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Construction quality management based on a collaborative system using BIM and indoor positioning

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ABSTRACT

Quality is one of the most vital aspects of a construction project, and inspection is the most important task in construction quality management. Despite the application of advanced information technologies, the omission of check items and in-efficiency of entering inspection results from paper-based inspection records into computers and collaboration among the construction stakeholders remain to be major problems. This paper proposes an approach to make the process of construction quality management more effective and collaborative by developing a system based on the integrated application of building information modeling (BIM) and indoor positioning technology. First, the system requirements of the collaboration platform are analyzed based on the standards for construction quality inspection in China, the technologies to be used for its implementation are justified, and a process model for the collaboration of multiple stakeholders is established. Next, the system architecture is developed, and the algorithm for generating inspection tasks and the technique for integrating with indoor positioning technology are formulated. Finally, the implementation of a prototype system is presented, and the effectiveness and efficiency of the approach for construction quality management are verified by using the system in an on-site test.

1. Introduction

Construction quality pertains to the lives and safety of the public, and its importance cannot be overemphasized. Hence, various standards exist to regulate the construction quality management in practice. Although these standards vary from country to country [1], their core is invariable in that inspections must be conducted after each major construction procedure through collaboration among the stakeholders of the project, i.e., the contractors are responsible for the check, and the supervisors and the owner/developer are responsible for the re-check and the double re-check, respectively. Since many check items must be inspected for numerous target objects at construction sites according to the standards, some of them may easily be missed by the inspectors, which endangers construction quality. Besides, as in many other countries, the use of paper-based files is still the main mode of information recording, preservation and transmission for construction quality management in China [2]. The inspectors thus need to record inspection data on paper at the construction site and then enter the data into some specific document management software at the office to get the data printed out in specified forms and signed by the relevant inspectors. In addition, the construction stakeholders' communication, such as requests for re-checks and rework, occurs through paper-based letters or E-mails, in which the information is fragmented and confined to only a few people so that the working efficiency of the inspectors and the collaboration efficiency among the stakeholders are low.

Researchers have endeavored to develop various approaches for construction quality management by using state-of-the-art technologies such as Building Information Modeling (BIM), mobile computing, and Augmented Reality (AR), to reduce the workload of the inspectors and lower the risks of construction quality management. Chen and Luo [3] utilized 4D BIM technology to establish a BIM-based construction quality model for construction quality management. Dong et al. [4] presented a telematic workbench that facilitates the on-site crew to use handheld mobile devices to collect defects and send them to the server with wireless communication, and the latter can facilitate the designer to compare the visual information with the design model to judge if it is acceptable. Chen et al. [5] introduced a framework for implementation on construction sites, which identifies the feature of mobile computing, construction personnel, information and construction sites and their interactions and gives system designers a clear structure for designing mobile computing systems from a technical perspective. Tsai et al. [6] proposed an approach for construction quality inspection based on BIM

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and mobile computing in which inspectors determine the inspection tasks and locations before a site inspection trip and enter inspection data at construction sites based on the pre-generated BIM images by using corresponding construction information forms on a mobile device. Lee et al. [7] proposed a construction defect management method using AR technology, which augments virtual objects to real-time input images from the camera, to enable the workers to discover defects efficiently. Based on the study of Lee et al., Park et al. [8] integrated ontology and AR with BIM to propose a conceptual framework for proactive construction defect management to avoid the reoccurrence of construction defects and support field defect management. The framework includes a defect data collection template, a defect domain ontology to search for and retrieve defect information, and an AR-based defect inspection system to capture defect information based on the defect data collection template. Using this framework, Kwon et al. [9] further developed a defect management system with two sub-systems: an image-matching system to detect defects by comparing the 2D virtual images of BIM models with the photos of actual works and a mobile AR app to help discover dimension errors and omissions at construction sites.

In order to support the collaboration among the stakeholders in construction, many studies have proposed collaborative models, frameworks and systems based on BIM and mobile devices. Singh et al. [10] established a theoretical framework that specifies the technical requirements for using a BIM-server as a multi-disciplinary collaborative platform, which enables better multi-disciplinary collaboration in design and construction. Pena-Mora et al. [11] developed a project management system to support the collaboration of distributed project management teams in complex projects by providing a platform for effective information sharing with few limitations on computing devices. Oh et al. [12] developed an integrated system for collaborative design based on BIM, which supports the collaboration of architecture and mechanical, electrical and plumbing (MEP) design with enhanced data quality and working efficiency.

Although these approaches and techniques support construction quality management either by enabling the automation of inspection or by providing pure data input and workflow functions on the web based on some technologies, they cannot solve the above-mentioned problems as a whole. However, the integration of latest and existing technologies are expected to solve the above-mentioned problems. Especially, indoor positioning technology can be used and integrated with BIM because of the necessity of positioning when BIM is used to identify the target objects for inspection at construction sites.

This study aims to establish an approach to support the quality management of construction projects by developing a collaboration platform in which the technologies of BIM and indoor positioning are integrated in order to solve the above-mentioned problems. To this end, this study focuses on three questions, i.e., how to establish a collaboration platform that facilitates the collaboration among the relevant stakeholders for construction quality management, how to identify the check items and corresponding target objects automatically based on BIM technology according to the standards to avoid omission of necessary inspection, and how to identify the correspondence between the elements in the BIM model and the objects on site to raise on-site working efficiency by using indoor positioning technology.

In the following, first of all, the system requirements of the collaboration platform are analyzed based on the standards for construction quality inspection in China, the technologies to be used for its implementation are justified, and a process model for the collaboration of multiple stakeholders is established. Next, the system architecture is developed, and the algorithm for generating inspection tasks and the technique for integrating with indoor positioning technology are formulated. Finally, the implementation of a prototype system is presented, and the effectiveness and efficiency of the approach for construction quality management are verified by using the system in an on-site test.

2. Current practices and relevant information technologies

2.1. Current practices of construction quality management

As stated in the previous section, although the details of the standards vary from country to country, the core of the standards remains invariable. Thus, in this study, the Chinese standards are taken as examples. In China, construction quality-related standards can be classified into four types: national standards, local standards, industrial standards and enterprise standards. Among them, the national standards are the most authoritative and form the basis for the other three types. The national standards on building construction quality include a unified standard and a series of 13 other standards covering various project work categories, including the main structure in concrete, steel, wood and masonry, the foundation, roofing, electricity, water supply and drainage, ventilation and air-conditioning, etc. Among the categories, "main structure" is the most crucial for construction quality, and thus, the check items and criteria for this category (particularly for concrete structures) constitute the majority among all work categories. In addition, although differences exist among the standards, the general process and methods for construction quality management are similar and are consistent with the conceptual framework specified in the unified standard. Therefore, this research focuses on the construction quality management of concrete structures based on two national standards: the unified standard for construction quality acceptance of building engineering (GB50300-2013) and the code for acceptance of construction quality of concrete structures (GB50204-2015). The construction quality management of other categories can be dealt with similarly.

