibull Distribution
How can the developed integration workflow be applied into practices to make contributions for building fabric maintenance?	Validate the feasibility of the maintenance cost planning based on the low-cost integration method in practices	Sensitivity Analysis
To what extent is the developed integration workflow valuable for cost planning of building fabric maintenance?	Develop a BIM-based panel prototype to implement automated cost planning of building fabric maintenance for case studies in China	Framework Application

Research Workflow

Review the current situation of digital development in China’s AEC industry and identify the current challenges to traditional AEC project lifecycle

↓

Develop BIM-based workflows for project lifecycle and a forecast system for design and construction phases in China

↓

Identify the gap-in-knowledge between BIM applications and practices in O&M phase, particularly for fabric maintenance

↓

Develop a low-cost mobile laser scanning method to implement indoor mapping and digital modelling for the purpose of building fabric maintenance

↓

Compare the scan results from developed mobile laser scanning method and traditional TLS-based reference experiment to check the discrepancies and validate its reliability in practices

↓

Integrate 5D BIM with the mobile laser scanning method to develop an efficient and low-cost method for cost estimation and planning of building fabric maintenance

↓

Validate the feasibility and reliability of the cost planning made by using the developed low-cost method in practices

↓

Develop a BIM-based panel prototype to implement automated cost planning of building fabric maintenance for practical applications in China

3.2 Research Methods

3.2.1 Method for Data Collection

3.2.1.1 Empirical Online Survey

To realize a rapid collection of the opinions about BIM and AEC industrial development from the global and China's AEC industrial practitioners, online questionnaire survey is an appropriate manner to achieve that goal in this study. Compared with face-to-face interviews, an online questionnaire not only requires shorter duration and less cost, but also permits respondents (industrial practitioners) to response the questionnaire at their ease (Fowler, 1993). For this study, self-designed online questionnaire surveys are proposed to be launched on a famous data collection website in China, which uses a screening system to select and encourage people who are working in this domain or have related professional backgrounds to participate in the surveys and give their empirical suggestions. Therefore, the collected information through the online survey could be more authentic and persuasive (Harris et al., 1996). The surveys include two parts, one focuses on an empirical investigation of industrial practitioners' opinions on BIM benefits for design coordination workflow in China's AEC industry, the other one aims to investigate the impact factors that can influence construction process in China's AEC projects. As maintenance can be done in different project phases including design, construction and O&M (Assaf, 1996), the most sustainable way is to consider the maintenance during the early stage of design and construction phase to minimize the overall maintenance cost and meet the professional requirements of maintenance quality (Dessouky and Bayer, 2002; Ofori et al., 2015), the results from the empirical surveys can be used to link the design and construction phase with later O&M phase to investigate the BIM-based coordination workflows and common impact factors for productivity and performance improvements of design, construction and O&M phases.

Commented [CC20]: The investigation surveys are used to link the design and construction phase with O&M phase to investigate the potential influences of BIM-based workflows and impact factors on the productivity and performance of construction and maintenance. Particularly maintenance can be early considered in design and construction to minimize the maintenance cost.

In this study, an investigation workflow for the empirical online survey was developed and shown in Fig.3.1.

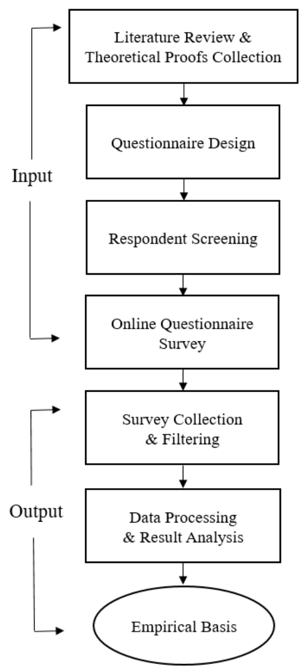

Fig.3.1 Workflow for Empirical Survey

The workflow is divided into input and output parts. The input focuses on the preparation work including theoretical proof collection, questionnaire design, respondent screening and online survey. The output is mainly about the executions of the survey results including survey collection, survey filtering, data processing, data analysis and generation of result-based empiricism.

3.2.1.2 Interview

Interview is a common approach to acquire empirical information from industrial experts and professionals through face-to-face communications or voice/video calls. Compared with the online survey, more information that is detailed to the questions can be obtained from the interviewees. Furthermore, positive interactions can be realized during the interview to help explore the opinion divergence among interviewees.

3.2.2 Method for Data Analysis

3.2.2.1 Grounded Theory

According to the literature review, we may have a preliminary understanding of the current situation of China's AEC industry and the benefits BIM can bring for AEC project design phase. In order to further investigate the potential impacts of BIM on China's AEC project design coordination and traditional workflows, a scientific research method is developed for data collection and result analysis. This method was developed based on the grounded theory, which was initially established by Glaser and Strauss in 1967. Grounded theory is widely used to generate theoretical conclusions for complex topics based on empirical researches (Glaser and strauss, 1967). The reason why this method is chosen for data analysis is due to its capability of finding out similarities and connections among different factors by using empirical data (Strauss and Corbin, 1990). The schematic process of this grounded theory method is shown in Fig.3.2.

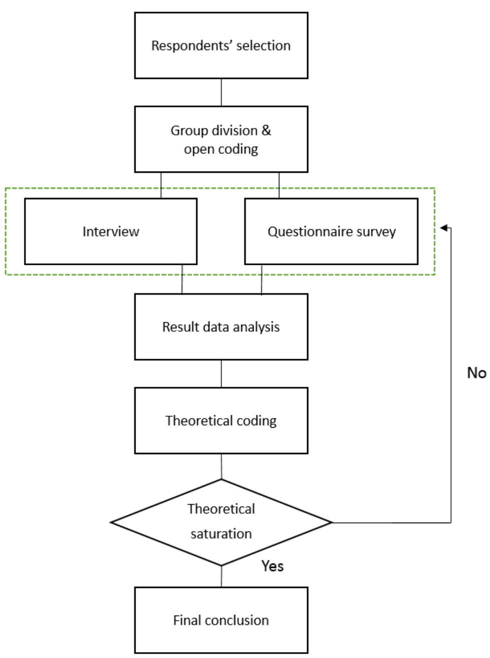

Fig.3.2 Process of grounded theory method

3.2.2.2 Likert Scale

For the investigation of impact factors during construction phase, rating is a necessary step to distinguish the significance of each potential impact factor (Homthong and Moungnoi, 2016). Therefore, a five-point Likert Scale was used in this study to achieve this rating purpose. Table.3.2 shows the ordinal scale that used integers in ascending order with an increase of impact.

Table.3.2. Five-Point Likert Scale Used for Factor Impact Rating

Item	**Not applicable**	**Applicable but no impact**	**Slight impact on it**	**Moderate impact on it**	**Strong impact on it**
Ordinal scale	**1**	**2**	**3**	**4**	**5**

The Relative Importance Index (RII) was proposed in this study to decide various respondents' opinions on the significance ranking of those impact factors in the construction process. The RII can be calculated as following (Cheung et al., 2004, Iyer and Jha, 2005, Ugwu and Haupt, 2007) (3.1):

$$\mathrm{RII} = \frac{\sum W}{A} \times N \tag{3.1}$$

Here W is the ordinal scale given to each factor by respondents and ranges from 1 to 5;

A is the highest scale = 5;

N is the total number of respondents.

3.2.2.3 Quantitative Statistical Method

For the data analysis, a quantitative statistical method was also used in order to calculate the weight each sub-factor accounts for in the corresponding group of the main impact factor. The weight in percentage can be determined as below (3.2):

$$\mathrm{WP} = \frac{RII}{\sum RII} \times 100\% \tag{3.2}$$

Here WP is the weight in percentage of each sub-factor in the corresponding main factor group; $\sum RII$ is the sum of all sub-factors' RII in the corresponding main factor group. The weight of each sub-factor directly correlates with their significances in the main factor. It also decides how much impact each sub-factor could have on the main factor, and this is vital to the later development stage of the impact factor forecast system for construction process, which is a significant contribution in this study.

In addition, sample size is usually calculated in order to achieve a 95% confidence level for the empirical online survey to ensure its reliability and validity for empirical statistics. However, a prerequisite for calculating sample size is that the sample distribution should obey a normal distribution. Due to the sample distribution in this survey not obeying a normal distribution, there is no need to calculate the sample size by specific formula as shown below (Moore et al., 2003, CRS, 2016).

Commented [CC21]: Explanation of why sample size calculation is not needed in this study.

$$ss = \frac{Z^2 \times p \times (1-p)}{c^2} \tag{3.3}$$

$$SS = \frac{ss}{1+\frac{ss-1}{pop}} \tag{3.4}$$

Here ss is the transition value of corrected sample size;

Z is 1.96 for a 95% confidence level;

p is the percentage of picking a choice, expressed as decimal and 0.5 is used for sample size needed;

c is the confidence interval, expressed as decimal (a 5% interval was used and c = 0.05);

pop is the entire population;

SS is the corrected sample size.

3.2.2.4 Cloud Compare

With the development of digital tools, the point clouds, which are the generated results comprising of massive 3D data points from laser scanning technology or other 3D imaging techniques, can be compared on a common platform. This common platform usually is a professional software tool for point cloud processing to rapidly and accurately check the discrepancies or variations between current reality capture and historical scan results. It is also available to compare the point cloud from reality capture with the design BIM model on the cloud compare tool. The root mean square (RMS) values and maximum errors are usually the key indicators for evaluating the comparison results and they can be automatically measured by using a professional cloud compare tool.

3.2.2.5 Sensitivity Analysis

Sensitivity analysis is a commonly used method to determine and analyze uncertainties in the economic assessment of an AEC project. In this study, it is utilized to find out the sensitivity from lots of uncertainties that have significant impact on the economic benefit indicators of the building fabric maintenance. Meanwhile its analysis results can highly affect the decision-makings on the cost planning of the building fabric maintenance. If the variance of an uncertainty can lead to a large change on the economic benefit indicators, this uncertainty can be called as a sensitivity (Hopfe, 2009). Such a sensitivity in maintenance planning could be caused by multiple factors including labor, weather, environmental issue, equipment, fluctuation of rate, material price, etc. (Nikakhtar et al., 2012; Ofori et al., 2015). This can be highly linked with the construction phase because the factors mentioned above also have large impacts on the construction process. Therefore, it is reasonable to consider the maintenance cost planning in the early stage of the construction phase due to the common concerned impact factors. In this study, the sensitivity analysis is applied to validate the feasibility of the maintenance cost plan of building fabric components by assuming and predicting the impact factors according to the conditions of the case study.

Commented [CC22]: Explanation of the uncertainty in the sensitivity analysis and its link with the common concerned impact factors that are mentioned in construction process.

Usually for the assessment of the maintenance cost plan, the economic benefit indicators include net benefits, internal rate of returns, benefit-cost (B/C) ratios, etc. Common decisions for accepting or rejecting cost plans depend on the calculations of these three indicators (Stenström et al., 2015). In this study, a sensitivity analysis was conducted on the B/C ratio, which also can be understood as the return of maintenance investment to compare costs with benefits for decision-makings of activities. This is because the decision makers including building owners and construction managers are usually interested in how to maximize the return of maintenance investment during the building lifecycle. Sensitivity analysis provides an appropriate resolution to settle down this issue in practice (Nikakhtar et al., 2012). Another reason of choosing B/C ratio as the key indicator is that PM can be assessed as a benefit from the maintenance investment and become more intuitive to perception through this ratio. Although this ratio has some limitations, such as its high sensitivity to negative values that are subtracted from benefits or added to costs, it is still appropriate to assess the value of the preventive maintenance (PM) as the benefit from unity investments (Stenström et al., 2015).

Commented [CC23]: The reasons of why choosing B/C ratio as the indicator in this study.

The main uncertainties that can have an impact on the B/C ratios are summarized into two parameters. One is the probability of detection (POD) of potential failure ($\alpha \in [0, 1]$) and the other is the potential to functional failure likelihood ($\beta \in [0, 1]$). The correlation between the B/C ratios and these two uncertainties can be expressed as follows (Stenström et al., 2015):

$$\text{B/C} = \frac{B_{PM}}{C_{PM}} = \frac{\alpha\beta\bar{C}_F}{\bar{C}_I + \alpha\bar{C}_R} \tag{3.5}$$

Here B_{PM} is the benefit of preventive maintenance, C_{PM} is the cost of preventive maintenance, $\bar{C}_F$ is the mean cost of functional failure of maintenance object, $\bar{C}_I$ is the mean cost of inspection, and $\bar{C}_R$ is the mean cost of potential failure repair. Functional failures are closely related to the corrective maintenance (CM). Inspections and potential failures provide data for the PM. To sum up, all these three mean costs are obtained from the initial cost estimation of building fabric maintenance. Furthermore, it is also known that the uncertainties of other maintenance related parameters can affect the B/C ratios due to their impacts on the three mean costs, such as the prices of fabric materials, labor costs, preventive costs, maintenance intervals, etc.

It also should be noticed that there is an interdependency between α and β; if the maintenance work becomes more strict to limit potential failures, then α will increase and β will decreases. Here α is also conceived as the probability that an inspection has to lead to replacement or repair work. When the B/C ratio is larger than 1, it means the benefit is higher than the cost when such a maintenance cost plan is implemented. Therefore, such a maintenance plan is positive and acceptable to be executed in practices.

3.2.3 Method for Data Generation

3.2.3.1 Pedestrian Dead-Reckoning

Pedestrian Dead-Reckoning (PDR) is an appropriate solution to overcome the accumulation of drifts caused by the numerical integration of IMU measurements over a long term as mentioned before (Hide et al., 2010). There are two PDR solutions, which can provide continuous navigation information for indoor built environment and model the motion trajectory of the carrier, where the IMU is mounted like the pedestrian body (usually foot or waist) or a trolley.

One solution is named zero velocity update (ZUPT) method, which integrates accelerations and provides a zero velocity update at stance for error corrections of foot-mounted IMU measurements. As the inertial sensor is mounted on a pedestrian’s foot, when the pedestrian is walking, there will be a stance phase that can provide a zero velocity measurement during each walking step (Li and Wang, 2014). If the stance phase of each step can be identified accurately by detecting the periods of zero velocity, then the IMU velocity errors can be corrected (Foxlin, 2005). The stance phase consists of five components including heel strike, foot flat, midstance, heel-off and toe-off. Particularly for a foot-mounted IMU, the magnitude of acceleration and gyroscopic measurement are stable during midstance (Ruiz, 2017).

The other solution is named stride length (SL) method over a certain orientation. This approach propagates stride length estimations along certain orientation angle at foot stance (Ruiz, 2017). The IMU can be mounted anywhere. For the navigation part of the indoor mobile laser scanning developed in this study, the IMU is mounted on a moving platform (trolley) handled by pedestrian rather than strapped on foot, therefore SL algorithmic solution is more appropriate for IMU data processing.

Before discussing the PDR solution in more details, it is necessary to understand some theoretical knowledge about coordinate frames in the navigation domain. There are four commonly used coordinate frames (Groves, 2008, Placer and Kovacic, 2013):

Body frame: It is the coordinate frame of the IMU itself. Usually its origin is located in the center of the accelerometer triad and all the measurements are resolved in this frame. The axes are aligned to the IMU casing.

Global frame (Navigation frame): It is a local geographic frame, to which we want to transform the body frame for navigation purpose, or in other words, we want to know the corresponding position and orientation of the body frame in this frame. On most occasions, it is stationary to the earth, unless the navigation is applied over large distances for which the global frame needs to be moved and rotated along the surface of the earth.

Inertial frame: It is a stationary and non-rotating frame in which the IMU measures linear accelerations and angular rates. Its origin is located at the center of the earth and the axes are aligned to the stars. In classic physics and special relativity, measurements in one inertial frame can be converted to measurements in another by a simple transformation.

Earth frame: This frame coincides with the inertial frame. However, it is not stationary, because its origin is also located at the center of the earth and its axes are fixed to the earth, which means it rotates with the earth.

Based on the four coordinate frames mentioned above, the angular rate in the IMU body frame can be expanded by using the following equation (3.6):

$$\omega_{ib}^{b} = R^{bg}\left(\omega_{ie}^{g} + \omega_{eg}^{g}\right) + \omega_{gb}^{b} \tag{3.6}$$

Where ω_{ib}^{b} is the angular rate of the body frame as observed in the inertial frame, R^{bg} is a rotation matrix, ω_{ie}^{g} is the earth rate, ω_{eg}^{g} is the transport rate and ω_{gb}^{b} is the angular rate of the body frame as observed in the global frame, which is required for navigation purpose.

For the linear acceleration of the IMU, it can be expanded as (5.2):

$$\alpha_{ii}^{g} = \omega_{ie}^{g} \times \omega_{ie}^{g} \times R^{gi}\alpha^{i} + 2\omega_{ie}^{g} \times \alpha_{g}^{g} + \alpha_{gg}^{g} \tag{3.7}$$

Where α_{ii}^{g} is the linear acceleration as observed in the inertial frame, $\omega_{ie}^{g} \times \omega_{ie}^{g} \times R^{gi}\alpha^{i}$ are the centripetal acceleration terms that can be absorbed in the local gravity, α_{g}^{g} is the ground speed in the local place and α_{gg}^{g} is the linear acceleration of the IMU body frame as observed in the global frame, which is also required for navigation purpose.

As a strap-down IMU is used in this research, the measurements are resolved in the body frame rather than in the inertial frame. Therefore, the schematic of a strap-down-IMU-based PDR solution is shown in Fig.3.3.

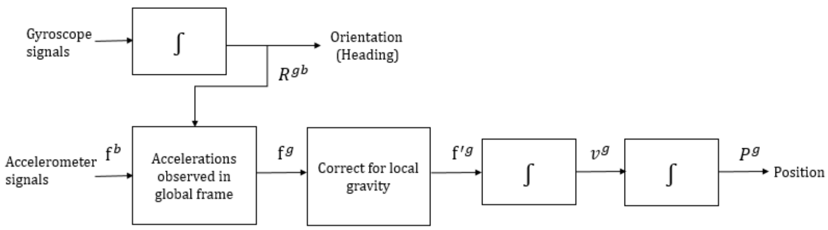

Fig.3.3 Schematic workflow of IMU-based PDR solution

Following the schematic, the IMU-based PDR solution can be divided into five phases, which are described as below:

I. Step Detection

The accelerometers are mainly used in this phase. The step events are detected by threshold-based step cycle detection on acceleration readings, which follows principle of stationary inertial sensors to find out repetitive acceleration pattern at stance (Krach and Robertson, 2008, Castaneda and Lamy-perbal, 2010). The acceleration readings are first processed by a low-pass filter with frequency condition that depends on the sampling rate of accelerometer (Zampella et al., 2017). The accelerations along three axes (x, y and z) of the IMU body frame can be obtained from the following formula, which also considers the vertical changes with respect to the time (Kang et al., 2012)(3.8):

$$a(t) = \sqrt{\left(a_x(t)\right)^2 + \left(a_y(t)\right)^2 + \left(a_z(t)\right)^2} - g \tag{3.8}$$

Where a_x, a_y and a_z are the accelerations along three axes at time (t) and g is the gravity, which needs to be eliminated from the vertical acceleration.

II. Stride Length Estimation

Here a bounce-based Weinberg Algorithm is used to estimate the stride length. The bounce is understood as the vertical movement of hip, which can be determined by using maximum and minimum acceleration values of each step event. It is also assumed that SL is proportional to bounce. Therefore, a hip bounce model for SL is proposed as below (Goyal et al., 2011) (3.9):

$$SL_i = \sqrt[4]{a_{max}(i) - a_{min}(i)} * K \ (i = 1,2, \dots, n) \tag{3.9}$$

Where SL_i is the stride length of the i^{th} step and K is a multiplication factor of penalty for calculation (Zampella et al., 2017). Compared with other step length estimation approaches, Weinberg Algorithm is more suitable for carrier mounted IMU due to the use of generalized calibration values (Jahn et al., 2010).

III. Heading Estimation

Gyroscopes and magnetometers of IMU are used to estimate the heading (orientation) in dead reckoning systems. However, external magnetic disturbance is always existing in real indoor environments and this can lead to errors which introduce a drift in the heading estimation (Goyal et al., 2011). Therefore, an EKF can be used to improve the accuracy of estimating the full 3D attitude of the IMU by using the data from gyroscopes, magnetometers and accelerometers. $\phi(t)$, $\theta(t)$ and $\psi(t)$ represent the pitch, roll and yaw directions along three axes of the IMU body frame at time (t). They can be determined by the equations shown as below (Ruiz, 2017) (3.10, 3.11 and 3.12):

$$\text{Pitch: } \phi(t) = \tan(\frac{a_y(t)}{a_z(t)})^{-1} \tag{3.10}$$

$$\text{Roll: } \theta(t) = \tan(\frac{-a_x(t)}{\sqrt{a_y(t)^2+a_z(t)^2}})^{-1} \tag{3.11}$$

$$\text{Yaw: } \psi(t) = \tan(\frac{-m_x(t)}{m_y(t)})^{-1} \pm \delta \tag{3.12}$$

Where m_x and m_y are the magnetometer readings of x and y axis at time (t), δ is a time-varying bias value. The modified angular rate in the IMU body frame with updating rotation matrix $R(t)$ of three axes can be used to estimate the heading of IMU in the global frame (Nilsson et al., 2012, Li and Wang, 2014) (3.13, 3.14, 3.15 and 3.16):

$$R_x(t) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta(t)) & -\sin(\theta(t)) \\ 0 & \sin(\theta(t)) & \cos(\theta(t)) \end{pmatrix} \tag{3.13}$$

$$R_y(t) = \begin{pmatrix} \cos(\phi(t)) & 0 & \sin(\phi(t)) \\ 0 & 1 & 0 \\ -\sin(\phi(t)) & 0 & \cos(\phi(t)) \end{pmatrix} \tag{3.14}$$

$$R_z(t) = \begin{pmatrix} \cos(\psi(t)) & -\sin(\psi(t)) & 0 \\ \sin(\psi(t)) & \cos(\psi(t)) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3.15}$$

$$R(t) = R_x(t)R_y(t)R_z(t) \tag{3.16}$$

Where $R_x(t)$ $R_y(t)$ and $R_z(t)$ represent the rotation matrixes along roll, pitch and yaw directions in the IMU body frame. The updating of rotation matrix $R(t)$ is based on angular rate changes along three axes as ω_x^t ω_y^t and ω_z^t at time (t). The overall angular rate rotation matrix W within time interval Δt in three directions then can be applied to the $R(t)$ in order to obtain the rotation matrix of next step at time t + Δt shown as below (Nilsson et al., 2012, Li and Wang, 2014) (3.17 and 3.18):

$$W = \begin{pmatrix} 0 & -\omega_z^t \Delta t & \omega_y^t \\ \omega_z^t \Delta t & 0 & -\omega_x^t \Delta t \\ -\omega_y^t \Delta t & \omega_x^t \Delta t & 0 \end{pmatrix} \tag{3.17}$$

$$R(t + \Delta t) = R(t) * \exp(W) \tag{3.18}$$

Additionally, the initial values of roll and pitch are determined by calculating the initial average changes of accelerations in the same directions and the initial yaw can be conceived as zero at the starting position of heading. To simplify the estimation process, the heading $\theta_{step}(t)$ is only related to the changes on yaw direction at each step (Racko et al., 2016, Zampella et al., 2017) and can be determined by (3.19):

$$\theta_{step}(t) = \arctan_2(R_{2,1}(t), R_{1,1}(t)) \tag{3.19}$$

IV. Position Estimation

Combining the calculation results from the three phases mentioned above, the position trajectory then can be estimated by accumulating SL along the headings. Therefore, a SL + θ algorithmic solution is formed as following (Ruiz, 2017) (3.20):

$$\begin{bmatrix} P_{E_i} \\ P_{N_i} \end{bmatrix} = \begin{bmatrix} P_{E_{i-1}} + SL_i \times \sin(\theta_{step}(t)) \\ P_{N_{i-1}} + SL_i \times \cos(\theta_{step}(t)) \end{bmatrix} \tag{3.20}$$

Where P_{E_i} and P_{N_i} represent the position along east and north direction in the global frame.

V. Position Calibration

The position estimations depend on the heading estimations, therefore the position calibration can be understood as the heading calibration. For the indoor positioning and mobile laser scanning experiment, the IMU will be mounted on a trolley rather than strapped to the pedestrian's body. To simplify the trajectory estimation process, the trolley mounted with IMU will be driven along the edge of the room internal wall in an approximately straight line, so the heading is assumed to be stable and consistent to the moving direction of the trolley. Based on the formula of position estimation mentioned above, the position then can be calibrated by changing the heading to a constant value and rescaling the stride length according to the total movement distance in the experiment. In addition, the relative distance between the gravity centers of the IMU and the trolley must be remained in order to eliminate the relative position errors.

3.2.3.2 Coordinate Frame Transformation

In this study, as the raw measurement results generated from the UWB system only can be saved as Xtreme Card Manipulation (XCM) format files, the results need to be converted from XCM files to Comma-Separated Value (CSV) files by using a Python-based transformation method. The CSV files can easily display the key measurement parameters including time, X, Y and Z coordinates.

To implement the transformation of the UWB measurement results from its own coordinate frame to the global coordinate frame for positioning purpose. The global coordinate frame is the WGS84 Coordinate System that is a widely used international system (Yavari, 2015). To implement this step, a transformation method named Helmert Transformation is used for this three-dimensional spatial transformation (Lancaster, 1965). This method is also called a seven-parameter similarity transformation (Datum Transformation Equations).

Usually Helmert Transformation is widely used in mathematical statistics for variance analysis (Clarke, 2008). Nowadays it is also frequently used in geodesy engineering to solve the distortion problems that occur during the data transformation from one coordinate frame to another (Mataija et al., 2014).

Seven standard parameters are used to support the transformation between the body frame and the global frame. They are three translation parameters(ΔX, ΔY and ΔZ), three rotation parameters (ω_X, ω_Y and ω_Z)

and one scale factor (m). Based on these seven parameters, the transformation formula can be expressed as following (Reit, 2013) (3.21):

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} = (1+m)R_1(\omega_X)R_2(\omega_Y)R_3(\omega_Z)\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \tag{3.21}$$

Where X_b, Y_b and Z_b represent the coordinate in the body frame, X_g, Y_g and Z_g represent the coordinate in the global frame. The scale factor m is a deviation from the scale unity $(1+m)$ (Mitsakaki, 2004). Three rotation parameters can be expressed in matrices as following (Reit, 2013) (3.22, 3.23 and 3.24):

$$R_1(\omega_X) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\omega_X & sin\omega_X \\ 0 & -sin\omega_X & cos\omega_X \end{bmatrix} \tag{3.22}$$

$$R_2(\omega_Y) = \begin{bmatrix} cos\omega_Y & 0 & -sin\omega_Y \\ 0 & 1 & 0 \\ sin\omega_Y & 0 & cos\omega_Y \end{bmatrix} \tag{3.23}$$

$$R_3(\omega_Z) = \begin{bmatrix} cos\omega_Z & sin\omega_Z & 0 \\ -sin\omega_Z & cos\omega_Z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.24}$$

Due to ω_X, ω_Y and ω_Z are minute angles in general conditions, the corresponding values of the elements mentioned above in three rotation matrices can be regarded as (Reit, 2013) (3.25):

$$cos\omega_X = cos\omega_Y = cos\omega_Z = 1$$

$$sin\omega_X = \omega_X, sin\omega_Y = \omega_Y, sin\omega_Z = \omega_Z$$

$$sin\omega_X sin\omega_Y = sin\omega_X sin\omega_Z = sin\omega_Y sin\omega_Z = 0 \tag{3.25}$$

Therefore, the transformation formula can be simplified as (Mitsakaki, 2004, Reit, 2013) (3.26):

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} = (1+m)\begin{bmatrix} 1 & \omega_Z & -\omega_Y \\ -\omega_Z & 1 & \omega_X \\ \omega_Y & -\omega_X & 1 \end{bmatrix}\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \tag{3.26}$$

This transformation formula is used when global or geodetic transformation parameters are estimated. The minimum number of common coordinate points that are used to solve the seven standard parameters is three. But more points are often encouraged and a least squares solution is applied in order to estimate the seven parameters. Therefore, the above transformation formula can be expressed as (Mitsakaki, 2004) (3.27):

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & X_b & 0 & -Z_b & Y_b \\ 0 & 1 & 0 & Y_b & Z_b & 0 & -X_b \\ 0 & 0 & 1 & Z_b & -Y_b & X_b & 0 \end{bmatrix}\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{3.27}$$

Where $a_1 = m + 1$, $a_2 = a_1\omega_X$, $a_3 = a_1\omega_Y$, $a_4 = a_1\omega_Z$.

3.2.3.3 Basic Cost Estimation Theory for Fabric Maintenance

For the corrective (unplanned) maintenance (CM) of the building fabric components, the accuracy of cost estimation depends on the available information including the condition of execution, the mode of execution, the costs of building materials and the labor costs (Lee and Phil, 1987). The costs of building materials account for the most percentage of the total maintenance cost. The common method to estimate the costs of building materials is to multiply the take-off quantity of the material by the corresponding unit rate. Such property information is available in 5D BIM, which integrates take-off quantity information from the 3D design model with the unit prices from the online database. This method provides a rational amount for the estimation of each building fabric component (Lee and Phil, 1987). Therefore, the replacement cost of the fabric corrective maintenance can be calculated by using the equation as below (3.28):

$$\text{Take-off quantity} \times \text{Unit rate} + \text{Labor cost} = \text{Corrective replacement cost} \quad (3.28)$$

Where the costs of execution are assumed to be zero. However, the unit rate is a fluctuating value and the take-off quantity information from the BIM is only the data of the design model, but not the data of the real building components. That is why the reality capture from the laser scanning is necessary for a more accurate and reliable cost estimation. It should be noticed that the ratio of PM cost to CM cost is a key factor that can affect the total maintenance cost, which is the sum of PM cost and CM cost. A relevant study indicates that a reasonable ratio of PM cost to CM cost is between 0.1 (where the total maintenance cost is highest) and 0.4 (where the total maintenance cost is the lowest) (Stenström et al., 2015). Another study also shows that an average ratio of PM to CM for electrical and mechanical systems is around 0.35 (Fajardo and Ortiz, 2011). As the PM cost for fabric components is lower than that for MEP systems due to the complexity of the latter, an average value of 0.25 (average value of the lowest and the highest ratios) that is smaller than the average ratio of MEP maintenance by 0.1 is assumed to be the ratio of PM cost to CM cost for building fabric maintenance (Stenström et al., 2015). Thus, the PM cost for each curtain wall is (3.29):

$$0.25 \times \text{Corrective maintenance cost} = \text{Preventive maintenance cost} \quad (3.29)$$

In addition, the inspection cost (IC) usually accounts for 80% of the PM cost (Stenström et al., 2015). So for the inspection of each curtain wall, the cost equals to (3.30):

$$0.8 \times \text{Preventive maintenance cost} = \text{inspection cost} \quad (3.30)$$

Therefore, CM cost, PM cost and inspection cost can be determined by using the equations mentioned above.

