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A navigation and positioning-integrated system for construction quality inspection under self-discipline of responsible personnel

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Abstract

Construction quality control is one of the major factors that ensure a project completed within budget and schedule. However, the quality inspection and management (QIM) process is usually inefficient and invalid, due to the scattered construction codes, the overlooked process monitoring, the complex data entry process, and especially the weak sense of responsibility. To address above issues, this paper proposes a UWB (Ultra-Wideband)-based Quality Inspection and Management System (UWB-QIMS). By integrating the application of BIM (Building Information Modeling), UWB and PDA (Personal Digital Assistant), navigation and indoor positioning for inspectors can be realized. Thus the UWBQIMS can promote the effective construction QIM under self-discipline of responsible personnel, which benefits mainly in two ways: 1) assisting the site work of inspectors by pushing navigation paths and checklists through a PDA, and then guiding inspectors to work on site effectively; 2) assisting the supervision and decision making of managers by tracing the inspection coordinates in BIM environment, and supporting to supervise the inspector's working condition and issue timely warnings. Finally, the prototype system was tested and evaluated in a quality inspection scene, aiming at the construction phase of a residential building. The testing results illustrated the effectiveness of the UWBQIMS in supporting effective QIM focusing on the sense of responsibility of responsible personnel. Besides, the potential applicability of integrating BIM, UWB, and PDA in construction quality control was proved.

Keywords: Construction quality inspection and management, sense of responsibility, BIM, UWB

1. Introduction

Due to the variabilities within project environment and the complexity of construction management, construction quality should be closely focused on and controlled throughout each stage of construction (Cheng and Ko, 2003). Quality inspection is the act of measuring or examining a product's quality and preventing defects to assure that the final product meets specifications and fulfills the customer's requirements (Pesante et al., 2010). Inspection omissions may cause construction errors and quality degradation, which have negative effects both on the costs and the schedule aspects of entire construction projects (Kwon et al., 2014). According to the statistics in previous work (Chen and Luo, 2014), the state of project-site accidents resulting from poor quality is relatively severe in China. Poor quality can be in part attributed to the inefficient and invalid quality inspection and management (QIM), which is mainly reflected in the following aspects:

1) The quality inspection criteria are usually scattered in different construction codes (e.g., national, industrial or local codes), which makes these specifications cross-reference and heavily depend on each other (Boukamp and Akinci, 2007). Thus, the substandard and unfitness reference to the quality control criteria is currently a common phenomenon. Usually, site managers carry out the inspection work by recording defect information on related documents, such as drawings and checklists, while walking around the site. Then the inspection information will be re-entered into the companies' web systems such as PMIS (Project Management Information System) at the site office (Kim et al., 2008). In that context, the traditional QIM process is tedious, time consuming and error prone.

2) Generally, quality inspection can be divided into two categories: 1) inspection performed during the work-in-process which checks work preparation for each work procedure and 2) inspection performed during end-product stage which detects defects or construction errors of the final construction product (Laofor and Peansupap, 2012). Efficient and valid inspection of either category is essential to quality control to ensure the quality of the end construction product. However, current quality inspection mainly focuses on the end-product stage, with much less attention to the work-in-process (Chen and Luo, 2014). Especially, for a hidden project, the process monitoring is necessary and critical to the final construction quality. Thus, only the quality inspection to the end-product is not enough to guarantee the quality of the entire working procedure.

3) It is noteworthy that the weak sense of responsibility under manual supervision is one of the critical reasons leading to the QIM problems, without comprehensive and valid management regulations and measurements. As an all-around task under manual supervision, quality inspection is usually considered as a formulaic burden by the inspection team involved different participates (e.g., supervisor, contractor and owner), which easily leads to the absence from duty (Zou, 2011). Besides, conflicts between these participates in the acceptable defect levels still exist, which leads to much more difficulties in identifying the responsibility for a quality problem (Laofor and Peansupap, 2012; Bass, 2000).

QIM is one of the critical parts in quality control (Wang, 2008). Considering the background listed above, there is a strong need to propose an effective QIM supporting system considering the selfdiscipline of responsible personnel. According to practical projects and research review, many approaches based on new technologies (e.g., BIM, GPS, RFID) have been proposed in construction quality control recently (Wang, 2008). For example, Kim et al. (2008) proposed an application system using Personal Digital Assistant (PDA) and wireless internet to improve the efficiency of quality management. Chen and Luo (2014) proposed a BIM-based construction quality management model integrating the 4D BIM and a POP (product, organization and process) model. Ma et al. (2018) presented a collaborative system using BIM and indoor position technologies (using magnetic field and Wi-Fi signals) to for increasing efficiency of the construction quality management, and supporting the collaboration of difficulties stakeholders in construction. However, to the authors' best knowledge, no research has been developed for coping with all the application requirements of the QIM supporting system discussed above, especially the requirements focusing on the sense of responsibility of responsible personnel.

