ICCEPM 2020
The 8th International Conference on Construction Engineering and Project Management
Dec. 7-8, 2020, Hong Kong SAR

A Framework for Automated Formwork Quality Inspection using Laser Scanning and Augmented Reality

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Abstract: Reinforcement steel fixing is a skilled and manually intensive construction trade. Current practice for the quality assessment of reinforcement steel fixing is normally performed by fabricators and has high potential in having errors due to the tedious nature of the work. In order to overcome the current inspection limitation, this study presents an approach that provides visual assistance and inspection enhancement for inspectors to assess the dimensional layout of reinforcement steel fixing. To this end, this study aims to establish an end-to-end framework for rebar layout quality inspection using laser scanning and Augmented Reality (AR). The proposed framework is composed of three parts: (1) the laser-scanned rebar data processing; (2) the rebar inspection procedure integrating with AR; and (3) the checking and fixing the rebar layout through AR visualization. In order to investigate the feasibility of the proposed framework, a case study assessing the rebar layout of a lab-scaled formwork containing two rebar layers is conducted. The results of the case studies demonstrate that the proposed approach using laser scanning and AR has the potential to produce an intuitive and accurate quality assessment for the rebar layout.

Keywords: rebar fixing, rebar layout inspection, laser scanning, Augmented Reality(AR), formwork inspection

1 INTRODUCTION

Reinforcement steel fixing in reinforced concrete (RC) structures is a skilled and labor-intensive construction task where there has not been much improvement in productivity over many decades. The task of fixing reinforcing bars named ‘rebar’ requires the ability to read 2D reinforcement drawings, mentally visualize the cage and an assembly sequence in 3D. One of the important activities for the steel fixing task is to check the number, dimensions, and locations of rebars as those dimensional properties dictate the structural performance and constructability of the RC structure. Current inspection on rebars and its formwork are carried out by qualified manufacturing or site engineers to check the dimensional compliance with national or international standards alongside project construction tolerance specifications. Although the rebars are expected to be placed the same as the dimensions and locations of the design drawings, precise rebar positioning is difficult to achieve even in a manufacturing environment. Therefore, there are specific tolerances set for several key rebar checklists to be inspected. The dimensional checklists for the rebars include 1) bar-to-bar spacing between rebars, 2) concrete cover and 3) the number of rebars. The primary issue of the dimensional inspection on rebars is that the task is a highly repetitive and time and cost demanding job due to the manual inspection by human workers. In addition, walking in the top rebar cages and climbing on vertical cages are common issues that can cause potential safety hazards for the inspectors and damage the integrity of the structure. Therefore, an automatic rebar inspection technique that achieves a quick and accurate dimensional inspection on rebars is necessary.

Laser scanners have been one of the most popular recent measurement tools in the construction industry. Thanks to the fact that laser scanning provides high inspection accuracy (typically 2–6 mm at 50 m [1]) and high measurement rate (up to 960,000 points/s), many researchers have investigated the effectiveness of using laser scanning for dimensional quality inspection in the construction industry. In terms of dimensional quality inspection during the manufacturing stage, the target objects of previous studies were post-production prefabricated components such as precast slabs [2-4] and precast girders [5]. However, since it is costly to repair miss-manufactured components after production, it is also more important to check the dimensional qualities of formwork and its rebars prior to concrete casting. However, little attention has been paid on the dimensional quality inspection of formwork and rebar during the manufacturing stage.

Other than accuracy on dimensional quality checking, intuitive information visualization for quality inspection is also important. As an emerging technology, Augmented Reality (AR) delivers virtual information to the real world, further enhances the interpretability of many domain-specific applications in the construction industry, including construction safety, facility management, operation training, and inspection [6-7]. There is little research effort put on using AR as a measurement tool directly for dimensional quality inspection of construction components. The main reason is that the nature of positioning approaches based on images has not yet reached the level of accuracy compared with conventional surveying techniques. Furthermore, AR input interfaces to be used on-site in handling detailed measurement results maybe not investigated comprehensively. The functions on mobile or wearable devices are not as complete as those on general PC. Nevertheless, to visualize rebar or formwork fixing results using AR display is still desirable, as long as integration made with other measurement tools (i.e., laser scanners) can be relied on to simplify input and manipulation, and at the same time achieving accurate inspection purposes.