3.2.3.4 Weibull Distribution

In this study, the cost planning information of the building fabric components is the core that needs to be estimated and generated through an effective and reliable method. Therefore, a classic estimation method named Weibull Distribution, which can provide a continuous distribution analysis for reliability calculations of preventive maintenance, is adopted to achieve this purpose (Weibull, 1951). As Weibull Distribution is widely utilized for modeling, analysis and problem solving with very little complex mathematical theory, it enables simplified parametric analysis for such a maintenance purpose and reliable prediction of cost related to maintenance quality (Dodson, 1994b, Saraneva, 2014). In addition to being the most popular and reliable analysis function used with small sample sizes and flexibility, Weibull Distribution can generate information needed for scheduling preventive and corrective maintenance (Dodson, 1994b).

In this study, Weibull Distribution analysis was conducted by using spreadsheet and computer calculation based on the equations, which are usually adopted for the reliability calculation of MEP system maintenance planning. The Weibull probability density function can be varied under different situations depending on the value of shape parameter that decides the shape of the distribution (Dodson, 1994b). Through simulations, it is able to determine which distribution is appropriate for the analysis of fabric maintenance. It indicates that the preventive maintenance cost is lower than the corrective maintenance cost. Because the former is to replace the element before it fails and the latter is to replace the element after it fails. Therefore, it is essential to determine the optimum preventive maintenance interval for improving the performance of maintenance work. In addition, the preventive maintenance interval can highly influence the cost per unit time, which is a key indicator for the cost planning of fabric maintenance. The unit time can be one day, one week or one month based on the cost performance in practice. The formula used for calculating the reliability of the building fabric component and the preventive maintenance time is shown as following (Dodson and Kirkland, 1994) (3.31 and 3.32):

$$R(t) = \int_{t}^{\infty} f(t)dt \tag{3.31}$$

$$1 - R(t) = \int_{0}^{t} f(t)dt \tag{3.32}$$

Where $R(t)$ is the reliability function, t is the usability time of the fabric component and $f(t)$ is the probability density function for the Weibull Distribution. Therefore, the formula related to the cost per unit time is as follows (Dodson and Kirkland, 1994, Chanter and Swallow, 2008) (3.33):

$$CPUT = \frac{c_p R(t) + c_f[1 - R(t)]}{TR(t) + \int_0^t tf(t)dt} \tag{3.33}$$

Where $CPUT$ is the cost per unit time, T is the time between preventive maintenance activities, c_p is the preventive maintenance cost and c_f is the corrective maintenance cost. Furthermore, a three-parameter Weibull, which contains shape parameter, scale parameter and location parameter, can be used to determine the optimum preventive maintenance interval by formula as below (Dodson, 1994a) (3.34):

$$T = m\theta + \delta \tag{3.34}$$

Where m is a function of the ratio of the CM cost to the PM cost, which can be determined from a reference table by using the ratio and the shape parameter β (Dodson, 1994a), θ is the scale parameter of the Weibull Distribution and δ is the location parameter of the Weibull Distribution. Additionally, the expected time length for replacement cycle usually is determined by using the formula as below (Jardine and Tsang, 2013) (3.35):

$$\text{Expected replacement cycle length} = t \times R(t) + M(t) \times [1 - R(t)] \tag{3.35}$$

Where $M(t)$ is the mean time to failure after preventive maintenance occurs, which is also considered as an expected length of an element failure cycle, and it can be expressed as (Jardine and Tsang, 2013) (3.36):

$$M(t) = \frac{\int_{-\infty}^{t} tf(t)dt}{1 - R(t)} \tag{3.36}$$

The aim of calculating expected replacement cycle length is to help determine the replacement schedule for the maintenance plan. Usually the schedule is presented within a Gantt chart and 4D BIM can help link the schedule with the maintenance work.

3.3 Research Tools

3.3.1 Software

This research study involves three main knowledge sections: indoor positioning, 3D laser scanning and BIM technology. Relevant software and hardware for each knowledge section are prepared before the start of site experiments.

For the use of professional software in this study, Revit (3D modelling), Recap (conversion of point cloud to model) and Vico Office (5D BIM cost estimation) are the software for the BIM section. Revit is developed by Autodesk Inc. and it is one of the most widely used BIM modelling tool particularly in China's AEC market. Recap is also developed by Autodesk Inc. in order to convert registered point clouds to 3D mesh results that can be presented in Revit according to customized settings for visual optimization. Vico Office is developed by Trimble to implement 4D schedule management and 5D cost estimation for AEC projects in the design and construction phase.

For 3D laser scanning section, Cyclone, which is a middleware developed by Leica Geosystems AG, is used for the registration and processing of the scan data. CloudCompare provides a common platform for the purpose of point cloud comparison in this study. In addition, 2D scan results generated from the low-cost laser scanner need to be presented and monitored by using the SOPAS Engineering Tool, which is a bundled support software for the 2D laser scanner used in this study.

For indoor positioning section, there are professional bundled software for the data collection and monitoring of IMU and UWB system respectively. In addition, the MATLAB tool is also used in this study for the development of algorithmic solutions including IMU-based PDR positioning, UWB-based coordinate frame transformation, data extraction from the 2D laser scanner, data integration of IMU/UWB with the 2D scan and generations of 3D point clouds.

3.3.2 Hardware

For the hardware used in this study, the main equipment includes indoor positioning sensors, a GPS module, a low-cost 2D laser scanner and a high-performance 3D laser scanner. Other auxiliary equipment includes a laptop for sensor connection, a power bank and a mobile carrier like a trolley.

A low-cost Xsens strap-down IMU (shown in Fig.3.4) is selected for the INS/IMU investigation section in this study. Usually it is connected with a laptop, which could be held by pedestrian or mounted on a trolley, in order to monitor the real-time data collection by using the IMU-bundled software and meanwhile provide power supply. The frequency of the Xsens IMU is 100 Hz, which means one measurement reading is generated at each 0.01s. For the sensor errors of the Xsens IMU, the in-run bias of accelerometer and gyroscope are 0.02 m/s^2 and 20 degree/h respectively. The scale factor error of the accelerometer is 0.03 percent of the true output and the misalignment error of accelerometer and gyroscope is 0.1 degree.

Fig.3.4 Xsens strap-down IMU

The UWB system used for this study has been already installed before for other localization services. The system consists of a small portable UWB transmitter (Ubisense, as shown in Fig.3.5) and six fixed UWB receivers, which are mounted at certain heights under the indoor environment. The measurement range of the UWB system is larger than 20 meters and total cost of the entire UWB system is not expensive. A bundled software tool can monitor the performance of the UWB system and meanwhile record the measurements.

Fig.3.5 UWB transmitter (made by Ubisense)

In this study, a SICK 2D laser scanner is used and the type is an LMS5xx LiDAR sensor that uses 905nm infrared as the light source (shown in Fig.3.6) (SICKAG, 2015). Compared with high-performance 3D laser scanners, its cost is much lower and it has much lighter weight and smaller size. Of course, the expense of this 2D laser scanner is also much cheaper. In addition, it has an operating range from 0-80m with high resolution and an aperture angle of 190^o (view setting from -5^o to 185^o) (SICKAG, 2015). If the viewing window of the 2D laser scanner is kept up horizontally as shown in Fig.3.7, the scanning field is like what Fig.3.8 shows.

Fig.3.6 SICK 2D laser scanner

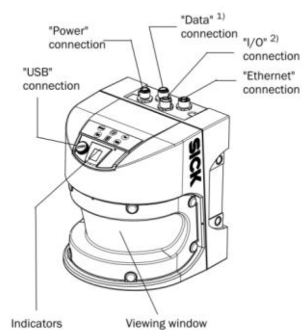

Fig.3.7 Instruction of laser scanner (from SICK AG)

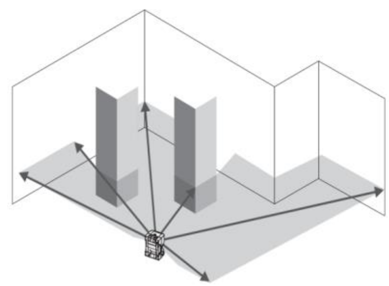

Fig.3.8 Scanning field in horizontal view (from SICK AG)

In addition, for the IMU-based indoor positioning and the integration of IMU/UWB with the 2D laser scanner, a GPS module is connected with the laptop in order to synchronize the setting time of the laptop with GPS time (shown in Fig.3.9). As IMU has its own measurement time record and the laser scanner uses laptop time, it is necessary to synchronize the IMU measurement time with laser scanning time by using the common GPS time. Furthermore, although the study focuses on the indoor application, the GPS time still could be retained continuously when we moved the module and laptop from outside into the indoor environment.

Fig.3.9 GPS module

For the TLS reference experiment, a high-performance Leica HDS7000 3D laser scanner (shown in Fig.3.10, which is the same as Fig.2.4), which is the most expensive and accurate equipment in the Department of Civil Engineering, is used for the comparison of scan results between TLS and the developed indoor MLS. It can provide a 360^o scanning field in horizontal view and a 320^o field in vertical view. Its maximum measurement range is 187m and the minimum is 0.3m (LeicaGeosystemsAG, 2012). The linearity error is controlled less than 1mm and the highest scan rate can reach over 1 million points per second. In addition, Leica has its own bundled software named Cyclone that is used to register and process the collected point sets from laser scanning. This makes the data processing more automatic and saves time. Currently, this terrestrial laser scanner is mainly used for two applications, which are related to 3D modelling of buildings. The first application is quality control of as-built constructions, and the other one is repair and restoration of existing or historical buildings.

Fig.3.10 Leica HDS7000 3D laser scanner

CHAPTER 4: Empirical Investigation and Site Experiment

4.1 Empirical Investigation

4.1.1 Investigation of BIM-Based Design Coordination for China's AEC Industry

To investigate the current situation of the design phase in China's AEC projects and potential impacts of BIM application on it, a questionnaire-based empirical survey was launched online following the steps of the empirical survey in order to collect and analyze relevant information from the people who are working for the AEC industry or have relevant professional backgrounds. Some industrial experts and executives were also invited for interviews to give professional insights on the BIM applications in the project design phase. In addition, the empirical investigation not only can establish BIM-based workflows for coordination in the project design phase, but also can make a contribution to cost savings in the O&M phase through applying BIM-based technical investments for O&M management into the early stage of design and construction. Such investments by maintenance in design can help conduct the design phase for maintainability procedures to minimize both the maintenance cost and the project lifecycle cost (Dell'Isola, 1991; Dessouky and Bayer, 2002).

Commented [CC24]: The link between the empirical investigation for project design and its potential contributions to the cost saving of maintenance.

As this investigation topic about design coordination is complex and refers to multiple factors, grounded theory is an appropriate choice to find out the connections among the factors based on collected empirical data (Glaser and Strauss, 1967). According to the method of grounded theory, the investigation was divided into the following steps (Strauss and Corbin, 1990):

Step 1: respondents' selection

The respondents are from China's local AEC industry associations, institutes and firms including different professions – architects, civil engineers, MEP engineers, contractors, consultants, owners, etc. They all have a basic understanding of BIM and over half of them have a certain level of proficiency in BIM software application.

Step 2：group division and open coding

All respondents were divided into two groups, one group was for interview purpose, and the other was for questionnaire survey. The contents of questionnaire and interview were established based on relevant activities, insights and process stages of AEC project design phase. We labeled these relevant elements, which were called codes and this step was named “open coding” in this research methodology. It was the key step to extract important ideas or concepts.

Step 3：interview and questionnaire survey

10 experts and executives from Chinese top AEC firms and industrial institutions were invited for our interview. Due to their different backgrounds, a table based on the connections between interviewees and background factors was established as shown in Table.4.1.

Step 4：theoretical coding

Based on the results collected from the interview and questionnaire, we discovered some connections between different project stakeholders (owner, designer, consultant and contractor). The connections were related to each stakeholder’s activities and processes, which are called codes in our research methodology (Liu et al., 2016).

Step 5：theoretical saturation

When the discovered connections and codes are adequate to support the establishment of a conceptual framework, it means a theoretical saturation in the analysis process. If not, then more interviews and surveys are required to discover the coding elements.

Table.4.1. Interviewees and Their Backgrounds

Background Factors	No.	Interviewee	Backgrounds
Project manager	1	A	2,3,5,6,7
Engineer	2	B	2,5,6
Local government consultant	3	C	1,2,5,6
University professor	4	D	1,2,5
Company general manager	5	E	1,2,3,5,6,7
Several institute memberships	6	F	1,4
Regional president/chairman of international institute	7	G	3,6,8
Chairman of Chinese industrial institute	8	H	1,5,6
		I	1,5,6
		J	7

4.1.2 Investigation of BIM-Based Workflows for China's AEC Project Lifecycle

Combining the empirical results from the online survey and interview for BIM-based coordination with the BIM guides compiled by China State Construction Engineering Corporation (CSCEC, 2017), it was possible for us to investigate the BIM application in the general workflow of AEC project lifecycle from planning to O&M and the sub-workflows of the design phase.

During this investigation process, a traditional CAD-based workflow for China's AEC project lifecycle (shown in Fig.4.1) was used to provide a theoretical basis for a comparative study with the later developed BIM-based workflow. The traditional CAD-based workflow includes each phase of an AEC project lifecycle including planning, design, construction, commissioning and O&M. This workflow is established according to the empirical study of BIM-based design coordination and relevant literature reviews (Eastman et al., 2011, Ding et al., 2014, Chen et al., 2017). All the information transfer, data storage and documentation delivery are implemented by using 2D CAD drawings and papers. This outdated mode can lead to the risks of information loss or communication failure, which would affect the progress of project and result in wastes of time, expense and resources. Furthermore, according to the research conducted by Talib et al. in 2014, lack of communications among stakeholders (owners, contractors and users), loss of information in understanding maintenance work and low-performance management methods during the inefficient design and construction workflows can also highly affect the later building maintenance in the O&M phase. The applications of BIM suggest a potential solution to address the issues of workflow improvements throughout the project lifecycle.

Commented [CC25]: The knowledge link between the design and construction workflows with O&M phase.

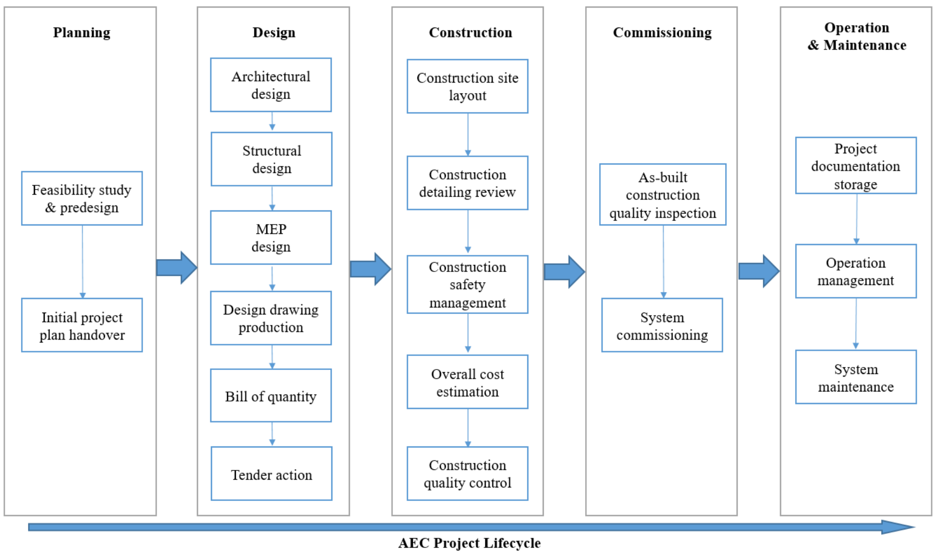

Fig.4.1 Traditional CAD-based workflow for China's AEC project lifecycle

4.1.3 Investigation of Impact Factor Resulting in Uncertainties of Construction Process

This investigation aims to find out the impact factors that can lead to uncertainties and variances on the schedule and cost plan of the construction process in China's AEC projects. It consists of two main parts: the first part is about the investigation and analysis of the potential impact factors resulting in uncertainties and variances during the construction process. The results from this investigation can also make a significant contribution to the study of maintenance cost planning. Because it has been mentioned before some factors that result in uncertainties to affect the maintenance cost planning also have high impacts on the construction process. These common impact factors concerned during both construction and O&M phase include weather, climate, site environment, labor, equipment, material and budget (Ajayi, 2014; Ofori et al., 2015; Talib et al., 2014). This investigation will subdivide these factors into more specific sub-factors to determine their impacts on schedule and cost of construction process. The results from this investigation could be important references to the further studies about factors influencing building maintenance in the O&M phase.

Commented [CC26]: The knowledge link between the impact factor investigation in construction process and the factors influencing building maintenance in the O&M phase.

The research methods used in this part include online survey, Likert Scale and quantitative statistical method for raw data processing to rank the impacts of the potential factors in construction process, a similar survey-based study was also conducted to rank the critical factors influencing the maintenance phase by using Likert Scale and quantitative statistical methods (Homthong and Moungnoi, 2016), therefore a knowledge link can be established between construction and O&M phases on the investigation of impact factors; the second part refers to the development of a forecast system based on the empirical investigation result and BIM simulation. This was implemented through relevant BIM professional software a secondary development of a professional BIM software. Furthermore, two typical case studies in China were also used to validate the feasibility and reliability of the forecast system in practices.

Commented [CC27]: Reference for supporting the link between construction and O&M phases on the investigation of impact factors.

To improve the productivity of the construction phase, it is necessary to conduct an empirical investigation of potential impact factors, which can increase uncertainties and result in variances between the real construction process and the plan of the project. The accumulation of these variances will result in variations on schedule and cost of the construction plan, and eventually affect the whole construction process management and its productivity (DeMarco et al., 2009). People who are responsible for the production of construction phase must meet their contractual obligations to take effective control of construction process, in order to complete the project successfully (Ballard, 2000). To achieve such an aim, a robust forecast system prototype based on the empirical study is presented in the second part to support scientific and effective predictions of uncertainties, which are caused by those impact factors and evaluating variances they will result in to the real construction process compared with plan. All the key findings and results then are used to establish a forecast system prototype, which can help enhance the production control of traditional construction phase. This forecast system is secondarily developed based on the Vico Office, which is a 5D BIM software strong in construction process simulation and cost estimation. Before selecting the Vico Office as the BIM tool for this investigation, it was tested by using some case studies in China to justify whether it was appropriate for the aim of this investigation and a positive answer was obtained eventually. Other BIM software were also tested before making this decision and a contrast among them is shown in Table.4.2.

Table.4.2. BIM Software Comparison

Software / Criteria	Revit + Microsoft Project	Synchro	Glodon BIM5D	Vico Office
3D modelling	Yes	Yes	Yes	Yes
Take-off quantity	Yes	No	Yes	Yes
Task Schedule	Yes	Yes	Yes	Yes
Resource allocation	No	Yes	Yes	Yes
4D simulation	No	Yes	Yes	Yes
Risk analysis	No	Yes	No	Yes
Quantity cost estimation	Yes	No	Yes	Yes
Overall cost estimation	Rough estimation	Rough estimation	Yes	Yes

(Yes: the software has this function; No: the software has no this function)

From Table.4.2, it can be seen that only Vico Office meets all the requirements of 5D BIM implementation. Therefore, it is proposed to provide technical references and visualization for construction process in this study.

Vico Office has its own data simulation modules to implement schedule management and cost estimation. Through the proficient operation tests, several characteristics of this software in schedule simulation and cost planning have been summarized as following:

1. There are three setting indicators – production factor, crew and consumption, which can be manually adjusted based on the empirical knowledge of planners to vary the schedule of construction process;

2. Crew can be conceived as the labor resource, when the crew is constant, which means the amount of labor resource is constant, the productivity will decline with the increase of consumption rate (= resource/production unit), the duration will become longer, vice versa;

3. If the consumption rate is constant, the production factor will become larger with the increase of crew, the productivity also will be improved, and the duration will be shortened, vice versa;

4. If the take-off quantity of the construction process is constant, with the increase of crew, the productivity also will be improved, and the duration will be shortened, vice versa;

5. Schedule buffers are available for the workflow variations of construction process. The buffers can be conceived as inserted certain time intervals between scheduled assignments, they also represent extra time added to the whole project duration (Ballard and Howell, 1994);

6. The cost of each assignment contains the take-off quantity cost, labor cost, overhead cost and social security expense.

Moreover, literature reviews on construction productivity control were also combined with the Vico Office simulation and estimation scenario to provide theoretical proofs for the classification of impact factors that could affect the construction process. Such a category-based analysis method has been adopted in a similar study for investigating impact factors on safety performance (Mohammadi et al., 2018). In this investigation, potential impact factors were extracted from empirical experience of real construction process management and relevant studies, then they were categorized into four groups: site environment, production factor, crew and consumption (Abdul et al., 2005, Iyer and Jha, 2005). Each group has sub-factors linked with the main factor and they are all shown in Table.4.3 (Koehn and Brown, 1985, Hassanein and Melin, 1997, Damodara, 1999, Thomas et al., 1999, Makulsawatudom and Sinthawanarong, 2004).

Table.4.3. Potential Impact Factors of Construction Process

Factor Group	**Sub-factor**	**Reference**
Site environment	Climate and weather	Koehn and Brown, 1985.
	Site access	Intergraph Corporation, 2012.
	Onsite safety inspection	Hanna and Heale, 1994.
	Natural disaster	Koehn and Brown, 1985.
Production factor	Construction rework	Kuykendall, 2007.
	Supervision	Kuykendall, 2007.
	Production efficiency of equipment	Hanna and Heale, 1994.
	Complexity of technique	Hanna and Heale, 1994.
	Clash and interference	Hanna and Heale, 1994.
	Consistency of instruction	Hanna and Heale, 1994.
	Delivery efficiency of last step	Hwang et al., 2013
Crew	Labor experience	Thomas and Sakarcan, 1994.
	Absenteeism	Thomas et al., 1999.
	Labor mobility	Thomas and Sakarcan, 1994.
	Fatigue	Intergraph Corporation, 2012.
	Age	Thomas and Sakarcan, 1994.
	Morale and attitude	Intergraph Corporation, 2012.
	Communication	Hassanein and Melin, 1997.

	Weekend and holiday	Kuykendall, 2007.
	Crew building	Hassanein and Melin, 1997.
	Crew size	Hassanein and Melin, 1997.
	Reassignment of manpower	Hassanein and Melin, 1997.
Consumption	Tool and equipment shortage	Makulsawatudom and Sinthawanarong, 2004.
	Material supply	Damodara, 1999.
	Logistics	Hwang et al., 2013
	Distance between site and supply source	Intergraph Corporation, 2012.
	Quality of material	Damodara, 1999.
	Allocation of resource	Damodara, 1999.
	Water and electricity supply	Intergraph Corporation, 2012.
	Price fluctuation of material	Damodara, 1999.
	Payment efficiency	Iyer and Jha, 2005.

It is found that some of the sub-factors mentioned above also have impacts on the maintenance management in the O&M phase. Here some critical factors which can highly influence the maintenance management are listed as follows (Ajayi, 2014; Homthong and Moungnoi, 2016; Ofori et al., 2015; Talib et al., 2014):

1) Lack of experienced maintenance crew;
2) Lack of communication and coordination among contractors, owners and users;
3) Lack of equipment for maintenance work;
4) Material quality and supply used for maintenance work;
5) Weather and climate;
6) Complexity of site environment;
7) Budget limitations caused by financial efficiency and prices of materials;

Factor 1) can be linked with the sub-factor of "Labor experience" in Crew; Factor 2) can be linked with the "Communication" in Crew; Factor 3) can be linked with "Tool and equipment shortage" in Consumption; Factor 4) can be linked with "Quality of material" and "Material supply" shown in "Consumption"; "Weather", "Climate" and "Site access" in Site environment can be linked with Factor 5) and 6) respectively; "Price fluctuation of material" and "Payment efficiency" can be linked with the budget limitations indicated in Factor 7). Therefore, the investigation of the impact factors affecting construction process can make a valuable contribution to relevant investigations of critical factors influencing particularly the deferred maintenance of building fabric components during the O&M phase.

Commented [CC28]: Link the impact factors of the construction process with the critical factors in the O&M phase.

To collect information from the global and China's AEC organizations about their opinions on the potential impact factors mentioned above, an online questionnaire survey is an appropriate manner. For this investigation, a self-designed questionnaire survey was launched to collect raw data on a famous survey website in China, which uses a screening system to select and encourage people who are working in this domain or have related professional backgrounds to participate in the survey, so the collected data could be more authentic and persuasive (Harris et al., 1996).

4.2 Site Experiment

4.2.1 Description of a Case Study in China

The case study is a four-floor teaching building located in the campus of University of Nottingham, Ningbo, China (UNNC). This building is mainly used for teaching, training and laboratory activities of science and engineering. Therefore, it has superiorities in conditions of equipment and site for the experiments of this study. The northern entrance (shown in Fig.4.2), atrium (shown in Fig.4.3) and a computer room (shown in Fig.4.4) in the building were selected as the indoor sites for IMU/GPS, UWB and mobile laser scanning experiments respectively.

There are four main reasons why this building is selected and justified as a typical case for this study. The first reason is the three selected sites in the building have low occupancy rates in the daytime and their indoor backgrounds are generally stable without being cluttered. Therefore, such experimental sites can provide the most real conditions to help improve the reliability of experimental results and meanwhile minimize the interference caused by cluttered backgrounds. Particularly in the atrium of the building, there are less obstructions, which means the effects of the NLOS condition can be significantly reduced in order to improve the accuracy of the UWB measurements. The second reason is the UWB receivers have been installed in the atrium of the building for other positioning experiments before this study, so there is no need to spend time on the preparation work for the UWB system installation and the layout of the UWB receivers also has been optimized in advance. It is quite significant to this study as time saving is also an important characteristic of the developed mobile laser scanning method. The third reason is that the building has been built for nearly six years, it is still in a normal operation but the aging and deterioration issues of the building fabric components have occurred. Therefore, it provides an opportunity to conduct such a study on the building fabric maintenance. The last reason is all the architectural and structural CAD drawings of this building are retained so that it is possible to create the BIM model for the building.

Commented [CC29]: More explanations for choosing the atrium of the target building as the experimental site in this study.

Fig.4.2 The atrium (left) into the northern entrance (right) of the teaching building as an indoor experimental site

Fig.4.3 The indoor atrium of the teaching building

Fig.4.4 The computer room in the teaching building

4.2.2 IMU/GPS-Based Indoor Positioning

Before the IMU was integrated with other sensor systems, it is essential to validate the accuracy and reliability of the IMU-based PDR positioning under the indoor environment. Therefore, an indoor tracking experiment based on IMU/GPS was conducted from the atrium into the entrance. The GPS module was used to synchronize the measurement time record of the IMU with GPS time for real-time positioning through the laptop time setting.

In this experiment, the Xsens strap-down IMU sensor was strapped to the tester’s body as shown in Fig.4.5. Before the start of the experiment, a walking trajectory plan for the tester’s motion was roughly designed in red color with start and end arrows based on the ground floor layout of the building as shown in Fig.4.6. The tester would start to walk towards the northeast orientation, then take a lap around and walk back to the initial start point in the end.

Fig.4.5 An IMU strapped to the tester’s body

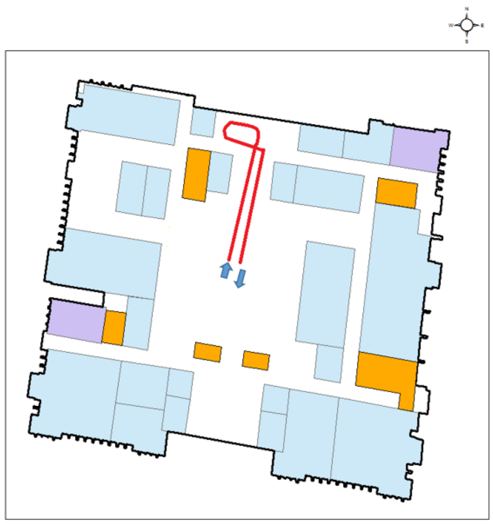

Fig.4.6 Walking trajectory plan based on the floor layout

4.2.3 IMU/GPS-Based Indoor Mobile Laser Scanning

This experiment aims to implement the integration of 2D scan images with a trajectory acquired from IMU/GPS positioning system for 3D mapping. Different from the horizontal posture of the 2D laser scanner, the viewing window of the laser scanner should be kept vertically as shown in Fig.4.7 in this experiment so that 2D scan images are presented in X and Z (or Y and Z) axes and the motion trajectory of the laser scanner is shown in Y (or X) axis. Only through this way, a 3D scan data can be generated from the integration of the 2D scan and the trajectory.

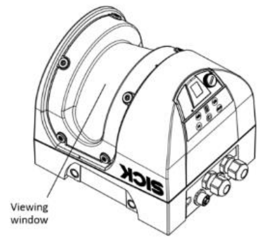

Fig.4.7 Scan setting in vertical orientation

In this experiment, the IMU/GPS positioning system was proposed to determine the motion trajectory of the 2D laser scanner (Stephen et al., 2006). This system consists of a strap-down IMU and a GPS module. However, GPS is not available for indoor positioning due to the signals will be obstructed by building fabrics such as walls and ceilings. Therefore, IMU was adopted in this research to predict reliable motion trajectory information and fill the vacancy of GPS signal outages (Klein and Filin, 2011).

This experiment was conducted in the computer room where the obstructions like computer desks and cabinets are stationary. The laser scanner and IMU were mounted on a trolley, which is regarded as a low-cost mobile platform (shown in Fig.4.8). The trolley was driven in an approximate linear motion from north to south and east to west. Then both the 2D laser scanner and the strap-down IMU were connected with a laptop by wires. The laptop was used to observe the scan profile and the IMU measurements. In addition, a GPS module was also connected with the laptop in order to synchronize the setting time of laptop with GPS time. As IMU has its own measurement time record and the laser scanner uses laptop time, it is necessary to synchronize the IMU measurement time with laser scanning time by using the common GPS time. Although the experimental site was indoor, the GPS time was maintained continuously when we moved the module and laptop from outdoors into the room.

Fig.4.8 Laser scanner and IMU mounted on a trolley

During the experiment, the scan was first implemented from the northern side of the room to the southern side by trying to keep the trolley in an approximate linear motion. Then this was again from the eastern side to the western side. Meanwhile, the relative positions of the 2D laser scanner and the IMU were maintained in order to eliminate the errors caused by relative displacement. This can be realized by fixing the centers of both devices on a vertical shaft. As the vertical elevation difference between the viewing window and the ground was 0.7m, the scan results would only show the profile images above this elevation.

4.2.4 UWB-Based Indoor Positioning

The low-cost IMU/GPS-based method for indoor positioning still has some limitations on its performance and the experimental result indicates that the only IMU-based method cannot provide enough confidence to realize a successful implementation of indoor positioning. Therefore, it is proposed that other indoor localization techniques can be integrated with IMU to improve accuracy and reliability of positioning. Considering the cost and the complexity of preparation work, an existing UWB system was adopted to conduct an experiment in the atrium (where the UWB receivers are installed) to investigate the improvements of the accuracy and reliability it could bring for current IMU-based indoor positioning.

