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Research Article

Design and Application of Intelligent Construction Quality Inspection System Based on BIM-RFID

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Building information modeling (BIM) and radio-frequency identification (RFID) technologies can assist with problems in the construction quality inspection process, such as difficulties with the intelligent positioning of components, data replication, and insufficient feedback information during rework and maintenance. A novel technology BIM-FRID-integration is competent for multiparticipant information sharing in construction sector by collecting, transmitting and processing the quality defect information found in the construction process. In this study, an intelligent positioning inspection system to ensure building quality was developed using leading BIM software (Autodesk Revit in a Microsoft Visual Studio environment) and RFID handheld terminal devices. To verify the effectiveness of the framework proposed in this paper, the system was applied to a practical project, and its modeling, unique identifier (UID) components, and other information generation and export processes were analyzed. The results demonstrated that the BIM-RFID-integrated building quality intelligent inspection system proposed in this paper could realize the correlation and interaction between the BIM model and the entity component information as well as accurately locate any components with quality problems and provide quick feedback of quality inspection information and visual construction annotation disclosures.

1. Introduction

Quality inspection plays a decisive role in ensuring the final quality of any construction project [1–3]. Quality control inspection refers to the quality acceptance of completed subprojects in accordance with national or local standards or criteria in the construction process. Traditional quality control inspection measures have, over time, been replaced by intelligent quality inspection systems that overcome problems such as excessive human interference, retranscription data, and underutilization of information in the feedback link [4]. With the dramatic increase in large volumes of super high-rise, complex buildings in China [5, 6], the intelligent detection system has emerged to realize intelligent management and control of engineering quality. However, despite representing a scientific breakthrough in comparison to traditional management and control methods, such intelligent systems still present challenges in practical applications, such as poor durability, the high requirements of complex construction environments, the inability to provide adequate visual data feedback, and difficulty in comprehensively utilizing detection information in testing. Therefore, in this study, a new intelligent quality inspection system was developed, based on building information modeling (BIM) and radio-frequency identification (RFID) technologies, via module analysis, system design, an application process, and other steps. This novel system then showed not only to carry out conventional intelligent detection but also to effectively provide the functions of intelligent tracking and positioning based on BIM, quick feedback of quality inspection information, and visual disclosure.

In recent years, with the rapid development of information technology, the BIM-based intelligent quality inspection system has become the main way of quality control inspection in construction sector [7]. While comprehensive and intelligent multifunctional systems have marked a scientific breakthrough in

Table 1: A comparison between construction quality inspection systems.

System form	Professional requirements	Durability	Construction environment	Intelligent positioning	Visual disclosure	Intelligent feedback
Computer + PB [8]	Higher	Good	No	No	No	No
BIM + 2D [9]	Low	Poor	High	Yes	Yes	No
BIM + Indoor mobile positioning [10]	Low	Good	No	No	No	No

traditional construction quality control, some challenges remain.

Construction quality refers to the comprehensive requirements for the safety, applicability, economy, environmental protection, aesthetics, and other characteristics of the projects in the current relevant laws, regulations, technical standards, design documents, and contracts.

During construction quality inspection, in order to improve efficiency, reliance on text and paper drawings should be replaced with modern management techniques. Pan [8] proposed that computer platforms and power builder (PB) software could be used to realize data entry, information queries, data collection, and the printing of engineering quality acceptance data. Although this approach does meet the requirements of authentic quality acceptance information, it cannot make further use of the information collected from computer systems nor can it be used to conduct intelligent positioning or track components.

Yang and Zhou [9] proposed that the combination of BIM technology and 2D barcode technology could realize the comprehensive application of information by storing equipment information and tracking equipment location, so as to improve construction management efficiency. However, in the early stage of modeling using Revit and other software, components with different information need to be drawn segment by segment, resulting in a heavy workload and slowing the speed of modeling. Furthermore, this technology can only locate the components with quality problems and cannot store information regarding the detection of quality problems nor provide information feedback functions. In addition, 2D barcode labels are easily damaged and lost, among other problems that may lead to the loss of project object tracking information and result in quality and safety risks for the project.

Ma et al. [10] developed an intelligent management system for construction quality by using a combination of BIM and indoor mobile positioning technology to solve problems such as inspection omissions and secondary transcription of data within current construction quality acceptance processes and the implementation of specifications. However, in terms of construction quality acceptance, the system only allows users to complete construction quality acceptance forms via their mobile phones, which are relative to the user's location on the construction site. Moreover, it is unable to quickly and accurately ascertain the component location problem or to share the issued quality inspection information with the construction team. To sum up, the comparison of commonly used construction quality inspection systems is shown in Table 1.