According to the application potentials of UWB technology, BIM and mobile devices in construction quality control, this paper proposes a UWB-based Quality Inspection and Management System (UWBQIMS), which integrates the navigation and positioning to facilitate the efficient QIM under selfdiscipline of responsible personnel. The UWB-QIMS achieves above purpose mainly in two ways: 1) assisting the site work of inspectors: Inspector attached with a UWB tag can work on site effectively under the guidance of navigation paths and checklists pushed by a PDA; and 2) assisting the supervision and decision making of managers: Site management center can conduct supervision by tracing the inspection coordinates of an inspector in BIM environment, and issue timely warnings if necessary.

2. Development of the UWB-based Quality Inspection and Management System (UWB-QIMS)

2.1 Architecture and function configurations of the UWB-QIMS

The scenario of the quality inspection and management using UWB-QIMS is described as follows, in which three parts correlating to each other (i.e. UWB-based location on site, mobile devices (PDA) and management center) are mainly involved (Fig. 1).

1) Every inspector on the construction site is attached a UWB tag, by which the location coordinates and working paths of the inspectors can be real-timely traced and instantly sent to the management center.

2) BIM data combined with navigation information and checklists is sent to the inspector through the PDA. Besides, the BIM is processed using the Web3D-based light weighting solution (Liu et al., 2016).

3) After typed inspect objects according to the inspection plan, the PDA can generate a navigation path to the inspector. The inspector can then find the inspection object based on the object visualization in BIM environment.

4) Within a certain scope of an inspection object, the inspector can click the target BIM object through the PDA, and checklists can be pushed to the interface. Then the inspector enters related quality inspection data into the electronic checklists through the PDA.

5) Quality inspection data in the electronic checklists is uploaded to the web server in the management center.

6) Through supervising the working path of the inspector and tracing the completion status of checklists, site managers in the management center can make reasonable decisions (e.g., issuing timely warnings to the inspector) for corrective actions when problems are found.

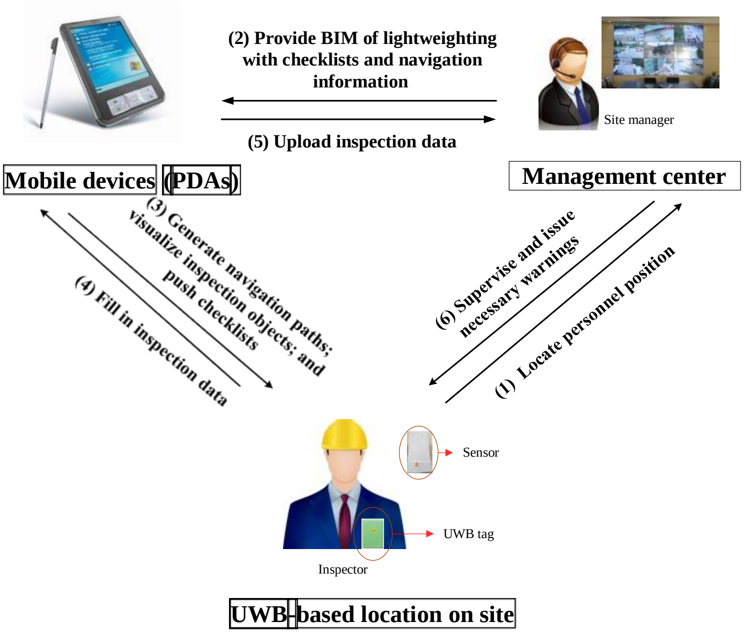

Figure 1: The quality inspection and management process using BIM, UWB and PDA.