The UWB system used in this experiment consists of a number of stationary receivers and a mobile transmitter. TOA measurements were used to determine the precise position of the transmitter. Usually the time at which the signal is received from the transmitter is unknown due to the transmitter clock is not accurate enough to give a precise time of transmission. Therefore, it makes the TOA measurements very similar to the GPS pseudo-ranged measurements (Misra and Enge, 2006). TOA can provide the information about the distance between the transmitter and the receivers due to the positions of the receivers are known. Therefore, the position of the transmitter is on a circle of determined radius. The prerequisite of TOA algorithm is the time synchronization between the transmitter and the receivers. So the equation of TOA measurements can be modeled as below (Hol et al., 2009) (4.1):

$$y_{u,i} = \tau + ||r_i - t||_2 + \Delta\tau_i + \delta_{u,i} + e_{u,i} \tag{4.1}$$

Where $y_{u,i}$ represents the TOA measurement of the i-th receiver, τ is the time of transmission, t is the position of the transmitter, r_i is the position of the i-th receiver and $\Delta\tau_i$ is the clock-offset of the i-th receiver, $\delta_{u,i}$ is a non-zero delay caused by NLOS or multipath interference and $e_{u,i}$ is a Gaussian noise (Hol et al., 2009). The process of using the TOA measurements to determine the position of the transmitter is an in-depth study topic named multi-iteration, for which lots of algorithms are developed without delays caused by NLOS and multipath. However, it is required to make the time synchronization between the transmitter and the receivers by using the TOA approach.

Here a more appropriate approach for UWB calibration in this experiment was to construct TDOA measurements based on pairs of TOA measurements. In this TOA-based approach, there is no need to synchronize the transmitter and the receivers. Because when the receivers are synchronized, even there is a clock-offset between the transmitter and the receiver, this offset is equal for all TOA measurements, which also means there is no need to calculate the time of transmission (Yavari, 2015). Therefore, the TDOA-based clock-offset difference can be estimated by (4.2):

$$\tau_{TDOA} = \Delta\tau_i - \Delta\tau_1 \tag{4.2}$$

As the clock-offset difference $(\Delta\tau_i - \Delta\tau_1)$ is directly obtained from TDOA measurements, the equation of TDOA measurements can be defined as (Hol et al., 2009) (4.3):

$$\begin{aligned} z_{u,i} &= y_{u,i} - y_{u,1} \\ &= ||r_i - t||_2 - \left||r_1 - t|\right|_2 + \Delta\tau_i - \Delta\tau_1 + e_{u,i} - e_{u,1} \end{aligned} \tag{4.3}$$

Where $z_{u,i}$ is the noisy result from the difference between the TOA measurements of the first receiver and the i-th receiver. However, a drawback of the TDOA measurements is that they are no longer independently distributed. So an alternative approach is to treat the τ as an unknown value to solve the problems of position and time. A calculation form of nonlinear least squares then is used to efficiently estimate the maximum likelihood of the transmitter position (Hol et al., 2009).

In this experiment of UWB-based indoor positioning, the transmitter was steadily mounted on a trolley to ensure a stable value of the UWB's elevation in the global coordinate frame. The trolley (or the UWB) was driven approximately to a linear motion from east to west in the atrium and meanwhile the signals from the transmitter were monitored by bundled software. After the experiment, the raw data were converted from xcm. files to csv. files by Python-based transformation method for more convenient data processing.

4.2.5 IMU/UWB Integrated Indoor Mobile Laser Scanning

There are some researches about integrating the positioning technology with laser scanning or other 3D imaging technology for mapping application. Thomson et al. presented an IMU-assisted indoor mobile mapping system to support SLAM for indoor modelling (Thomson et al., 2013). Klein and Filin (2011) proposed a LiDAR and INS fusion system for mobile laser scanning applications in periods of GPS signal outages. Tappero et al. (2009) introduced an indoor UWB and laser scanner system for decimeter-level positioning. RIEGL also presented an outdoor mobile laser scanning approach, which integrated an IMU/GPS system and a digital camera with a 2D laser scanner on a mobile platform (RIEGL, 2007). Durrant-Whyte et al. (2006) introduced a robotic SLAM system to implement consistent mapping in an unknown environment.

The previous experiments have validated that the integration of the UWB system and the strap-down IMU is an appropriate method to estimate and measure the motion trajectory of the object under the indoor environment. For indoor mapping application, a 3D result is required, so that the measured motion trajectory needs to be integrated with 2D scan profiles to generate a 3D point cloud. Compared with traditional TLS, this integrated mobile laser scanning method has advantages such as lower cost, higher portability and time saving.

For the integration of data from IMU and UWB, it is common to use a loosely coupled system model. The reason is that the IMU and UWB are heterogeneous sensor systems and both have their own coordinate frame respectively so that the measurements from both systems need to be pre-processed before the estimation of combined position trajectory. The loosely coupling means the measurements from one or more individual sensors are pre-processed before they are combined to determine the final result (Youssef et al., 2011). Fig.4.9 shows a loosely coupled idea for the data integration of IMU and UWB sensors, which provides an idea to improve the performance of indoor positioning for further studies in the future.

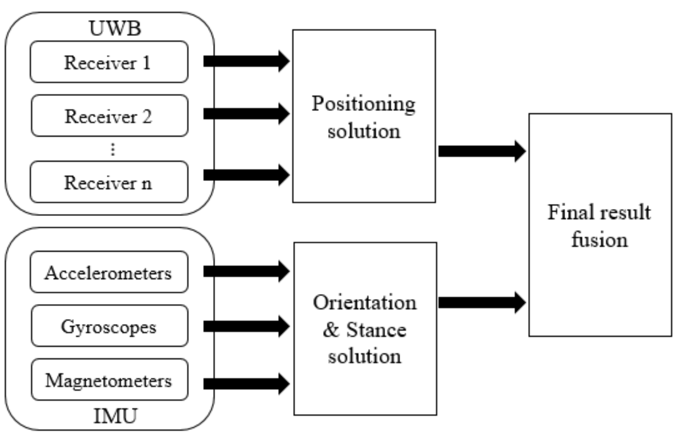

Fig.4.9 Loosely coupled system model of IMU and UWB

There are two algorithmic solutions developed based on the MATLAB tool for the purpose of data integration. The first one is to find out the time point at which the absolute value of time difference between the IMU and the laser scanner is the minimum. The purpose of this step is to minimize the errors caused by time synchronization between the IMU and the laser scanner. Then the relevant equations of three rotation matrices (for roll, pitch and yaw) as shown below (4.4, 4.5, 4.6 and 4.7), are multiplied to convert the measured position difference between the UWB transmitter and the laser scanner from the local coordinate frame to the global coordinate frame (Reit, 2013).

$$R_1(Roll) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(Roll) & \sin(Roll) \\ 0 & -\sin(Roll) & \cos(Roll) \end{bmatrix} \tag{4.4}$$

$$R_2(Pitch) = \begin{bmatrix} \cos(Pitch) & 0 & -\sin(Pitch) \\ 0 & 1 & 0 \\ \sin(Pitch) & 0 & \cos(Pitch) \end{bmatrix} \tag{4.5}$$

$$R_3(Yaw) = \begin{bmatrix} \cos(Yaw) & \sin(Yaw) & 0 \\ -\sin(Yaw) & \cos(Yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.6}$$

$$R_{bg} = R_1(Roll)R_2(Pitch)R_3(Yaw) \tag{4.7}$$

Where R_{bg} is the general rotation matrix. When the local position differences (including the differences in north, east and height) between the UWB transmitter and the laser scanner are measured, we can use the general rotation matrix to transform the local differences (d_l) into global position differences (d_g) by using the formula below (4.8):

$$d_g = R_{bg} \times d_l \tag{4.8}$$

After the UWB-based position coordinates are measured, combining the results with the transformed position differences mentioned above, we can obtain the new coordinates of the measurements from the SICK laser scanner by using own developed MATLAB-based algorithms, which refers to the following formula (4.9, 4.10 and 4.11):

$$\text{NewEast} = \text{EastUWB} + d_g(East) \tag{4.9}$$

$$\text{NewNorth} = \text{NorthUWB} + d_g(North) \tag{4.10}$$

$$\text{NewHeight} = \text{HeightUWB} + d_g(Height) \tag{4.11}$$

The second one is to do an estimation based on an assumption of a linear motion trajectory of the laser scanner. For our UWB system, it can generate 10-point data per second. So when the UWB measurements along x-axis or y-axis have a variance, it is possible to determine how long time it takes for the corresponding position variance. Due to the motion of mobile platform is close to a linear motion with a velocity that could be assumed as a constant, it is possible for us to calculate the velocity of the platform according to the linear position variance and the time. When the velocity is determined, it is available to calculate the distance between each two UWB data points as the time interval of UWB data has been known.

Furthermore, when the coordinate of x-axis or y-axis of the UWB measurement suddenly has a significant change, which means the trolley where the transmitter is mounted starts to move. Therefore, the time point at the start of the motion can be found out and the corresponding scan result after that time point is the mobile scan result, which can be accumulated for the integration with motion trajectory to generate a 3D point cloud.

In this experiment, the SICK 2D laser scanner was mounted on a trolley to improve the mobility and the portability of this method. However, limited to the real conditions of the mobile platform and the experimental site, the trolley was only driven from north to south in a linear motion approximately and the reality captures were only from the eastern facade, the western façade and the top roof of the indoor site. It is possible to divide the north-to-south motion distance into unit distance with the same time interval (according to the frequency of UWB) due to the assumption of a uniform motion speed. Therefore, it is possible for us to estimate each position of the laser scanner along the linear motion trajectory and then match the time point of each position to the 2D laser scanning view, which is generated at the same time point. Through this approach, a 3D point cloud finally would be presented on the screen.

Fig.4.10 shows the generation workflow of indoor mapping and digital modelling based on the novel mobile laser scanning method. The data processing for generating 3D point clouds is implemented by using two developed algorithmic solutions that are compliant with MATLAB-based programming. The 2D scan images are integrated with the motion trajectory according to the matching of measurement time nodes for three sensors. The 3D point clouds generated from two algorithmic solutions need to be compared with the reality, in order to pick out the one with better performance. Finally, an indoor mapping model based on the 3D point cloud will be built for further practical applications, such as indoor spatial management, virtual navigation services or discrepancy check between reality and design, etc.

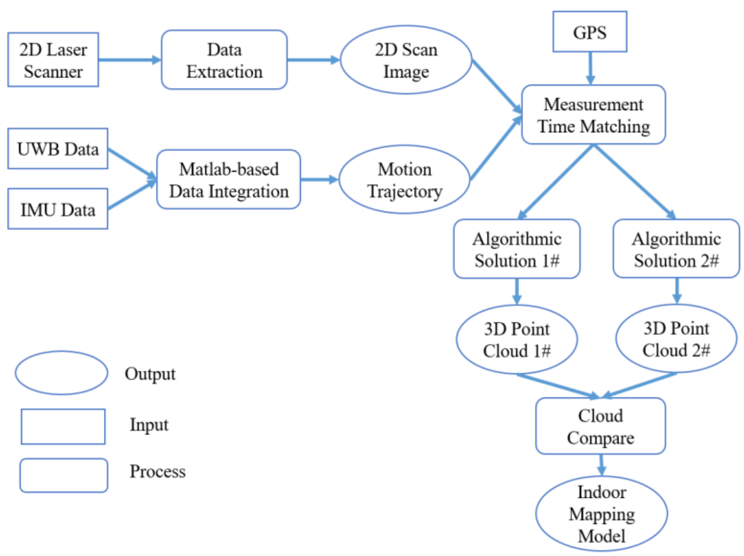

Fig.4.10 Generation workflow of indoor mapping and digital modelling

The experimental site is still the atrium of the teaching building due to it is the only site installed with a UWB system that consists of six receivers. As the UWB system was pre-installed in the atrium for other researches before, there is no need to do any setup work for the UWB system during this study. A UWB transmitter, an Xsens IMU and the SICK 2D laser scanner were all mounted on a trolley as shown in Fig.4.11. Their relative positions were determined before the experiment started and shown in Table.4.4.

Table.4.4. Relative Positioning of Three Sensors (Unit: Meter)

	UWB Transmitter	IMU	Laser Scanner
Height	0	-0.112	-0.372
North	0	0	-0.066
East	0	0.042	-0.13

Fig.4.11 Sensors mounted on a trolley

The offset between the center of the laser scanner and the ground was 0.67 m from the measurement. The laser scanner and IMU were connected with a laptop for power supply, data monitoring and collection. To achieve the time synchronization between the IMU and the laser scanner, a GPS module was connected with the laptop in order to set the common GPS time for both sensors.

Before the experiment started, the trolley was planned to move following an approximately linear trajectory with a uniform speed. The moving direction was from north to south following the centerline of the atrium. Therefore, the laser scanning will capture the real view of the eastern facade, the western facade and the curtain roof of the atrium as shown in Fig.4.12.

In addition, both the UWB system and the IMU were initiated at nearly the same time to reduce the error caused by time difference. When the experiment started, the motion of the trolley was kept in a planned linear trajectory with an assumed uniform speed. The overall experimental duration from preparation step to completion was within 15 minutes. The experiment was designed to drive the trolley from the north to the south and meanwhile scan the space between the western and the eastern façade in the atrium. During the motion process of the trolley, its trajectory was kept the motion trajectory as linear as possible in order to improve the ease of later data processing.

Fig.4.12 Western façade and eastern facade of the atrium

4.2.6 TLS-Based Reference Experiment

The purpose of this TLS-based reference experiment is to provide a comparison reference to assess the reliability of the results from the developed MLS method. This experiment was conducted under the same indoor environment where the experiment of the developed indoor MLS method was conducted before. To determine the position of the terrestrial laser scanner, the UWB system, which has been installed in the atrium before, is adopted to provide positioning information of the TLS scanner due to the conventional GPS signals are obstructed inside the building.

The terrestrial laser scanner used in this reference experiment is a HDS7000 3D laser scanner developed by Leica Geosystems AG. The maximum range and minimum range of this scanner are 187m and 0.3m respectively. It can provide a 360º horizontal scan when the prism of the scanner rotates around the Z-axis (change in yaw) and a 320º vertical scan when the prism rotates around the Y-axis (change in pitch). The maximum scan rate can reach more than one million points per second and its linearity error is controlled less than 1mm (LeicaGeosystemsAG, 2012). The generation workflow of indoor mapping model also has been updated by adding the steps of TLS-based reference experiment as shown in Fig.4.13.

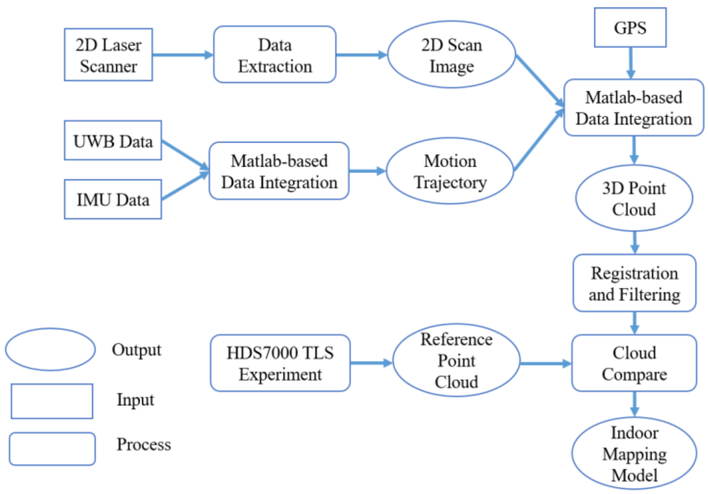

Fig.4.13 Workflow of point cloud modelling including TLS-based reference experiment

During the experiment, the scanner was mounted on a tripod and located in the center of the atrium (as shown in Fig.4.14). Due to the large range, the scan was able to cover the entire view of the field. In addition, to determine the position of the scanner, a UWB transmitter was mounted on the top of the scanner (as shown in Fig.4.15). Through the UWB signal transmission between the transmitter and the receivers by using antennas, the approximate position of the scanner was measured and recorded by using a bundled tool for UWB data processing. In addition, the relative position distances in 3D space between the center of the transmitter and the center of the scanner were also measured before the scanning to minimize the errors.

In this experiment, the scan resolution was set to high quality and the scan duration took nearly half an hour. After the experiment, the scan result of TLS, was extracted and registered to form a 3D point cloud model by using the Cyclone tool. Usually the point cloud contains the 3D coordinate (XYZ) information of each point and the corresponding intensity. Then the point cloud was used as the reference and compared with the result obtained from the developed MLS by using the CloudCompare tool to analyze the potential discrepancies between the scan results of both TLS and developed MLS.

Fig.4.14 HDS7000 scanner located in the atrium

Fig.4.15 UWB transmitter mounted on the top of HDS7000 scanner

CHAPTER 5: Result Processing and Analysis

5.1 Result Processing and Analysis of Empirical Survey

5.1.1 Development of BIM-Based Design Coordination for China's AEC Industry

After the survey, there were 283 valid questionnaire collected. The profession distribution of the survey participants is shown in Fig.5.1. The content of the questionnaire mainly focused on the participants' opinions in current situation, technical application, implementation barrier, potential benefit and future development of BIM in China. Although according to literature reviews, BIM is an emerging and promising technology to bring lots of potential benefits like 3D visualization, design optimization, clash detection, spatial analysis and multidisciplinary coordination for the project design phase (Eastman et al., 2011; Krygiel and Nies, 2008), it is still necessary to explore and understand how BIM improves the design coordination for China's AEC industry by empirical investigation. In addition, the BIM implementations in other developed countries and regions also meet economic, technical and normative barriers like high capital costs, lack of BIM talents, insufficient BIM standards, etc. (Both et al., 2012). Therefore, what barriers BIM development may encounter in China is another concerned question for which the survey participants may give their opinions.

Commented [CC30]: Barriers and advantages of BIM implementation.

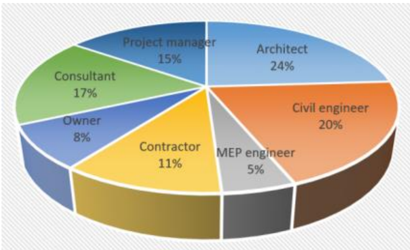

Fig.5.1 The profession distribution of survey participants

Combining the collected data with empirical evidence from relevant case studies (Eastman et al., 2011), we have analyzed the connections among nine paired codes to help establish the conceptual framework of BIM-based design coordination:

I. Deepening of drawings & Deepening of BIM model

Designers need to deepen the initial design drawings, construction drawings and other relevant documentations after the planning phase. Usually the drawings are in traditional 2D CAD format. Then based on the deepened drawings, consultants provide deepened BIM 3D models which are established by uniform BIM standards and software such as the Revit.

II. Deepening of BIM model & Multidisciplinary coordination

Based on the deepened BIM model, multiple disciplines including MEP, civil and architect work together to implement clash detection, network optimization, spatial analysis, etc. (Singh et al., 2011).

III. Multidisciplinary coordination & Approval comments

The deepened model and analysis results are delivered from the BIM consultants to the owners for comment approvals.

IV. Approval comments & Completion of design modification

When the comments are approved by the owners, designers start to complete the modification of all design drawings according to the comments from BIM-based inspections.

V. Completion of design modification & Completion of model modification

Based on the modified design drawings, BIM consultants are able to provide completed modifications of BIM model.

VI. Constructability analysis & Completion of model modification

It is crucial for contractors to check the modified design and do constructability analysis in 3D browsing.

VII. Completion of model modification & Aided design communication

After completing the BIM model modifications, consultants deliver relevant files to owners with who they have an aided model design communication.

VIII. Creation of modified model & Completion of model modification

According to the completed modifications, consultants create a deepened and modified model for the project, and meanwhile assist the output of deepened design drawings.

IX. Submission of deepened professional design & Creation of modified model

Construction contractors need to submit the deepened design drawings of each profession such as curtain wall drawings, which are also important files to the creation of final design model.

By using the analysis results from the investigation and referring to relevant empirical case studies from other BIM developed countries (Eastman et al., 2011), a conceptual framework of BIM-based design coordination system for China' AEC industry is developed and shown in Fig.5.2.

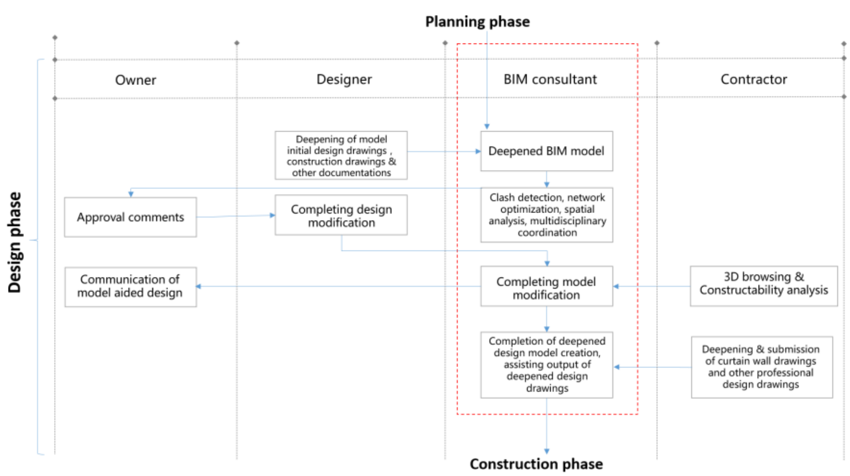

Fig.5.2 A conceptual framework of BIM-based design coordination system

It can be seen from the figure that BIM plays an important role during the whole design phase. The BIM-based coordination is reflected not only in technological advance, but also in workflow innovation (Krygiel and Nies, 2008). Compared with traditional design phase, this new design coordination system is able to enhance the communication and collaboration among different stakeholders. Meanwhile it can realize the consistency of project information delivery and synchronization of updating, which are key factors to improve the overall efficiency of the design phase (Isikdag and Underwood, 2010).

However, it still needs more local practical case studies to verify the application validity of this system in China's AEC industry. In addition, due to the research was set up based on empirical evidence and theoretical knowledge, more detailed data measurements and analysis methods should be adopted to improve the reliability of theoretical results (Laan et al., 2012). The survey participants also gave their concerns about the barriers of BIM implementation in China: firstly, compared with BIM developed countries, China's AEC industry is lack of BIM technicians and BIM project managers, therefore, it is not easy to accurately evaluate the BIM values that can make a significant contribution to this industry; secondly, current inefficient management patterns of the local AEC industry and existing technical barriers highly influence the applications and the development of BIM in China (Yan and Damian, 2008); furthermore, it is still uncertain what potential risks BIM may also bring for the project design phase, particularly for its current normative system (Both et al., 2012). Nevertheless, through the connections among different paired codes based on the method of grounded theory, a conceptual framework of BIM-based design coordination still has been established reduce the design errors and improve the coordination of multi-disciplines and multi-professionals in China's AEC industry (Chen et al., 2017).

Commented [CC31]: Potential barriers of BIM implementation in China.

5.1.2 Development of BIM-Based Workflows for China's AEC Project Lifecycle

Based on the traditional CAD-based workflow for China's AEC project lifecycle, BIM was applied into the workflow to make an innovation on it as shown in Fig.5.3 (Eastman et al., 2011, Bheda et al., 2017, Chen et al., 2017). The main difference between the traditional workflow and the BIM-based workflow is the mode of information delivery and storage. For BIM-based workflow, all important project information are stored in a digital model for 3D representation and relevant details can be extracted from a specific project database. The information delivery between two project phases or two disciplines is implemented by using digital model documentations. This BIM-based workflow mode can effectively solve the problems such as information loss or update delay. In addition, combined with BIM N-D concept, all information will be integrated, classified and then distributed to the stakeholders who need the information in different project phase (Eastman et al., 2011). This can help realize multi-disciplinary collaboration and real-time synchronization to improve the performance of project.

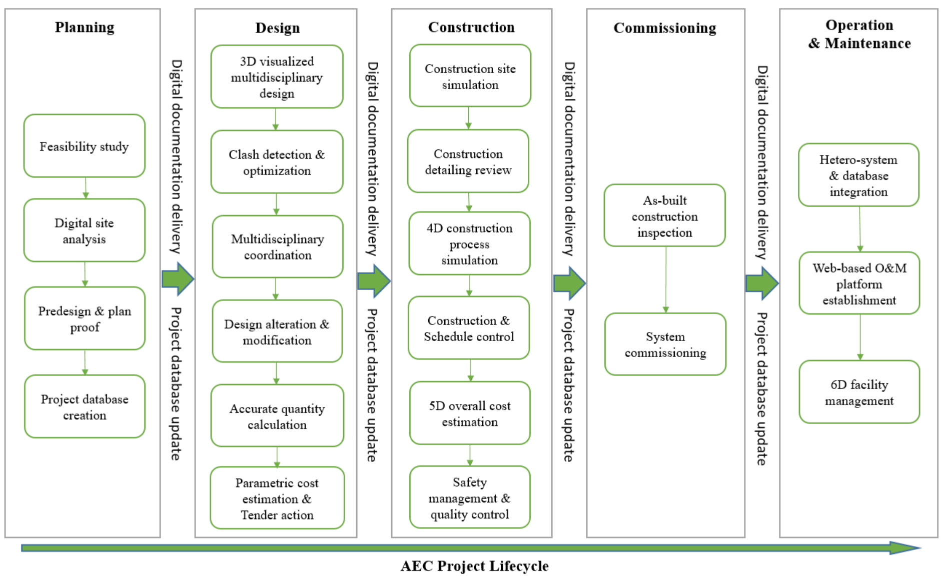

Fig.5.3 Innovative BIM-based workflow for China's AEC project lifecycle

Moreover, the BIM-based sub workflows for the design phase were also developed referring to the standard guides published by China State Construction Engineering Corporation Ltd. (CSCEC). As the design phase is the initial and the most variable stage in a project, it can be seen in Fig.5.4 that the created BIM model carries the information of initial architectural design plan, then is reviewed by architectural discipline (Chen et al., 2017). If the design model meets the requirements from stakeholders, then it will be further integrated with the information from other disciplines. Otherwise, it will be sent back for redesign. This step aims to check the collaborations among multi-disciplines. When the integrated BIM model, which combines the professional knowledge of multi-disciplines, successfully passes through multi-disciplinary reviews, it can produce architectural 2D drawings from the model. Then the drawings and the model will be stored into a specific project BIM database and delivered to the next phase.

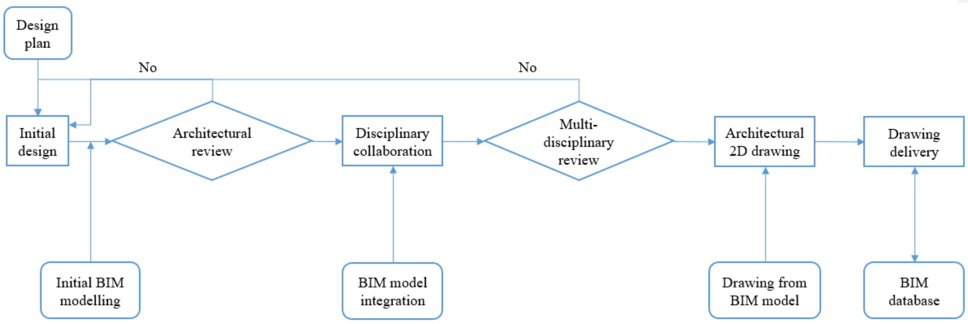

Fig.5.4 BIM-based workflow for project initial planning and architectural design

Fig.5.5 shows a workflow for the project general design knowledge integration of multi-disciplines including architecture, structure, MEP, etc. All the disciplinary designs can be implemented in Revit or other BIM design software (Eastman et al., 2011). Compared with the BIM-based architectural planning and design workflow, one more step named general analysis is added into the general design workflow. This step aims to analyze the potential design clashes among multi-disciplines and provide evidence for disciplinary review.

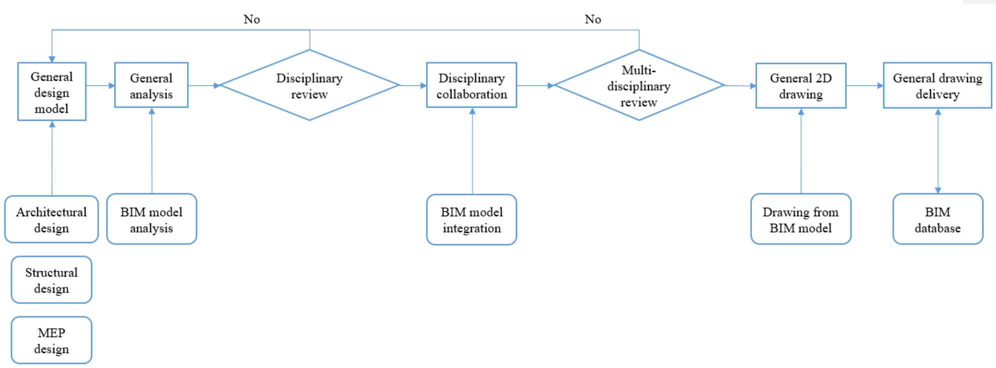

Fig.5.5 BIM-based workflow for project general design

Construction design drawings should be generated to ensure that the construction phase could successfully start. Fig.5.6 shows a BIM-based workflow for project construction drawing design. In disciplinary collaboration step, clash detection, which is a powerful function provided by BIM software such as Navisworks or BIMx, can highly reduce the clash issues between multi-disciplines and rework during the construction phase. Additionally, there is also a BIM model deepening design step for the confirmation of construction drawing design (Chen et al., 2017). This step optimizes the details used for construction process. Furthermore, take-off quantity calculation is also involved to make an initial cost estimation of the materials and this is very useful to the project procurement phase (CSCEC, 2017).

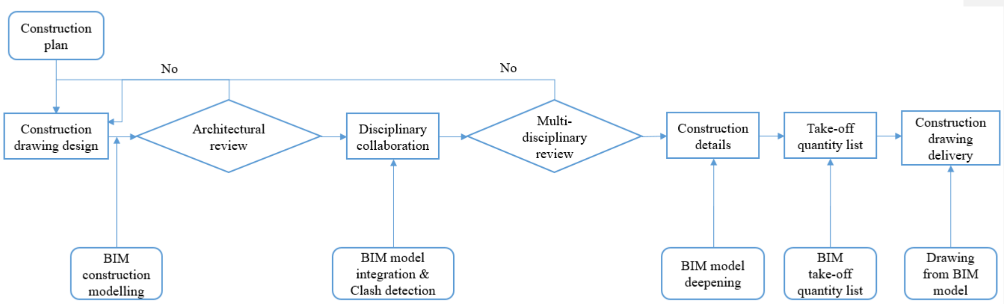

Fig.5.6 BIM-based workflow for project construction drawing design

In this study, the developments of these BIM-based workflows not only give ideas of how to apply the BIM technology into design and construction phases for productivity improvements, but also makes an innovative contribution to realizing a consistent and valuable information flow for the later O&M phase. These developed workflows can help address the inconsistency issue of "international BIM in China's local AEC industry" as mentioned in the introduction. Meanwhile, they provide examples of management framework and efficient data flow designs for later research parts of narrowing the knowledge gap between BIM theories and practice in building fabric maintenance.

Commented [CC32]: Explanation of why using these BIM-based workflows and their potential contribution to later research parts of building fabric maintenance.

5.1.3 Development of BIM-Based Forecast System for Predicting Impact Factors in Construction Process

A total of 140 professionals from global and China's AEC industry were invited to participate in the online questionnaire survey of the investigation of impact factors in construction process. Through filtering based on survey completion, there were 105 valid questionnaires received finally for data analysis. Statistics about basic background information (including organization, working years and job position) of these 105 respondents are shown in Fig.5.7, Fig.5.8 and Table.5.1.