In GB50300-2013, an inspection lot is defined as a group of objects for inspection that are produced under the same conditions or organized in a specified manner [13]. Each inspection lot corresponds to a number of check items, and the target objects for inspection corresponding to a check item are determined to be the whole objects contained in the inspection lot or only the sampled objects, depending on the check items [14]. For example, in the construction of a building, since concrete slabs and beams of the same floor are cast in the same batch, their concrete appearance is thus defined as an inspection lot. The deviation of the sectional dimension of the slabs and beams is a check item, and the to-be-checked samples of the slabs and beams in the inspection lot are the target objects according to the standards. It is worth noting that among the inspection lots, except for the raw materials and processed materials that need to be inspected in batch, most inspection lots are associated with the objects in buildings and thus need to be inspected with regard to the objects.

Quality inspection needs to be conducted along with the construction process. As shown in Fig. 1, the quality engineers of the contractor usually make a plan in which the inspection tasks, including inspection lots, check items and corresponding target objects, are identified before construction. With regard to an inspection lot, the contractor needs to conduct a check first on the target objects with regard to the check items immediately after the associated construction procedure is completed. During the check, the inspector records the inspection result of each target object on paper-based on-site forms. After the check on the inspection lot, the inspector needs to complete an inspection lot checklist form based on the on-site forms and then submit it to the supervisor. The inspection lot checklist forms contain brief inspection results, such as "90% pass", without the details on each target object. Then, the inspector from the supervisor re-checks the inspection results before the contractor can continue the next construction procedure. For important inspection lots, the owner/developer may conduct double rechecks. The on-site forms and the inspection lot checklist forms are the most important inspection documents because they act as the certification of the construction quality and indicate the people in charge. To preserve the inspection data in a clear form, the inspection lot checklist forms are required to be printed and signed by the relevant inspectors

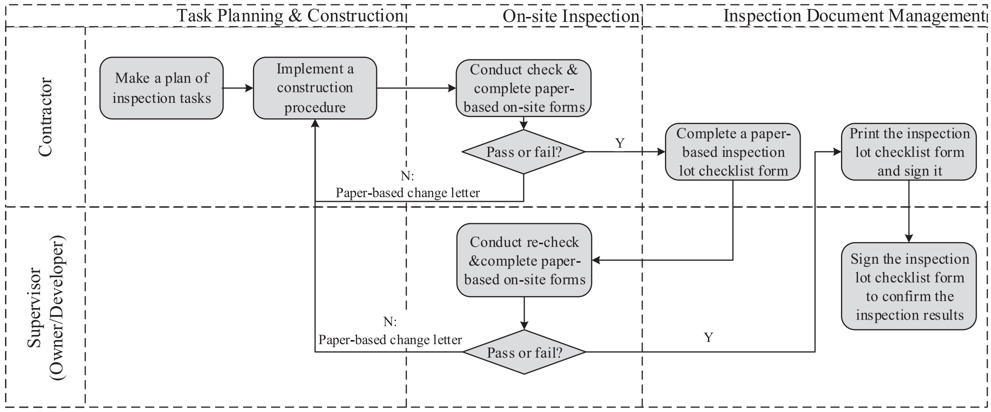

Fig. 1. Current process of construction quality management.

Table 1
Comparison of existing indoor positioning technologies.

Technology	Accuracy	Benefits	Limitations
Ultrasound	mm-scale	High accuracy	Attenuate quickly with the increase of distance; Weak penetrability
RFID	m-scale	Reliable performance; strong anti-interference	RFID readers and tags are needed
WLAN	m-scale	Low cost; embedded sensors on smart phones; Reuse the widely available WLAN	Stable WLAN connection and data for network training are needed; affected by man-made sources such as concrete
UWB	10 cm-scale	Strong penetrability; strong anti-interference ability	High cost; large-size hardware; not supported on smart phones
Vision analysis	m-scale	Large coverage area	Susceptible to lighting, background color, etc.; less accurate in dynamic environment
Magnetic field	m-scale	Embedded sensors on smart phones; no extra hardware or infrastructure required	Affected by man-made sources such as concrete

from the relevant stakeholders.

2.2. Relevant information technologies

BIM provides a comprehensive database that can be used not only for visualizing construction products using 3D models but also for conducting various analyses in the models [15]. In addition, it can be used as a convenient tool to manage information such as quality management information. Hence, BIM is used as a basis for construction quality management in this study.

The emergence of mobile computing provides an effective way to transfer data, voice and video. With its rapid development, functions such as GPS navigation, touch screens, digital cameras, sensors and high-speed data transfer have become standard functions for almost any smart phone, tablet and even wearable device [16]. These functions significantly enhance the efficiency of information transmission and promote the applicability of mobile computing in construction activities to reduce costs and labor time. In this study, mobile computing, integrated with BIM, is used by the inspectors to enter and transmit the inspection data at construction sites.

Real-time positioning is critical for an inspector to identify and track his/her location in reference to target objects. There has been an increase in research on the use of real-time positioning at construction sites [17]. Taneja et al. [18] and Vähä et al. [19] have summarized the potential use of indoor location tracking technology in the construction industry. Although GPS is the most widely used positioning technology in the outdoor environment [20], its accuracy cannot meet the needs of indoor positioning. As common indoor positioning technologies, RFID, ultra-wideband (UWB), vision analysis, WLAN, and ultrasound have already been used at construction sites. Ding et al. [21] proposed an early warning system that integrates Fiber Bragg Grating (FBG) sensor and RFID technology for labor tracking in a metro tunnel project. Woo et al. [22] proposed a Wi-Fi-based indoor positioning system that can be used for tracking labor and monitoring the locations of construction resources such as vehicles and materials. Cheng et al. [23] developed a construction safety and monitoring system based on UWB. Park et al. [24] employed stereo cameras and proposed a vision-based method to track on-site construction resources. Ultrasound technology has also been used for construction asset tracking [25]. Moreover, combining GPS with RFID is also recommended to improve positioning accuracy [26]. These technologies have the potential to track the position of materials or people within construction sites, support the estimation of cyclical activities of equipment, and monitor the safety of construction workers. In this study, indoor positioning technology is needed to display the position of the inspector in the BIM model to facilitate the inspector to determine the target objects at construction sites quickly; thus, an accuracy of 2 to 3 m is required. Moreover, in order to be commonly applied in construction sites, the cost and ease of learning and use are also the most important factors to consider. By comparing the existing indoor positioning technologies in Table 1, we determined to use an indoor positioning technology that combines magnetic field and Wi-Fi signals, and the details of which are described in Section 4.3.