This study presents a systematic framework for automated formwork quality inspection using laser scanning and AR technology. This study aims to investigate the feasibility of the integration of the two technologies, and specific objectives are to 1) develop a framework that integrates laser scanning and AR for automated formwork and rebar inspection and 2) validate the framework through AR prototype development and laboratory experiment.

2 LITERATURE REVIEW

2.1 Rebar Dimensional Inspection

Regarding the rebar and formwork inspection, there have been few studies. Han et al. [8] proposed a vision-based technique that estimates the configuration and position of rebars. They used a density histogram of scan points generated from structure-from-motion and multi-view stereo algorithms for the rebar layout inspection. In that study, a validation test was performed using fifteen targets placed near or on the rebars and 850 images were taken for generating a set of point cloud data. However, the limitations of the study are that 1) detailed DQA results such as the overall dimension estimation accuracy are missing but focusing on data acquisition, and 2) numerous high-resolution photos are required from different angles for the generation of geometric data on the formwork and rebar. As an extension study of [8], Akula et al. [9] proposed a drilling monitoring and control framework that maps the locations of rebars within a bridge deck in order to provide timely feedback to the drill operator about whether it is safe to continue drilling based on the position and orientation of the drill. In that study, the same specimen used in [8] was used for generating point cloud data to map the locations of the rebar and the zones safe for drilling. A validation test was conducted on a lab-scaled rebar cage and the prediction accuracies from the vision-based technique were 69.5% while a terrestrial laser scanning (TLS) based method resulted in 98.4%. However, it was found in the study that 1) the vision-based technique requires a large number of images and the accuracy of the safe zone prediction is relatively low compared to the TLS approach, and 2) there was a large registration error caused by the targets placed near and on the rebars. On the other hand, Nishio et al. [10] proposed a method that extracts core wires of rebar from noisy scan data. A density distribution function was introduced to filter out unwanted scan points near the rebars and a parameter effect test was conducted by varying voxel sizes. However, the study was focused on only the extraction of rebar scan points. In addition, further analysis of the DQA checklists including the recognition and extraction of rebar spacing and the concrete cover is missing. From the literature, there has been no study investigating the key DQA checklists including rebar spacing, formwork dimension and concrete cover during the fabrication stage.

2.2 AR Application for Inspection

AR technology can be used in facilitating the visualization of domain-specific information on-site, and previous research works also considered such technology in quality inspection applications [6, 14, 15]. In a tunneling construction, Zhou et al. [14] developed an AR-based displacement inspection approach and conducted a case study to prove its feasibility. According to the displacement tolerance, adjacent tunnel segments have to be installed close to each other with the displacement less than 5mm. They combined static images and AR to realize the quality evaluation of the segment placement tasks. Besides the static and careful adjustments, other approaches are also studied by researchers to improve the positioning accuracy of AR visualization. Tavares et al. [7] directly project the related BIM information onto steel frames through light beams for a welding alignment system. The technique is called Spatial Augmented Reality (SAR). The virtual information can be shown and observed through naked eyes, and accurate enough (under 3 mm) to identify the drilling positions on steel frames during manufacturing processes. SAR can be potentially implemented for dimensional inspection applications, while such projection is only useful on planar objects instead of the hallow structures like formwork and rebars allocated in it. As for the general usages of AR in dimensional inspection applications, it still not yet to be treated as a direct measurement tool. Feng et al. [16] have developed AR marker-based positioning algorithm and maintained the error of pose estimation within one inch (2.54mm). The experiment suggests that the proposed algorithm can achieve such a level of accuracy and even robust enough for detecting a target 10m away from the camera. However, the accuracy is not satisfied with certain requirements of dimensional quality of formwork and rebar arrangement. For instance, the errors of concrete depth measured by the distance between rebar and formwork top/bottom sides should be less than 9.5mm. Further enabling measurement tools need to be collaborated with AR visualization to achieve accurate and intuitive inspection. These include laser scanner [17], depth-sensing camera, RTK-GPS [6], projector [15] and so on. Despite the fact that enabling tools and integration strategies are getting mature, research works are rarely focused on the formwork and rebar dimensional inspection. Furthermore, the integrations of AR and enabling measurement tools to improve such critical inspection tasks lack a systematic framework to describe suitable work procedures. All these topics are worthy to be investigated in order to improve the current practice and address the tedious nature of the work.