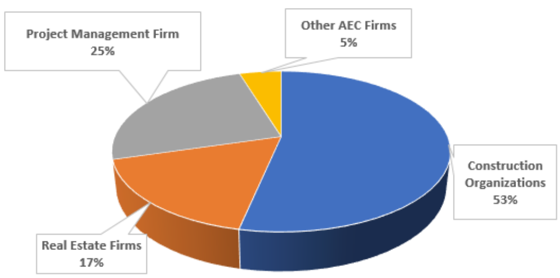

Fig.5.7 Organization types of respondents

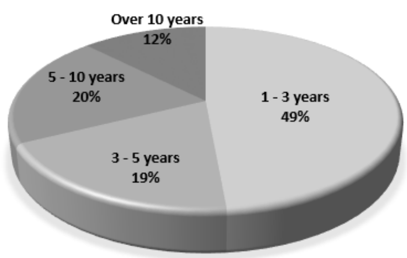

Fig.5.8 Working experiences of respondents

Table.5.1. Job Positions of Respondents

Job position	Number of respondents
Engineer	16
Architectural designer	11
Department head	7
Project manager	22
Quality Inspector	4
Quantity surveyor	8
Procurement manager	7
Executive director	4
Site supervisor	5
Construction worker	12
Accountant	4
HR manager	3
Warehousing & logistics worker	2

From the figures and the table shown above, it can be found that more than half of the respondents are from construction organizations, which are responsible for the production control of construction phase. In addition, over 50% of the respondents have three years working experience or above. The top three job positions of these respondents are project manager, engineer and construction worker.

In addition, to better investigate the potential relationships between the background information of the respondents and their opinions on the impact factors, detailed distributions of respondents with different working experiences in different organizations are also compared as shown in Table.5.2. It can be found from the table that except the organization of "Other AEC firm", the respondents with 1 – 3 working years account for the largest percentages in "Construction organization", "Real estate firm" and "Project management firm". Only in "Other AEC firm", the respondents with over 10 year-working experience are the most. In other organizations, the respondents with over 10 year-working experience occupy for the smallest percentages respectively.

Commented [CC33]: Detailed distributions of respondents with different working experiences in different organizations.

After the ratings based on the Likert Scale and quantitative statistical methods, the results were classified and displayed in tables for further analysis. Table.5.3 shows a comparison of factors with the highest impact and the lowest impact in respondents' views from different organizations. It can be seen from the table that respondents from different organizations have the same views on the rankings of the highest and the lowest impact factors. For example, “Natural disaster” and “Site access” are the highest and the lowest impact factors in the site environment of construction process according to a common view from the respondents who are working for real estate firms, project management firms and other AEC firms such as design institutes, consultancy, etc. However, respondents from different organizations also have different views on the rankings of impact factors. For the practitioners who are working in construction organizations, they thought “Onsite safety inspection” and “Climate and weather” are the highest and the lowest impact factors in the site environment.

Commented [CC34]: A comparison of factors with highest impact and lowest impact in respondents’ views from different organizations.

Table.5.2. Distributions of Respondents with Different Working Experience in Different Organizations

Organization	Working Years	Number	Percentage
Construction Organization	1 - 3 years	28	50.0%
	3 - 5 years	10	17.9%
	5 - 10 years	11	19.6%
	Over 10 years	7	12.5%
Real Estate Firm	1 - 3 years	8	44.5%
	3 - 5 years	4	22.2%
	5 - 10 years	4	22.2%
	Over 10 years	2	11.1%
Project Management Firm	1 - 3 years	14	53.8%
	3 - 5 years	5	19.2%
	5 - 10 years	5	19.2%
	Over 10 years	2	7.8%
Other AEC Firm (Design Institute, Consultancy, etc.)	1 - 3 years	1	20.0%
	3 - 5 years	1	20.0%
	5 - 10 years	1	20.0%
	Over 10 years	2	40.0%

Table.5.3. Comparison of Factors with the Highest Impact and the Lowest Impact in Respondents' Views from Different Organizations

Organization	Impact Factors	Factor with Highest Impact	Factor with Lowest Impact
Construction Organization	Site Environmental Factors	Onsite safety inspection	Climate and weather
	Production Factors	Delivery efficiency of last step	Supervision
	Crew Factors	Labor experience	Age
	Consumption Factors	Material supply	Price fluctuation of material
Real Estate Firm	Site Environmental Factors	Natural disaster	Site access
	Production Factors	Production efficiency of equipment	Construction rework
	Crew Factors	Crew building	Age
	Consumption Factors	Material supply	Payment efficiency
Project Management Firm	Site Environmental Factors	Natural disaster	Site access
	Production Factors	Delivery efficiency of last step	Construction rework
	Crew Factors	Communication	Weekend and holiday
	Consumption Factors	Material supply	Distance between site and supply source
Other AEC Firm (Design Institute, Consultancy, etc.)	Site Environmental Factors	Natural disaster	Site access
	Production Factors	Clash and interference	Supervision
	Crew Factors	Labor experience	Weekend and holiday
	Consumption Factors	Material supply	Price fluctuation of material

In addition, the views from respondents with different working experiences in construction organizations and project management firms were also compared and the results are shown in Table.5.4 and Table.5.5 respectively. The reason of why the respondents from real estate and other AEC firms were not compared based on different working experiences is due to their limited numbers of respondents. As the number of respondents is less than 20, particularly the number of respondents from other AEC firms is only 5, it is too difficult to distribute enough respondents according to their working experiences. This is adverse to fair and scientific rankings of factors according to respondents' views and it will bring some very individual subjective results because there is even only 1 respondent distributed in some groups with different working experiences.

Commented [CC35]: Comparison of views from respondents with different working experiences in the common organization to find out the same and the different views on rankings of impact factors.

Table.5.4. Comparison of Views from Respondents with Different Working Experiences in Construction Organizations

Working Years	Impact Factors	Factor with Highest Impact	Factor with Lowest Impact
1 - 3 years	Site Environmental Factors	Onsite safety inspection	Climate and weather
	Production Factors	Delivery efficiency of last step	Supervision
	Crew Factors	Communication	Age
	Consumption Factors	Material supply	Price fluctuation of material
3 - 5 years	Site Environmental Factors	Onsite safety inspection	Climate and weather
	Production Factors	Delivery efficiency of last step	Consistency of instruction
	Crew Factors	Labor experience	Weekend and holiday
	Consumption Factors	Material supply	Price fluctuation of material
5 - 10 years	Site Environmental Factors	Onsite safety inspection	Climate and weather
	Production Factors	Delivery efficiency of last step	Supervision
	Crew Factors	Labor experience	Weekend and holiday
	Consumption Factors	Material supply	Price fluctuation of material
Over 10 years	Site Environmental Factors	Onsite safety inspection	Climate and weather
	Production Factors	Delivery efficiency of last step	Construction rework
	Crew Factors	Labor experience	Weekend and holiday
	Consumption Factors	Material supply	Price fluctuation of material

It can be found from Table.5.4 that respondents with different working experiences have the same view on the ranking of the highest and the lowest impact factors for site environment and consumption. However, for crew factors, respondents with 1 - 3 years working experience have totally different views on the ranking of the highest and the lowest impact factors compared with other respondents who have 3 - 5 years, 5 - 10 years and even over 10 years working experiences. For production factors, respondents with different working experiences have the same view on the factor with the highest impact and multiple views on the factor with the lowest impact.

Similarly in Table.5.5, respondents with different working experiences also have the same and different views on the ranking of the highest and the lowest impact factors. As the number of respondents with over 10-year working experience from other AEC firms is only 2, their views are not included in this comparison to ensure the fairness of the comparison.

Commented [CC36]: Comparison of views from respondents with different working experiences in the common organization to find out the same and the different views on rankings of impact factors.

Table.5.5. Comparison of Views from Respondents with Different Working Experiences in Project Management Firms

Working Years	Impact Factors	Factor with Highest Impact	Factor with Lowest Impact
1 - 3 years	Site Environmental Factors	Natural Disaster	Site access
	Production Factors	Delivery efficiency of last step	Supervision
	Crew Factors	Communication	Weekend and holiday
	Consumption Factors	Material supply	Distance between site and supply source
3 - 5 years	Site Environmental Factors	Natural Disaster	Site access
	Production Factors	Delivery efficiency of last step	Construction rework
	Crew Factors	Communication	Age
	Consumption Factors	Allocation of resource	Price fluctuation of material
5 - 10 years	Site Environmental Factors	Natural disaster	Climate and weather
	Production Factors	Delivery efficiency of last step	Construction rework
	Crew Factors	Labor experience	Weekend and holiday
	Consumption Factors	Allocation of resource	Price fluctuation of material

For the rating part, all potential impact factors are ranked according to the statistical results and shown in Table.5.6 – Table.5.9.

Table.5.6. Rating of Site Environmental Factors

Factors	RII	Rank	WP
Onsite safety inspection	8904	1	25.53%
Natural disaster	8799	2	25.22%
Climate and weather	8778	3	25.17%
Site access	8400	4	24.08%

Table.5.7. Rating of Production Factors

Factors	RII	Rank	WP
Delivery efficiency of last step	8967	1	15.04%
Complexity of technique	8883	2	14.90%
Production efficiency of equipment	8841	3	14.83%
Consistency of instruction	8631	4	14.48%
Clash and interference	8295	5	13.91%
Supervision	8106	6	13.60%
Construction rework	7896	7	13.24%

Table.5.8. Rating of Crew Factors

Factors	RII	Rank	WP
Labor experience	9219	1	10.44%
Communication	8715	2	9.87%
Morale and attitude	8358	3	9.46%
Crew building	8274	4	9.37%
Crew size	7980	5	9.03%
Fatigue	7938	6	8.98%
Reassignment of manpower	7938	6	8.98%
Labor mobility	7854	8	8.89%
Absenteeism	7749	9	8.77%
Age	7203	10	8.15%
Weekend and holiday	7119	11	8.06%

Table.5.9. Rating of Consumption Factors

Factors	RII	Rank	WP
Material supply	8862	1	11.78%
Water and electricity supply	8736	2	11.61%
Quality of material	8673	3	11.53%
Tool and equipment shortage	8610	4	11.45%
Allocation of resource	8547	5	11.36%
Payment efficiency	8232	6	10.94%
Logistics	8106	7	10.78%
Distance between site and supply source	7791	8	10.36%
Price fluctuation of material	7665	9	10.19%

After the analysis of raw data, the next step is to combine the acquired information with the software simulation. If the preliminary schedule of construction plan is conceived as the reference calendar, all sub-factors in corresponding factor groups of the plan will be presumed as the numerical values, which equal to 1 for initial assumptions. Therefore, the values of four main factors can be evaluated from the formula as below (5.1):

$$W_1 \times f_1 + W_2 \times f_2 + \cdots + W_n \times f_n = \text{Main Factor} \qquad (5.1)$$

Here f is the numerical value of the corresponding sub-factor, for preliminary plan, f = 1;

W is the decimal value of the weight percentage of the corresponding sub-factor;

For instance, the value of site environmental factor based on the preliminary construction plan is (5.2):

$$0.2553 \times 1 + 0.2522 \times 1 + 0.2517 \times 1 + 0.2408 \times 1 = 1 \qquad (5.2)$$

If during the construction process, any contingency caused by sub-factor occurs, the value of that corresponding sub-factor will have a variation due to the impact of the contingency. That also means there should be a value range of each sub-factor according to the impact level. Based on relevant literature review and working experience of professionals, the value range of each sub-factor is shown in Table.5.10 (Thomas and Sakarcan, 1994). Here the value range is determined through combining the empirical references from a planning tool named SmartPlant Construction with the function of "Schedule Planner" in Vico Office (Intergraph Corporation, 2012). The larger negative impact each sub-factor has on the construction process, the larger the corresponding value is.

Commented [CC37]: Explanation of the references that are used to determine the value ranges of the impact factors.

Table.5.10. Value Range of Site Environmental Sub-Factor

Factor	Value range
Onsite safety inspection	1 – 1.5
Natural disaster	1 – 1.4
Climate and weather	1 – 1.4
Site access	1 – 1.3

For example, if a typhoon is forecasted to pass through the city where the construction site is, this natural disaster will seriously affect the construction safety and site access, and meanwhile result in rainy weather. According to the empirical analysis, the value of the "Onsite safety inspection" would be adjusted to 1.4, the value of "Natural disaster" would be changed to 1.3, both values of the "Climate and weather" and "Site access" would be adjusted to 1.2, therefore the value of new site environmental factor will be (5.3):

$$0.2553 \times 1.4 + 0.2522 \times 1.3 + 0.2517 \times 1.2 + 0.2408 \times 1.2 = 1.28 \quad (5.3)$$

If there is no variation on the other three main factors, the impact caused by the site environmental factor will be reflected through the variance of construction duration. The value of the site environmental factor can be conceived as a coefficient of duration calculation as below (5.4):

$$\text{Site Environmental Factor Coefficient} \times \text{Planned Duration} = \text{Predicted Duration} \quad (5.4)$$

The planned duration of the construction assignments was 10 days. Now it is predicted that the duration will be 13 days due to the impact of typhoon. So there is a three-day duration variance between prediction and plan. As construction is a schedule-driven phase, this added time can be understood as a "schedule buffer" inserted into the planned schedule of construction process. It is also summarized that the larger impact the site environmental factor has on the construction process, a larger factor coefficient will be obtained and a longer duration will be predicted.

Similarly, it is also available to obtain the value ranges of the other three factor groups. For consumption, the value ranges of each sub-factor are shown in Table.5.11. As the same as the site environmental sub-factors, the larger negative impact each sub-factor has on the construction process, the larger the corresponding value is. Based on the findings from software simulation in Section II, the consumption factor coefficient can correlate with the consumption rate through the following equation (5.5):

$$\text{Consumption Factor Coefficient} \times \text{Planned Consumption Rate} = \text{Predicted Consumption Rate} \qquad (5.5)$$

From the equation, it is predicted that with the larger impact the consumption factor has on the construction process, the larger the factor coefficient will be and a higher predicted consumption rate will be obtained, which means the productivity will decline and the duration will become longer.

For both production factor and crew, the correlation between impact levels and value ranges is diametrically opposite to that of site environment and consumption. Based on the findings from software simulation, it is conceived that the production factor coefficient and the production factor should have the following correlation (5.6):

$$\text{Production Factor Coefficient} \times \text{Planned Production Factor} = \text{Predicted Production Factor} \qquad (5.6)$$

It is known from the above equation that the larger the production factor coefficient is, the larger the predicted production factor will be, which also means the productivity will be improved and the duration will be shortened. Therefore, with the larger negative impact each sub-factor of production has on the construction process, the smaller the corresponding value should be to reduce the overall production factor coefficient.

Similarly for the crew factor coefficient, there is also a correlation between it and the crew number as shown below (5.7):

$$\text{Crew Factor Coefficient} \times \text{Planned Crew Number} = \text{Predicted Crew Number} \qquad (5.7)$$

It has been known that when the crew factor coefficient increases, the predicted crew number becomes larger, the productivity will be higher and the duration will be shortened. So with the larger negative impact each sub-factor of crew has on the construction process, the smaller the corresponding value should be to reduce the overall crew factor coefficient. The value ranges of production sub-factors and crew sub-factors are shown in Table.5.12 and Table.5.13 respectively.

Table.5.11. Value Range of Consumption Sub-Factor

Factor	**Value range**
Material supply	1 – 1.8
Water and electricity supply	1 – 1.8
Quality of material	1 – 1.7
Tool and equipment shortage	1 – 1.6
Allocation of resource	1 – 1.6
Payment efficiency	1 – 1.5
Logistics	1 – 1.5
Distance between site and supply source	1 – 1.5
Price fluctuation of material	1 – 1.3

Table.5.12. Value Range of Production Sub-Factor

Factor	**Value Range**
Delivery efficiency of last step	0.5 – 1
Complexity of technique	0.5 – 1
Production efficiency of equipment	0.5 – 1
Consistency of instruction	0.6 – 1

Clash and interference	0.8 – 1
Supervision	0.8 – 1
Construction rework	0.9 – 1

Table.5.13. Value Range of Crew Sub-Factor

Factor	**Value Range**
Labor experience	0.5 – 1
Communication	0.5 – 1
Morale and attitude	0.6 – 1
Crew building	0.6 – 1
Crew size	0.6 – 1
Fatigue	0.7 – 1
Reassignment of manpower	0.8 – 1
Labor mobility	0.8 – 1
Absenteeism	0.9 – 1
Age	0.9 – 1
Weekend and holiday	0.9 – 1

Combining empirical experience from real construction process management and relevant studies, all potential construction impact factors were categorized according to four classifications – site environment, consumption, production and crew. Through quantitative statistical methods, all impact factors were ranked according to the results of ratings. Then the value range of each impact factor was determined and this information would be used to support the predictions of uncertainties and variances that are caused by impact factors. These uncertainties and variances can affect the construction process, particularly the construction schedule, and further studies based on the investigation results of impact factors should be conducted in order to solve the issue about how to efficiently and effectively predict uncertainties and variances during the construction process. Therefore, 5D BIM should be involved to help realize such functions for China's AEC projects by digital modelling and virtual simulation.

Based on the analysis results, the next step is to develop a forecast system prototype, which can predict the variance of construction schedule between the real process and the plan (Thomas and Sakarcan, 1994). Although schedule, cost, quality and safety will be affected by construction impact factors, it is indicated that there are two reasons why this system currently is only used to forecast the schedule variance.

The first reason is project construction is always schedule-driven. A well-structured schedule not only ensures that the construction duration is in accordance with the contract, but also can guarantee an effective production control of construction process and meanwhile maximize the productivity (Hinze, 1999). Reversely, the delay of schedule not only results in the failure of completion in time, but also leads to more cost and resource input, meanwhile increase the risks of the whole project. To ensure the construction quality and safety, it is also necessary to adjust the schedule for duration extension. Factors that are associated with project schedule have been recognized to be critical to project success (Hwang et al., 2013). Therefore, schedule (or duration arrangement) is a key indicator to judge whether the production control of construction process is successful (Ballard and Howell, 1994).

The second reason is all the impact factors discussed in this study can directly or indirectly affect the schedule, which is their common criteria (Li et al., 2017). In the Vico Office or other 4D simulation software, schedule planner is also a key module to make the simulation valuable for real project construction (Pučko et al., 2014).

Fig.5.9 presents the current interface of setting methods in the Vico Office schedule planner. As mentioned above, there are three indicator setting methods including production factor, crew and consumption. Adjusting these three indicators respectively, the same desired durations will be obtained.

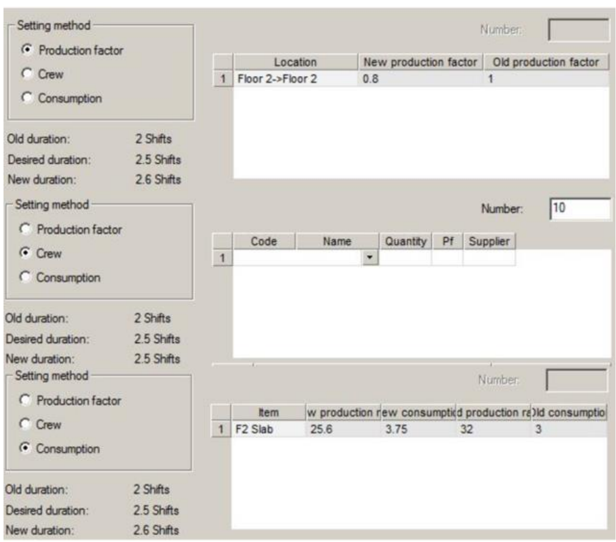

Fig.5.9 Current interface of setting method in software schedule planner

Based on the findings from this study, a forecast system prototype, which correlates with the schedule setting methods in the software, has been developed to improve the feasibility and reliability of predicting variances between the real construction process and the plan. The operation interfaces of this system prototype are shown in Fig.5.10 and Fig.5.11. It also can be conceived as a plug-in unit of the schedule planner module for secondary development based on the Vico Office in the near future.

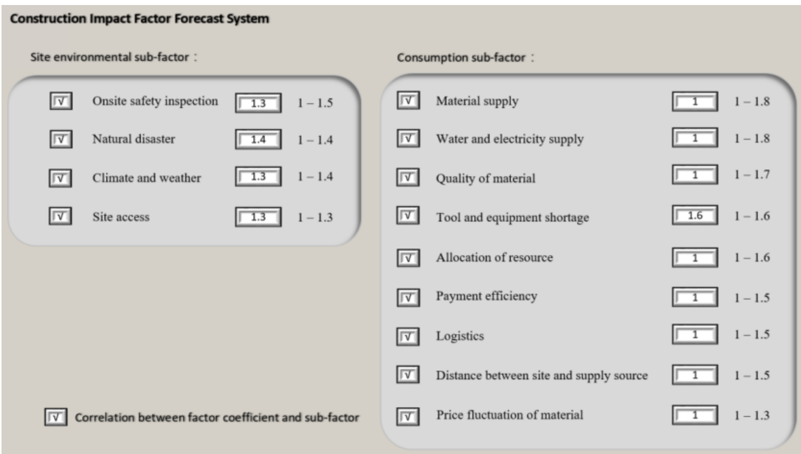

Fig.5.10 Sub-factor setting (site environment & consumption) of the forecast system

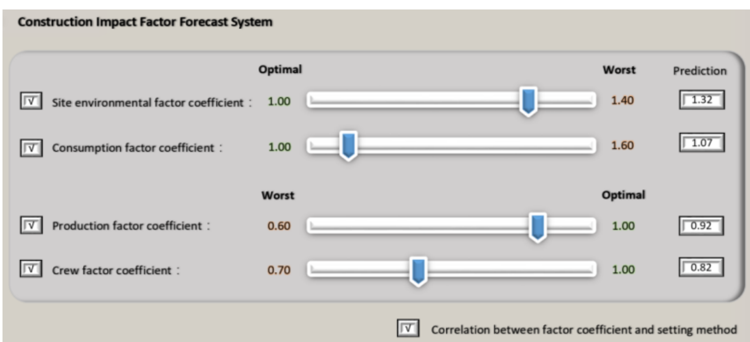

Fig.5.11 Impact factor coefficient setting of the forecast system

To validate the preliminary feasibility and reliability of the system prototype, this prototype has been applied to several pilot AEC projects located in China. Here two case studies will be briefly introduced. One is a residential building project and the other one is a commercial public building project.

For the case study of the residential building project in China, Table.5.14 shows the original construction schedule plan of its three-floor structure. However, during the construction process, it was told that raw material supply, equipment number, water and electricity supply were the potential problems to impede the construction tasks completed in time. After finding out which construction tasks would be affected by variances, the software was used to generate a predicted schedule of construction process based on the analysis results from the forecast system (shown in Fig.5.12). It could be seen that there was a three-day duration variance, which can be conceived as a three-day schedule buffer between the predicted schedule and the original plan. In addition, project managers and other planners can also check and confirm a visualized construction process with schedule simulation at each task point by using the BIM software, as shown in Fig.5.13. This can help them to compare the software simulation with the real construction process. When the construction process was completed, the final results also indicated that there would be a delay if following the original plan, and the prediction roughly matched the real construction process.

Table.5.14. Original Schedule Plan of the Residential Building Construction Process

Construction Task	Duration	Start Date	End Date
Floor 1 Column	3 days	4/18/2017	4/20/2017
Floor 1 Beam & Slab	4 days	4/21/2017	4/24/2017
Floor 2 Column	3 days	4/25/2017	4/27/2017
Floor 2 Beam & Slab	4 days	4/28/2017	5/1/2017
Floor 2 Structural Wall	3 days	5/2/2017	5/4/2017
Floor 3 Column	2 days	5/6/2017	5/7/2017
Floor 3 Beam	2 days	5/8/2017	5/9/2017

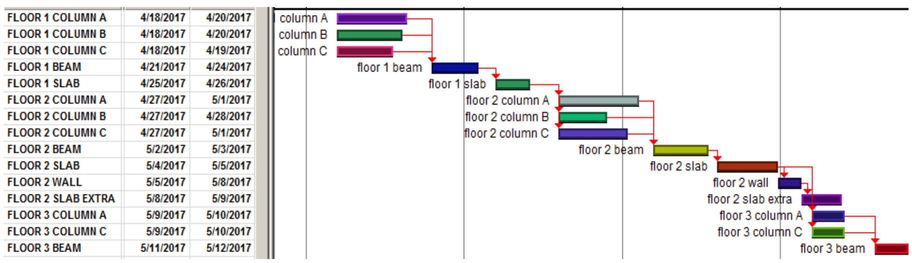

Fig.5.12 Predicted schedule plan based on analysis of impact factor forecast system

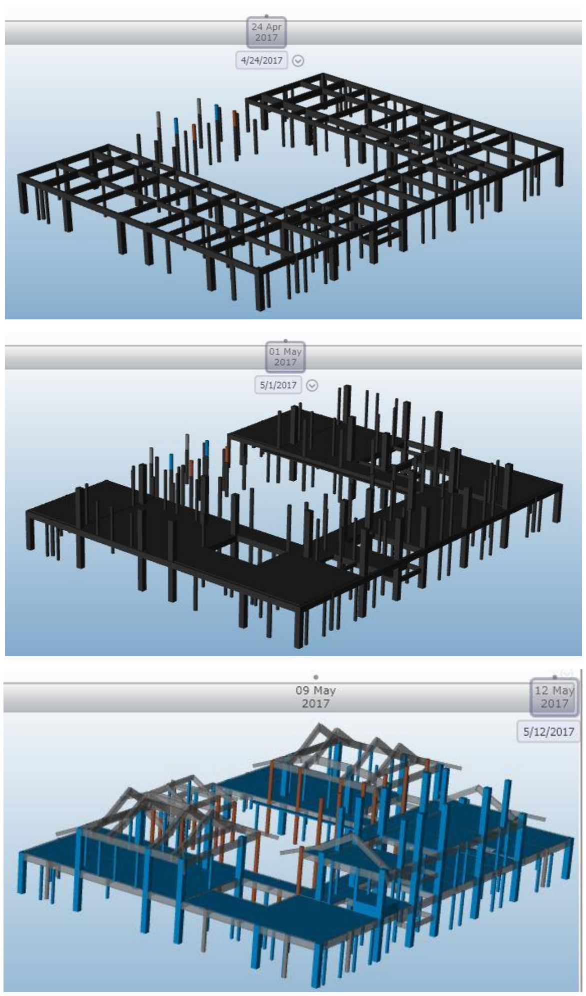

Fig.5.13 3D visualization of construction process with schedule simulation (residential building)

For the construction process of the other China's commercial public project, there were also some impact factors, which were not considered when making the original schedule plan, such as heavy rainy days, temporary onsite safety inspection, labor reassignment and allocation. Therefore, the new generated construction schedule gave a five-day schedule buffer (comparison between Table.5.15 and Fig.5.14), which was also obtained from the forecast system analysis. The visualization of construction process with schedule simulation is also provided to the planners to check the progress compared with the real construction process (shown in Fig.5.15). Afterwards the real construction process was completed successfully within the predicted schedule.

Table.5.15. Original Schedule Plan of the Commercial Public Building Construction Process

Construction Task	Duration	Start Date	End Date
Floor 1 Column 1	4 days	5/1/2017	5/4/2017
Floor 1 Beam & Slab	10 days	5/5/2017	5/14/2017
Floor 2 Column 2	5 days	5/15/2017	5/19/2017
Floor 2 Beam & Slab	7 days	5/20/2017	5/26/2017
Floor 3 Column 1	5 days	5/27/2017	5/31/2017
Floor 3 Beam & Roof	7 days	6/1/2017	6/7/2017
Other	3 days	6/8/2017	6/10/2017

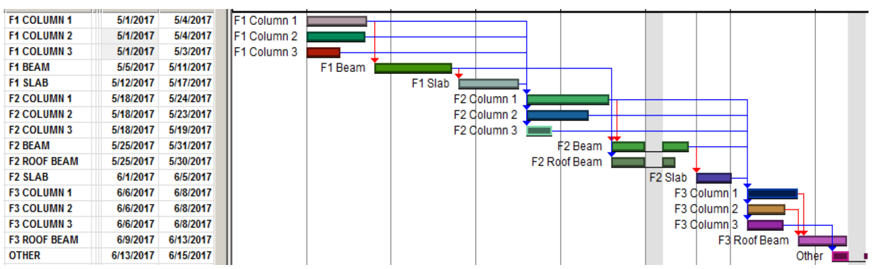

Fig.5.14 Predicted schedule plan of the commercial public building construction process

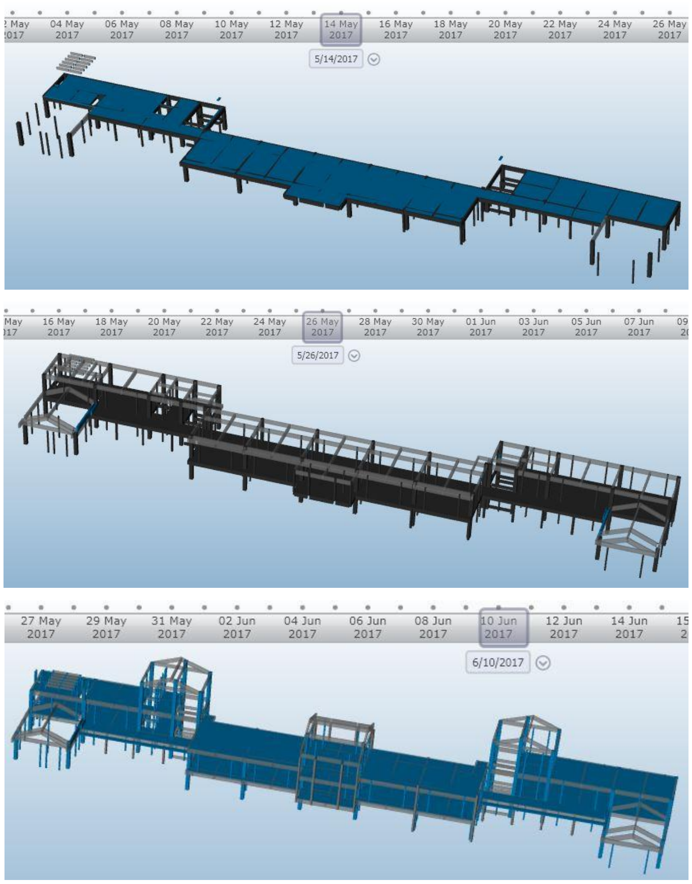

Fig.5.15 3D visualization of construction process with schedule simulation (commercial building)

According to the results of case studies, it preliminarily proves that the feasibility and reliability of the impact factor forecast system in applications of practical construction process.

In current, it is rare to provide effective means for predicting the variances and their causes between the real construction process and the plan. BIM software has the capability to simulate and estimate the construction process without any semi-automatic or automatic optimization of the construction process (Fan et al., 2015, Li et al., 2017). If such a forecast system developed in this study can be improved from current semi-automatic impact prediction means to automatic means in the near future, the first step of automatic production control of construction process will then be implemented (Thomas and Sakarcan, 1994).

This investigation currently focuses on how the impact factors will affect the schedule of construction process and provide an empirical reference for further studies, which will be based on this to concern about how the factors will have impact on cost, quality and safety of construction process. The investigation results based on four criteria of impact factors would be finally combined with software simulation together, in order to enhance the productivity and the efficiency of construction phase in China's AEC projects.

In addition, although successful production control and effective management of those four criteria in construction process is a common aim of "Last Planners" from worldwide AEC industry, different countries and regions have different construction rules and process system. Therefore, the impact forecast systems will be further developed based on those characteristics to provide measurable references for production control of construction process in global and China's AEC industry (Fischer and Tatum, 1997).