3. A new process model for construction quality management

Considering the current process of construction quality management and the potential use of the relevant information technologies, the functional requirements for this system are formulated as follows.

First, the system should provide the users with functions for pre-inspection work, including generating inspection lots, check items and target objects from the BIM model and linking the on-site forms to the target objects according to the standards to prepare the inspector before the site inspection trip. Second, the system should display marks on the BIM element that correspond to the target objects and associate the target objects with on-site forms so that the system will pop-up an on-site form for him/her to fill in or select choices when the inspector clicks on the marked element. The check items and qualification criteria for each item in the on-site form are generated depending on the type of target objects contained in the inspection lot according to the standards. Furthermore, the system should display the real-time position of the

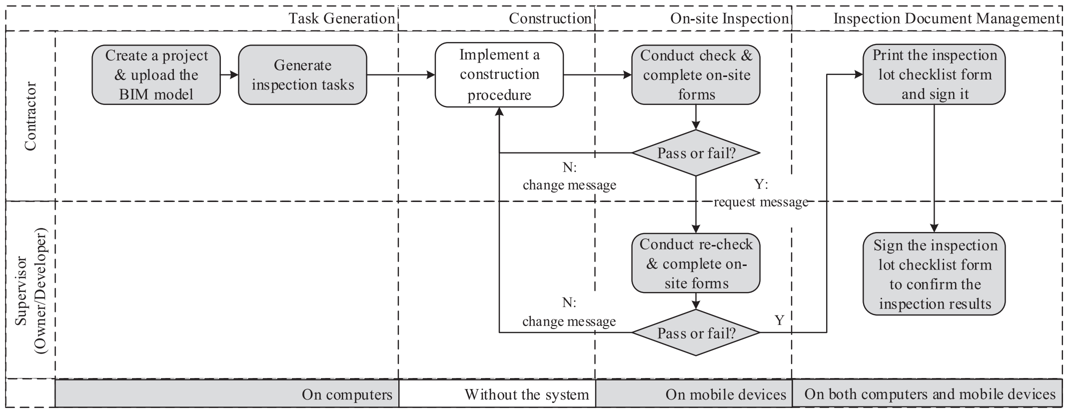

Fig. 2. A new process model for construction quality management.

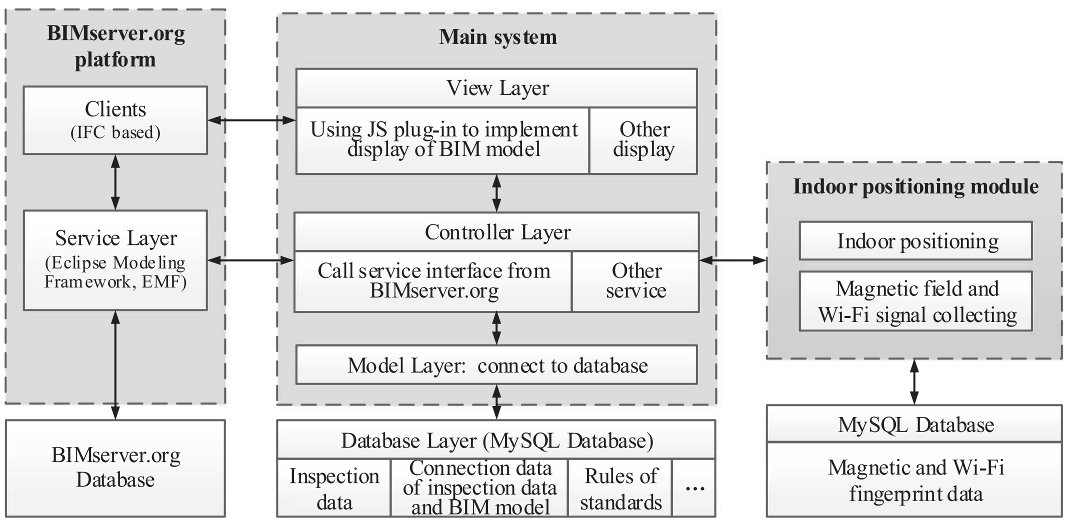

Fig. 3. System architecture.

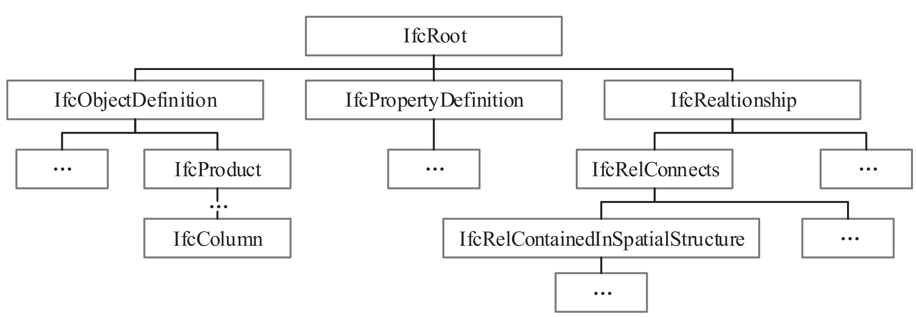

Fig. 4. Part of IFC data model.

inspector in the BIM model so that the inspector can easily associate the actual target object that he/she is inspecting at the construction site with the corresponding BIM element to click on in order to enter the inspection data in the corresponding on-site form. Lastly, the system should support the output of the inspection documents by integrating the entered inspection data and generating the inspection lot checklist forms to be printed as required by the standards.

In addition to the above-mentioned functional requirements, the system should also provide a workflow engine and a number of templates for communication messages to replace paper-based letters, such as confirmation request messages and change messages, to facilitate collaboration among the stakeholders on the Web.