3 INSPECTION FRAMEWORK

To develop an accurate and productive dimensional quality inspection on formwork and rebar fixing tasks, a framework with the integration of two enabling technologies, laser scanning and AR, has been proposed. As can be seen in Figure 1, the inspectors are involved in the loop of inspection with further inspection enhancement. Firstly, laser scanners can be used to acquire dimensional information of formwork and rebar arrangement. It is assumed that the inspection target is manufactured and the laser scanner is located on top of it where a comprehensive scan on inner-surfaces and reinforcements is possible. The laser scanned data (i.e., point clouds) can be stored in the database after a noise filtering and scoping process. Then the computer performs a series of processing, including formwork/rebar component recognition and dimension estimation. The resulting information can be further compared with the as-designed one stored as BIM models in advance, further identifying whether there is any discrepancy in between the manufacturing plan and actual product, which exceeded the tolerance of quality assessment. Once the list of the discrepancy is confirmed, it can be interpreted and downloaded to mobile devices for inspectors to conduct AR-based evaluation on the real target. The inspectors can not only perform their subjective visual inspections but also get the objective ones through AR display for their more accurate confirmation and fixing decisions. The scanning and AR-based inspection may be executed with the potential delay due to data transmission, processing, and comparison. Nevertheless, the inspection is able to be achieved efficiently, if the number of targets to be inspected are considered large. For realizing such a quality inspection flow, the following issues in terms of implementation should be addressed: (1) which scan parameter should be selected for dimension estimation; 2) how to visualize the analysis results via AR display, and 3) what kind of interface should be adopted for easy communications. The following section will elaborate on an implementation detail based on the proposed framework, including data processing, and AR visualization and guiding interfaces.

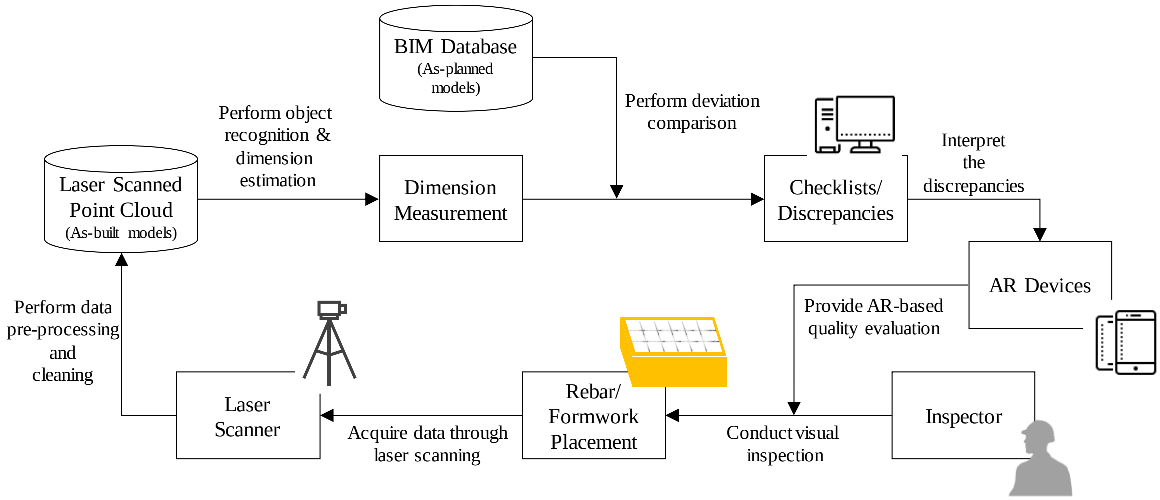

Figure 1. Overview of the proposed rebar fixing framework

4 SYSTEM DESIGN AND DEVELOPMENT

4.1 Data Acquisition and Processing

This section presents the data acquisition and processing details of the system. In this section, two layers rebars placed on the top and bottom on a formwork are taken as an example for the explanation.