5.2 Result Processing and Analysis of Site Experiment

5.2.1 IMU/GPS-Based Indoor Positioning

For the IMU/GPS-based indoor positioning, after the raw data was extracted from the bundled software in the laptop, the next step was to obtain velocity, attitude and positioning trajectory by using the SL + θ algorithmic solution mentioned above. This solution was developed in the MATLAB tool as shown in Fig.5.16 to implement raw data processing and error calibration.

```
% Apply INS to obtain Pos,Vel y Att:
disp('Apply SL+theta PDR...');
%-----Step detection------
idx_fig=20;
[Num_steps,Step_events,StancePhase,idx_fig]=StepDetection_Acel(Acc,1,idx_fig);
%-----SL-Heading (Thetas θ) Estimation-----------
[StrideLengths, Thetas, Positions,idx_fig]=Weiberg_StrideLength_Heading_Position(Acc,Gyr_unbiased,Step_events,StancePhase,1,idx_fig);
```

Fig.5.16 MATLAB-based SL + θ algorithmic solution

Fig.5.17 shows the acceleration changes against the time. In this figure, the red line represents the fluctuation of the acceleration and the red circles are the detected steps. It can be found that the steps only appear when there is a fluctuation of the acceleration, which also means the tester was moving in a random speed at that time. For the periods in which there is no fluctuation of the acceleration and detected steps, the tester was keeping in a static state or moving in a constant speed during those periods. After the experiment, there are 40064 readings obtained, which means the total experimental time (including static and motion states) is 400.64 seconds (due to 100 readings/s). Fig.5.18 indicates the changes of stride length and heading against steps. In this figure, the "Thetas" with a positive value means the heading towards the northern orientation and with a negative value means the heading towards the southern orientation. According to the headings, the obtained stride lengths were connected in order to generate the position trajectory as shown in Fig.5.19.

Commented [CC38]: Explanation of the parameters shown in figures.

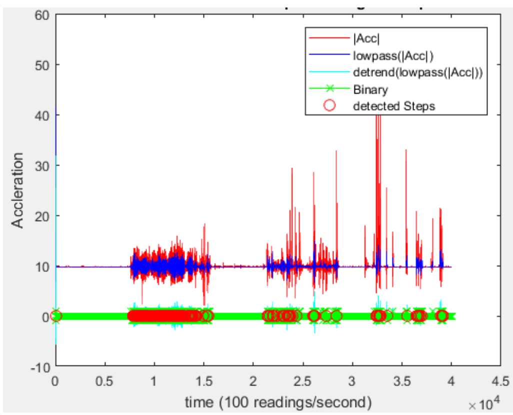

Fig.5.17 Accelerometer processing for step detection

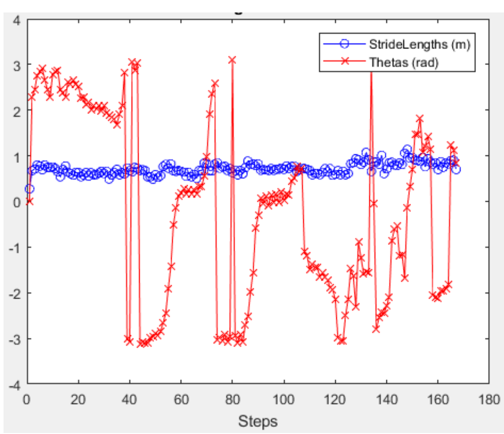

Fig.5.18 Stride length and Thetas

It can been seen from Fig.5.19 that the estimated position trajectory by using the SL + θ algorithmic solution has some heading biases compared with the real trajectory. Particularly when the tester walked back after taking a lap around, the bias of heading increased dramatically. It was mainly caused due to the measurement error accumulation over a relatively long test period. Although an EKF has been added in order to improve the accuracy and reliability of the estimation result with statistically minimum errors, some errors are still possible to occur due to the inherent drawbacks of the sensor itself.

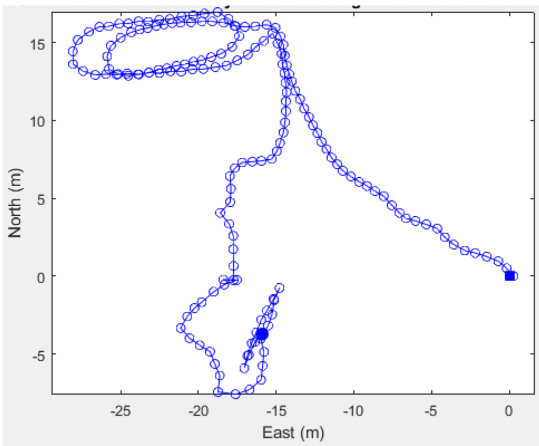

Fig.5.19 Position trajectory in the global frame

The experimental result indicates that although an EKF was adopted to help improve the measurement accuracy, the bias of the trajectory measurement was still dramatic. This could result from several limitations of the experiment. The first limitation can be the performance of the sensor itself. As the IMU used in this experiment is a low-cost type, its accuracy, precision and stability are lower than those high-cost IMU sensors. The second limitation could be the condition of experimental site, due to there were some steps that cannot be avoided in the walking path, the obvious variations on the height of the IMU's position could affect the measurements when the tester walked through the steps. Another limitation could be the absence of GPS. It is known that IMU/GPS systems are widely used for outdoor localizations. However, the GPS signals are obstructed under indoor conditions, only IMU can be used to roughly estimate the positions of the target. This greatly reduces accuracy and reliability of measurements.

Although from the result analysis of this experiment, there were some limitations that constrained the performance of this method, it is still possible to overcome the limitations in the further studies by using better sensors, rearranging the experimental site and combining with other indoor positioning techniques, such as the UWB system. In addition, errors caused by manual operations also can have an impact on the experimental results. Usually these errors occur in the data collection and the data processing phase. To address this issue, more automated platform like robots can be used for the mounting of the IMU sensor and more accurate sensor can be utilized to enhance the quality of collected data. Computer-based data processing plug-ins also can be developed to improve the work efficiency and accuracy of data processing.

5.2.2 IMU/GPS-Based Indoor Mobile Laser Scanning

After the experiment, 2D scan results were displayed and saved by using the SOPAS Engineering Tool, which is a bundled support software for data monitoring and collection from the SICK 2D laser scanner. The main parameter values including 2D axial coordinates and intensity were extracted from the acquired scan results through a MATLAB-based algorithm. For the motion trajectory, a step length and heading estimation based on PDR algorithm was applied in order to determine relatively accurate positions of laser scanner at each time interval point (the time interval was 1 second) (Kang et al., 2012, Ruiz, 2017). Then each position was matched with the corresponding scan data at the same time point. Eventually, when all the extracted scan results were combined with the positioning trajectory measurements, a 3D point cloud was generated as shown in Fig.5.20 and Fig.5.21. Here the quality of the produced 3D point cloud depends on the combination level of 2D scan data with positioning trajectory and the accuracy of positioning measurements (Randall, 2011).

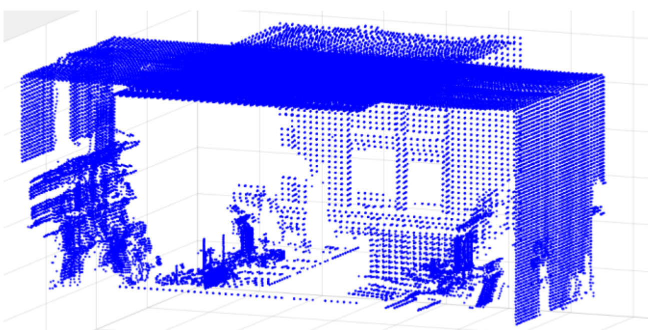

Fig.5.20 Integrated 3D point cloud (without northern walls)

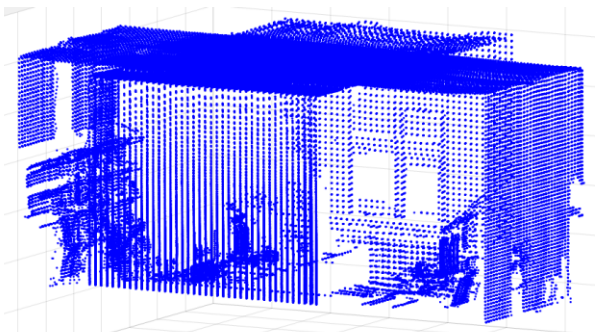

Fig.5.21 Integrated 3D point cloud (with northern walls)

The next step was to import the scan point clouds into BIM tools. The objective of this step is to realize the integration of real site conditions with BIM design models for indoor mapping and discrepancy inspection. In this research, Cyclone and Autodesk Recap were used to implement the import of point clouds into Autodesk Revit (Tang et al., 2010). Fig.5.22 and Fig.5.23 respectively display the processed point clouds in Cyclone and Recap. Fig.5.24 shows the initial BIM design model of the target room, which was created in Revit according to the CAD drawings of the building.

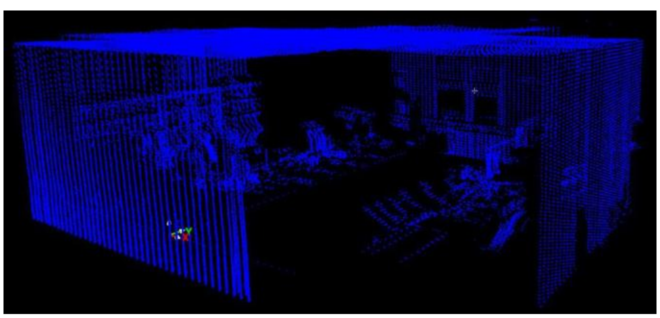

Fig.5.22 Generated point cloud in Cyclone

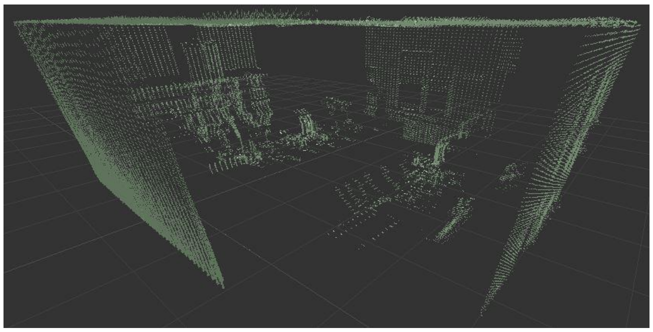

Fig.5.23 Generated Point cloud in Autodesk Recap

Fig.5.24 BIM design model of the target room

After the integration, it can be seen from Fig.5.25 that the indoor conditions above the ground 0.7m are almost reproduced (except the corners), and the scan profiles of room elements including windows, walls and ceiling, roughly match their dimensions in the BIM design model. However, there are still some discrepancies between the scan results and the design. These discrepancies may result from the errors which occurred during the experiment and later data processing, or the alterations in the actual construction phase of the room.

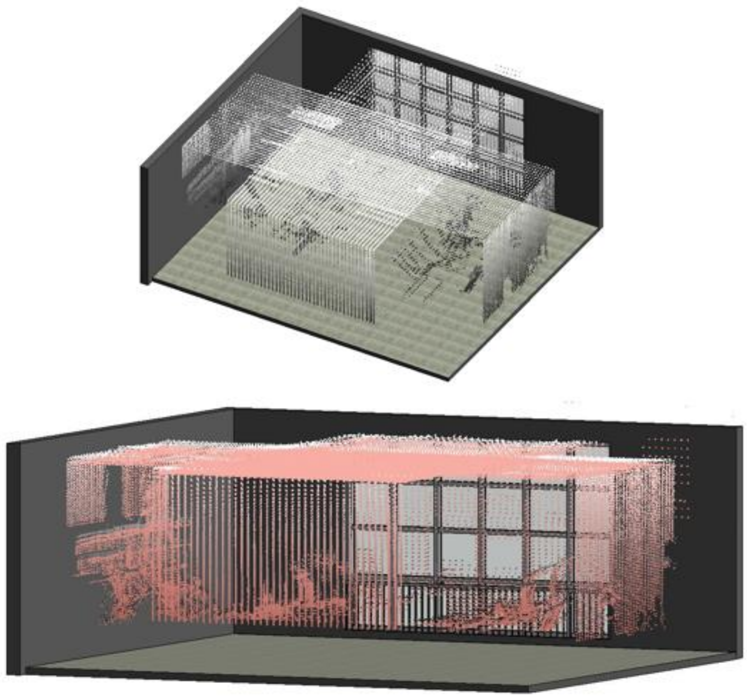

Fig.5.25 Scan result integrated with BIM design model

Limited to the equipment and site conditions, the scan was not panoramic, which means the results did not provide a complete scan of the entire room. If high-quality 3D point cloud comparisons between existing buildings and designs are anticipated, we will need to improve the scan method to realize a panoramic scan of the indoor conditions, maybe both wheel-platform and handheld scanning methods will be experimented (Zlot et al., 2014). In addition, as several middleware were used for the data transfer from scan to BIM tools, the current data processing is complex and should be simplified to meet the requirements of large-scale indoor scan applications.

Although there are some weaknesses existing in this novel laser scanning method, the experimental results still indicate a good feasibility and potential of its application in indoor digital mapping. Compared with stationary TLS, this IMU/GPS and 2D laser scanning integrated method shows mobility, flexibility and other advantages including cost and time saving. As the quality of final 3D point clouds acquired from this method depends on the combination level of 2D scan data with positioning trajectory and measurement accuracy, errors caused by the IMU/GPS system may impact the final experimental results in this research. Therefore, better indoor positioning methods such as UWB system will be applied in further relevant studies to improve the overall performance of the method developed in this research (Tappero et al., 2009). More tests will be run in narrow and complex indoor environments to prove the reliability of this method. It is also expected that the BIM integrated with this method will make the quality controls of as-built constructions, the indoor mappings of existing buildings and the restorations of historical heritages more digital, more efficient and more reliable.

5.2.3 UWB-Based Indoor Positioning

According to the coordinate transformation method of the UWB data, a MATLAB-based algorithm was developed to implement the data coordinate transformation from the UWB frame to the global frame. There are six receivers in the UWB system and they were simplified to six points with coordinates. The coordinates of these six points in the UWB its own frame were determined from the UWB monitoring tool, and the corresponding coordinates of them in the global frame (WGS84 Coordinate System) were measured by using a total station. Fig.5.26 shows the coordinates of six receiver points in both the UWB its own frame and the global frame.

```
% coodinate a (UWB frame)
% There are 6 UWB receivers, therefore 6 coordinates of these receivers
a=[-5.404   13.864  9.505
6.853   14.278  9.542
9.895   4.271   9.461
9.961   -9.193  9.421
-13.031 -9.194  9.402
-13.038 4.259   9.413];

%coordniate b (global frame)

b=[360545.3498  3297831.8741    24.1535
360557.5614 3297830.8053    24.1905
360559.3741 3297820.5039    24.1101
360557.8128 3297807.1332    24.0711
360534.9896 3297809.9170    24.051
360536.6144 3297823.2663    24.0619];
```

Fig.5.26 Coordinates of six receivers in both UWB and global frames

According to the Equation 3.21 and 3.27, 3×7 sub-matrixes for the six points can be expressed as shown in Fig.5.27.

```
a1=[1 0 0 a(1,1) 0 -a(1,3) a(1,2)
    0 1 0 a(1,2) a(1,3) 0 -a(1,1)
    0 0 1 a(1,3) -a(1,2) a(1,1) 0];

a2=[1 0 0 a(2,1) 0 -a(2,3) a(2,2)
    0 1 0 a(2,2) a(2,3) 0 -a(2,1)
    0 0 1 a(2,3) -a(2,2) a(2,1) 0];

a3=[1 0 0 a(3,1) 0 -a(3,3) a(3,2)
    0 1 0 a(3,2) a(3,3) 0 -a(3,1)
    0 0 1 a(3,3) -a(3,2) a(3,1) 0];
a4=[1 0 0 a(4,1) 0 -a(4,3) a(4,2)
    0 1 0 a(4,2) a(4,3) 0 -a(4,1)
    0 0 1 a(4,3) -a(4,2) a(4,1) 0];
a5=[1 0 0 a(5,1) 0 -a(5,3) a(5,2)
    0 1 0 a(5,2) a(5,3) 0 -a(5,1)
    0 0 1 a(5,3) -a(5,2) a(5,1) 0];
a6=[1 0 0 a(6,1) 0 -a(6,3) a(6,2)
    0 1 0 a(6,2) a(6,3) 0 -a(6,1)
    0 0 1 a(6,3) -a(6,2) a(6,1) 0];
```

Fig.5.27 Sub-matrix for each point

In fact, at least four sub-matrixes of the measured points are enough to be used for obtaining an inverse matrix. So only four sub-matrixes were selected in this study. In Fig.5.28, A is derived as a 12×7 matrix which combined four sub-matrixes and B is a 12×1 matrix including the coordinates of four points in the global frame. X is an inverse matrix of (A' *A)* A' *B and it has a scale factor of $m + 1$. Therefore, by subtracting and dividing the initial reference scale, which equals to 1, from the scale value and three rotation parameters, a transformation matrix (X2) with seven parameters (ΔX, ΔY, $\Delta Z, m, \omega_X$, ω_Y and ω_Z) was determined.

```
% only choose 4
A=[a1;a2;a3;a4];
B=[b(1,1);b(1,2);b(1,3);b(2,1);b(2,2);b(2,3);b(3,1);b(3,2);b(3,3);b(4,1);b(4,2);b(4,3)];
X=inv(A'*A)*A'*B;
m=X(4,1)-1; %  sep.scale = mtrResult[3, 0],-1 because 1 is the initial reference scale; ;
w_x=X(5,1)/X(4,1);% sep.Ex = mtrResult[4, 0]/ sep.scale;
w_y=X(6,1)/X(4,1);% sep.Ey = mtrResult[5, 0] / sep.scale;
w_z=X(7,1)/X(4,1);% sep.Ez = mtrResult[6, 0] / sep.scale;
X2=[X(1,1);X(2,1);X(3,1);m;w_x;w_y;w_z]; % X(1,1),X(2,1),X(3,1) are the delta translation on x,y and z axis;
```

Fig.5.28 Determination of seven-parameter matrix

After the seven-parameter matrix was determined, the raw position measurements with UWB coordinates were imported into the MATLAB-based algorithm that was developed according to the Equation 3.26. As the output of UWB measurements contains four parameters: time, X, Y and Z. The time interval of UWB measurement in this study is 0.108s, thus the time at i th measurement is equal to the time at $i-1$ th measurement plus 0.108s. Eventually, the coordinates of each measurement were successfully transformed from the UWB frame to the global frame as shown in Fig.5.29, which also means that the UWB positioning measurements were all based on the real-world navigation.

```
% from UWB frame coordinate (X1,Y1,Z1) to global (navigation) frame coordinate (X2,Y2,Z2),
% [X2,Y2,Z2]= (1+m)*[1 w_z -w_y;-w_z 1 w_x;w_y -w_x 1][X1,Y1,Z1] + [X(1,1);X(2,1);X(3,1)]

uwb_2=csvread('C:\Users\zx20391\Desktop\24_01_18\test2_335584499_UWB.csv',1,0);
UWB_2(:,1)=uwb_2(:,1);
UWB_2(:,2)=(1+m)*(uwb_2(:,2)+w_z*uwb_2(:,3)-w_y*uwb_2(:,4))+X2(1);
UWB_2(:,3)=(1+m)*(uwb_2(:,2)*(-w_z)+uwb_2(:,3)+w_x*uwb_2(:,4))+X2(2);
UWB_2(:,4)=(1+m)*(uwb_2(:,2)*w_y-w_x*uwb_2(:,3)+uwb_2(:,4))+X2(3);
UWB_2(1,1)=27013.0870;
for i=2:size(UWB_2,1);
    UWB_2(i,1)=UWB_2(i-1,1)+0.108;
end
save('UWB_2','UWB_2');

scatter(UWB_2(:,2),UWB_2(:,3),'b.');
```

Fig.5.29 Coordinate transformation from UWB frame to global frame

Based on the transformed positioning measurements, the motion trajectory of the trolley (or UWB) was plotted as shown in Fig.5.30. Because the atrium is located in a south by west orientation, the motion of the trolley also indicates a south by west trajectory. Although there are some noises presented in the Fig.5.30, the overall motion trajectory is close to a line and the performance of the measurement result is reliable.

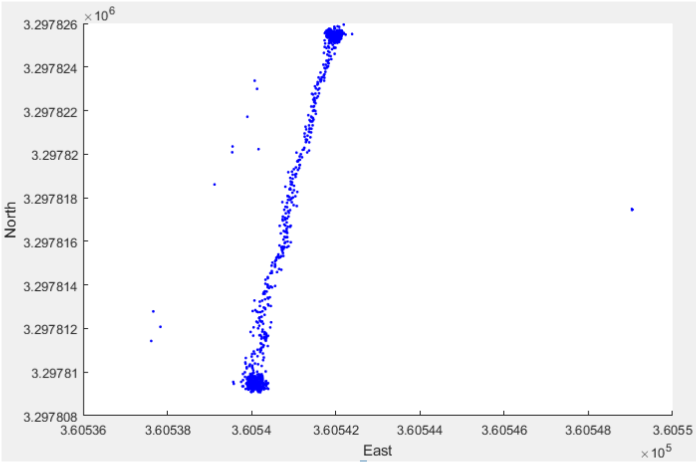

Fig.5.30 Motion trajectory generated from UWB measurements

5.2.4 IMU/UWB Integrated Indoor Mobile Laser Scanning

After the raw data from three sensors were collected, it was able to generate a 3D point cloud based on the modified coordinates of the measurements from both the UWB system and the 2D laser scanner. Both MATLAB-based algorithmic solutions were used to process the scan data. For the first solution with a frame transformation, the generated point cloud is shown in Fig.5.31.

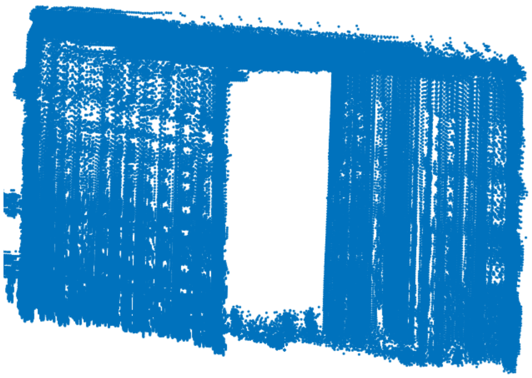

Fig.5.31 3D point cloud generated from the first algorithmic solution

The generated result indicates that the first algorithmic solution needs some improvements to reduce the noises, which has severely affected the quality of the point cloud and the boundaries of building components are difficult to recognize. It is suggested that a KF may be used to improve the quality of the point cloud. However, that means the data processing based on the first algorithmic solution will become more complex. In addition, a high performance KF also requires a higher cost due to more labor input and a longer duration for data processing.

Then the second algorithmic solution was adopted to generate a 3D point cloud through an estimation of a linear motion trajectory and the results are shown in Fig.5.32 and Fig.5.33 from quarter view and horizontal view respectively.

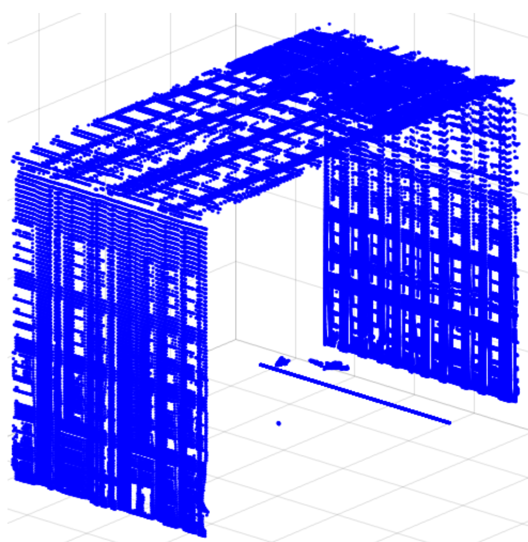

Fig.5.32 3D point cloud generated from the second algorithmic solution (quarter view)

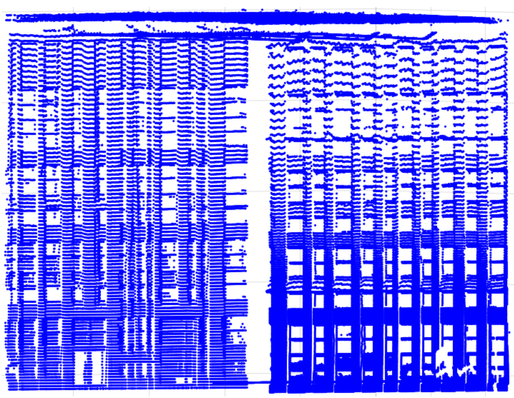

Fig.5.33 3D point cloud generated from the second algorithmic solution (horizontal view)

It can be seen that the 3D point cloud generated from the second algorithmic solution shows a better performance than the result obtained from the first one. The boundaries of most building components are easy to recognize and the fabric structures of the top roof, the eastern and the western facades of the atrium are also clearly presented. However, it is also noticed that there are some rough and fuzzy image presentations of the upper half part of the generated point cloud. This is primarily caused due to the high material reflectivity of curtain walls and glazing roof so that the laser beam is interfered. Although there are still some small discrepancies between the real image and the point cloud, but it still indicates a fairly high quality of the point cloud by using the second solution, particularly under the conditions of low-cost and time saving requirements. After the processing by Cyclone, an indoor mapping model based on 3D point cloud was created as shown in Fig.5.34 to implement the indoor mapping for the experimental site.

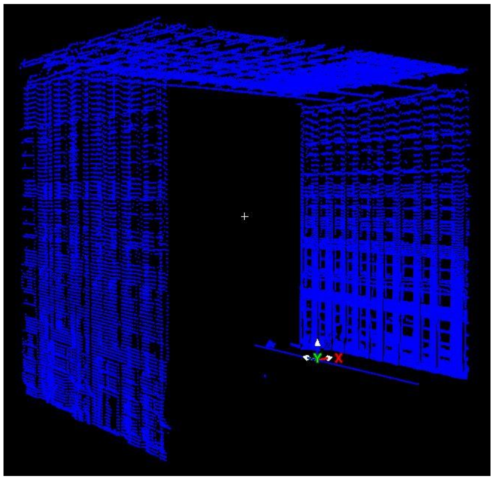

Fig.5.34 Indoor mapping model based on generated 3D point cloud

Furthermore, due to the limitation of equipment and the complexity of site environment, we separated the scan experiment of the whole atrium into five times and then combined the scan results according to time matching and positions of building components. Fig.5.35 shows the combined point cloud of the scan for the atrium compared with the reality shown in Fig.4.3. It cannot be denied that the quality of the generated point cloud is limited by local degradation due to several reasons. These reasons include the performance of the low-cost sensor, cluttered backgrounds, partial occlusions and reflectivity of building materials (Huang et al., 2016). The performance of the sensor can be improved if more cost is allowed to purchase a better 2D laser scanner and its cost should be still much lower than the average cost of 3D terrestrial laser scanner. Because low cost is the main advantage of the developed MLS method. Cluttered backgrounds cannot be avoided particularly in an indoor environment where occupancy is always high. Partial occlusion can be easily found from Fig.5.35 due to the limitation of the scanner's motion in the atrium. The high reflectivity of some materials, particularly glazing (such as curtain walls and windows) makes the laser beam fully reflected so that some component objects only show fuzzy profiles, but surface profiles of most building fabric components can be recognized.

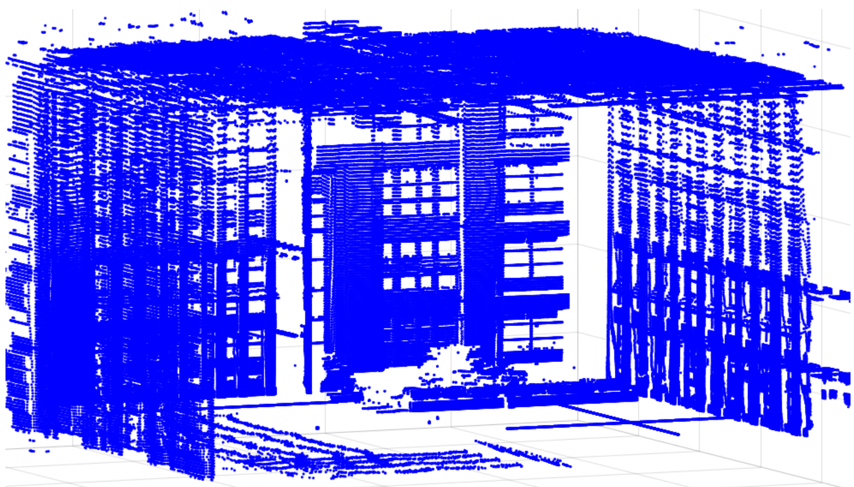

Fig.5.35 Combined point cloud of the scan for the atrium

The development of this low-cost indoor mobile laser scanning method is a successful exploration to the integration of data from heterogeneous systems by using a novel workflow, and then generate a valuable 3D point cloud for indoor mapping and digital modelling.

However, there are still some limitations that should be overcome in further relevant studies. Due to the use of a trolley and the constraints of the site environment, the scan was not panoramic, which means the current method did not provide a complete scan result of the entire atrium. Robotic systems may be proposed to solve this issue. The UWB system is also easily disturbed by variance of the environment and this can highly affect the data accuracy. In addition, the programming algorithms used in data automatic processing still need to be modified to reduce the potential errors. Less manual operations during the workflow are also required to reduce the manual errors, which can lead to large result variances. Moreover, better devices should be utilized to improve the data accuracy and precision when they are within acceptable costs, which means the improved method is still much lower-cost compared with traditional TLS techniques.

5.2.5 TLS-Based Reference Experiment

After the raw scan result was registered and processed, a 3D point cloud model of the atrium was generated and presented in RGB values. The scan results of the atrium from the developed MLS method and TLS are shown in Fig.5.36 for visual comparison and the result of the western façade is shown in Fig.5.37. It can be seen that although TLS provides a clearer reality capture from the indoor environment in this experiment, there is no obvious difference between two point clouds. Then the point cloud of TLS was extracted in ptx. format file and manually loaded into the CloudCompare tool to regenerate the model.

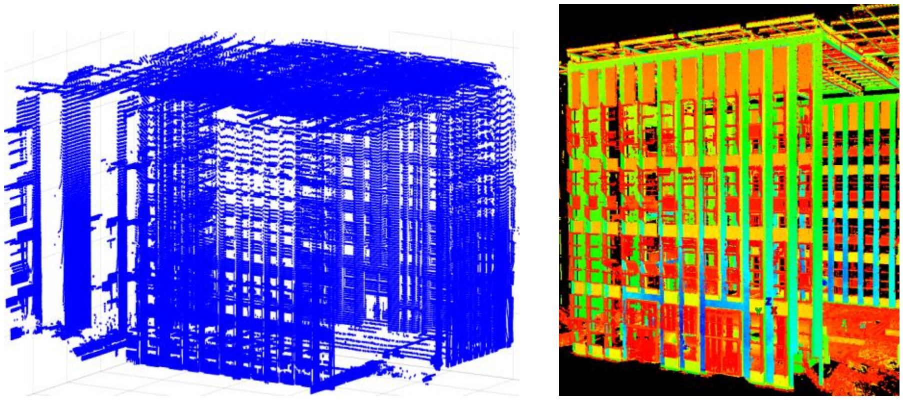

Fig.5.36 Scan results of the atrium from developed MLS method (left) and TLS (right)

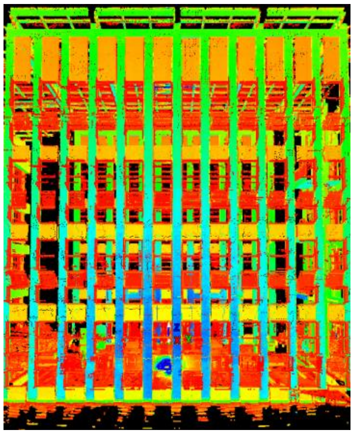

Fig.5.37 Scan result of the western façade of the atrium

Fig.5.38 and Fig.5.39 show the views from eastern and western façade of the point cloud model in CloudCompare respectively. The point cloud is presented in different colors that denote the intensity levels. The blue color denotes the lowest intensity and the red color denotes the highest intensity. Due to the curtain walls and glazing on the building façades and the roof can absorb the laser beam transmitted from the scanner and the reflectance would be highly reduced, that is why the intensities of curtain wall and glazing parts are much lower than that of other building elements and displayed in blue color.