Based on the above analysis, a process model is established to illustrate the relationship between the functions when the system is used, as shown in Fig. 2. The users of the system include the contractor, the supervisor and the owner/developer. The contractor creates a new project and uploads the structural BIM model into the system. With the BIM model, the inspection tasks are generated in the system. When a construction procedure is completed, the contractor checks the target objects included in the corresponding inspection lot with regard to the check items by using the system and completes the on-site forms on a mobile device. If the corresponding inspection lot passes the check, a request message is sent to the supervisor for inspection confirmation. The supervisor re-checks the same inspection lot to confirm the inspection results, and the owner/developer may perform a double re-check if required. After the confirmation, the inspection lot checklist

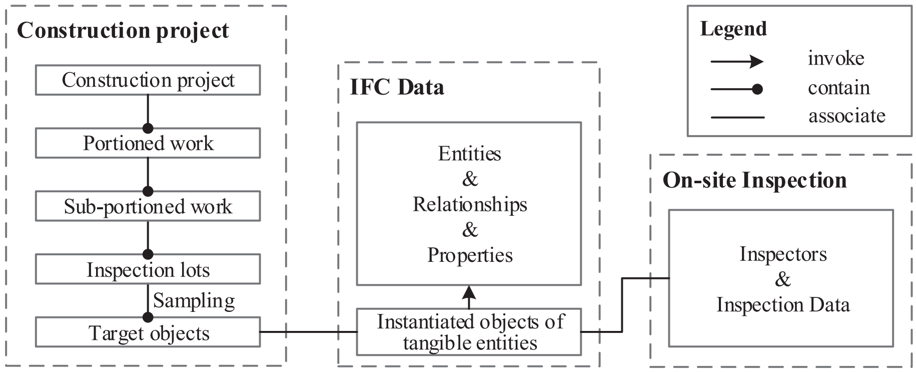

Fig. 5. Construction quality inspection model based on BIM.

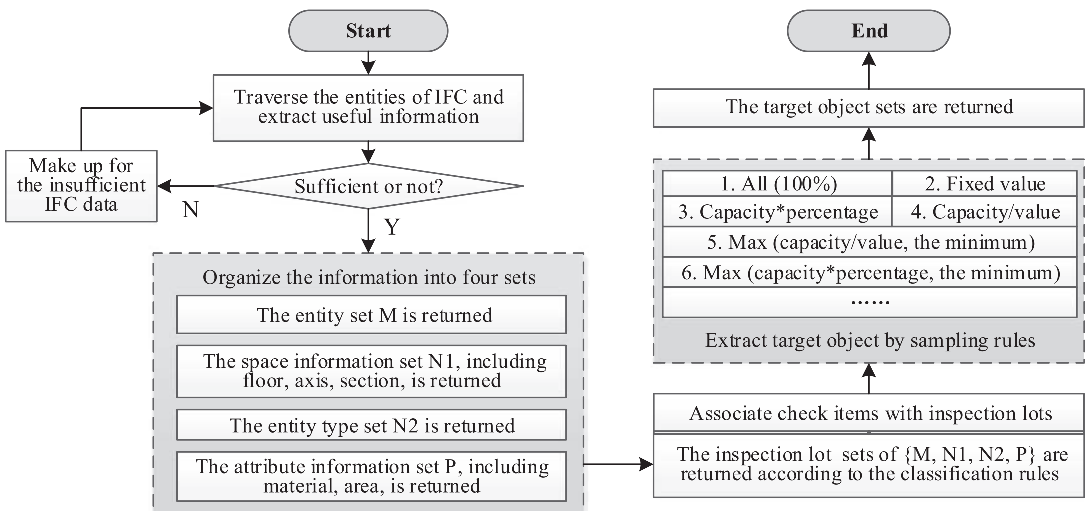

Fig. 6. Algorithm for generating inspection tasks.

forms are printed and signed by the relevant inspectors from both the contractor and the supervisor. In addition, if the supervisor rejects the results of the check, a change message will be sent to the contractor to request repair or rework.

4. System development

4.1. System architecture and implementation

The proposed system is a web-based application that runs on both desktop computers and mobile devices without client installation. In this system, the BIM model is stored in the Industry Foundation Classes (IFC) file format and managed by using the BIMserver.org platform, which also serves as an IFC parser and viewer. The BIMserver.org platform is an open-source IFC model server provided by the Netherlands Organization for Applied Scientific Research (TNO) that enables users to handle BIM data in the IFC format, which is an open and neutral data format for BIM.

The architecture of the system is shown in Fig. 3. The main system invokes BIMserver.org for BIM model services and the indoor positioning module for positioning services. The stem adopts a Model-View-Controller (MVC) architecture. It is divided into four layers, i.e., the database layer, the model layer, the controller layer, and the view layer [1]. The database layer deals with the information resource of the system, storing information such as the inspection data, standard criteria, and the connection data of inspection data and BIM model. The model layer organizes the information retrieved from the database layer according to the commands from the controller layer. The view layer provides the user interface composed of HTML elements. It displays information, such as BIM models and diagrams, to the users. The controller layer is responsible for the main logic and workflow of the system between the model layer and view layer, handling incoming requests and redirecting for the appropriate response. When the user gives a request by clicking on a button, the controller layer invokes the corresponding data from the model layer and user interface from the viewer layer.

Based on the above analysis, a prototype system was implemented by the authors using the development languages of Java, JavaScript, jQuery, and SQL. The development environment includes Windows 10, MySQL 5.7.10, Tomcat 7.0, Java 1.7 and BIMserver.org 1.4.0.

4.2. Algorithm for generating inspection tasks

To generate the inspection tasks including the inspection lots, the check items and the corresponding target objects based on the BIM model, an algorithm is established by assuming that the BIM model is in IFC format. As a well-recognized standard for BIM data, the IFC standard defines hundreds of classes, including tangible entities such as columns and beams, and abstract concepts such as the relationships and property sets of entities. In the IFC standard, IfcRoot is the common super type of most IFC entities [27]. IfcRoot is subdivided into three subtypes, i.e., IfcObjectDefinition, IfcPropertyDefinition and IfcRelationship, which are further subdivided, as shown in Fig. 4. IfcObjectDefinition is used to derive entities corresponding to tangible objects, such as columns and beams; IfcPropertyDefinition is used to provide the dynamically extensible properties of the objects; and IfcRelationship is