It is evident that, among the previous quality inspection systems only that which incorporates BIM technology + 2D technology can simultaneously realize intelligent positioning and visual construction disclosure. Unfortunately, this system, however, has poor durability and does not provide the fast feedback of quality inspection information. Furthermore, it is common for a 2D barcode to become deformed or damaged by the end of a project, thus hindering the entire intelligent detection system [11]. Hence, in order to solve this problem, this study employed BIM + RFID technology to develop an intelligent detection system with improved durability which can realize intelligent detection and ensure an efficient and sustainable quality management contribution to construction projects.

2. Design and Application of Intelligent Construction Quality Inspection System

BIM and RFID technologies focus mainly on three aspects, namely, facility asset operation and maintenance management, project construction safety management, and project life-cycle management. There are, however, few reports on the real-time feedback of the construction quality inspection information and intelligent tracking and positioning achieved via BIM and RFID. This paper presents a new quality intelligent inspection system developed through module analysis, system design, and the application process of these three stages and, furthermore, verifies its effectiveness.

2.1. Module Analysis. BIM, which emerged in the 1970s [12, 13], is the creation and application of coordinated, reliable, and computable data for construction projects. Such data are often parametric and can be applied to rapid design generation, planning, decision-making, document creation, and cost estimation, among other related functions [14–17]. As an emerging industrial technology in the fields of architecture, engineering, and construction, BIM enables different parties involved in a project to combine and coordinate their work into a three-dimensional (3D) parametric model with embedded information. Such a model comprises digital objects that represent various elements of a building. These mainly include the geometric shape of buildings and other attribute information, which provide global unique identification [13, 18, 19]. BIM provides a comprehensive database that can be used not only for visualizing construction products using 3D models but also for conducting various analyses within the models [13]. Consequently, BIM has rapidly gained popularity in multiple fields, from academic research to project planning, structural design as well as facilities management [18, 20].

At present, the main BIM software used in construction includes Autodesk Revit, Navisworks, AutoCAD Architecture, MicroStation V8i, and Digital Project, among which Autodesk Revit is most widely applied by researchers in China due to its advantages of facilitating secondary development, high-frequency usage, and extensible BIM data. Autodesk Revit is favored as modeling software for architects, structural engineers, engineers, mechanical/electrical/plumbing (MEP) engineers, designers, and contractors as it enables users to design architecture, structures, and their components in 3D models, to annotate models with 2D drafting elements and to acquire building information from the model database [21].

As building projects become more complex, the integration and collaboration allowed by BIM software plays an increasing role on construction quality. Gokcen et al. [22] developed the building information modelling (BIM) capability assessment reference model (BIM-CAREM) for assessing the BIM capabilities of individual building life cycle stages and their processes. David et al. [23] proposed that the convergence of the capabilities of BIM, virtual reality (VR), and augmented reality (AR) are integrated solutions to reduce the impact of rework in design change. As the retrofit strategy determines the success of the retrofitting process, Chen et al. [24] proposes a decision support framework for retrofitting that integrates the building information modeling (BIM) with large-scale group decision-making, which is a new application of digital technology for the retrofitting of existing buildings.

Due to the varying construction industry standards in different countries, Autodesk provides users with the interface for secondary development for Autodesk Revit and enables them to develop external applications and record them automatically [25]. However, with the scale, complexity, and level of knowledge required in construction engineering, the original platform can no longer meet the needs of safety management, data interaction, and information sharing. Many software developers have, thus, introduced related Autodesk Revit application programming interfaces (API), as shown in Table 2.

All the studies detailed in Table 2 were secondary developments of the Autodesk Revit platform and, thus, increased the functions of this BIM software and expanded its application scope. However, few research studies have investigated related practical engineering problems during construction quality inspections, such as the difficult intelligent positioning of components, repeated transcription of data, and lack of feedback information during rework and maintenance.

The principle of wireless RFID [31] involves the utilization of the characteristics of radio frequency signals and spatial coupling transmissions to realize identification and data exchange [32]. The identification process does not require human intervention, can be applied to various harsh environments, and has strong resistance to substances such as water, oil, and chemicals. The RFID system is comprised of electronic tags and readers. The electronic tag is composed of a microchip and an antenna [33], which can repeatedly add, modify and delete data stored in its internal storage, which is convenient for information updating and includes large data capacity.

BIM technology has increasingly provided prominent advantages in construction project management [34], while RFID provides unique benefits for information identification and data interaction. Therefore, based on the integration of BIM and RFID technologies, a new building construction intelligent quality inspection system was developed in this work. By realizing real-time correlation and interaction between the BIM model and the quality problem information stored in the RFID, all project participants can intelligently locate and track problem components at any time, carry out construction maintenance, visual disclosure, and information feedback, and realize the precise management and quality control of the construction.