4.1.1 Data Acquisition

An essential step of the data acquisition of laser scanning data is the selection of scan parameters of the laser scanner. This step aims to obtain the best data quality that achieves a highly accurate inspection result. For the scanning of rebar cage and formwork, the best scanning position would be the point where the laser scanner can see the rebar and formwork surfaces. For this reason, the scan position is an important aspect to be considered and selected because it influences the quality and completeness of the scanned points. Two factors need to be considered in identifying a proper scan position. Firstly, there should be no scan blocking issue. The bottom layer of the rebar needs to be captured well without line-of-sight blocking due to the top layer of the rebar. The other scan parameters including angular resolution and scan distance to the object mainly affect the data quality of scan data. Generally, the higher the density of scan points is, the better the inspection accuracy is. However, increasing the density of the scan points leads to increasing scan time and computing cost. Hence, a trade-off among accuracy, computing cost, and efficiency is necessary to be considered based on the inspection requirements of a project. The second factor is associated with high incident angle defined as the angle between a laser beam incident on a surface and the line perpendicular to the surface at the point of incidence. Because a high incident angle leads to an erroneous positioning of scan points due to a high range error, Kim et al. recommended avoiding scans with an incident angle of over 45° [2]. In addition, this high incident angle effect is much worse especially on the surfaces of smooth and metallic materials. Since identifying the best scan parameters for rebar cage specimens is a complex and challenging problem, it must be performed cautiously in advance, to maintain the high accuracy of the data acquisition process.

4.1.2 Data Processing

Once a set of point cloud data is acquired, data processing consisting of four steps is followed to extract dimensional features and then compute the key dimensions. The details of the four steps can be seen as follows:

Step 1 – Noise removal: This step aims to filter out unwanted background noises. First, raw scan data is sliced with respect to the Z-axis based on the fact that the key categories of scan data corresponding to ground noise, bottom formwork, bottom, and top layers are distinctly separable. Figure 2(a) shows the result of the segmentation of five scan data elements that are (1) background noises; (2) bottom surface of the formwork; (3) bottom rebar layer; (4) top rebar layer and (5) top edge surface of the formwork. In order to remove the scan points of background noises, the multiple Otsu thresholding [11] is used based on the Z values of the scan data to generate thresholds.

Step 2 – Rebar and formwork recognition: This step aims to recognize the rebar and the formwork scan data. In order to recognize the scan data of the formwork surfaces (bottom and top edge surfaces and side inner surfaces), the bottom and top formwork planes are first estimated using the RANdom SAmple Consensus (RANSAC, [12]) algorithm. The inner surfaces of formwork are then estimated using the Principal Component Analysis (PCA, [13]). As for rebar scan data recognition, multiple line RANSAC is performed to identify both the transversal and longitudinal rebars in each layer. Figure 2(b) shows the recognition result of the formwork and rebar.

Step 3 – Feature point extraction and dimension estimation: Once each scan data set is recognized, feature points of the formwork and rebars are extracted. The feature points include 1) corner points of the inner side surfaces of the formwork that are obtained by intersecting the planes estimated in Step 2; and 2) center points of the sliced rebar section. Once the feature points are extracted, the key dimensions are computed. First, formwork dimensions including length, width and depth are computed using the intersection points. Second, the rebar spacing is estimated by calculating the distance between two adjacent rebar center points. Third, concrete cover is estimated by calculating the distance between one edge rebar surface and the bottom surface of the formwork. In addition, the number of rebars is computed the number of rebars recognized in Step 2. Figure 2(c) shows the result of dimension estimation.

Once the key dimensions are computed, discrepancies between the as-design dimension and the as-built dimensions are calculated. If the discrepancy in rebar spacing for rebar is larger than the allowed tolerance, the rebar is recognized as a fault one, so spacing correction is needed. This recognition and correction are visualized in the proposed application which will be elaborated in the following sub-sections.