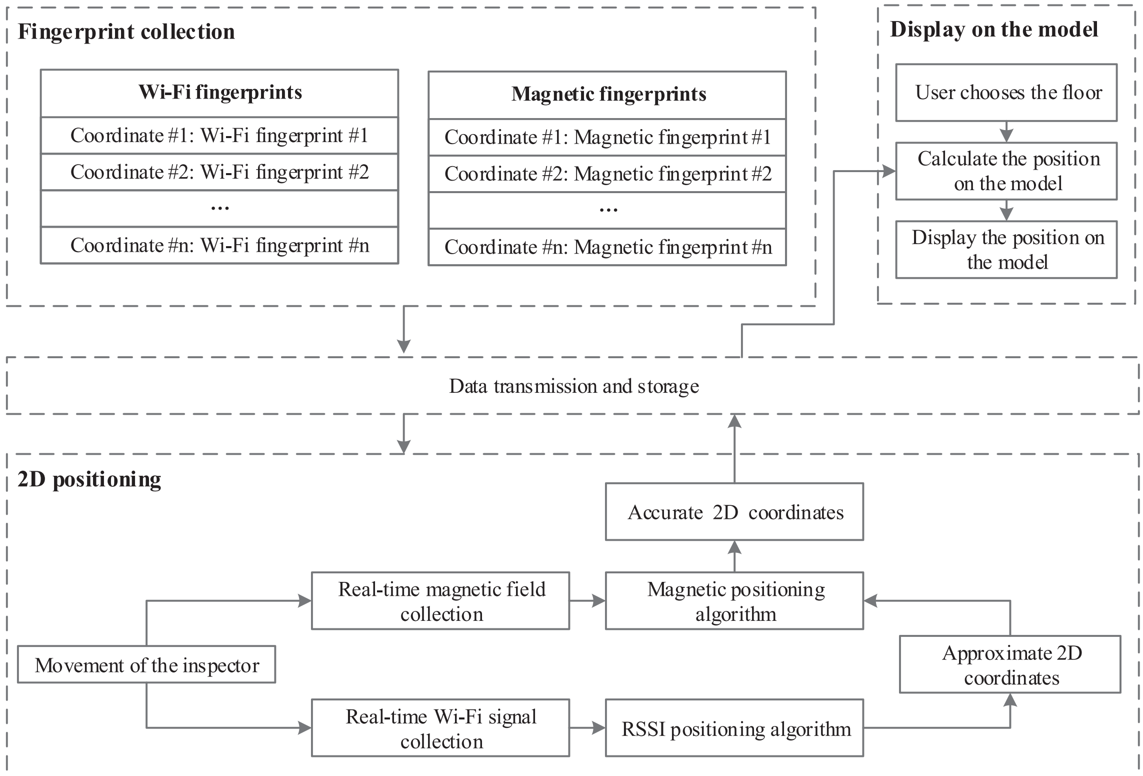

Fig. 7. Workflow with integration of indoor positioning system.

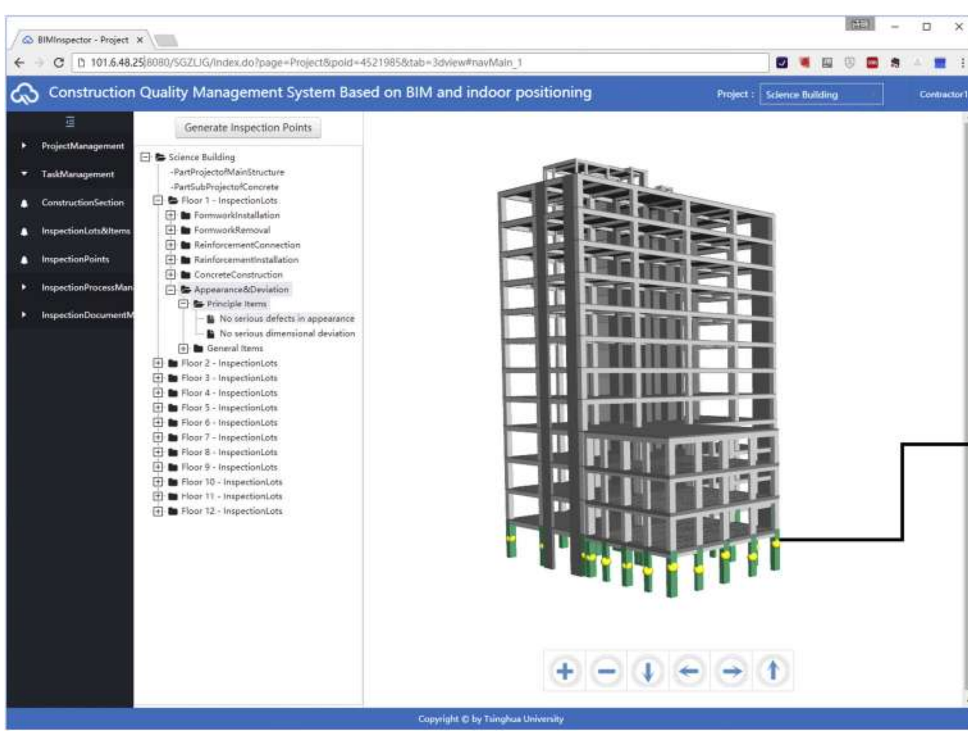

Fig. 8. BIM model with generated target objects.

used to describe the relationships among objects, such as the relationship of the objects and the floors. Therefore, the information for generating the inspection lots, the check items and the corresponding target objects comes from the instantiated objects of these three types and their subtypes. The construction quality inspection model based on BIM is thus established as shown in Fig. 5.

Based on the analysis of IFC data model relevant to construction quality management and taking into account the rules specified in quality-related standards, the algorithm for generating inspection tasks is formulated as shown in Fig. 6 [1].

First, the system traverses the entities in IFC data and extracts relevant information. The information is organized into four sets: 1) the