2.2. System Design

2.2.1. Development Concept. The essence of BIM technology is derived from the storage and expression of information, which can be shared with multiple software systems. However, this information must be closely integrated with field management to exert its value. Internet technology can realize data exchange and information sharing, thereby realizing the collection of information such as people, things, and space, and these functions are currently widely used in barcodes, such as 2D barcode and RFID technology. RFID technology can read component information, store data and replicate it repeatedly, and from a distance [35]. A comparative analysis of the applications of BIM and RFID technology is presented in Table 3.

From Table 3, it can be seen that both BIM technology and RFID technology present disadvantages in information application when applied individually, such as untimely information connection, untimely problem solving, and an inability to correlate with the progress of the project. However, combining BIM and RFID technology can complement each other's advantages and achieve precise management and control of construction quality.

The system proposed in this paper involves the combined development of an Autodesk Revit and a RFID reader to realize the real-time association and interaction between the Autodesk Revit and the building component information in the RFID. Autodesk Revit provides API interfaces for secondary development and enables users to execute programming in any language that is compatible with its own .NET platform, such as Visual Basic, .NET, C#, C++, and F# [36]. The development of the RFID reader can be carried out directly via Android internal programs, and RFID tag information can be read and recorded via the API in Android software development kit (SDK), thereby improving the function of the RFID reader. This novel system plans to develop an application (app) for use on an RFID handheld terminal that can provide quality information feedback on building components. First, the design tag of building components is coded, the RFID tag is attached to the building components for scanning, and those building

Table 2: Functional development of Autodesk Revit API.

Developer	Development technology	Research results
Fang et al. [20]	(1) Secondary development of Autodesk Revit API; (2) RFID technology and cloud technology	Indoor positioning of the construction site was realized, thereby improving security control, safety management, asset management, and productivity monitoring of the construction site
Cao and Zheng [21]	(1) Secondary development of Autodesk Revit API; (2) Analytic hierarchy process (AHP)	Cost decision-making process designed based on BIM and AHP
Chen and Nguyen [26]	(1) Web Map Service (WMS) technologies; (2) Secondary development of Autodesk Revit API	Plug-in developed to streamline the certification process of site location and transportation analysis in LEED (leadership in energy and environmental design)
Kannan and Santhi [27]	(1) Secondary development of Autodesk Revit API; (2) Data acquisition mechanism; (3) CONSTaFORMT add-in	Automated constructability rating framework developed for the different concrete formwork systems most commonly used in the construction of reinforced concrete residential buildings
Yarmohammadi and Castro-Lacouture [28]	(1) Secondary development of Autodesk Revit API; (2) Critical path method (CPM)	(a) Automatic collection of detailed model development data directly from BIM software packages in real-time; (b) the efficient calculation of several modeling performance measures during schematic and design development phases of building projects
Shao et al. [29]	Secondary development of Autodesk Revit API	Plug-in developed for the classification and statistics of steel consumption of underground garage structure; classification and statistics of steel consumption completed; statistical function of Revit steel reinforcement list extended
Deng et al. [30]	(1) Secondary development of Autodesk Revit API; (2) C# language	Based on the Revit platform, the C# language is used for secondary development, ultimately creating a hazard source security management module

Table 3: Comparison of BIM and RFID technology applications [35].

Application	Information collection method	Information processing method	Characteristics of information use
BIM and RFID not applied	Manual input, photography, and scanning	DOC files, Excel sheets, images, folders, and databases	Information connection is not timely; it is not easy to find information; it cannot be associated with project progress; it can be archived
BIM only	Manual input, photography, and scanning	BIM model	Information connection is not timely; information is easily accessed; it can be associated with project progress; it can be archived
RFID only	RFID, mobile terminal, and web-based client acquisition	DOC files, Excel sheets, images, folders, and databases	Information connection is timely; it is not easy to find information; it can be associated with project progress; it can be archived
BIM and RFID combined application	RFID, mobile terminal, and web-based client acquisition	BIM model	Information connection is timely; information is easily accessed; it can be associated with project progress; it can be archived

components exhibiting quality problems are written into the .XML file and fed back to the computer. Each problem component can then be accurately located within the Autodesk Revit model and highlighted. The novel system can store the information in the background database to ensure its long-term validity and accessibility.

2.2.2. Design Process. The novel system should effectively meet the requirements for accurate component location, quick feedback of quality inspection information, and comprehensive utilization of information. In order to ensure the process universality and applicability of the system, a secondary development of Autodesk Revit was conducted in this study via the combination of the C language and SDK provided by Autodesk. At the same time, the RFID reader was developed based on Java language and the data transmission technology provided by Android. The design process of the system is shown in Figure 1.