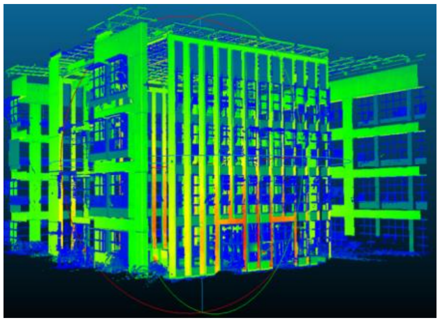

Fig.5.38 Eastern view from TLS point cloud model in CloudCompare

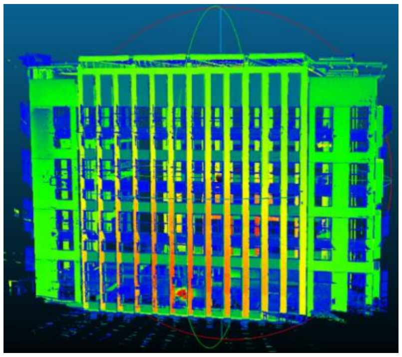

Fig.5.39 Western view from TLS point cloud model in CloudCompare

5.2.6 Comparison between TLS and Developed Indoor Mobile Laser Scanning

The point cloud of the developed MLS then was also imported into the tool for comparison analysis. The automatic matching for these two point cloud models as shown in Fig.5.40, was realized by using at least four-point coordinate transformation matrix in the tool. Here the point cloud from the TLS experiment was regarded as the reference (yellow color in Fig.5.41) and the other one from the developed MLS experiment was the target (red color in Fig.5.41). When the matching was completed, the root mean square (RMS) value was also automatically calculated, which approximately equals to 8.6 cm as shown in Fig.5.42. In addition, due to the initial scales of both point cloud models were different in their own frames, the scale factor was also modified to the value of 1.08 for better matching. Furthermore, the distance between the points from two models was also calculated and the maximum error is around 13.2 cm in Fig.5.43. Considering the limitations of experimental conditions for the developed MLS method, such a RMS value and maximum error are used to help prove the acceptable discrepancy between the result of the developed MLS and the reference TLS.

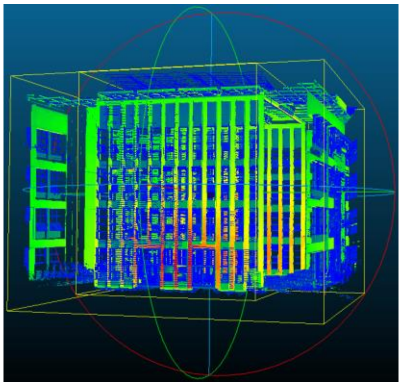

Fig.5.40 Automatic matching between two point cloud models

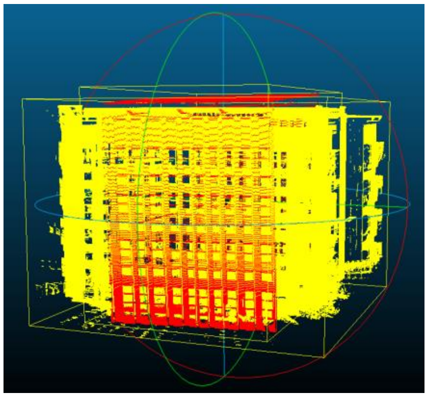

Fig.5.41 Point cloud matching between the reference and the target

Final RMS: 0.0855051

Transformation matrix
1.075 -0.098 0.051 9.437
0.099 1.076 -0.008 3.072
-0.050 0.013 1.079 -1.551
0.000 0.000 0.000 1.000

Scale: 1.08018 (already integrated in above matrix!)

Refer to Console (F8) for more details

Fig.5.42 Analysis of final RMS after automatic matching

1	Min dist.	0
2	Max dist.	3.14531
3	Avg dist.	0.799854
4	Sigma	0.515593
5	Max error	0.131974

Fig.5.43 Analysis of maximum error between two point clouds

The result analysis indicates that although both generated point cloud models are the reality captures from a construction indoor environment, lots of factors, such as manual operation, algorithmic solution, data transformation, still can affect the final accuracy of the MLS result. This is due to the data processing of the developed MLS method comprises of a number of steps, at which the potential errors would accumulate.

Although the accuracy and the reliability still need to be proved through more experiments under various conditions, this study provides a new idea to reduce the cost and save the operation time of laser scanning for indoor mapping applications. Low cost is particularly the key merit that has been realized by using this method. It can be found from Table.5.16 that the total sensor cost of the developed indoor MLS method is much lower than that of conventional Leica TLS method. In addition, the former also shows advantages over the latter on scan duration and mobility. But accuracy and automation level of the developed indoor MLS method still need to be improved due to the difference between the MATLAB-based algorithmic solutions and the automatic data processing system of the TLS approach.

Table.5.16. Comparison between TLS and Developed Indoor MLS

	Leica HDS7000 TLS	Developed indoor MLS
Cost of laser scanner	>RMB 1,000,000	<RMB 40,000
Cost of IMU	/	<RMB 1,000
Cost of UWB	/	<RMB 30,000
Total sensor cost	>RMB 1,000,000	<RMB 71,000
Accuracy	High	Medium
Scan duration	30 minutes	15 minutes
Mobility	Low	High
Automation level	High	Medium

Moreover, different from the applications of TLS or ALS for outdoor or as-built environment, now this developed MLS is applied to an implementation of indoor mapping and modelling for an existing built environment with complex conditions including various building fabric components and cluttered background. It also means the developed MLS can be adopted for specific contexts. Furthermore, Roca et al. (2013) proposed a low-cost aerial method for geometric data acquisition of building outdoor facades. Correspondingly, this study provides a low-cost mobile scan method for geometric data capture of building indoor facades.

The experimental results indicate that the discrepancy existing between the point cloud model generated from the developed indoor MLS method and the model generated from TLS reference experiment is theoretically acceptable when considering the limitations during the experimental process. Although both point cloud models are the reality captures from a construction indoor environment, the accuracy of the MLS result still can be affected by manual operation, algorithmic solution, coordinate transformation and other factors due to its data processing comprises of a number of steps, at which the potential errors would increase. However, the reliability of this developed MLS method is still validated in this case study and it shows the advantages particularly on the capital cost. In addition, although TLS and the developed MLS can generate the 3D scan results with similar accuracies, the former requires repositions for multiple scene captures and it highly increases the complexity in operations. Therefore, the developed MLS also shows its advantages in time saving and high portability during the scan process over the conventional TLS. These merits make the developed indoor MLS method could be an applicable option for construction indoor mapping. In further researches, the 3D point cloud from the laser scanning would be compared with the BIM design model in order to investigate the potential discrepancies between reality and design, which may provide a novel idea to help the implementation of building fabric maintenance work.

Commented [CC39]: Explanation of the developed MLS's advantages in time saving and high portability over the conventional TLS.

CHAPTER 6: Integration of 5D BIM and Mobile Laser Scanning for Cost Estimation of Building Fabric Maintenance

6.1 Development of Integration Workflow Design

With a long-term operation of a building, ageing and potential damages are the most threats to the building performance, particularly to the building fabric components. To sustain the existing buildings as long as possible, effective ways must be found out to retain the same quality of buildings with time and meanwhile reduce the costs of maintenance work. Therefore, a proper maintenance plan is regarded as a serious concern by building stakeholders, due to it can lead to lower depreciation costs and higher profitability. Furthermore, a proper maintenance plan also can reduce the expenditures on replacement of building fabric components.

This chapter aims to introduce a low-cost semi-automated method that can realize 5D BIM and mobile laser scanning integration for the cost estimation of building fabric maintenance. This method integrates 5D BIM concept with the developed mobile laser scanning method that has been introduced in the last chapter due to its advantages like low cost, time saving and high portability over the traditional TLS. Compared with the manual quantity surveying (QS) of building fabric components, this developed method shows higher reliability, higher efficiency and lower cost. Furthermore, different from other integration studies of BIM and laser scanning (Hichri et al., 2013, Barazzetti et al., 2015, Alomari et al., 2016), this study not only proposes an innovative low-cost and time saving mobile laser scanning for indoor mapping applications, but also extends 3D BIM modelling to a higher-level application of 5D BIM for cost estimation of building fabric maintenance plan.

The study of this chapter focuses on the data integration of heterogeneous systems, which utilize different techniques to provide heterogeneous information from multi-disciplines including indoor positioning, laser scanning and BIM modelling, which are required for achieving the aim. Therefore, a workflow design of this low-cost method is developed as shown in Fig.6.1. This workflow concisely introduces the process from the heterogeneous data integration to the cost estimation of building fabric maintenance and meanwhile presents a logical organization of inputs, outputs and procedures related to the aim of this study. Here a prerequisite should be emphasized for this workflow, which is although there might be some discrepancies determined, the 3D design model is fairly consistent with as-built model for existing buildings so that the estimation result can be convincible.

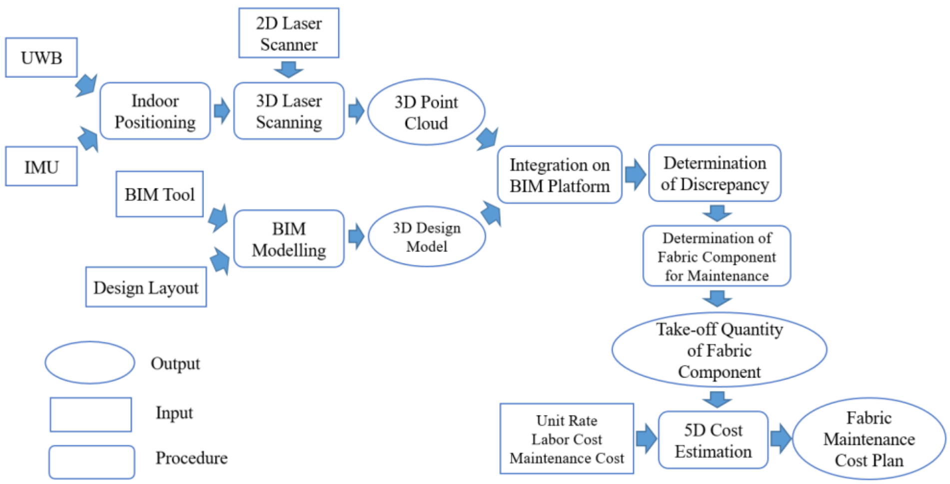

Fig.6.1 Workflow design from integration of BIM and mobile laser scanning to cost estimation of building fabric maintenance

In this workflow, MLS is realized by integrating a low-cost and high efficient 2D laser scanner with an indoor positioning approach that combines the IMU/GPS with the UWB system. The reasons of using these two techniques for indoor positioning purpose are due to the considerations of low cost, high accuracy and no specific requirements of site environment. The 2D laser scanner is much cheaper, more portable and more time saving than the traditional TLS.

After the data from MLS are collected, the next step is to register and process the data to form a 3D point cloud that captures the real surface conditions of building indoor fabric components. Then the 3D point cloud is transformed from point cloud tools to a BIM platform, where the data integration of a BIM 3D design model and the point cloud is implemented. This integration can help project managers and owners to find out the geometric dimensional discrepancies of indoor fabric components between the real condition and the design model. Based on the result of discrepancy, stakeholders can determine the fabric components that might need maintenance.

Then with the assistance of the 5D BIM tool, the take-off quantity of the fabric component can be extracted from the 3D model and combined with other property information such as material, unit rate, labor cost and maintenance cost to implement a cost estimation. Based on the result of the 5D cost estimation, managers and owners are able to estimate the potential cost of fabric maintenance through digital modelling and make a cost plan for the maintenance work of building fabric components.

As the method is semi-automated, it means some steps in the workflow are computer-based semi-automated but some are still based on manual operations. The semi-automated steps include:

- Generation of 2D laser scanner's motion trajectory based on indoor positioning;
- Integration of indoor positioning results and 2D laser scanning data;
- Generation of the 3D point cloud;
- Transformation of the 3D point cloud into BIM-based platform for heterogeneous data integration;
- Extraction of take-off quantity and other property information related to the building fabric component;

Steps based on manual operations and calculations include:

- BIM 3D modelling based on the design layout;
- Process of mobile laser scanning;
- Determination of discrepancies between the 3D point cloud from reality capture and the BIM design model;
- Cost estimation of building fabric maintenance.

6.2 Data Integration and Comparison

With the assistance of middleware, which was Cyclone in this study, the generated 3D point cloud from the low-cost mobile laser scanning was presented on the Autodesk Recap for geometric dimensional measurement as shown in Fig.6.2. The discrepancies between the dimensions from the point cloud and the corresponding BIM design model are shown in Table.6.1. Then the point cloud was integrated with the BIM design model on a platform, which was Revit in this study, to further determine the geometric dimensional discrepancies of the fabric components between the reality capture and the design. This integration was implemented by overlapping several edge points and the integrated result was shown in Fig.6.3.

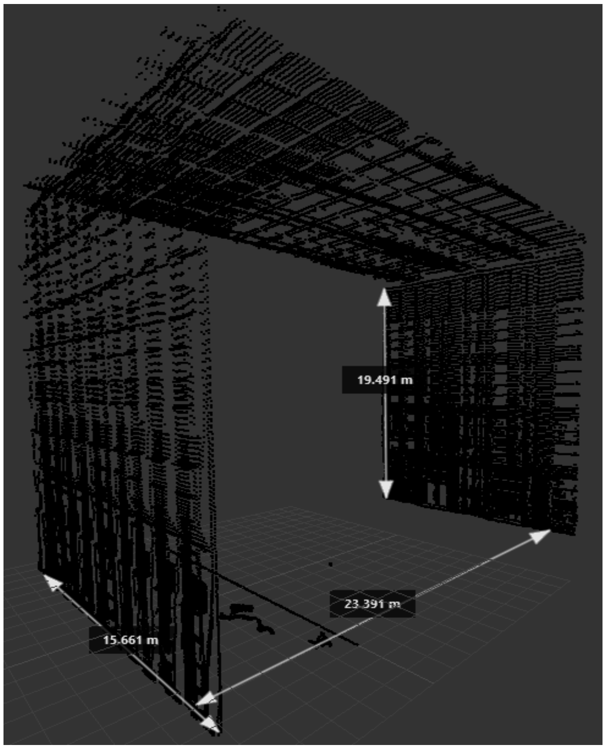

Fig.6.2 Dimensional measurement of the generated 3D point cloud

Table.6.1. Dimensional Comparison between Generated 3D Point Cloud and BIM Design Model

	Length (North to South) (m)	Width (East to West) (m)	Height (floor to roof) (m)
Captured 3D Point Cloud	15.661	23.391	20.161 (including offset 0.67)
BIM Design Model	15.646	23.340	20.100
Error Percentage	+ 0.096%	+ 0.219%	+ 0.303%

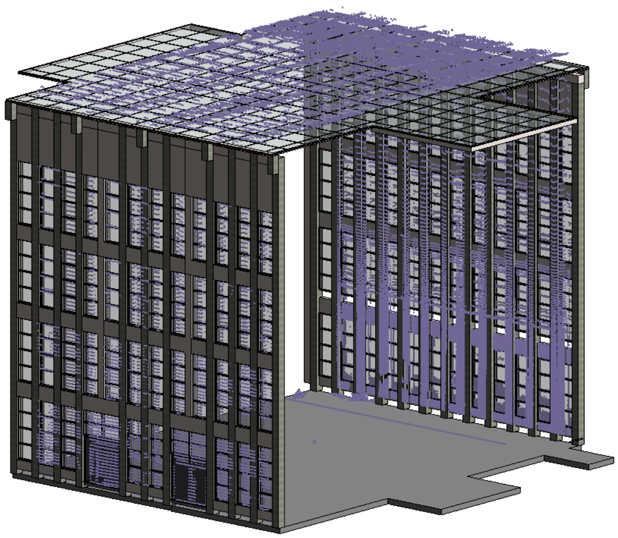

Fig.6.3 Generated 3D point cloud integrated with BIM design model

The BIM design model can provide geometric dimensional information of the fabric components of the atrium including walls, curtain walls, columns, roof and door, which were presented in the generated point cloud. To validate the feasibility and reliability of this integration method in practices, we used the curtain walls of the internal western and eastern facades in the atrium as a case study to investigate the application of the method in the cost estimation of building fabric maintenance. There are two reasons for why the curtain walls are selected for this study. The first reason is that the curtain walls are the most easily recognized components from the 3D point cloud of the laser scanning due to the high reflectivity of the glazing materials. Therefore, it is easier for us to determine the dimensions and quantities of the curtain walls from reality capture under the indoor environment.

The second reason is that this building has been built for five years and its fabric components have been affected by deterioration and need maintenance services. Particularly the internal western and eastern facades of the atrium in the building consist of many curtain walls, which require both periodic preventive (cleaning, polishing, etc.) and corrective maintenance due to a high occupancy and safety concerns on campus. Currently some curtain walls are not in proper conditions as shown in Fig.6.4 due to long-term degradation or aging.

Fig.6.4 Current conditions of some curtain walls

The discrepancies of geometric dimensions between the reality capture and the BIM design model for some selected curtain walls that might need maintenance are shown in Table.6.2.

Table.6.2. Discrepancy between Reality Capture and Design Model for Selected Curtain Walls

Code of Fabric component	Location of curtain wall	Design width from BIM model (m)	Design height from BIM model (m)
		1.050	3.400
		Measured width from 3D point cloud capture (m)	Measured height from 3D point cloud capture (m)
Curtain wall 1	Floor 1, West	1.035	3.310
Curtain wall 2	Floor 1, West	1.018	3.332
Curtain wall 3	Floor 2, West	1.035	3.388
Curtain wall 4	Floor 2, West	0.997	3.350
Curtain wall 5	Floor 3, West	0.900	3.328
Curtain wall 6	Floor 1, East	1.040	3.399
Curtain wall 7	Floor 1, East	0.984	3.374
Curtain wall 8	Floor 2, East	1.035	3.341

Curtain wall 9	Floor 3, East	1.035	3.382
Curtain wall 10	Floor 3, East	0.900	3.313
Average		0.998	3.352
Discrepancy rate		3.57%	1.4%

It can be seen from the table that acceptable discrepancies are existing between the reality capture and the design model of each selected curtain wall. They may result from the variances that occurred in the real construction process or the errors during the data collection and processing. The dimensional information provided by 3D design model would be further validated in 5D BIM. The report of discrepancy can help the owners and building users to conduct maintenance inspections on the specific fabric components without ladders and tedious preparation work, such as the curtain walls and the roof.

6.3 Cost Estimation and Analysis of Fabric Maintenance Based on the Case Study in China

In this study, a fabric maintenance plan based on the cost estimation of building fabric component was also developed through a maintenance planning model as shown in Fig.6.5. This specific maintenance workflow model refers to a maintenance model proposed by Marquez in 2007. It combines traditional maintenance management framework with the functional characteristics that 5D BIM can achieve to meet the purpose of cost planning for fabric components and mainly focuses on cost estimations and time scheduling, which are based on determinations of building objects in 5D BIM. Cost estimations consist of corrective maintenance cost, preventive maintenance cost, inspection cost, etc. Time scheduling includes regular preventive maintenance intervals and replacement cycle length according to inspection and regulatory requirements, which refer to safety conditions of O&M, environmental regulations, etc.(Marquez, 2007). Weibull Distribution method was adopted to model and analyze the maintenance plan, in order to determine the sequence and the level of the corresponding maintenance work in practices. This can help decision makers understand the significance of each maintenance work and the corresponding maintenance level, which refers to immediacy, expense and safety. Finally, all resources that were related to the maintenance plan would be identified in 5D BIM for management of maintenance progress.

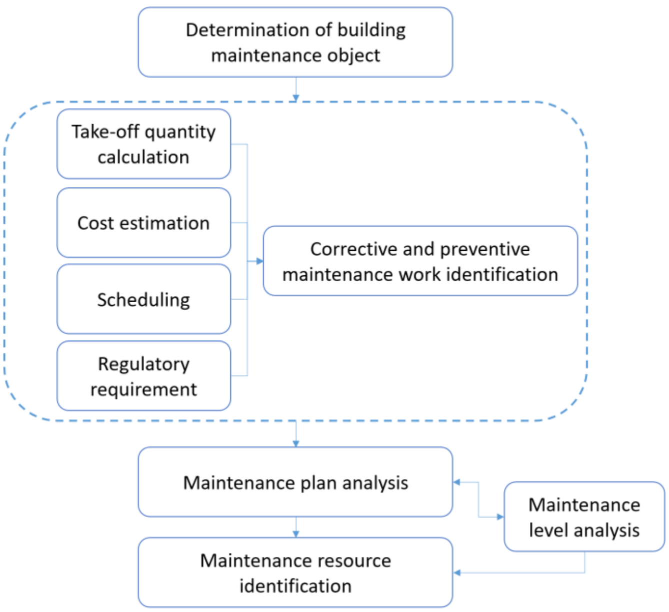

Fig.6.5 Building maintenance planning model

According to the discrepancy report of the curtain walls, it is necessary to make a maintenance plan for the curtain walls based on the maintenance planning model to analyze and validate its feasibility in practices of case studies in China.

The first step is to calculate the take-off quantity of the selected curtain walls. The design area of each curtain wall is 3.57m^2, which is extracted from the BIM design model. Each curtain wall consists of four pieces of glazing with stainless steel frames. The 3D design model of the atrium then was imported into a 5D BIM tool for the information extraction of the building components. Fig.6.6 shows the take-off quantity information of the selected curtain walls from the 5D BIM tool.

Curtain wall (west)		No	192
Name	Unit	Mapped	Project
Count	EA	No	192.00
Piece Count	EA	No	192.00
CAD Net Surface Area	M2	No	171.36

Curtain wall (east)		No	184
Name	**Unit**	**Mappec**	**Project**
Count	EA	No	184.00
Piece Count	EA	No	184.00
CAD Net Surface Area	M2	No	164.22

Fig.6.6 Take-off quantity information of curtain walls from 5D BIM tool

The total numbers of glazing in western façade and eastern façade are 192 and 184 respectively, which means the numbers of curtain walls in western façade and eastern façade are 48 and 46. Therefore, the total areas of curtain walls in western façade and eastern façade are 171.36 m^2 and 164.22 m^2 respectively, which are as the same as the data shown in 5D BIM.

After the take-off quantities of curtain walls were determined, a cost planner function in 5D BIM was used to link the quantities with cost calculation formula as shown in Fig.6.7. According to online manufacturing cost resources, the unit rate of the curtain wall materials in Chinese currency is RMB ¥ 135/m^2 (including VAT) in the local market of building materials.

Code	Description..	Value	Unit
	Curtain wall (west)		
	Count	192.00	EA
	Piece Count	192.00	EA
	CAD Net S...	171.36	M2
	Column (west)		
	Wall (west)		
	Side wall (west)		

Enter formula

fx= Curtain wall (west).CAD Net Surface Area

Fig.6.7 Take-off quantity linked with cost calculation formula

Therefore, the quantity costs of curtain walls in western and eastern façade were determined and shown in Fig.6.8, which displays total quantity cost planning for various building elements in the atrium. The percentages of which western curtain walls and eastern curtain walls account for the total take-off quantity cost are 4.75% and 4.55% respectively.

Description	Source Qty	Cons..	Cons..	Waste	Qty	UOM	Unit Cost	Base Cost	Cost/Parent ..	%/Parent ..
Atrium	**1.00**	**1.000**	**1.000**	**1.000**	***1.00***		***487,296.89***	▲ ***487,296.89***	***N/A***	***N/A***
Door (east)	6.88	1.000	1.000	1.000	*6.88*	m2	495.00	3,403.26	*3,403.26 /*	*0.70 %*
Vertical wall (east)	5.99	1.000	1.000	1.000	*5.99*	m3	350.00	2,097.96	*2,097.96 /*	*0.43 %*
Top wall (east)	7.71	1.000	1.000	1.000	*7.71*	m3	350.00	2,698.92	*2,698.92 /*	*0.55 %*
Bottom wall (east)	1.01	1.000	1.000	1.000	*1.01*	m3	350.00	352.80	*352.80 /*	*0.07 %*
Mid wall (east)	8.29	1.000	1.000	1.000	*8.29*	m3	350.00	2,900.52	*2,900.52 /*	*0.60 %*
Column (east)	44.10	1.000	1.000	1.000	*44.10*	m3	325.00	14,333.96	*14,333.96 /*	*2.94 %*
Curtain wall (east)	164.22	1.000	1.000	1.000	*164.22*	m2	135.00	22,169.70	*22,169.70 /*	*4.55 %*
Roof glazing	564.36	1.000	1.000	1.000	*564.36*	m2	125.00	70,544.70	*70,544.70 /*	*14.48 %*
Floor	468.54	1.000	1.000	1.000	*468.54*	m2	220.00	103,078.72	*103,078.72 /*	*21.15 %*
Glazing frame	624.00	1.000	1.000	1.000	*624.00*	EA	350.00	218,400.00	*218,400.00 /*	*44.82 %*
Side wall (west)	6.41	1.000	1.000	1.000	*6.41*	m3	350.00	2,242.27	*2,242.27 /*	*0.46 %*
Wall (west)	15.39	1.000	1.000	1.000	*15.39*	m3	350.00	5,385.34	*5,385.34 /*	*1.11 %*
Column (west)	50.94	1.000	1.000	1.000	*50.94*	m3	325.00	16,555.13	*16,555.13 /*	*3.40 %*
Curtain wall (west)	171.36	1.000	1.000	1.000	*171.36*	m2	135.00	23,133.60	*23,133.60 /*	*4.75 %*

Fig.6.8 Take-off quantity cost planning in 5D BIM tool

According to the equations and theories mentioned in Section 3.2.3.3 of Chapter 3, the local labor cost is around 1/3 of the unit rate, which is ¥ 45/m^2. Therefore, the corrective replacement cost for each curtain wall is (6.1):

$$CMC = 3.57\text{m}^2 \times (¥\ 135/\text{m}^2 + ¥\ 45/\text{m}^2) = ¥\ 642.6 \tag{6.1}$$

Thus, the PM cost for each curtain wall is (6.2):

$$PMC = 0.25 \times ¥\ 642.6 = ¥\ 160.7 \text{ per time} \tag{6.2}$$

And the inspection cost of each curtain wall equals to (6.3):

$$IC = 0.8 \times ¥\ 160.7 = ¥\ 128.6 \text{ per time} \tag{6.3}$$

Then Weibull Distribution was used to analyze and make the maintenance cost plan for the curtain walls. This distribution can be adopted in various situations and highly dependent on the shape parameter. When the shape parameter β equals to the value of 2.5, which is a critical value for the assumption in this study due to the specific cases of fabric maintenance. This value also represents a wear-out replacement of fabric components and the Weibull Distribution approximates a lognormal distribution (Dodson, 1994b). This assumption was also validated through computer simulations based on the variations of the shape parameter. As the ratio of the preventive cost to the corrective cost has been known, the value of the function m then can be determined from the reference table, which equals to 0.555 (Weibull, 1951, Brick et al., 1989). The scale parameter θ and the location parameter δ are 30 weeks and 10 weeks respectively. Therefore, the optimum preventive maintenance interval for each curtain wall is (6.4, reference to Equation 3.34):

$$T = (0.555) \times 30 \text{ weeks} + 10 \text{ weeks} = 26.65 \text{ weeks} \tag{6.4}$$

As the location parameter is not zero, the probability density function $f(t)$ then can be expressed as (Saraneva, 2014) (11.13):

$$f(t) = \frac{\beta}{\theta}(\frac{t-\beta}{\theta})^{\beta-1} \times e^{-(\frac{t-\beta}{\theta})^{\beta}} \tag{6.5}$$

In addition, the reliability function $R(t)$ also can be expressed as (Saraneva, 2014) (11.14):

$$R(t) = e^{-(\frac{t-\delta}{\theta})^{\beta}} \tag{6.6}$$

Therefore, when t = T =26.65 weeks, the $R(t)$ approximately equals to 0.795 and the $f(t)$ approximately equals to 0.034. The cost per unit time for each curtain wall then can be calculated (6.7, reference to Equation 3.33):

$$CPUT = \frac{160.7 \times 0.795 + 642.6 \times 0.205}{26.65 \times 0.795 + 0.8968} = ¥\, 11.7\ per\ week \tag{6.7}$$

The $M(t)$ then equals to 4.37 weeks according to the Equation 3.36 mentioned in Section 3.2.3.4 and the expected replacement cycle length based on inspection is 22.08 weeks according to the Equation 3.35.

Another basic function named failure rate λ(t) also can be used to help calculate the probability of building element failure. It is expressed as (6.8):

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{6.8}$$

In this study, the failure rate of curtain walls is assumed to be a constant value over time due to the determination of optimum preventive maintenance time. Therefore, the reliability function is converted to (Marquez, 2007) (6.9):

$$R(t) = e^{-\lambda t} \tag{6.9}$$

Where λ equals to 0.043. Therefore, the failure rate and reliability function is shown in Fig.6.9. It can be seen that the reliability decreases over the usability time when the failure rate is constant.

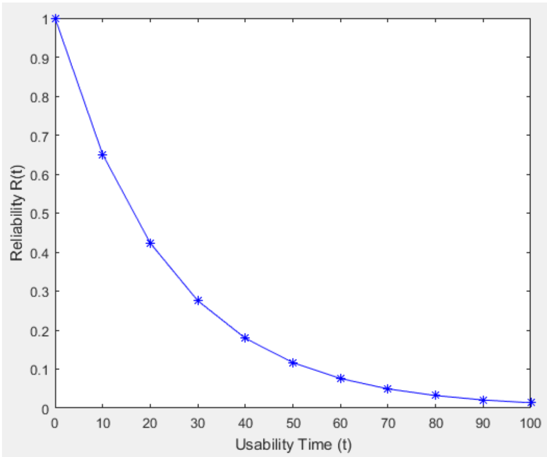

Fig.6.9 Failure rate and reliability function

To implement the maintenance work more scientifically and efficiently, building owners and estate managers made a maintenance cost plan for all curtain walls in the atrium (as shown in Table.6.3) based on the calculation results.