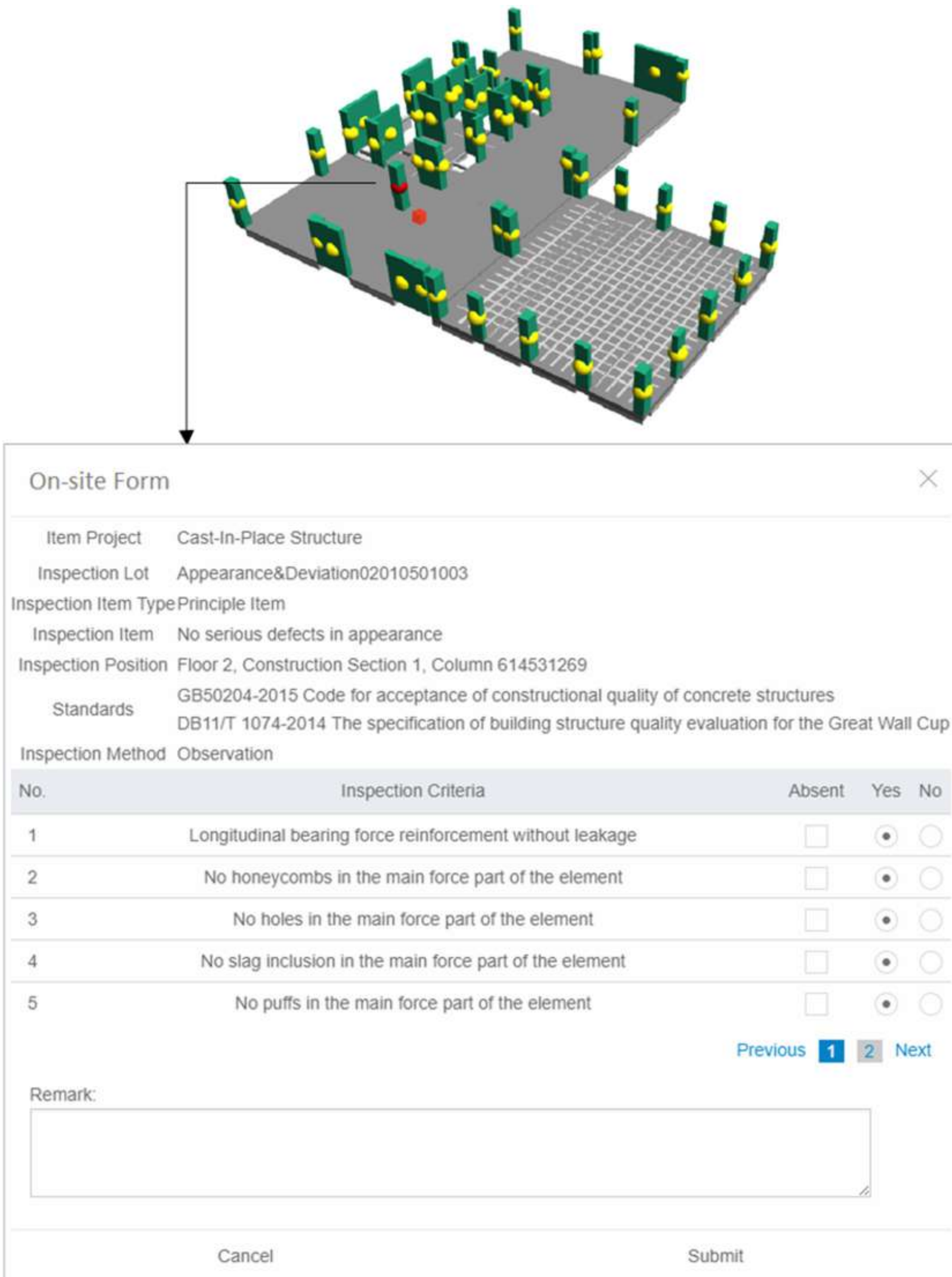

Fig. 9. On-site form of a target object.

entity set (M), including the building elements such as columns and beams; 2) the space information set (N1), including the spatial properties, such as floor and axis; 3) the entity type set (N2), such as a beam or a column; and 4) the attribute information set (P), such as material and area.

Then, the system uses the data in the four sets to generate the inspection lots, associate the inspection lots with the check items, and determine the corresponding target objects according to the sampling rules specified in the standards. The check items for all kinds of inspection lots, and the rules for determining inspection lots and target objects, which are all specified in the standards, are saved in the MySQL database. For example, the check items for an inspection lot of “appearance and deviation inspection” includes appearance of concrete, deviation of axis position and section area, etc.; the cast-in-situ walls and columns belonging to the same floor and the same cast batch can be determined in the same inspection lot; and the sampling rule of target objects for the check item "deviation of axis position and section area" can be "more than 10 percent of the objects in the inspection lot should be checked".

Finally, the inspection lots, check items and target objects are stored in the database. It should be mentioned that some fundamental data, such as the number of target objects in each inspection lot, are provided in the process, and they are very useful for the users to make a detailed plan for their inspection schedule.

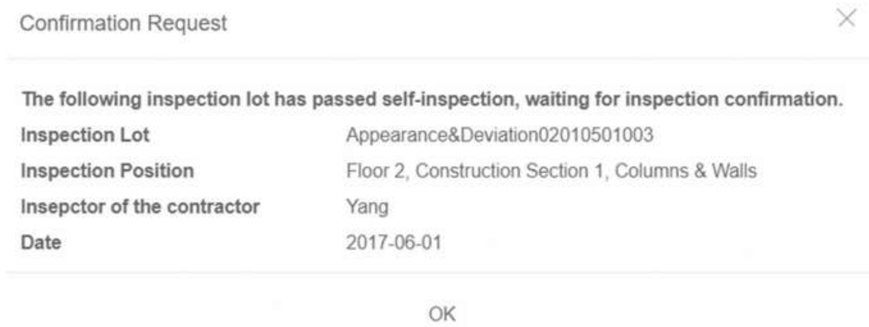

Fig. 10. Confirmation request from the contractor.

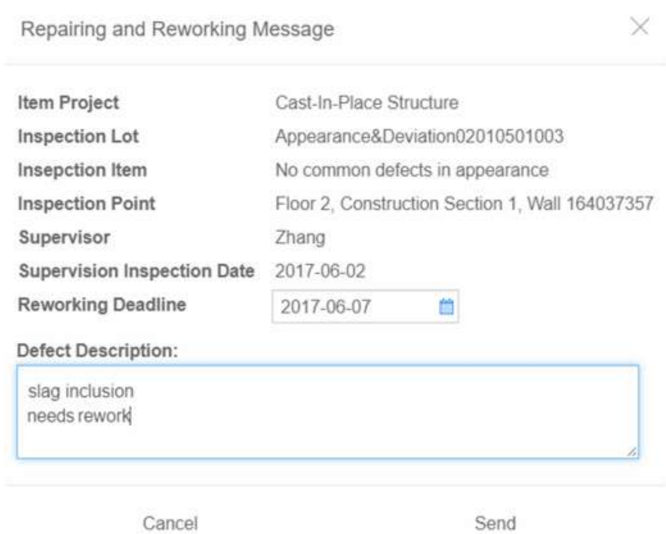

Fig. 11. Repairing and reworking message from supervisor.

Due to the file format conversion in different software and various styles of modeling, the IFC data are not always sufficient for this algorithm. Therefore, interactive data input interfaces are provided for the algorithm to complement the data. For example, when a BIM model does not contain information about which concrete slabs and beams on the second floor are cast in the same batch, the user is provided with the function to choose the elements in the same batch from the model, because it influences the determination of inspection lots. In addition, if the user is unsatisfied with the generated result of inspection lots, check items and target objects, he/she can use an interactive function in the system to adjust the result manually.

4.3. The technique for integrating real-time indoor positioning

As mentioned in Section 2.2, in this research, we employ an indoor positioning technology using the magnetic field and Wi-Fi signals. The module that we use is called the enhanced MaLoc, which is obtained from MaLoc [28] by combining WLAN for higher computational efficiency. The mobile devices can scan and collect the Wireless Access Point (AP) signals, obtain the Media Access Control (Mac) of each AP and the corresponding Received Signal Strength Indication (RSSI), and send them to the server. The module provides 2D positioning services with an accuracy of 1–2.8 m. As shown in Fig. 7, the requirements and workflow for using the enhanced MaLoc in this study are described as follows.