(1) Step 1. Acquisition of Component UID and Export. The primitive component of each graphic in Autodesk Revit has a unique identifier or identification number. Select the model component via the Autodesk Revit software, and then check the UID number of the selected graphic element in the "Management" menu. Additional information, such as that pertaining to manufacturer and incoming inspections for all devices and building components, can also be supplemented by harnessing the built-in functions of Autodesk Revit. The UID numbers, manufacturer information, and material information for building components can subsequently be exported into a .XML file by selecting, first, the "Inspection tool" tab and then selecting "Get component UID." The operation process is shown in Figure 2.

(2) Step 2. Insert UID Information into RFID Tags. Following Step 1, as described above, the .XML file containing the component UID can be transmitted to the RFID handheld device via a wireless network, data cable, or Bluetooth. The "Fast read" app developed in the RFID handheld terminal can independently select the path to store the file after it has been received. Place each blank RFID tag under the RFID tag scanning RFID handheld terminal and execute the "Start writing UID" command when prompted by the app. Subsequently, the display will advise the following: "UID writing successful, please create a new RFID tag," or "UID writing is complete," as shown in Figures 3–4.

(3) Step 3. Insert and Preserve Quality Problem Information.

①Read the RFID Tag

During an on-site construction quality inspection of problematic components, the RFID handheld terminal can be used by running the "Fast Read" app and selecting the "Read information" tag to obtain information via the app interface such as the UID, material, and location of the component. The analysis of such information is helpful in the diagnosis of component quality problems.

②Write Quality Problem Information into the RFID Tag

Component quality problems that are detected by an on-site quality inspector can be entered or edited directly in the "Problem Record" column of the app or simply recorded by selecting one of the common component problems provided by the system. Finally, the "Record Information" tab should be selected to save the edited component problem information to the RFID tag, as shown in Figure 6.

(4) Step 4. Transfer of Quality Inspection Files. Information regarding a quality problem that is entered into an RFID tag is automatically saved by the handheld background system in a bimtmp.xml file, which can subsequently be transferred to a personal computer (PC) or other device via wireless network, data line, or Bluetooth.

(5) Step 5. Reading and Execution of. XML Files on a PC. A bimtmp.xml file that has been transferred a PC can be read by running Autodesk Revit and selecting the "Problem record file path" tab from the menu. The problematic building component can be selected from within the file, where it will be intelligently positioned and highlighted in the BIM model, with the location information and related quality problems displayed in the pop-up information dialog box.

2.3. Application Process. To verify the effectiveness of the intelligent quality detection system proposed in this paper, it was applied in the construction of an actual residential building as described below.

2.3.1. Project Overview. The construction project upon which the intelligent system was tested is located in Aba Prefecture, Sichuan Province, China, a high-altitude mountainous area and, thus, a harsh construction environment. It is a self-build project covering an area of approximately 93 m^2, with a construction area of 183 m^2, total building height of 8.2 m, and a total of two floors. The project adopts a frame structure, the main purpose is residential, the design service life is 50 years, and the total project cost is approximately 340,000 RMB.

2.3.2. System Application

(1) To ascertain the correlation and interaction between the BIM model and the entity's component information, first, the building must be modeled using Autodesk Revit. After modeling, the Autodesk Revit system will automatically assign a UID number to each graphic element within the model, thereby enabling the correlation and interaction between the BIM model and the component information.
(2) For the accurate positioning of those components possessing a quality defect, the electronic tags embedded with information such as UID number are placed into the corresponding construction entity.