Through above steps, the UWB-QIMS can support the QIM by assisting the site work of inspectors and the supervision and decision making of managers. Especially, in the application scenario described above, self-discipline of the inspector is visualized. In practical projects, inspectors should be at the right construction place for the quality inspection or checking work. In other words, the inspector should be close to the inspection object. Thus, one of the premises to ensure a valid quality inspection is that the inspector shows up at the place (or near the place) where the object locates. According to practical projects and previous study (Taneja et al., 2011), the distance of 3 m is small enough to guide an inspector to the scope where an inspection object locates, which is also taken as the standard for the supervision by managers. Tracing the working path and the synchronized checklist uploading, the work performance of the inspector can be described and recorded, which can then be used for responsibility identification. As a specific intelligent quality control system, the architecture of the UWB-QIMS is composed of 5 functional parts: BIM module, UWB module, Web service module, Database module, and User database module (Fig. 2).

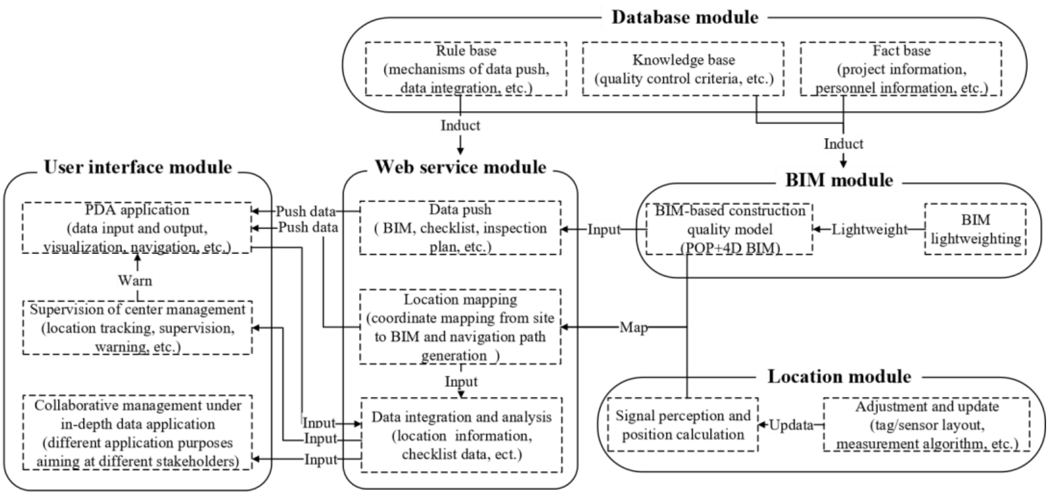

Figure 2: Architecture of the UWB-QIMS.

1) BIM module:

- The BIM-based construction quality model which combining POP model and the 4D BIM provides a visualization of the quality progress. Besides, fully standardized and structured inspection criteria are integrated in the model to provide clear task requirements for quality inspection and management.

2) Location module:

- UWB-based RTLS with TDOA measurement algorithm is conducted to tracking the positioning of an inspector on site.
- Base on the application requirements (for example, positioning applicability, positioning accuracy, etc.) of practical project environment, the layout of tags/sensors and measurement algorithms can be correspondingly adjusted and updated.

3) Web service module:

- Practical location on site is mapped to the BIM based on the Unity3D platform. Besides, the navigation path is generated.
- Data of real-time location in BIM and inspection information in electric checklists are collected and integrated, as the basis of data analysis.

4) Database module:

- Rule base contains mechanisms which can induct the functions in the Web service module run, such as data push mechanisms, location mapping mechanisms, data integration mechanisms, etc.
- Knowledge base contains quality control knowledge (such as criteria and manuals), which can induct the functions in the BIM module run.
- Fact base contains project information (such as project schedule) and personnel information (such as staff duty), which can induct the functions in the BIM module run.

5) User database module:

- In the inspection process, an inspectors can receive the guidance of navigation path together with required checklists generated through the PDA. Inspection data on site can be recorded via the specially designed interfaces of the PDA.
- The supervision work of the site managers are executed under the data of personnel location and quality inspection data. Necessary warnings from the management center can be given to the inspector by PDA in time.
- Aiming at different stakeholders, collaborative management under in-depth data application can be carried out. For example, an integrated BIM, in which quality results of every construction stage are attached to the building elements, can be used to conduct the follow-up quality control work.