Before using the module, Wi-Fi signals must be available at the construction site, and the collection of magnetic field and Wi-Fi signals must be conducted before positioning. To do this, the user must upload the floor plan of the building to be inspected onto the mobile device where the route for the collection is given in advance. The user then needs to walk along the route carrying the mobile device with the enhanced MaLoc installed and the dedicated signal collection application running. The magnetic field and Wi-Fi signal fingerprints, i.e., the strength data of magnetic field and Wi-Fi signals from each AP, and the corresponding coordinates of the floor are thus collected automatically by the sensors in the mobile device and uploaded into the database on the server.

When the module is used during positioning, it first makes an approximate estimate with the Wi-Fi signals. Then, based on the approximate estimate, the module obtains accurate 2D coordinates by matching the current magnetic field with the fingerprints in the database and posts the data to the server. The system obtains the coordinates and asks the user to choose the floor he/she is on. The coordinates are then transformed into the position on the corresponding floor in the BIM model. The position is displayed with a positioning mark, providing real-time positioning and enabling the inspector to locate the neighboring building elements in the BIM model for correct entry of inspection data into the system.

5. An on-site test of the prototype system

To verify the proposed system, an on-site test was conducted at the construction site of an office building in Beijing, China. The building is a 12-story frame-shear wall building with a 4-story podium building and a gross floor area of 34,012.10 m^2.

The BIM model of the building used in the test was a structural model created by using the Autodesk Revit software and then exporting to an IFC format file. The hardware environment includes the following: 1) a server with CPU Intel Core i7, 3.40 GHz and 8 GB RAM; 2) a client PC with CPU Intel Core i5, 3.00 GHz and 4 GB RAM; 3) a client tablet with 2 GB RAM and a battery capacity of 5000 mAh; and 4) three 4G mobile Wi-Fi hotspots with a battery capacity of 1500 mAh and 4G LTE 150 Mbps, the dimensions of which are 96.8 mm × 58.0 mm × 12.8 mm. The software environment of the server comprises Windows 7, MySQL 5.7.10, Tomcat 7.0, Java 1.7 and BIMserver.org 1.4.0. The client browsers in this test are Chrome and Mozilla Firefox. Both the check by the contractor and the re-check by the supervisor were tested by using the system. The following processes were operated by the authors to simulate a typical practical scenario.

The user from the contractor created a new project in the system and uploaded the BIM model in IFC format. Before the inspection at the construction site, the user clicked the button to generate the inspection tasks including inspection lots, check items and target objects, and the target objects were marked on the BIM model. As shown in Fig. 8, the yellow balls on the midpoint of the columns on the first floor mark the target objects.

Then, the inspector from the contractor went on a site inspection trip to perform the check with a tablet. The real-time position of the

Checklist for the Inspection Lot of Appearance and Deviation

Inspection Lot No. 02010501025

Project	*Science Building*	Part Project	*Main Structure*	Item Project	*Cast-in-place*
Contractor	*Beijing Urban Construction Engineering Co., Ltd.*	Project Manager		Inspection Lot Capacity	*11 Columns, 36 Walls*
Sub-contractor		Sub-contractor Manager		Inspection Lot Position	*Floor 2, Construction Section 1*
Standard for Construction	*Code for construction of concrete structures GB50666-2011*		Standard for Quality Acceptance	*Code for acceptance of constructional quality of concrete structures GB 50204-2015 The specification of building structure quality evaluation for the Great Wall Cup DB11/T 1074-2014*	

Inspection Items				Inspection criteria	Num of Sampling (Min/Actual)			Inspection Records	Inspection Results
Principle Items	1	No serious defects in appearance		8.2.1	*47*	/	*47*	*47 Inspected, 47 Qualified*	*Pass*
	2	No serious dimensional deviation		8.3.1	*47*	/	*47*	*47 Inspected, 47 Qualified*	*Pass*
General Items	1	No common defect in appearance		8.2.2	*47*	/	*47*	*47 Inspected, 47 Qualified*	*Pass*
	2	Axis Position	Columns, Walls and Beams	5	*5*	/	*10*	/	/
			Independent Foundation	10		/		/	/
			Block Foundation	10		/		/	/
	3	Perpendicularity	Storey Height of Columns and Walls ≤ 5 m	5	*5*	/	*10*	*10 Inspected, 10 Qualified*	*100%*
			Overall Height(H) ≤ 300 m	H/30000+20		/		/	/
			Storey Height of Columns and Walls > 5 m	8		/		/	/
			Overall Height(H) > 300 m	H/10000&H≤80		/		/	/
	4	Elevation	Storey Height	±5		/		/	/
			Overall Height	±30		/		/	/
	5	Sectional Dimension	Columns,Beams, Floors and Walls	±3	*5*	/	*10*	*10 Inspected, 10 Qualified*	*100%*
			Foundation	±5		/		/	/
			Height Difference between Stair Steps	±3		/		/	/
	6	Elevator Shaft	Center Position	+20, 0	*5*	/	*5*	*5 Inspected, 5 Qualified*	*100%*
			Length and Width	+25,0	*5*	/	*8*	*8 Inspected, 8 Qualified*	*100%*
	7	Surface Eveness		3	*5*	/	*10*	*10 Inspected, 10 Qualified*	*100%*
	8	Center Position of Embedded Parts	Embedded Plates	3	*5*	/	*5*	*5 Inspected, 5 Qualified*	*100%*
			Embedded Pipes	3		/		/	/
			Embedded Bolts	+5, 0		/		/	/
			Other	10		/		/	/
	9	Center Position of Preformed Holes		10	*5*	/	*5*	*5 Inspected, 5 Qualified*	*100%*

Inspection Comments of Contractor		Quality Inspector	
		Section Chief	
		Date:	
Inspection Conclusion of Supervisor		Supervisor	
		Date:	

Fig. 12. Quality inspection lot checklist form for appearance quality of subsection work cast in situ.

user was shown on the BIM model with which the user could easily associate the neighboring building elements on-site to the target objects in the model. To enter the inspection data, the user selected the floor number from the tree view and clicked on an inspection lot and a check item, e.g., the appearance and deviation of the cast-in-situ structure. The BIM model of the selected floor was displayed in the main view of the tablet interface. The inspector handled the model using the zoom, translation and rotation function and clicked on the elements to select a target object. A row of buttons was displayed above the model. The user could click on the buttons to enter inspection data in the forms, take pictures of the target objects or view the pictures taken previously. Instead of having to carry thick books of standards and paper-based on-

Table 2
Comparison of time consumption with traditional and system-based methods for one inspection lot.