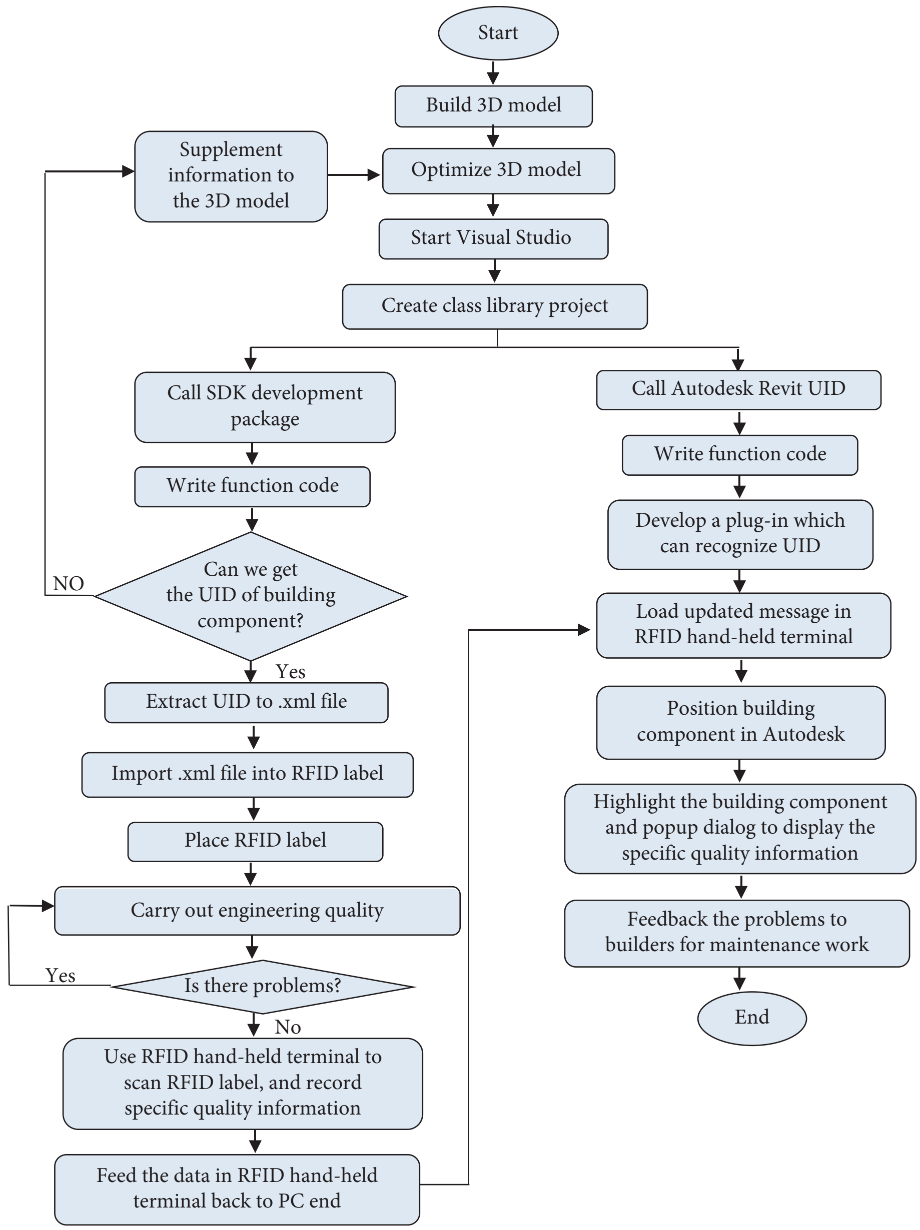

Figure 1: Schematic representation of novel system's design process.

The packaging modes available for RFID tags in different construction environments are listed in Table 4.

Different packaging methods are best applied to suit appropriate construction environments so as to ensure that the RFID tags remain intact during the construction of the entire project, thus ensuring the integrity and validity of quality-related information. The identifying information of components with quality problems should be recorded via the hand-held terminal to maintain knowledge of the precise positioning of the component.

(3) For quick feedback of quality inspection information, all .XML files containing quality problem information are generated by the handheld terminal and transferred to a computer terminal. Building components can be intelligently positioned and highlighted within the BIM model, and the complete list of quality problems for each component can be displayed in the pop-up dialog box, thus achieving the rapid feedback of quality inspection information.

(4) In terms of visual construction disclosure, technical personnel may be permitted to share relevant information with their construction teams through the BIM model and to issue visual construction disclosures. Following required repairs, maintenance, and rework, quality inspection personnel will check to ensure quality requirements and then enter the maintenance information and processing conditions into the relevant RFID tags to realize information

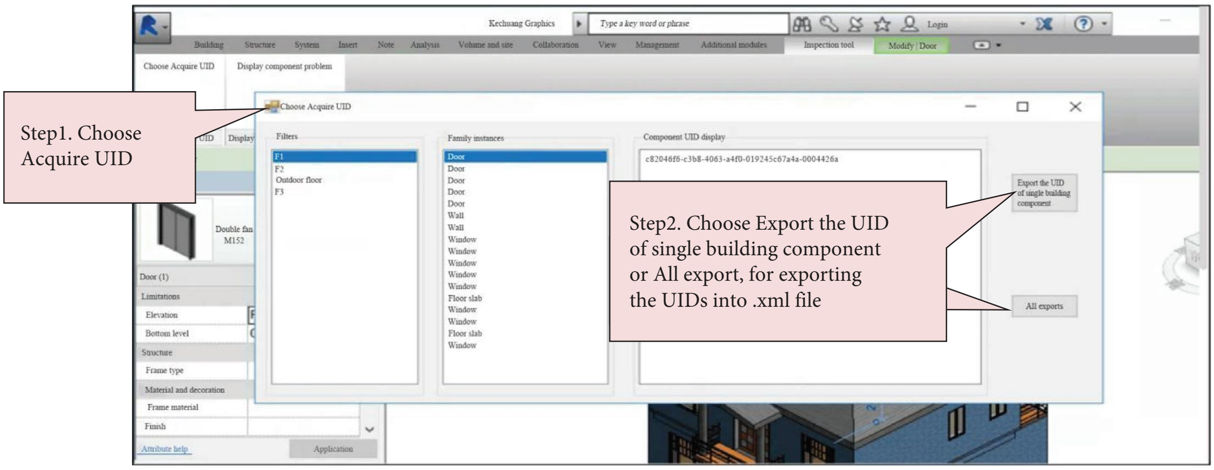

Figure 2: Acquisition of component UID.