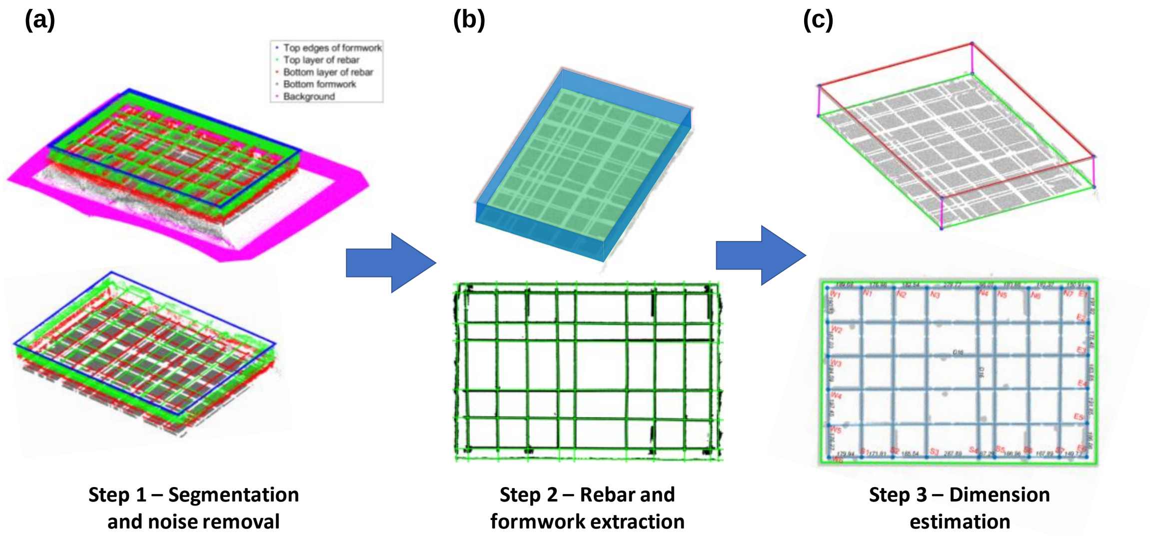

Figure 2. Data processing steps for rebar inspection

4.2 Inspector Application Development

An Android application, named AR Inspector, for dimensional quality inspection on formwork and rebar fixing tasks is developed in this study. It is developed based on a Game Engine, Unity3D, and its related AR package, Vuforia. The system architecture of AR Inspector consists of server-side databases with a processing unit, and a client-side visualization platform for AR display on mobile devices. In this study, laser-scanned point clouds and their as-designed BIM models are stored in the server-side databases. The external analytic software, MATLAB, is used as the processing unit to develop the segmentation and estimation algorithms on the point clouds, as mentioned in the previous sub-section. Once the processing is done, further information such as discrepancies with their related positions on the models/point clouds is annotated for further queries. As long as server-side processes have been finished, data can be downloaded to the client-side application through different IO functions. In this study, AR Inspector allows the as-designed model in FBX or IFC format to be imported into the client-side application. They are standard and compatible 3D and BIM file formats. As for the laser-scanned data, the application accepts an import through the PLY file format as the data with polygons. An Unity3D package called PCX library is used to support such data import function. Regarding the quality inspection information (discrepancy) generated through previous data processing, it can be queried through SQL once the client-side application needs to present it due to the requests by inspectors.

On the client-side application, three modules are implemented, including 1) Inspection Interpreter; 2) AR Display and 3) Inspector Guiding Interface. Inspection Interpreter module helps organize the annotated quality analysis results and presents them to the user systematically. AR Display module identifies the coordination system of as-designed models and establishes a discrepancy-embedded overlapping for the models to superimpose onto the real-world entities. About the Guiding Interface module, it is implemented for inspectors to check with the discrepancy results generated objectively by computers to conduct confirmation processes. The details on the three modules are shown as below:

Inspection Interpreter – This module is helpful for requesting annotated evaluation results from the database. It further converts all the discrepancy information into a generic representation. If an inspector raises an information query through Inspection Interpreter, such as showing the rebar spacing, the server-side database will provide necessary data as responses. In general, the positioning of components is treated as a Cartesian point (X, Y, Z). For distance measurement, it is described by two endpoints with a distance value. In this module, all the discrepancies that will be used for AR visualization are described as homogenous 4x4 matrix (translation X, Y, Z and rotation along X, Y, Z axes). They indicate the transformation needed in order to fix the current posture of the component to that of its as-designed one. For example, misplaced rebar can be fixed by going through a certain translation and rotation movements. These movements should be conducted based on the identified matrix.