2.2 Critical technologies for performing the UWB-QIMS

2.2.1 The UWB-based indoor location

Compared to other location technologies, UWB technology has many advantages: 1) It has longer read ranges than laser scanning or vision-based detection and tracking systems (up to 1000 m); 2) It has ability to work both indoors and outdoors; 3) It is of low average power requirement which results from the low pulse rate; 4) Compared with RFID systems, UWB does not need to be integrated with other technologies to provide an accurate 3D location estimate (Shahi et al., 2012). Further, the accuracy of the UWB technology reaches centimeter level which is consistent with the above assumption. Correspondingly, TDOA-based system is proved to have a good accuracy with the high time resolution (wide bandwidth) of the UWB signals (Shen et al., 2008). Considering the need for measurement accuracy of RTLS, the TDOA (a range-based measurement algorithm), is suitably used to determine the spatial location of the inspector. Thus, the UWB with the TDOA is chosen as the reasonable location technology for realizing the visualization of inspector's working condition.

A basic UWB-based RTLS typically consists of a tag, a Hub, a monitoring terminal, and four sensors (one master sensor and three slave sensors, which can be used to locate an object three-dimensionally). In this research, a limited number of sensors are arranged in the inspected zone. Each tag registers with its containing sensor cell, and is inserted into the schedule for that cell. When a tag emits a signal, this signal is picked up by the four sensors in the cell. The sensors decode and send the speeds and time differences of arrival of different UWB signals to the Hub through an Ethernet connection. Then the positioning server accumulates all sensed data and computes the location based on the TDOA measurement algorithm. The location information can be used in the third-part system of different applications (e.g., supervision of site manager in management center and data push for inspectors through PDAs). A brief schematic of this UWB-based indoor location for the visualization of inspector's working condition is shown in Fig. 3.

The following presents a brief summary of technical specifications of the UWB-based indoor location that are selected and utilized in this research. The utilized product uses 5.7 GHz to 7.2 GHz frequency band, its update rate is range from 1/60 Hz to 10 Hz. When the update rate is adjusted at the lowest rate, 200 terminals can be positioned at most, and achieve an average power consumption as low as 0.1 mAH to save energy. Its operation range area is up to 360 m×360 m with 2D accuracy of 15 cm and 3D accuracy of 30 cm in real-time, which can meet the application requirements mentioned above.

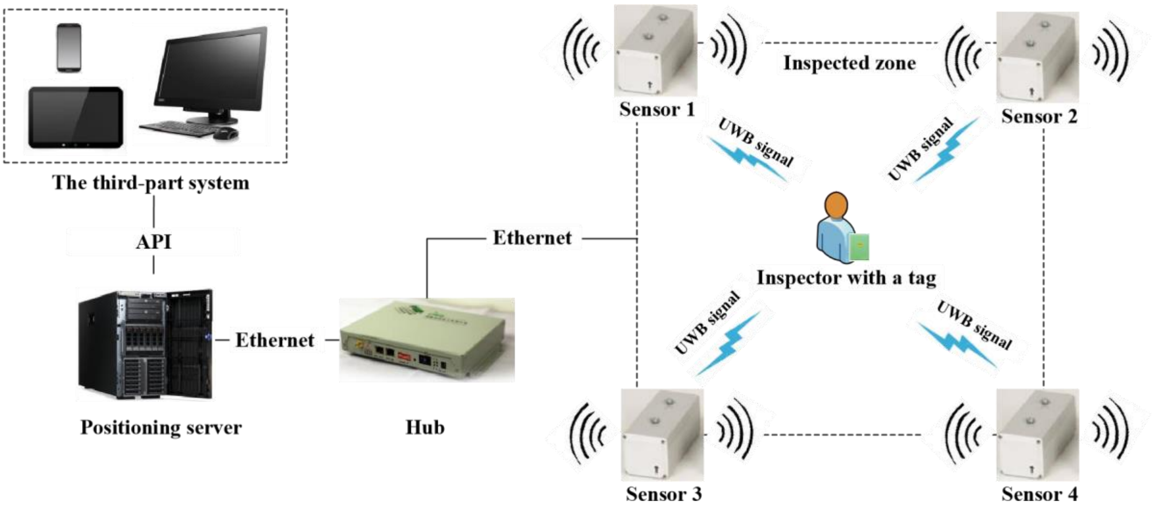

Figure 3: The UWB-based indoor location for the visualization of inspector's working condition.

2.2.2 The visualization and tracking of inspector's working condition

This section deals with UWB location tracking based on the utility of BIM. That is, the location of an inspector can be visualized real-timely in the BIM model, which will aid in the generation of a navigation path of the inspection objects to the inspector. In addition, by tracing inspector's working condition recorded in BIM, site manager in the manager center can conduct the supervision tasks.