	Inspection task planning	On-site inspection	Inspection results summarizing	Letter/ message-based communication	Total
Traditional method	40 min	60 min	50 min	20 min	170 min
System-based method	5 min (adjusting the generated plan)	80 min	0	3 min	88 min

Notes: the data of system-based method is an average of the 12 inspection lots in this test while the data of the traditional method is an approximate estimate by the on-site engineers.

site forms, the inspector took a tablet and completed the forms provided by the system as shown in Fig. 9 without worrying about inspection omissions. When the inspector submitted the on-site forms, the data was uploaded onto the server, while the target object marks automatically turned from yellow to blue. When all check items in an inspection lot passed the check, a confirmation request was automatically sent to the supervisor, as shown in Fig. 10.

After receiving the confirmation request, the inspector from the supervisor conducted a site inspection trip for the re-check at the construction site. The inspection process of the re-check was similar to the check procedure except that this inspector selected the target objects with blue marks to conduct the re-check. Assuming that the inspector from the supervisor disagreed on the results of the check, the inspector was entitled to ask for repair or rework with a message, as shown in Fig. 11. Then, the color of the target object mark would turn red. In this case, the inspector from the supervisor would describe the defects, set a deadline for reworking and send the message to the contractor. The contractor would then repair or rework the inspection lot until it passed both the check and the re-check, changing the color of the target object mark to green.

The inspection lot checklist forms were automatically generated with the original inspection data according to the requirements of the standard, as shown in Fig. 12. The user can click on the check item in the checklist to refer to the original inspection data.

During the on-site test, we fixed three mobile Wi-Fi hotspots on the second floor of the building, and the positioning accuracy was 1.5 to 2.5 m, which is enough for the inspectors to determine the target objects at the construction site. However, construction progress, especially concrete construction, has an effect on the magnetic field and the Wi-Fi signals. Therefore, before each inspection, the fingerprints of the magnetic field and Wi-Fi signals require to be calibrated for accurate positioning. After all the inspections are completed on one floor, the hotspots should be moved to the next floor.

Using this prototype system, we collected the inspection data of 12 typical inspection lots on the second floor of the building and obtained a complete set of inspection documents for that floor. Compared with the traditional paper-based inspection, the on-site inspection with the system requires approximately 30% more time because of the unskilled operation and fingerprint collection of the magnetic field and Wi-Fi signals. However, the work of planning the inspection tasks, summarizing the inspection results and entering the results into the computer is avoided, while the writing and delivery of the communication letters are replaced by the online messages with templates. With these improvements, the system can save approximately 50% of the time in the whole process of inspection. The time consumption for one inspection lot with the traditional method and the system-based method is compared in Table 2.

We showed the process and results to seven site engineers and collected their comments on both the quality inspection approach and the prototype system. The involved engineers have specialized abilities and working experience of beyond three years at construction sites, including a project manager from the developer, a supervising engineer from the supervisor, a project manager from the contractor, and four construction quality engineers who conduct inspections. A questionnaire was presented to the engineers to collect their grading and comments of the system, including evaluations of the major functions and the overall inspection process. The grading results are shown in Table 3.

The following advantages of the system were recognized by the site engineers.

- The system ensures that the stakeholders strictly follow the rules of the standards, without omissions in the inspection lots, check items and target objects.
- The system avoids entering inspection data from paper records into computers, which significantly improves the working efficiency.
- Both the inspection results in the inspection lot checklist forms and the details in the on-site forms can be preserved, and the data can be easily consulted.
- The communication among the stakeholders of the project is more efficient, and the rework/request messages during the construction management process are saved as records to clarify the responsibilities of the stakeholders.
- The project managers can keep up with the latest inspection progress from the BIM model.

The drawbacks and suggestions are presented as follows:

- Typing data into a smart tablet is not as easy as writing it down on a paper and voice input may be more convenient.
- It would be better to record the walking track of the inspectors so that the project manager can monitor the work of the inspectors.
- The fingerprint collection of the magnetic field and Wi-Fi signals for each inspection is acceptable, but it would be better if this were simplified.

As a supporting evidence to justify the system, we have presented the system in an academic conference and two industrial conferences in China. After our presentation, we were commented by five practitioners in total from different types of organizations including two construction companies, a supervising company, a developer of real estate and a government agency. All of them gave positive reactions on the system, and two of them even suggested early commercialization of the system. Recently, a senior manager from a leading software vendor for construction in China showed interest to do so.

Table 3
Grading results.

	Inspection task generation	On-site inspection	Inspection results summarizing	Communication among the stakeholders	The overall inspection process
Average grade	4.3	4.2	4.6	4.5	4.6

Notes: the survey questions are “How would you grade the performance of the system in XXX? (1-worst, 5-excellent)”, in which “XXX” can be substituted by “inspection task generation”, “on-site inspection”, etc.

6. Conclusions

This study proposed an effective and collaborative approach for construction quality management by developing a BIM and indoor positioning-based system. The system covers the major steps of construction quality management, i.e., generating the inspection tasks, collecting the inspection data, and summarizing the inspection results. For the generation of the inspection lot, check items and target objects, an algorithm was established based on BIM technology according to the standards. To make the inspection data collection efficient, an indoor positioning technique was integrated to identify the correspondence between the target objects on site and the corresponding elements in the BIM model. An information system was then developed, which includes the above particular inspection tools for processing the inspection results and facilitates the collaboration among the relevant stakeholders through the Web. The system was tested in a real building project, which proves the efficiency and effectiveness of the system and demonstrates the usability at real construction sites.

The proposed system is a powerful tool for the project stakeholders to follow the rules of standards for construction quality management. It can lower the risk of missing check items and target objects during the inspection and avoid the existing tedious tasks, such as inspection task planning and inspection data re-entry, which reduces the workload of the inspectors. The collaboration of the stakeholders can be facilitated efficiently. It is expected that these developments will also contribute to the improvement of construction quality management.

The research presented demonstrates that construction quality management can be made more efficient and effective through the integrated use of BIM and indoor positioning technologies based on a web-based collaborative system.

The system can be improved in several aspects, and our future work will concentrate on the following issues:

1) Automatic association with construction schedules and inspector assignment with the system to generate a more detailed inspection plan;
2) Customization of the check items and criteria from the standard for different application scenarios;
3) Integration of more technologies to collect the inspection data more conveniently, such as voice input, AR and image-matching technologies.

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