AR Display Module – This module is developed to superimpose as-designed information onto the real formwork/rebar structure, further helping the AR-based inspection in the field. Such visualization provides an effective and intuitive method for inspectors to identify and confirm potential discrepancies. It just likes the virtual models actually exist in the real world. The virtual as-designed models are not always 100% matched with their as-built ones. It means that the relationship between the coordination system of virtual as-designed rebar/formwork and that of actual product contains potential deviation. Such deviation is considered in this module and the overlapped results of AR visualization show such deviation for inspectors to perform not only confirmation of the discrepancy reports generated by computers but also conducting their own judgments during the inspection.

Inspector Guiding Interface – The interface is designed for assisting the inspector to double-check the correctness of the computer-recognized discrepancies. It is useful for the inspector to deal with overwhelming dimensional information to avoid oversight or inaccurate judgments to be made. The discrepancies will be presented by the module one by one, for the inspectors to examine whether the issue really severe and necessary to be reported, or it just can be treated as error under tolerance and can be ignored. The discrepancy is shown with the fixing instructions. For example, misplaced rebar can be highlighted by the module and the inspectors need to drag it, on the touch screen of the mobile device, to its correct position where its as-design one located. Then the discrepancy is officially recorded in the final report. This is the main function that inspectors will utilize alongside with their own visual inspection and personal judgments.

5 VALIDATION

In order to validate the feasibility and usability of the proposed framework, a laboratory experiment was conducted. The proposed formwork dimensional quality assessment techniques were utilized in the experiment, including laser scanning data processing, AR display, and guiding interface. The details are shown below:

5.1 Test Specimen and Laser Scanning Results

One of the specific goals of this laboratory test was to estimate the two key dimensions of the formwork and rebar using laser scanning. Note that the estimation values will be fed to the AR Inspector for fabricators to facilitate their inspection using a tablet display. The test specimen with dimensions of

1500 mm (length) × 1000 mm (width) × 200 mm (height) was made of layered plywood and has 18 mm thickness. Two (top and bottom) rebar layers were installed in the wood formwork, and the diameters of the top and bottom rebars are 12 mm and 16 mm, respectively. Also, each top and bottom layer consists of 6 longitudinal and 9 transverse rebars. In addition, C-shape rebars were used to connect the top and bottom rebar layers. In the experiment, a phase-shift laser scanner, FARO M70, having a ranging error of 3 mm at 20 m was used. Figure 3 shows the specimen and the estimation results of the bottom and top rebar layers.

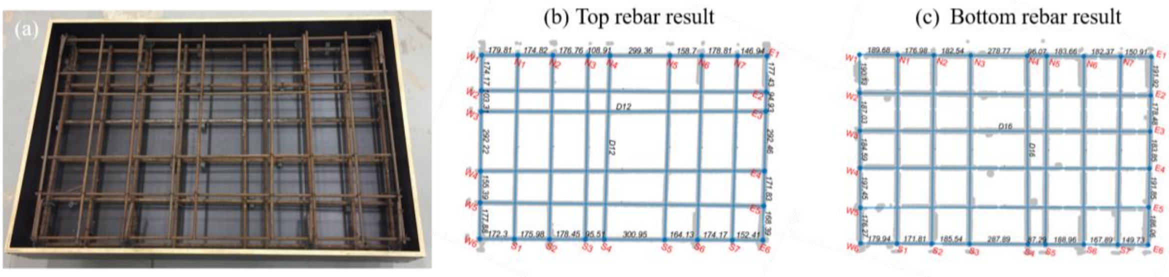

Figure 3. The specimen: (a) Overview; (b) estimation results of top rebar layer and (c) estimation results of bottom rebar layer

The dimension of two rebar checklists, including rebar spacing and concrete cover, were estimated by the proposed recognition steps described in Section 4.1. Note that N, E, S and W notations refer to the directions of North, East, South, and West, respectively, and the value shown between two rebar intersection points refers to the rebar spacing in mm. In addition, D16 and D12 shown in the middle stand for the rebar diameters of 16 mm and 12 mm, respectively. Table 3 shows rebar spacing and cover estimation results under the laser scanner's angular resolution of 0.036. By comparison with the actual measurement by measurement tape, the overall estimation accuracy of rebar spacing and the concrete cover was 1.72 mm, indicating the applicability of the laser scanning approach for the formwork and rebar inspection.