In this research, Unity3D engine, which combines visual simulation capabilities with interactive functions (Indraprastha and Shinozaki, 2009), is chosen as the integration platform of UWB location technology and BIM. In addition to the openness of the Unity3D, relative calculation programming and other functions of the engine (programming module, script, and language) are used in this platform. Based on previous study in (Costin et al., 2014), the platform is developed in Visual C# 2010 to connect the ThingMagic API (UWB) and Tekla API (BIM).

The framework of the coordinates mapping (from the construction site to the BIM environment) based on the Unity3D platform is presented in Fig. 4. For realizing the real-time localization of an inspector in the BIM environment, the (x,y,z) coordinate information is firstly calculated and read from the positioning server based on UWB. Then, the location is then sent to the 4D BIM model, and the updated location is displayed on the user interface.

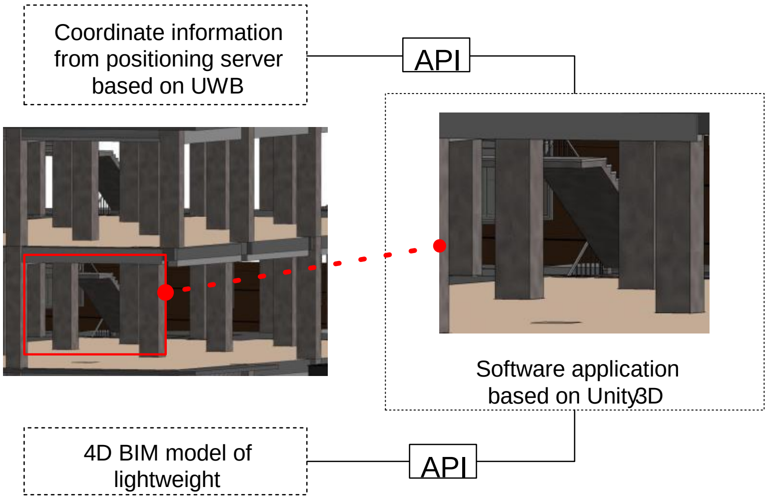

Figure 4: Overview of the mapping of the working coordinates to the BIM.

2.2.3 Push of electronic checklists

Due to the complexity of a construction project and its environment variability, quality inspection tasks should be conducted and controlled throughout various stages of the entire construction lifecycle. Given the quality control criteria and project schedule, inspection plans of different construction stages assigned to an inspector are different (Chen and Luo, 2014). Considering the work implementation of practical QIM in compliance with construction schedule, corresponding electronic checklists of inspection objects should be pushed to the inspector thorough the interface of PDA.

This research refers the BIM-based construction quality model proposed in previous study (Chen and Luo, 2014), which combines BIM and the quality POP (product, organization and process) model, to realize the above application purposes. The BIM-based construction quality model is a 4D BIM integrated the scheduling information, so that construction process in accordance with the construction schedule can be virtually presented in time sequence. The inspection plan can be arranged, adjusted, and pushed dynamically along with the practical construction process. The inspection criteria are in the structured expressions of “inspection object—characteristic attribute—quality control requirement”. Thus, electric checklists containing required quality control requirements can be traced to certain inspection objects in BIM. During the quality inspection on site, the inspector within the inspection scope of an inspection object (within the distance of 3 m) can identify and click corresponding BIM element through PDA. Then the object-oriented quality checklists matched with the inspection plan are located and pulled out at the interface of PDA (Ma et al., 2018). As a result, checklists can then be tapped and completed by inspectors with on-site data conveniently and efficiently. The sketch of electronic checklists retrieval and push based on BIM and PDA is shown in Fig. 5.