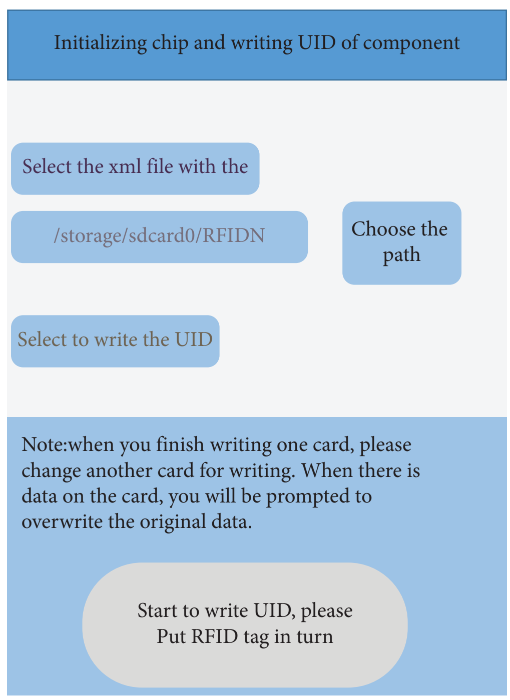

Figure 3: Start writing UID.

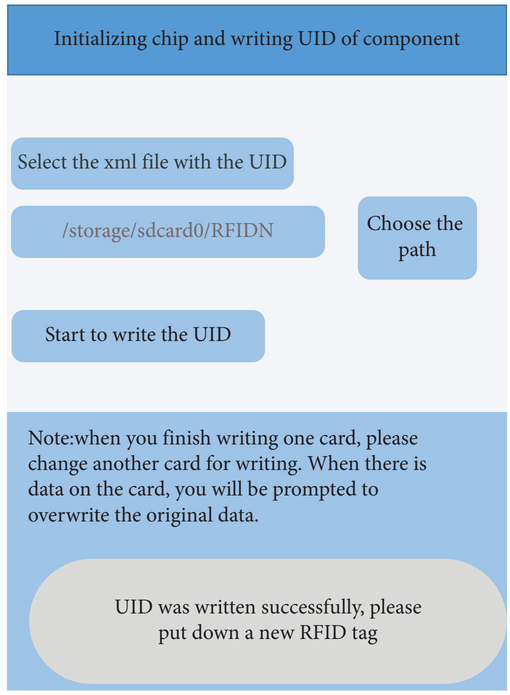

Figure 4: Continue writing UID.

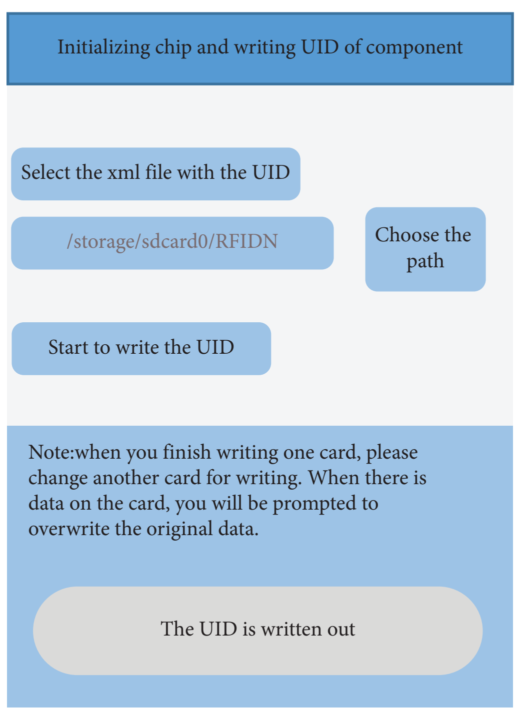

Figure 5: Finish writing UID.