Table.6.3. Cost Plan for Fabric Maintenance of Curtain Walls

Maintenance property	**Western facade**	**Eastern facade**
Fabric component	curtain wall	curtain wall
Material	double-glazing	double-glazing
Number of curtain walls	48	46
Area (m^2)	171.36	164.22
Take-off quantity cost for replacement (RMB)	23,133.6	22,169.7
Labor cost for replacement (RMB)	7,711.2	7,389.9
Preventive maintenance cost (RMB/per time)	7,713.6	7,392.2
Inspection cost (RMB/per time)	6,172.8	5,915.6
Optimum preventive maintenance interval (week)	26.65	26.65
Cost per unit time (RMB/per week)	561.6	538.2
Replacement cycle length (week)	22.08	22.08

This maintenance cost plan mentioned above only indicates the current situation. Thus, the present value method, which has been applied to the maintenance cost analysis of facility management, is also proposed in order to help estimate the maintenance cost with the timeline of building lifecycle. The equation of the present value method is shown as below (Cummings, 2008) (6.10):

$$PV = FV \times \frac{1}{(1+r)^{n-1}} \tag{6.10}$$

Where PV is the present value, FV is the future value, n is the number of years and r is the real discount rate, which is obtained from the Central Bank of China and the value is equal to 2.25%. Therefore, the present values and the future value fluctuations, which are used for the maintenance cost estimation of the curtain walls in next ten years can be roughly estimated in 5D BIM and the results are shown in Table.6.4.

Table.6.4. Present Value and Future Value for the Maintenance Cost Estimation of Curtain Walls

For each curtain wall	Take-off quantity cost for replacement (RMB)	Labor cost for replacement (RMB)	Preventive maintenance cost (RMB/per time)
Present value	481.95	160.65	120.50
Year 2	492.79	164.26	123.21
Year 3	503.88	167.96	125.98
Year 4	515.22	171.74	128.82
Year 5	526.81	175.60	131.72
Year 6	538.66	179.55	134.68
Year 7	550.78	183.59	137.71
Year 8	563.18	187.73	140.81
Year 9	575.85	191.95	143.98
Year 10	588.81	196.27	147.22
Year 11	602.05	200.68	150.53

By using the same method, the maintenance cost plans for other building fabric components also can be made according to the 5D-BIM-based cost estimation and the empirical information from relevant projects.

The levels and the locations of preventive or corrective maintenance work depend on the comparison results between the reality capture provided by mobile laser scanning and the design model. Finally, when the maintenance plan is assessed through sensitivity analysis and then accepted by decision makers, the resources that are related to the maintenance plan will be identified and distributed to maintenance work in details through location systems and take-off planners, which are provided by 5D BIM.

6.4 Sensitivity Analysis

Sensitivity analysis is a commonly used method to determine and analyze uncertainties in the economic assessment of an AEC project. It aims to find out the sensitivity from lots of uncertainties that have significant impact on the economic benefit indicators of the building fabric maintenance. If the variance of an uncertainty can lead to a large change on the economic benefit indicators, this uncertainty can be called as a sensitivity (Hopfe, 2009). In this study, the uncertainty could be caused by multiple factors including labor, weather, environmental issue, equipment, fluctuation of rate, material price, etc. (Nikakhtar et al., 2012; Ofori et al., 2015). Here sensitivity analysis is conducted to validate the feasibility of the maintenance cost plan of the curtain walls by assuming and predicting these factors in the case study.

Usually for the assessment of the maintenance cost plan, the economic benefit indicators include net benefits, internal rate of returns, benefit-cost (B/C) ratios, etc. Common decisions for accepting or rejecting cost plans depend on the calculations of these three indicators (Stenström et al., 2015). In this study, a sensitivity analysis was conducted on the B/C ratio, which also can be understood as return of maintenance investment to compare costs and benefits for planning and decision-makings of activities (Nikakhtar et al., 2012). In addition, another reason of choosing B/C ratio as the key indicator is that PM can be assessed as a benefit from the maintenance investment and become more intuitive to perception through this ratio. Although this ratio has some limitations, such as its high sensitivity to negative values that are subtracted from benefits or added to costs, it is still appropriate to assess the value of the preventive maintenance as the benefit from unity investments (Stenström et al., 2015).

The main uncertainties that can have an impact on the B/C ratios are summarized into two parameters. One is the probability of detection (POD) of potential failure ($\alpha \in [0, 1]$) and the other is the potential to functional failure likelihood ($\beta \in [0, 1]$). The correlation between the B/C ratios and these two uncertainties can be expressed as follows (Stenström et al., 2015) (6.11):

$$\text{B/C} = \frac{B_{PM}}{C_{PM}} = \frac{\alpha\beta\bar{C}_F}{\bar{C}_I+\alpha\bar{C}_R} \tag{6.11}$$

Here B_{PM} is the benefit of preventive maintenance, C_{PM} is the cost of preventive maintenance, $\bar{C}_F$ is the mean cost of functional failure of maintenance object, $\bar{C}_I$ is the mean cost of inspection, and $\bar{C}_R$ is the mean cost of potential failure repair. Functional failures are closely related to the CM. Inspections and potential failures provide data for the PM (Stenström et al., 2015). To sum up, all these three mean costs are obtained from the initial cost estimation of building fabric maintenance. Furthermore, it is also known that the uncertainties of other maintenance related parameters can affect the B/C ratios due to their impacts on the three mean costs, such as the prices of fabric materials, labor costs, preventive costs, maintenance intervals, etc.

It also should be noticed that there is an interdependency between α and β; if the maintenance work becomes more strict to limit potential failures, then α will increase and β will decreases. Here α is also understood as the probability that an inspection has to lead to replacement or repair work. The maintenance of curtain walls was used as an instance to calculate the B/C ratio. According to the empiricism of regular inspections, α for curtain walls is approximately to 0.5 (47 potential failures from 94 inspections), and β is around 0.75, which is obtained from decision making through professional experts (Stenström et al., 2015). By using the estimated costs from maintenance plan, the B/C ratio for curtain wall maintenance is determined to be 1.15. As the ratio is larger than 1, it means the benefit is higher than the cost when such a maintenance cost plan is implemented. Therefore, the maintenance plan is still feasible and acceptable to decision makers although the ratio is not large.

6.5 Summary

The integration of 5D BIM with the developed indoor mobile laser scanning method provides a new idea to implement maintenance cost estimation and planning for building fabric components in practices in China. A conventional maintenance planning for building elements usually consists of four steps, including determination of maintenance objects (fabric components), arrangement of preventive and corrective maintenance work, plan analysis and maintenance resource identification. However, in the current situation, budgets for the maintenance work of buildings cannot meet the increasing maintenance needs any more due to outdated strategies and technical barriers (Shen et al., 1998).

Although it is unlikely that this problem can be solved completely, the low-cost semi-automated method developed in this chapter still provides an idea to make the cost estimation and planning of maintenance work more digital, more efficient and more reliable. To some extent, traditional workflows for design, construction, O&M and even demolition are outdated and their drawbacks are gradually enlarged, such as high waste, high cost, low efficiency, unstable performance, etc. Digitalization should be implemented throughout the building lifecycle to make it more sustainable, and meanwhile bring social and economic benefits. Although currently some steps of the workflows still highly depend on manual operations and calculations, the improvements on data collection, processing and analysis will be further made through the technique integration with artificial intelligence (AI). In addition, people who are concerned about the building O&M management in China are still looking for a balance between costs and long-term benefits, in order to make the phase sustainable. This study proposes a feasible and low-cost way to help them make more reasonable and scientific decisions by using advanced concepts and digital techniques.

CHAPTER 7: Development of a BIM-Based Panel Prototype for Cost Planning of Building Fabric Maintenance

7.1 Framework Design of the BIM-Based Panel Prototype

In this chapter, development of a BIM-based panel prototype will be introduced to implement the cost planning of building fabric maintenance in a more automated way for practical applications in China. The workflow of this panel prototype is designed according to the knowledge integration of 5D BIM and building maintenance. The aim of this panel prototype is to link the professional knowledge and empirical data with digital techniques and approaches, in order to make the conventional building maintenance planning more automated, faster and smarter to support the decision-makings, meanwhile reduce the probability of errors caused by manual operations.

For the framework application, this developed panel prototype uses two core computer-based languages – HTML and JavaScript, to realize web-based interactions and applications for building maintenance services. Both of them are also the worldwide-recognized key technologies for web-based services. HTML is the standard markup language to describe the structure of a functional web page (which can be understood as the web-based content presentation of the panel prototype) semantically and originally included cues for the appearance of the important documents (W3C, 2017). JavaScript is a high-level interpreted programming language that can execute the interactions on web pages and support imperative programming including object-oriented and prototype-based styles (Flanagan, 2011). On the detailed executions of the developed panel prototype, JavaScript-based programs can be embedded into the HTML document to implement the effects on behaviors and content presentation of the building fabric maintenance planning panel, which is executed as a web page (Rau and Cheng, 2013).

In addition, it is also necessary to ensure the geometric and the semantic information of the initial BIM model can be correctly transmitted to the panel prototype for background processing. Therefore, an official ISO data format named Industry Foundation Classes (IFC) is adopted in this study for realizing a consistent information flow between different BIM tools and implementing an extension for lifecycle costing (Fu et al., 2004). This decision was made after comparing various data formats, which are used for different BIM and CAD software in data transforming. Table.7.1 shows a summary of comparisons among different data formats (Chen and Clarke, 2017).

Table.7.1. Summary of Comparisons among Different Data Formats

	Geometric Information	**Semantic Information**	**Spatial Referencing**	**Level of Details (LoD)**
IFC	Parametric; BRep-boundary; Tessellation	Object support	Engineering; Geodetic	Level 0 - 5
CityGML	BRep-boundary	Object support	Engineering; Geodetic	Level 0 - 1
DXF/DWG	BRep-boundary; Tessellation	None or simple	Engineering	N/A
COLLADA	BRep-boundary; Tessellation	Object support	Engineering; Geodetic	User defined
X3D	BRep-boundary; Tessellation	None	Engineering; Geodetic	User defined
SVG	Only line and area	None	Engineering; Geodetic	User defined
KML	BRep-boundary	Only geodetic	Geodetic	User defined

From the table, it can be seen that IFC is the most comprehensive data format in supporting geometric information, semantic information, spatial referencing and level of detail for 3D representation compared with other formats (Chen and Clarke, 2017). In addition, IFC is also suggested as the main format to realize the delivery of transactable and interoperable data for future building projects according to BIM Level 3 as mentioned in Chapter Two (DassaultSystem, 2014). As the BIM modelling tool adopted in this study is Revit 2016, the corresponding version of the IFC format is IFC2×3, which was published by International Alliance for Interoperability (IAI) in 2006 (IAITech, 2009).

Commented [CC40]: Knowledge link between the implementation of BIM Level 3 concept and the developed workflow design.

The workflow design of the panel prototype is summarized as shown in Fig.7.1 and it is conceived as an integration of theories and empirical case studies to implement the development of the BIM-based panel prototype for building fabric maintenance. The idea of this workflow design was inspired by the maturity model of BIM Level 3 as shown in Fig.2.2, which shows the basic concept of using integrated web services ("BIM Hub") to link the BIM database with the project lifecycle management (PLM) platform for implementing sustainable management (DassaultSystem, 2014). This workflow design can be understood as a detailed extension of the BIM Level 3 concept for exploring its real value in practice. In addition, the current design mainly focuses on the BIM-based digitalization of building fabric maintenance. It can be further extended to provide an overall design of digital management workflow throughout project lifecycle including planning, design, construction, O&M phases. This refers to more complex multi-disciplinary coordination and heterogeneous data integration based on interoperable formats, which are the technical challenges of realizing BIM Level 3 and will be investigated in further studies.

Commented [CC41]: Knowledge link between the implementation of BIM Level 3 concept with the developed workflow design and further relevant studies.

According to the workflow design shown in Fig.7.1, the development of the panel prototype can be divided into three main steps. The first step is a preparation step, which is to determine the building fabric components that need maintenance behaviors through intuitive visual check or 3D imaging technologies such as laser scanning and photogrammetry (GSA, 2009). Then key information of the determined components such as take-off quantity and unit rate can be extracted from the initial BIM model as an input and a Web SQL (Structured Query Language) database (Mensah, 2006). This database is designed as a SQLite according to the encoding specification of HTML5, which can support direct access to the SQL database without using a web server (Gutiérrez, 2018). This can highly improve the efficiency of data access and processing. This Web SQL database enables the management of (store, entry, extract.) massive client data related to building fabric maintenance (Chatham, 2012) with high efficiency of access and processing. These client data come from two sources: one is the empirical project and the other is the simulation of Weibull Distribution analysis (Weibull, 1951).

However, this step faces a main technical barrier, which is how to extract the complete take-off quantity information from the BIM model and then share it with other tools or programs for further interactions. Therefore, a potential solution is to adopt IFC format to support the extraction, transfer and entry of the BIM model data (Sampaio and Simões, 2014). The geometric and semantic information of the selected building fabric components then can be extracted into an IFC file for the preparation of the next step.

The second step is an execution step. This step integrates the take-off quantity information from IFC files with the data like unit rate extracted from the SQL database through a JavaScript Application Programming Interface (API), which allows users to access the database and execute relevant operations such as query and extract. In addition, it is applicable to use the JavaScript to encode functions based on the calculation formulas of Weibull Distribution and quantity take-off. Then the specific data outputs such as TQ-based cost and PM cost can be automatically calculated by invoking those formula functions. Such automatic data calculations are much faster and more accurate than manual calculations. Meanwhile labor and time costs on complex calculations can be highly reduced through the JavaScript-based programming. Furthermore, an extra API is also provided to support the geometric data interaction between the IFC files and OBJ files (a file format of 3D modelling), in order to realize 3D representations of BIM models by Web Graphic Library (WebGL) in the context of HTML5 and JavaScript (Xia et al., 2016).

Commented [CC42]: Explanation of the "Data Calculation" based on JavaScript in the workflow design.

The third step is to present the calculated results on a web page to support the decision making on building fabric maintenance planning. Through the data calculations at the second step, different costs and optimum maintenance interval that is calculated according to CM/PM ratio function and parameters provided by the SQL database, can be determined to provide key information for the preliminary maintenance plan for the selected building fabric components. Meanwhile, the 3D visualization of BIM model and the animation of maintenance schedule can be implemented under the support of WebGL (Xia et al., 2016).

When feasibility and reliability of the maintenance plan are validated or further it is accepted by building owners and managers, the information of the plan would be conceived as empirical data to update the SQL database. Similarly, any adjustment or correction from the decision makers will be regarded as feedback to the database in order to ensure its timeliness and data accuracy.

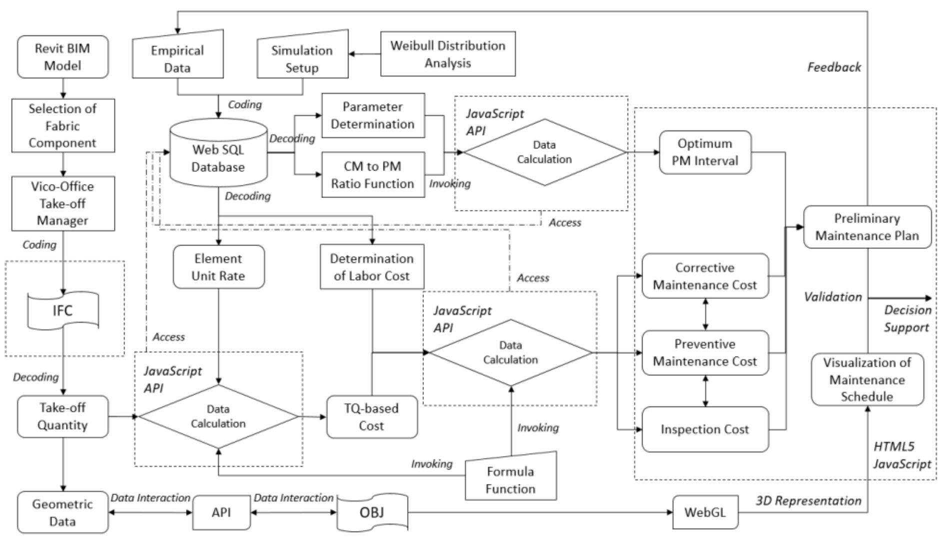

Fig.7.1 Workflow design of the BIM-based panel prototype for cost planning of building fabric maintenance

7.2 Development of the Panel Prototype

To implement the maintenance planning according to the workflow design, first the curtain wall components were all selected and filtered from the initial BIM model of the atrium as shown in Fig.7.2.

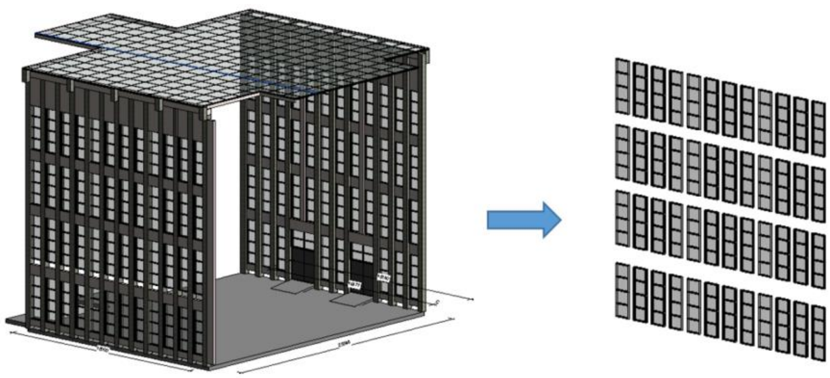

Fig.7.2 Select and filter the curtain wall components of the western façade

Then the selected building fabric components were imported into the Vico Office tool for the information management of the corresponding take-off quantity, including the geometric recognition, calculation of quantity, classification of component type, etc. The curtain walls on the western façade were selected and then exported into an IFC file that can be checked on any IFC-support viewers in an IFC-based building component structure as shown in Fig.7.3 or in a 3D model presentation of selected curtain walls as shown in Fig.7.4 for intuitive visualization.

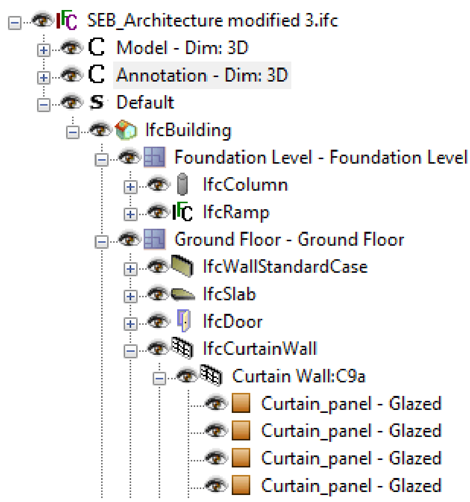

Fig.7.3 IFC-based building component structure

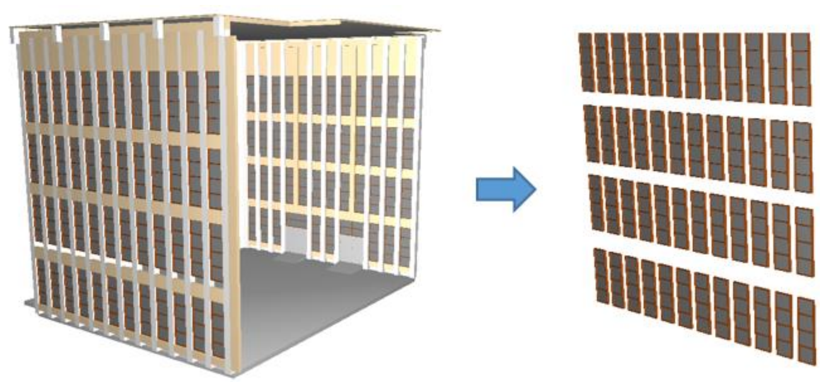

Fig.7.4 3D model presentation of the whole building model (left) and the selected curtain walls (right) in an IFC viewer

For the management of empirical data and simulation settings, we classified essential information of building fabric maintenance into two tables accoridng to component types, Weibull parameters, locations, materials, take-off quantities, unit rate, labor cost, etc (as shown in Table.7.2 and Table.7.3). These tables are integrated as the basic components of the SQL database.

Table.7.2. "Building Fabric Component" Table for SQL Database (Part)

Element ID	Element	Unit	Shape Parameter	Scale Parameter	Location Parameter	CM/PM
0001	Structural Wall	m^3	2	60	20	3.5
0002	Architectural Wall	m^3	2	60	20	3.5
0003	Curtain Wall	m^2	2.5	30	10	4
0004	Column	m^3	5	50	20	4
0005	Beam	m^3	5	50	20	4

Table.7.3. "Curtain Wall Component" Table for SQL Database (Part)

Element ID	Element	Location	Material	TQ	Unit	Unit Rate	Labor Cost
CW001	Curtain Wall	First Level West 1	Double Glazing, Stainless Steel Frame	3.57	m^2	135	45
CW002	Curtain Wall	First Level West 2	Double Glazing, Stainless Steel Frame	3.57	m^2	135	45
CW003	Curtain Wall	First Level West 3	Double Glazing, Stainless Steel Frame	3.57	m^2	135	45
CW004	Curtain Wall	First Level West 4	Double Glazing, Stainless Steel Frame	3.57	m^2	135	45
CW005	Curtain Wall	Second Level West 1	Double Glazing, Stainless Steel Frame	3.57	m^2	135	45

The operations on the SQL database are divided into DML (Data Manipulation Language) part and DDL (Data Definition Language) part. DML is used to access the database and manipulate the object data. DDL is developed to define the type and the structure of the object data that are stored in the database. The key operation clauses for the management of the SQL database are listed as shown in Fig.7.5 and they help realize the extraction of key data for maintenance planning and the entry of new empirical and simulation data.

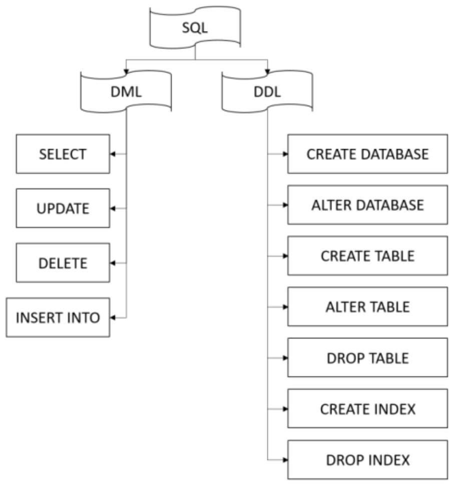

Fig.7.5 DML and DDL for operations on SQL database

The next step was to combine the input data with pre-defined formula functions to calculate relevant maintenance costs or intervals in the context of the case study. For instance, the curtain walls on the western façade of the atrium were selected and the parameters required to determine the take-off quantity of the selected curtain walls were extracted from the IFC file, and then input into a created JavaScript-based program to execute the calculation of the take-off quantity according to the pre-defined formula function (part of the program is shown in Fig.7.6).

```
<script>
function myFunction1()
{
    height=3.4;
    width=1.05;
    number=48;
    x1=height*width*number;
    x1=Math.round(parseFloat(x1)*10000)/10000;
    document.getElementById("demo1").innerHTML=x1;
}
```

Fig.7.6 JavaScript-based program (part) for automatic calculation of take-off quantity

After the calculations were executed through the JavaScript-based programs, a functional HTML document that the programs are embedded into was created to realize a content presentation of the required maintenance information on the planning panel prototype, which is executed as a web page.

7.3 Commissioning of the Developed Panel Prototype

After the calculations were executed through the JavaScript-based programs, a functional HTML document that the programs are embedded into was created to realize a content presentation of the required maintenance information on the planning panel prototype, which is executed as a web page.

Fig.7.7 shows the basic operation interface of the web-based panel prototype through an instance of how to obtain the take-off quantity information of the selected curtain walls by using the planning panel prototype: first step is to select the type of building fabric component, then just click on the execution button, later the calculation result is automatically presented on the panel with a numeric value and a corresponding take-off unit.

Similarily, through the interactions executed by JavaScript and content presented by HTML, it is also able to directly obtain other information related to the building fabric maintenance, such as unit rate of component, corrective maintenance cost, preventive maintenance cost, inspection cost, optimum preventive maintenance interval, etc. We used the curtain walls on western façade as an instance for commissioning test, and some test results are shown in Fig.7.8. In addition, to determine the optimum preventive maintenance time, it is also available for manual input of parameter values according to users' preference in order to avoid the limitations caused by database (as shown in Fig.7.9).

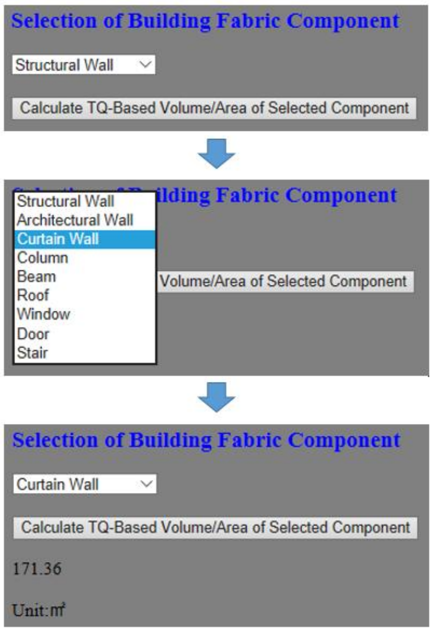

Fig.7.7 Automatic calculation of component take-off quantity on the planning panel prototype

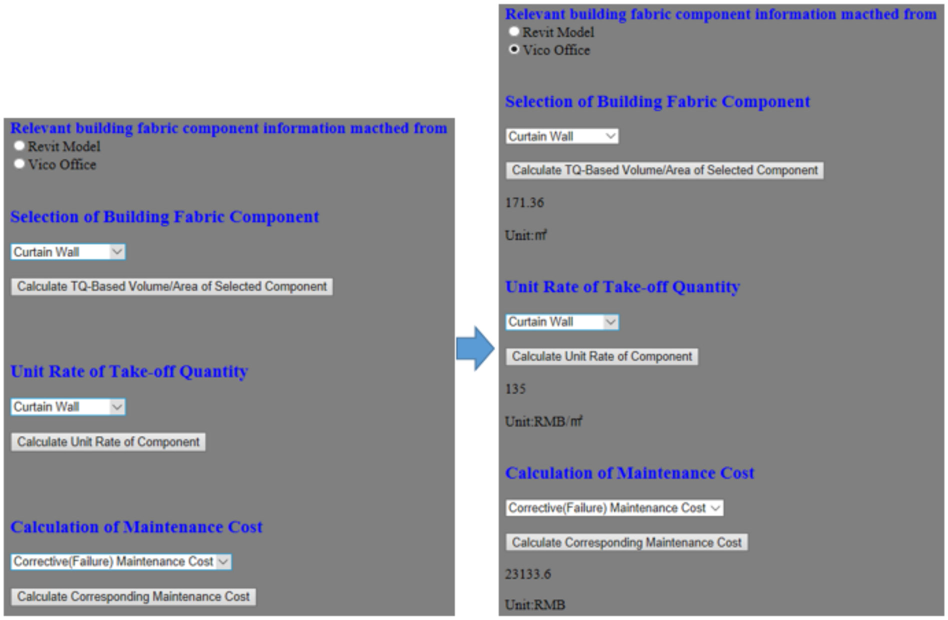

Fig.7.8 Commissioning test of selected fabric component (curtain walls on western façade)

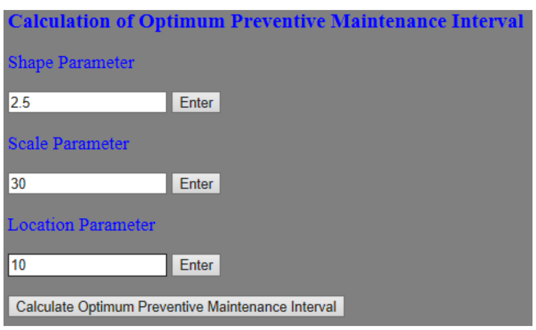

Fig.7.9 Manual input of parameter values

Furthermore, the prototype also provides a 4D schedule simulation based on the optimum preventive maintenance interval. Fig.7.10 indicates a function of execution sequence of fabric maintenance work. For instance, if the sequence is from ground level to top level, then Fig.7.11 and Fig.7.12 show a schedule simulation of the maintenance activities from the ground floor to the third floor of the atrium (yellow-color components are the repaired curtain walls) with Gantt chart and animation respectively. Due to the optimum interval equals to 27 (26.65) weeks, so the CM work starts from Week 28.

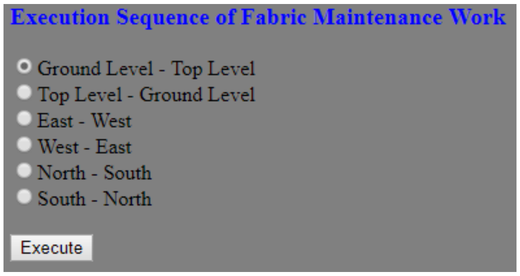

Fig.7.10 Execution sequence of fabric maintenance work

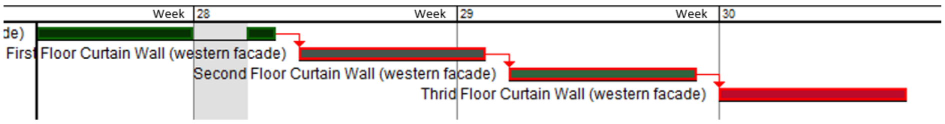

Fig.7.11 Gantt chart of maintenance work schedule

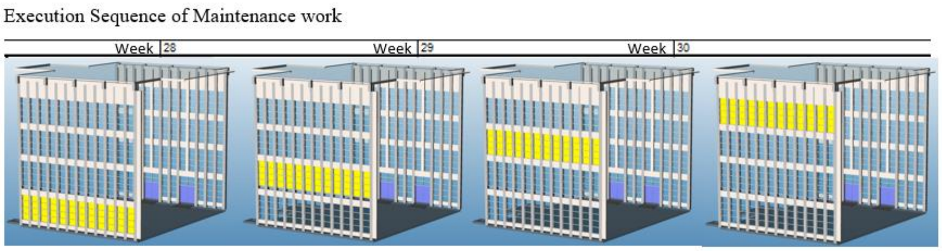

Fig.7.12 Animation of maintenance work schedule

Users can also check the cash flow within the progress of the CM work as shown in Fig. 7.13. It indicates a stable increase of maintenance cost with schedule due to the amount of the maintenance work for each floor is the same. This cash flow can help owners or managers to monitor the change of the maintenance cost according to the work schedule.

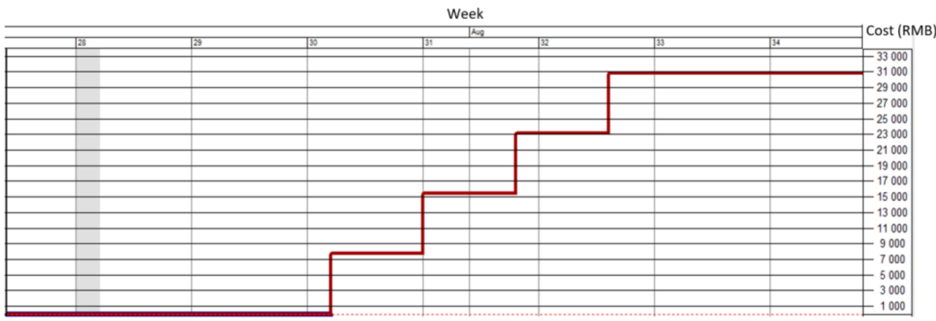

Fig.7.13 Cash flow of the corrective maintenance (CM) cost of the curtain walls on the western façade

Through the test based on the case study, it is found that the execution of automatic calculation on this panel prototype only took 3 - 4 seconds and the accuracy of preliminary calculations reached 100% compared with the results from manual calculations. In current, the only potential error source is the extraction of fabric component data from IFC files due to the geometric recognitions and classifications. Although it is still necessary to further demonstrate the reliability of this panel prototype in more practical projects that are under more complex maintenance conditions, the commissioning results preliminarily demonstrates the feasibility of this novel idea. It cannot be denied that such digital implementation is more convenient and faster than traditional manual calculations.