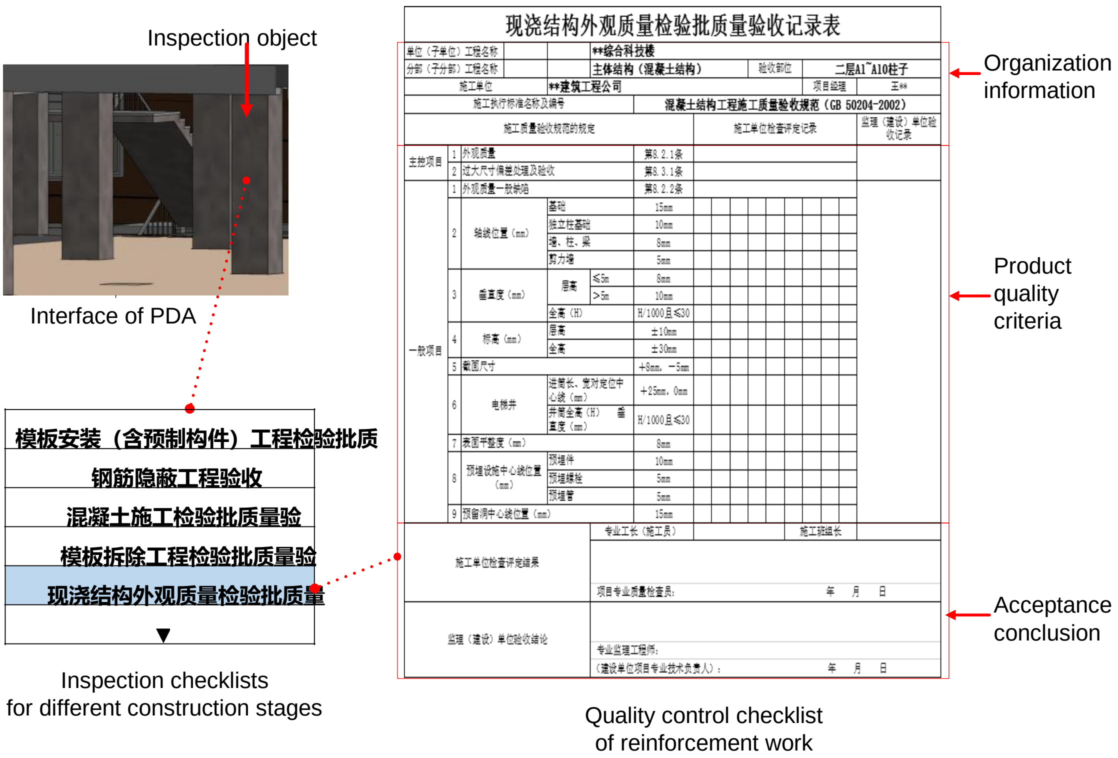

Figure 5: Overview of the BIM-based retrieval of the electronic checklists for quality inspection and management (taking inspection of reinforcement work of columns as an example).

3. Field QIM testing using prototype UWB-QIMS

For assessing the overall performance of the UWB-QIMS in QIM, a field testing was designed in this research. The testing was conducted in a residential building in Wuhan, Hubei province, in an inspection scene of the surface quality of cast-in-situ concrete structure. Before the field testing, a prototype UWBQIMS was established, and the QIM procedure based on the UWB-QIMS was briefly introduced to testing participants. As shown in Figure 6, the field testing process is described and discussed in detail as follows.

Figure 6: Examples of PDA interface using UWB-QIMS.

1) An inspector with a UWB tag and a PDA walked around the construction site, and entered the inspection scope under the instruction of the inspection plan (e.g., cast-in-situ concrete walls of No.A1~A10 of the 2nd storey).

2) A navigation path was generated in PDA according to the quality inspection task, which was for guiding the inspector to the target objects. Especially, the navigation path can be switched between 2D and 3D (i.e. shown in 2D drawings or BIM).

3) After the inspector clicked on the target wall in BIM environment, checklists related to the wall were pushed in the interface of the PDA. The inspector chose the checklist for the surface quality inspection of cast-in-situ concrete structure, and then filled it with inspection data on site. During testing process, completed checklists were saved and submitted in turn and timely to the management center.

4) By integrating the traced personnel location and the uploaded electrical checklists, the supervision results in the management center illustrated that the inspector performed his duty according to the inspection plan.

The testing results demonstrates that the UWB-QIMS has potential benefits in guaranteeing working quality. 1) The navigation path and the visualized working coordinates can ease inspectors' workloads. As a result, the time spent on inspection tasks is reduced. 2) The supervision work of high-efficiency can be executed through web service, without requiring site managers and side-standing system to visit the construction site. Further, proactive and in time feedbacks (e.g., issuing warnings to the inspectors) from the management center help to prevent rework and rectification costs, especially for the hidden projects. 3) The entire inspection process could be recorded in the form of inspection paths and checklists of time-tracking combined with BIM, which can be used in further quality control work (e.g., the re-inspection task and responsibility identification).