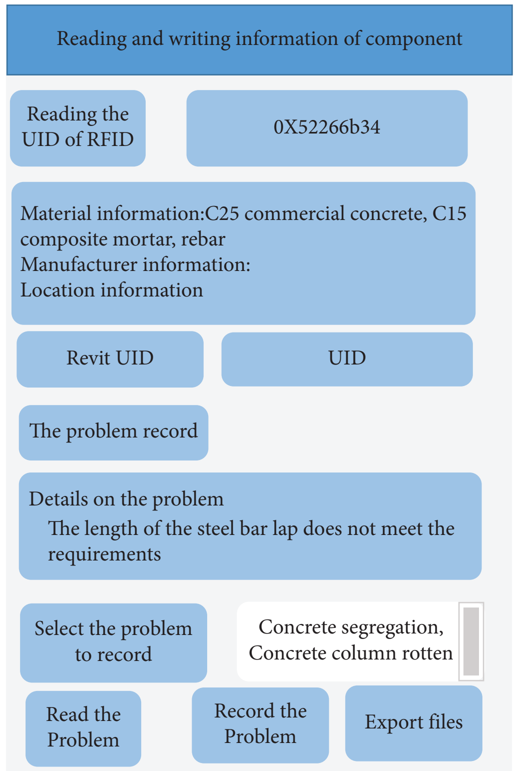

Figure 6: Reading and writing of tabs on RFID hand-held device.

Table 4: Packaging modes for RFID tags within various construction environments.

Environment feature	Packaging modes
Natural environment (e.g., the surface of wall, beam, and column)	PVC, PET, paper, and other materials are used for packaging
Damp environment (e.g., beams and columns which do not provide strength)	PVC and other waterproof materials are used for packaging; paper is NOT suitable
Exposed environment (e.g., rooftop and parapet)	PVC and other composite plastic materials are used for packaging; plastic materials that age easily after exposure to the sun are NOT suitable

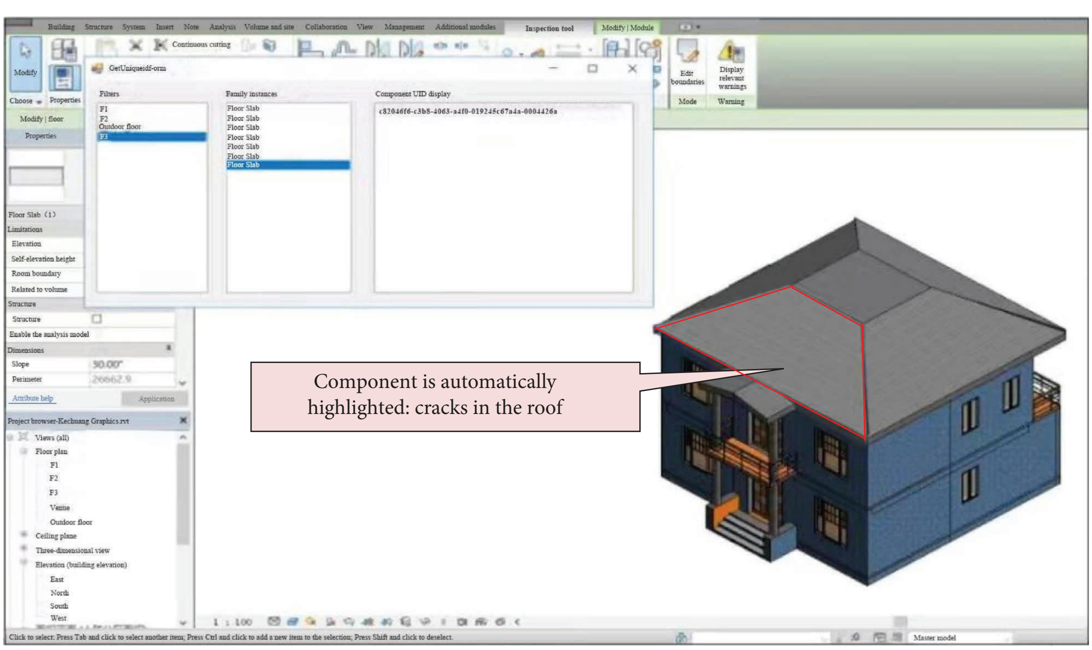

Figure 7: Highlighting of roof building components with quality defect.