Compared with traditional workflow methods for the implementation of building fabric maintenance, this BIM-based panel provides a faster, smarter, more digital and automated approach to realize a feasible and reliable planning for the building fabric maintenance in a Chinese case study. The commissioning result of this panel prototype not only indicates a successful integration of heterogeneous system data (such as IFC files, SQL tables, HTML files, texts, etc.) and multi-disciplianry tools (Revit, Vico Office and JavaScript), but also preliminarily demonstrates the feasibility and the reliability of the workflow design for BIM-based building fabric maintenance planning.

However, this study also exposes some limitations on both technical and economic levels. On technical level, the current workflow design is still lengthy due to the complex data transfer from Revit model to

Vico Office, and finally to JavaScript-based programs. A Revit-based maintenance plugin may be a better option to avoid the issues of data consistency and reduce the intermediate steps for data transfer to improve the efficiency. In addition, with the growth of the database and the deepening of the workflow design, AI could be a future way to help improve the overall performance of such BIM-based maintenance work by reducing manual interventions. On economic level, the extension of the SQL database requires lots of empirical data from relevant projects and this refers to a cooperation assurance with relevant AEC companies or institutes who provide empirical data, or the share of the SQL database needs to be charged. Furthermore, the routine maintaining and the updating of the planning panel also needs the input of manpower and resouces and that would lead to an extra cost fee.

Even there is still a long way to realize the digitalization of traditional building O&M phase, this study still provides a novel idea to help promote the applications of computer-based technologies (BIM and programming) on practical productions. In addition, 3D imaging technologies such as the developed mobile laser scanning method that is mentioned in previous chapters, also can be combined with the panel prototype to realize a seamless data integration between reality captures and design. More improvements on this panel prototype will be investigated in further studies.

CHAPTER 8: Conclusion

8.1 Research Objectives

The research objectives that have been achieved in this study are summarized as followings:

I. Reviewed the current situations of global and China's BIM development and found out potential applications of BIM in different project phases, particularly in O&M phase of China's AEC project lifecycle;

II. Determined the impact factors that can result in uncertainties to influence the construction process and even the later maintenance stage, then successfully developed a 5D BIM-based forecast system for predictions of uncertainties caused by these impact factors;

III. Successfully integrated IMU and UWB positioning systems with a low-cost 2D laser scanner to realize a low-cost and time-saving mobile laser scanning for a case study of indoor mapping and digital modelling in China;

IV. Conducted a TLS-based reference experiment for the comparison of the scan results between the developed mobile laser scanning and traditional TLS under the same experimental conditions to ensure the reliability of MLS for further practical applications in building fabric maintenance;

V. Developed an efficient and low-cost method based on the integration of 5D BIM with mobile laser scanning for cost estimation and planning of building fabric maintenance in the case study;

VI. Validated the feasibility of the maintenance planning obtained from the low-cost BIM/laser scanning integrated method by using the case study, then a BIM-based panel prototype was successfully developed in order to implement automated cost planning of building fabric maintenance for practical applications in China.

Commented [CC43]: Modification of achieved research objectives in this study.

8.2 Research Deliverables

Research deliverables from this study consist of two types –paper publications and patent application. Paper publications include three conference papers (already published) and three journal papers (one already accepted for publication, two under review). For conference papers, two focus on the development of multi-dimensional BIM-based workflow for improving design coordination and overall productivity throughout China's AEC project lifecycle and the other one is about the integration of mobile laser scanning with BIM for indoor mapping and digital modelling. For the accepted journal paper, it introduces the development of a low-cost and time-saving mobile laser scanning method for construction indoor mapping and modelling. For the journal papers under review, one elaborates the investigation of impact factors in construction process and further development of forecast system based on the investigation results. The other one proposes the development of a BIM-based panel prototype for cost planning of building fabric maintenance in a local case study.

The patent application is based on the development of an innovative forecast system for variance prediction and production control of real construction process, which can be further linked with the later maintenance stage to explore common factors that can influence both project construction and O&M phases in China. This patent also can be regarded as an outcome from the collaboration with relevant BIM software development team. In addition, the patent is also a key deliverable of a NSFC project in China, which has been successfully completed by the end of May, 2018.

8.3 Limitations

Due to the limitations of major background and research budget, this study still can be further improved and extended in technical, economic and normative aspects. In technical aspect, other types of portable 2D laser scanners from various manufacturers are suggested for a comparative study to improve reliability and accuracy. However, their performance still cannot reach the same level as 3D laser scanners due to the cost difference (Wulf et al., 2004). Actually, Leica Geosystems has already developed a mobile mapping backpack system named Leica Pegasus, which uses five cameras and two portable laser scanners to implement reality capture from indoor environments with high positioning accuracy and colored textures based on SLAM (Masiero et al., 2018). It also supports direct transformations between raw scan results and Recap point cloud models. It definitely simplifies the data processing of 3D point cloud and meanwhile ensures the quality of results. Nevertheless, there are still issues about the large dimensions of the equipment for back carrying and the high cost due to high-performance sensors and cameras. It is estimated that the price is over 1,000,000 RMB (LeicaGeosystemsAG, 2018).

In addition, the laser scanning result from the conventional TLS, which was regarded as a reference, has shown a high-quality performance when it was compared with the result from the developed indoor mobile laser scanning. As the data collection and processing of the developed method comprises of a number of steps, at which the deviations from different error sources (such as manual operations, data transformation, algorithmic generation, etc.) would accumulate and lead to the final discrepancy between the reality capture from the developed method and the conventional TLS.

Furthermore, this study only focuses on the scan of curtain walls, which are exposed building fabric components and measured with areas. It is difficult to only use the developed mobile laser scanning method to obtain the scan of other fabric components such as columns and beams that are buried inside. Therefore, a projection method could be combined with the current mobile laser scanning to realize the conversion of 3D point clouds (volume-based) to 2D profile images (area-based) through spherical projection under a scan environment of sphere around the scanner (K¨ashammer and N¨uchter, 2015). This combination will be helpful to further maintenance studies of other building fabric components that are measured with volumes, such as walls, columns, beams, etc.

Commented [CC44]: Limitations and a potential solution of the scan of buried building fabric components such as columns and beams.

It is also found that the laser scanner and the 5D BIM software that were used in this study still requires a lot of manual operations and manipulations to realize the integration of heterogeneous data. Nevertheless, this resulted in errors during the data collection and processing. Although algorithms developed in this study have implemented semi-automations in several steps of the whole technical workflow, more automated algorithm-based operations are desired to make the workflow smarter and faster in order to save time and labor input. This requires high-level skills of computer programming and it is difficult to be realized in this study due to the major background.

Additionally, this study focuses on the digital maintenance cost estimation and planning of building fabric components, which were rarely investigated before, compared with functional building systems like MEP systems. Therefore, the analysis methods applied into the study of fabric maintenance need further validations in more different case studies in China, and even modifications according to specifications of various building fabric components under different built environments. Moreover, the developed panel prototype still needs more improvements and tests under practical conditions and the framework design of the web-based panel also needs to be modified after there is a breakthrough on seamless transformation between heterogeneous system data.

In economic aspect, the budget has limited the purchase of new hardware and updating of software. Although low cost is a main merit that has been realized in this study, higher-cost hardware and software definitely can improve accuracy and reliability of study results when the increase of capital cost is acceptable and still much lower than that of conventional TLS technique, even there will be a decrease on the cost of TLS due to the rapid development.

In normative aspect, currently most of specification manuals and standards for building maintenance are only used for building MEP systems, replacement and repair regulations for building fabric components are few and this can affect regulatory implementations of maintenance work. Moreover, a uniform data format also should be specified to help simplify the data transfer process between heterogeneous systems at different workflow steps, and meanwhile implement seamless data integration according to China's local standards to avoid information loss and inconsistency.

8.4 Future Work

This study introduces a low-cost mobile laser scanning method for indoor mapping and digital modelling, which is integrated with 5D BIM to implement a feasible and reliable cost estimation and planning for building fabric maintenance based on a typical case study in China. This method is regarded as an integration outcome based on multi-disciplinary researches, including low-cost indoor positioning approaches, development of low-cost and time saving indoor mobile laser scanning, BIM-based workflows for building lifecycle and maintenance management, integration of the mobile laser scanning with 5D BIM, maintenance cost estimation and planning of building fabric components and the development of framework application of the BIM-based panel prototype. Information from different systems was digitalized and integrated with the assistances of various research tools and algorithmic solutions in this study.

The result of this study indicates that 3D scan data with an efficient quality from the developed low-cost mobile laser scanning method can be integrated with 5D BIM for maintenance cost planning of building fabric components under an indoor environment. The feasibility and reliability of such an application based on heterogeneous data integration has been preliminarily validated in a typical case study in China.

However, although the feasibility and the reliability of the mobile laser scanning method proposed in this study has been preliminarily validated, there are still some technical and economic issues that need to be solved in further studies. As the sensors were mounted on a trolley that was driven manually, it had an anthropogenic impact on the motion states of the trolley. Therefore, robots with high stability can be considered as the mobile platform for the sensors (Wulf et al., 2004). The only concern is about the cost. Moreover, if the equipment cost increases within an acceptable range, we are planning to purchase a higher efficient 3D laser scanner which is portable for construction indoor mapping and still much cheaper than high-performance TLS scanner. Its application will be used as a case study and compared with the integration method of positioning approaches and 2D laser scanner, in order to investigate that which way is better in both technical and economic aspects.

Furthermore, low cost and short duration are the merits of the developed mobile laser scanning method, current the study only focuses on the laser scanning technique without cameras. It is known that the photogrammetry based on digital cameras can provide detailed information such as colors and textures for the building component (Balsa-Barreiro and Fritsch, 2018). In further studies, this developed MLS method can be combined with a digital camera to provide better and more detailed results for indoor mapping and modelling.

In addition, a secondary development of BIM software for specific building maintenance application is also required to create a collaborative platform, which will provide simulation, monitoring, inspection and maintenance for building components. Other AI-related potential algorithms or methods are also expected to be involved for the practical applications of such BIM-based maintenance workflow. These algorithms and methods require lots of empirical data about maintenance management from real China's AEC projects. With the accumulations of empirical experience, the AI algorithms can help realize automated data processing, data analysis and result assessment of the integrated workflow method.

Particularly for building maintenance part, this study mainly focuses on the maintenance of fabric components. The scan for MEP systems also can be integrated with N-D BIM to design a similar maintenance management workflow. It is anticipated that the internal structures of fabric components, such as the buried columns and beams mentioned above, also can be inspected by such a low-cost and time saving scan method but with high reliability and accuracy.

Moreover, in this study, it has been emphasized that O&M phase has a tight connection with design and construction phases. Not only the management performances during design and construction phases can affect the maintenance plan and work in the early stages, but also the maintenance, particularly the deferred maintenance, which requires a long duration maybe throughout the entire project lifecycle, can highly influence the normal construction schedule and the site access during construction process due to budget limitations, the availability of access, inclement weather, etc. They are the common factors that can have high impacts on both construction and maintenance managements. Therefore, a potential solution for reducing such negative interdependence between construction and maintenance phases is to establish a BIM-based interactive management system that can consider the maintenance in the early stage of construction and meanwhile provide appropriate strategies to minimize the impacts of those common factors.

Commented [CC45]: How to address the issues caused by negative interdependence between the deferred maintenance and the construction phase.

In the near future, with implementations and extensions of BIM-based maintenance management in various

China’s AEC projects, relevant workflow standards and regulations also will be developed to ensure the quality of maintenance work, and meanwhile provide facility management services based on N-D BIM throughout the project lifecycle. The results of this study indicate that BIM and other advanced technologies can make a significant contribution to the renovation and digitalization of traditional AEC industrial management pattern for narrowing the gap between global advanced development level and China’s local development level. More adoptions of new digital technologies are expected to help realize the values of information for the sustainable developments of both industry and society in the future.

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Appendix 1: Matlab Programing Code for Data Processing of IMU Measurement, UWB Coordination Transformation, SICK Laser Scanning and Integration of Sensors

IMU-based Positioning by SL calculation

```
%data input:
ins_file = 'C:\Users\zx20391\Desktop\7-3-2018-imu-test3.txt';
ins=importdata(ins_file);
Acc=ins.data(:,[7:9 4]);
Gyr=ins.data(:,[10:12 4]);
samples=5000;  % asumo 50 segundos parado (y fs=100 Hz)
bias_Gyr=[mean(Gyr(1:samples,1)), mean(Gyr(1:samples,2)),
mean(Gyr(1:samples,3))];
Gyr_unbiased=Gyr;  %[nx4]
Gyr_unbiased(:,1:3)=[Gyr(:,1)-bias_Gyr(1), Gyr(:,2)-bias_Gyr(2), Gyr(:,3)-
bias_Gyr(3)];

% Apply INS to obtain Pos,Vel y Att:
disp('Apply SL+theta PDR...');
%-----Step detection------
idx_fig=20;
%[Num_steps,Step_events,StancePhase,idx_fig]=StepDetection_Acel(Acc,1,idx_fig
);
[Num_steps,Step_events,StancePhase,idx_fig]=StepDetection_Acel_smartphone(Acc
,1,idx_fig);
%-----SL-theta-----------
%[StrideLengths, Thetas,
Positions,idx_fig]=Weiberg_StrideLength_Heading_Position(Acc,Gyr,Step_events,
StancePhase,1,idx_fig);
[StrideLengths, Thetas,
Positions,idx_fig]=Weiberg_StrideLength_Heading_Position(Acc,Gyr_unbiased,Ste
p_events,StancePhase,1,idx_fig);
```

Transformation from UWB frame to global frame

```
% coodinate a (UWB frame)
% There are 6 UWB receivers, therefore 6 coordinates of these receivers are

a=[-5.404   13.864  9.505
6.853   14.278  9.542
9.895   4.271   9.461
9.961   -9.193  9.421
-13.031 -9.194  9.402
-13.038 4.259   9.413];

%coordniate b (global frame)

b=[360545.3498  3297831.8741    24.1535
360557.5614 3297830.8053    24.1905
360559.3741 3297820.5039    24.1101
360557.8128 3297807.1332    24.0711
360534.9896 3297809.9170    24.051
360536.6144 3297823.2663    24.0619];

a1=[1 0 0 a(1,1) 0 -a(1,3) a(1,2)
    0 1 0 a(1,2) a(1,3) 0 -a(1,1)
    0 0 1 a(1,3) -a(1,2) a(1,1) 0];

a2=[1 0 0 a(2,1) 0 -a(2,3) a(2,2)
    0 1 0 a(2,2) a(2,3) 0 -a(2,1)
    0 0 1 a(2,3) -a(2,2) a(2,1) 0];

a3=[1 0 0 a(3,1) 0 -a(3,3) a(3,2)
    0 1 0 a(3,2) a(3,3) 0 -a(3,1)
    0 0 1 a(3,3) -a(3,2) a(3,1) 0];
a4=[1 0 0 a(4,1) 0 -a(4,3) a(4,2)
    0 1 0 a(4,2) a(4,3) 0 -a(4,1)
    0 0 1 a(4,3) -a(4,2) a(4,1) 0];
a5=[1 0 0 a(5,1) 0 -a(5,3) a(5,2)
    0 1 0 a(5,2) a(5,3) 0 -a(5,1)
    0 0 1 a(5,3) -a(5,2) a(5,1) 0];
a6=[1 0 0 a(6,1) 0 -a(6,3) a(6,2)
    0 1 0 a(6,2) a(6,3) 0 -a(6,1)
    0 0 1 a(6,3) -a(6,2) a(6,1) 0];

A=[a1;a2;a3;a4;a5;a6];
B=[b(1,1);b(1,2);b(1,3);b(2,1);b(2,2);b(2,3);b(3,1);b(3,2);b(3,3);b(4,1);b(4,
2);b(4,3);b(5,1);b(5,2);b(5,3);b(6,1);b(6,2);b(6,3)];
X=inv(A'*A)*A'*B;
m=X(4,1)-1;
w_x=X(5,1)/X(4,1);
w_y=X(6,1)/X(4,1);
w_z=X(7,1)/X(4,1);
X1=[X(1,1);X(2,1);X(3,1);m;w_x;w_y;w_z];

% only choose 4 coordinates
```

```
A=[a1;a2;a3;a4];
B=[b(1,1);b(1,2);b(1,3);b(2,1);b(2,2);b(2,3);b(3,1);b(3,2);b(3,3);b(4,1);b(4,
2);b(4,3)];
X=inv(A'*A)*A'*B;
m=X(4,1)-1; %  sep.scale = mtrResult[3, 0],-1 because 1 is the initial
reference scale; ;
w_x=X(5,1)/X(4,1);% sep.Ex = mtrResult[4, 0]/ sep.scale;
w_y=X(6,1)/X(4,1);% sep.Ey = mtrResult[5, 0] / sep.scale;
w_z=X(7,1)/X(4,1);% sep.Ez = mtrResult[6, 0] / sep.scale;
X2=[X(1,1);X(2,1);X(3,1);m;w_x;w_y;w_z]; % X(1,1),X(2,1),X(3,1) are the delta
translation on x,y and z axis;

% from UWB frame coordinate (X1,Y1,Z1) to global (navigation) frame
coordinate (X2,Y2,Z2),
% [X2,Y2,Z2]= (1+m)*[1 w_z -w_y;-w_z 1 w_x;w_y -w_x 1][X1,Y1,Z1] +
[X(1,1);X(2,1);X(3,1)]

uwb_2=csvread('C:\Users\zx20391\Desktop\24_01_18\test2_335584499_UWB.csv',1,0
);
UWB_2(:,1)=uwb_2(:,1);
UWB_2(:,2)=(1+m)*(uwb_2(:,2)+w_z*uwb_2(:,3)-w_y*uwb_2(:,4))+X2(1);
UWB_2(:,3)=(1+m)*(uwb_2(:,2)*(-w_z)+uwb_2(:,3)+w_x*uwb_2(:,4))+X2(2);
UWB_2(:,4)=(1+m)*(uwb_2(:,2)*w_y-w_x*uwb_2(:,3)+uwb_2(:,4))+X2(3);
UWB_2(1,1)=27013.0870;
for i=2:size(UWB_2,1);
    UWB_2(i,1)=UWB_2(i-1,1)+0.108;
end
save('UWB_2','UWB_2');

scatter(UWB_2(:,2),UWB_2(:,3),'b.');
```

Extraction of SICK scan data

```
%% Define user parameters here
% Unfortunately some things are still hard coded in this script, such as
% the maximum and minimum angle setting.
sick_file = 'C:\Users\zx20391\Desktop\24_01_18\24_01_18_2_SICK.csv';

angle_min = -5;
angle_max = 185;
angle_res = 0.5;
samples = (angle_max - angle_min) / angle_res;
angles = angle_min:0.5:angle_max;

%% Load the dataset into the workspace
% A default csv file has column names on the first line, but their names
% are too long to use properly as MATLAB table headers. Therefore, this
% script skips them and uses the default Var# column names. The column
% numbers are unfortunately hardcoded in the rest of this script.
T = readtable(sick_file, 'Delimiter', ';', 'HeaderLines', 1, ...
    'ReadVariableNames', false);

%% Perform some simple sanity checks on the loaded data
% The DIST# columns are at 25 + n*1146 for n = 0, 1, 2, 3, 4
% The RSSI# columns are at 25 + n*1146 for n = 10, 11, 12, 13, 14
% Relationship: 1146 = 191 samples at min 1/6 degree angular resolution
for n = 0:4
    assert(isequal(unique(table2array(T(:, 25+n*1146))), ...
        {['DIST', num2str(n+1)]}), 'not a DIST# column');
end
for n = 10:14
    assert(isequal(unique(table2array(T(:, 25+n*1146))), ...
        {['RSSI', num2str(n-9)]}), 'not a RSSI# column');
end
%% Extract the date and time and into UTC
% There is a bug in some MATLAB versions that causes the CST timezone to
% not be properly recognised. A simple fix is to remove it as the time
% offset is also given between brackets.
if strfind(T.Var2{1}, 'CST')
    dt_fmt = 'yyyy-MM-dd HH:mm:ss.SSS (Z)';
    dt = datetime(strrep(T.Var2, 'CST', ''), 'TimeZone', 'UTC', 'Format',
dt_fmt);
else
    dt_fmt = 'yyyy-MM-dd HH:mm:ss.SSS z(Z)';
    dt = datetime(T.Var2, 'TimeZone', 'UTC', 'Format', dt_fmt);
end

% Ignoring the date here! Be careful with that!
tod = seconds(timeofday(dt));

%% Extract only the data from the first return
scale_factor = unique(T.Var26);
scale_offset = unique(T.Var27);
assert(scale_offset == 0, 'scale offset other than 0 found')
```

```
start_angle = unique(T.Var28);
res_angle = unique(T.Var29);

assert(angle_min == start_angle/10000, 'angular resolution mismatch')
assert(angle_res == res_angle/10000, 'angular resolution mismatch')

% The scale factor is taken into account, a possible scale offset is not.
% The main reason for the latter is that I haven't seen one yet...
% 30 = 25 + 0*1146 + 5
dist1 = repmat(table2array(T(:,26)),1,samples+1) .* table2array(T(:,
30:30+samples));
% 11490 = 25 + 10*1146 + 5
rssi1 = repmat(table2array(T(:,11486)),1,samples+1) .* table2array(T(:,
11490:11490+samples));

%% The data can quickly be filtered here
% The following will for instance remove distances larger than 80m, i.e.
% the specified maximum scanning range of the LMS511.
dist_filter = dist1 > 80000;
dist1(dist_filter) = NaN;
rssi1(dist_filter) = NaN;

%% Calculate the position of each point
% No for-loop, ridiculously fast on a complete array :-)
%repmat(cosd(angles),size(dist1)./size(cosd(angles)))
x = (dist1 .* repmat(cosd(angles),size(dist1)./size(cosd(angles)))) / 1000;
y = (dist1 .* repmat(sind(angles),size(dist1)./size(sind(angles)))) / 1000;
% plot(x(1,:), y(1,:), 'r.')
sind(angles);
% axis equal

%% Provide each sample with a time
% How to do this? Does the first measurement correspond with the time from
% the second column?

scan_freq = unique(T.Var17) / 100; % Hz

% Inverse of the time between two measurement shots (in 100 Hz)
% Example: 50 Hz, 0.5?resolution -> 720 shots/20 ms -> 36 kHz
meas_freq = unique(T.Var18) * 100; % Hz
a=repmat(tod,1,samples+1);b=repmat((0:samples) / meas_freq,size(tod,1),1);
timestamps=a +b;

%% Create a matrix with time, x, y, i and save it
sick = [reshape(timestamps', [], 1), reshape(x', [], 1), ...
    reshape(y', [], 1), reshape(rssi1', [], 1)];

save('sick.mat', 'sick');
```

Integration of IMU, UWB and laser scan data (Algorithmic Solution 1)

```
% IMU UWB SICK integration
%% Enter the filenames to use here
ins_file = '24_01_2018_test_2.txt';
load 'sick.mat';
load 'UWB_2.mat';

%% Load the INS data file
ins = readtable(ins_file, 'Delimiter', '\t', 'CommentStyle', '//', ...
    'Format', '%u%u%u%f%d%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%d');

% The following loop removes the columns that only contain zero values
ins_variable_names = ins.Properties.VariableNames;
for k = 1:numel(ins_variable_names)
    if unique(ins.(ins_variable_names{k})) == 0
        ins.(ins_variable_names{k}) = [];
    end
end
% then rotation matrix (Cbn) is used to convert the vector from body frame to
% global frame
for i=1:size(sick,1);
    [X I]=min(abs(ins.Second-sick(i,1)));
    [Y J]=min(abs(UWB_2(:,1)-sick(i,1)));
    if X<=0.1||Y<=0.1 ;


PSI_nb(3)=ins.Yaw(I)*pi/180;PSI_nb(2)=ins.Pitch(I)*pi/180;PSI_nb(1)=ins.Roll(
I)*pi/180;
    C1 = [  1              0            0           ;...
        0       cos(PSI_nb(1))  sin(PSI_nb(1))  ;...
        0       -sin(PSI_nb(1)) cos(PSI_nb(1))] ;

C2 = [  cos(PSI_nb(2))      0       -sin(PSI_nb(2)) ;...
            0               1           0           ;...
        sin(PSI_nb(2))      0       cos(PSI_nb(2))] ;

C3 = [  cos(PSI_nb(3))      sin(PSI_nb(3))      0       ;...
        -sin(PSI_nb(3))     cos(PSI_nb(3))      0       ;...
                0               0               1]      ;

Cbn = (C1*C2*C3);

local_difference=[-0.13;sick(i,2)-0.066;sick(i,3)-0.372];
Global_difference=Cbn*local_difference;

     EastS = UWB_2(J,2);
     NorthS = UWB_2(J,3);
     HeightS = UWB_2(J,4);

     NewE(i) = EastS + Global_difference(2);
    NewN(i) = NorthS + Global_difference(3);
```

```
    NewH(i) = HeightS + Global_difference(1);

    else
        NewE(i)=0;NewN(i)=0;NewH(i)=0;
    end
end

Data=[NewN' NewE' NewH'];
A=find(Data(:,1)>0);
Data=Data(A,:);

plot3(Data(:,1),Data(:,2),Data(:,3),'.');
```

Integration of IMU, UWB and laser scan data (Algorithmic Solution 2)

```
%UWB produces 4 measurements (4 measurements = 1 point)per 108ms, therefore,
%there will be around 10 UWB point data per second.
%It was observed from the UWB measurements that 20 UWB points per change of 1
meter in distance on y direction, that means
%the speed of trolley was around 0.5 m/s == 0.05m/per UWB point interval.

%First time, North to South, IMU measurement start time: 27013.097,27013.107,
27013.117...the time interval is 0.01s,
%from SICK data "31243"(corresponding time is also 27013,which is the start
time of IMU and UWB measurements, IMU and UWB started to record measurement
at the same time),3810points/s == 381points/per UWB point interval.
%from UWB data "631"
%3810/10=381,381 scan points/per UWB point interval;
%when UWB "Y" DATA had an obvious change, which means the trolley started
%to move, so when "Column 630 of UWB test 2 data" started to change,
630/10=63s;
%So the trolley started to move at time:"27013+63=27076", the corresponding
SICK data point is 31243 + 3810*63 = 271273;


u=ones(381,1)*6.9;
for n=0:351
X=sick(271273+381*n:271272+381*(n+1),2); %get X values in per-range (381
points);
Z=sick(271273+381*n:271272+381*(n+1),3); %get Z values in per-range (381
points);
Y=ones(381,1)*(-0.05*n+6.9);
scatter3(X,Y,Z,'b.');
XX=sick(271273:271272+381*(n+1),2);
ZZ=sick(271273:271272+381*(n+1),3);
YY=u;
u=[u;ones(381,1)*(-0.05*(n+1)+6.9)];
end
scatter3(XX,YY,ZZ,'b.');
xlim([-25 10]);
ylim([-25 20]);
hold on;

%This step aims to filter the generated point cloud by using Gaussian
distribution

save('24-01-18 NS XXYYZZ.txt');
scan1=importdata('24-01-18 NS XXYYZZ.txt');

x=scan1(:,1);
y=scan1(:,2);
z=scan1(:,3);

k1=1;

len=length(x);
```

```
average1=mean(x);
standard1=std(x);
average2=mean(y);
standard2=std(y);
average3=mean(z);
standard3=std(z);

% abs(x(i)-average1) < 2*k1*standard1 & abs(y(i)-average2) < 2*k1*standard2
% & abs(z(i)-average3) < 2*k1*standard3

X=x(1);
Y=y(1);
Z=z(1);
for i=2:len
    if x(i)<5.7 & x(i)>-19 & z(i)>-0.75

        X=[X;x(i)];
        Y=[Y;y(i)];
        Z=[Z;z(i)];
    end
end

scatter3(X,Y,Z,'b.');
xlim([-25 10]);
ylim([-25 20]);
hold on;
```

Appendix 2: List of Patents and Publications

Patents:

[1] Name: Functional Module Design System for BIM-based Integrated Cloud Platform

Inventor: Tang, L., **Chen, C.**, Ye, Z., Ying, M. & Wen, Y.

Patent Number: 201710141434.7

Date: 20th Sep. 2017

[2] Name: BIM-based Forecast System Method for Predictions of Construction Process

Inventor: Tang, L., **Chen, C.**, Xia, L., Jing, Y. & Yang, L.

Patent Number: 201810184692.8

Date: 6th Mar. 2018

Publications:

[1] **Chen, C.** & Tang, L. 2019. Development of BIM-based Innovative Workflow for Architecture, Engineering and Construction Projects in China. *International Journal of Engineering and Technology*, Volume 11(2), 119 – 126.

[2] **Chen, C.** & Tang, L. 2018. Development of BIM-based Innovative Workflow for Architecture, Engineering and Construction Projects in China. *ICCEN 2018 Conference*, November 21-23, 2018, Seville, Spain.

[3] **Chen, C.**, Tang, L., Hancock, M., Yan, J., Ligt, D.H. & Zhang, P. 2018. 2D-based Indoor Mobile Laser Scanning for Construction Mapping Application, *FIG Congress 2018*, Embracing our smart world where the continents connect: enhancing the geospatial maturity of societies, May 6-11, 2018, Istanbul, Turkey.

[4] **Chen, C.**, Yang, L., Tang, L. & Jiang, H. 2017. BIM-based Design Coordination for China's Architecture, Engineering and Construction Industry. *2nd International Conference on Building Information Modelling (BIM) in Design, Construction and Operations*. May 10-12, 2017, Alicante, Spain. & *WIT Transactions on the Built Environment*, Volume 169.

[5] **Chen, C.**, Tang, L., Hancock, C. & Zhang, P. Development of Low-Cost Mobile Laser Scanning for 3D Construction Indoor Mapping by Using Inertial Measurement Unit, Ultra-Wide Band and 2D Laser Scanner. *Engineering, Construction and Architectural Management.* (Published)

[6] **Chen, C.** & Tang, L. Development of a BIM-Based Panel Prototype for Cost Planning of Building Fabric Maintenance. *Construction Management and Economics*. (Under review)

[7] **Chen, C.** & Tang, L. An Empirical Study of Impact Factors on Production Control of Construction Process within BIM. *Frontiers in Built Environment (Construction Management)*. (Under review)

[8] Tang, L., **Chen, C.**, Tang, S. & Wu, Z. 2017. Building Information Modeling and Energy Efficiency Optimization. In: DENG, W. ed. *Earth Systems and Environmental Sciences, Encyclopedia of Sustainable Technologies*, *Elsevier*, 311 - 320.

[9] Jin, R., Hancock, C., Tang, L., **Chen, C.**, Wanatowski, D. & Yang, L. 2017. Empirical Study of BIM Implementation-Based Perceptions among Chinese Practitioners. *Journal of Management in Engineering*, Volume 33, Issue 5.