4. Conclusion

This research aims to facilitate the efficiency of QIM in construction under self-discipline of responsible personnel. Thus, the UWB-QIMS, which integrates the application of BIM, UWB and PDA, is proposed. The architecture of the UWB-QIMS with 5 functional parts has been introduced. By integrating navigation and indoor positioning, the UWB-QIMS benefits the QIM mainly in two ways: 1) assisting the site work of inspectors: push navigation paths and checklists to an inspector through a PDA, and then guide him to work on site effectively; 2) assisting the supervision and decision making of managers: tracing the inspection coordinates of an inspector in BIM environment, managers can supervise the inspector’s working condition and issue timely warnings for corrective actions.

The QIM based on the UWB-QIMS does have the following limitations: 1) This research mainly focuses on the technical feasibility of the three critical technologies mentioned in this paper, without considering the network condition (wireless internet) of general construction site in practice, as well as the legality of it in the future; 2) Due to the judgment to the working condition of an inspector on site greatly depends on the distance to the inspection objects, the criteria of the distance values aiming at different project types and inspection lots should be set in detail in advance; 3) The system performance is only tested through a field testing in a practical project, with the background of the surface quality inspection of cast-in-situ concrete walls. For a more objective evaluation of the UWB-QIMS, tests on more practical construction sites and under more complicated conditions should be done in the future.

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References

Bass, R. (2000). Quality control of soil-cement construction for water resources. In Soil-Cement and Other Construction Practices in Geotechnical Engineering, pp. 13-25.

Boukamp, F., and Akinci, B. (2007). Automated processing of construction specifications to support inspection and quality control. Automation in construction, 17(1), pp. 90-106.

Chen, L., and Luo, H. (2014). A BIM-based construction quality management model and its applications. Automation in construction, 46, pp. 64-73.

Cheng, M., and Ko, C. (2003). Object-oriented evolutionary fuzzy neural inference system for construction management. Journal of Construction Engineering and Management, 129(4), pp. 461469.

Costin, A., Pradhananga, N., and Teizer, J. (2014). Passive RFID and BIM for real-time visualization and location tracking. In Construction Research Congress 2014: Construction in a Global Network, pp. 169-178.

Indraprastha, A., and Shinozaki, M. (2009). The investigation on using Unity3D game engine in urban design study. Journal of ICT Research and Applications, 3(1), pp. 1-18.

Kim, Y., Oh, S., Cho, Y., and Seo, J. (2008). A pda and wireless web-integrated system for quality inspection and defect management of apartment housing projects. Automation in Construction, 17(2), pp. 163-179.

Kwon, O., Park, C., and Lim, C. (2014). A defect management system for reinforced concrete work utilizing bim, image-matching and augmented reality. Automation in Construction, 46, pp. 74-81.

Laofor, C., and Peansupap, V. (2012). Defect detection and quantification system to support subjective visual quality inspection via a digital image processing: A tiling work case study. Automation in Construction, 24, pp. 160-174.

Liu, X., Xie, N., Tang, K., and Jia, J. (2016). Lightweighting for Web3D visualization of large-scale BIM scenes in real-time. Graphical Models, 88, pp. 40-56.

Ma, Z., Cai, S., Mao, N., Yang, Q., Feng, J., and Wang, P. (2018). Construction quality management based on a collaborative system using BIM and indoor positioning. Automation in Construction, 92, pp. 35-45.

Pesante, J., Williges, R., and Woldstad, J. (2010). The effects of multitasking on quality inspection in advanced manufacturing systems. Human Factors & Ergonomics in Manufacturing & Service Industries, 11(4), pp. 287-298.

Shahi, A., Aryan, A., West, J., Haas, C., and Haas, R. (2012). Deterioration of UWB positioning during construction. Automation in Construction, 24, pp. 72-80.

Shen, G., Zetik, R., and Thoma, R. (2008). Performance comparison of TOA and TDOA based location estimation algorithms in LOS environment. In 2008 5th Workshop on Positioning, Navigation and Communication, pp. 71-78. IEEE.

Taneja, S., Akcamete, A., Akinci, B., Garrett Jr, J., Soibelman, L., and East, E. (2011). Analysis of three indoor localization technologies for supporting operations and maintenance field tasks. Journal of Computing in Civil Engineering, 26(6), pp. 708-719.

Wang, L. (2008). Enhancing construction quality inspection and management using RFID technology. Automation in construction, 17(4), pp. 467-479.

Zou, W. (2011) Discussing of the quality supervision and management of construction projects. China Urban Economy, 2011(3), pp. 144-144.