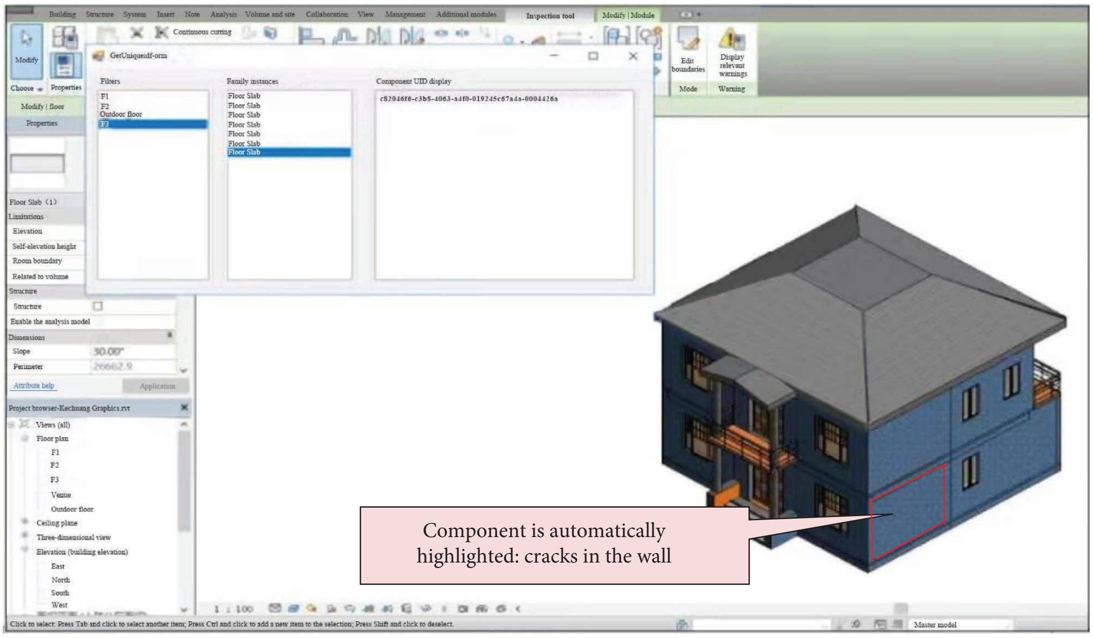

Figure 8: Highlighting of wall building components with quality defect.

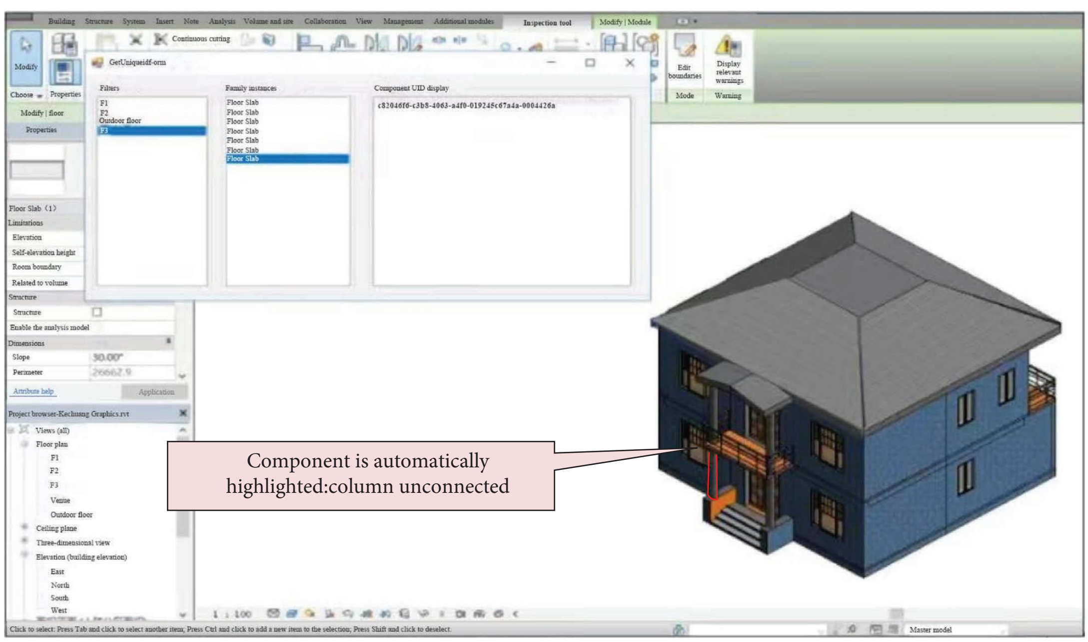

Figure 9: Highlighting of column building components with quality defect.

feedback and tracking. This process is illustrated in Figures 7–9.

3. Conclusion

The functions of intelligent positioning and visual annotation in construction project quality detection are currently widely realized through BIM and 2D barcode technology. However, this system has some important limitations, such as poor durability and a lack of quick feedback of quality information in practical application. Therefore, this study combined BIM and RFID technology to develop a novel intelligent detection system, subsequently verifying the effectiveness of this method through practical application. It was found that the novel system simultaneously realized the intelligent detection function and enhanced durability, thereby ensuring its efficient and sustainable role during the construction phase of a project. The conclusions obtained via this paper are as follows:

(1) The novel intelligent building quality detection system, based on BIM and RFID technology, can

realize the correlation and interaction between a BIM model and RFID tag storage information.

(2) The system can realize the sharing of building quality problem information and visual exchange, while realizing real-time feedback and the positioning tracking of quality problem information.

(3) This system can be adopted under harsh construction environments and, since it is easy to operate, the professional requirements for its use among quality inspectors are not high. Consequently, it can be used to assist with management and visualization, thereby contributing to the efficiency of construction quality management.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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