5.2 AR-based Inspection Results

The settings for generating AR visualization is shown in Figure 4(a). To accurately superimpose the virtual model of the specimen, a paper-based tracking target (with a unique textured pattern on it) was put on top and in the middle of the real specimen. It is supported by two aluminum rods hanging on two end-side of the formwork. Figure 4(b) shows the results of the AR visualization by using a tablet during the experiment.

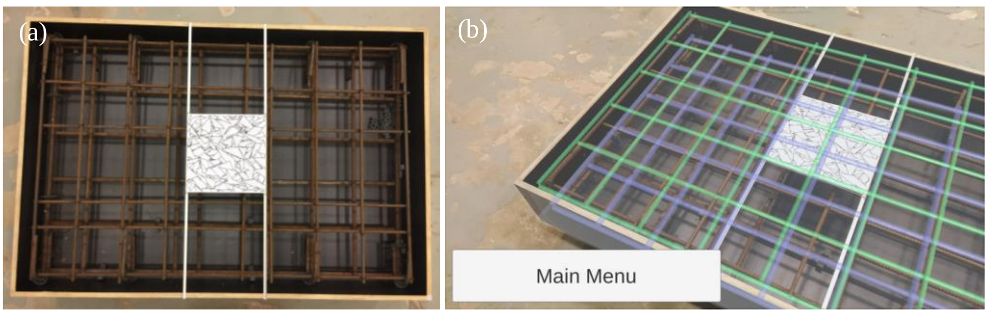

Figure 4. AR-based inspection process: (a) The tracking target; and (b) AR display

In this experiment, the Implemented AR Inspector prototype provides three basic functions for operations: 1) discrepancy report briefing; 2) manual inspection mode; and 3) discrepancy confirmation assistant. The discrepancy report briefing function is used off-line, showing the virtual models and discrepancy information on the screen of the tablet only. It is useful for the inspector to get an understanding of the application and preview the evaluation results automatically generated by computers. As for manual inspection mode, it is an attempt to identify where the tracking target and estimate it postures in order to put the virtual as-designed specimen on the real one. It requires the inspector present aside from the specimen and manual quality evaluation judged by the inspector is possible. Figure 4(b) shows such a visualization. The virtual rebars in the top layers are colored as green, those in the bottom layers are in blue, and the formwork in transparent white, respectively.

The discrepancy confirmation assistant is implemented to show the content of the discrepancy report. The report is generated through the comparisons between the extracted dimensional information of laser-scanned data and that from its corresponding as-designed model. In this experiment, three rebars in the specimen are designed to be placed in the wrong positions. As shown in Figure 5, the discrepancy confirmation assistant shows the discrepancies in order for the inspector's reference. Corresponding instructions to fix the displacement are also provided in text or through AR display. In the case shown in Figure 5, the fixing instruction is shown: one transversal rebar (TT3) in the top layer (in red) is misplaced. The way to fix it is to follow the provided instruction "Please move TT3 misplaced rebar with red color to correct position with green color by 100mm." The arrows from the red bar to green one indicate the fixing direction. As long as the inspector acknowledges the discrepancy, all he/she needs to do is to drag the bar in red, along with the arrow direction and release it in the place where the bar in green located. Then the discrepancy will be officially issued in the final confirmed discrepancy report. Such a report contains the inspection outcomes and needs to be addressed through further manufacturing processes. Alternatively, the inspector can reject the discrepancy record generated by computers by simply clicking on the "That's OK, Next!" button. The discrepancy record will be discarded, judged by inspector's own professional experience. At the end of the experiment, all three discrepancies have been identified successfully at the data processing stage. And the related transformation matrices regarding the rebar fixing are also determined. They have been displayed to the inspector for further decision making. These show the feasibility of the proposed AR-based dimensional inspection approach.

Figure 5. The inspector guiding interface showing a discrepancy of a top transversal rebar

6 CONCLUSION

In this study, the research teams propose a systematic framework for formwork quality inspection in order to identify the requirements of performing formwork/rebar fixing tasks. A mobile application with developed data processing techniques on laser-scanned data, named AR Inspector, is implemented based on the proposed framework. Related experiment at the laboratory level is conducted to validate its feasibility. The results of the experiment show that the dimensional information of the selected specimen can be accurately extracted through dimension estimation processes and is capable to be used for compliance of the formwork and rebar design. The contributions of the study are thus drawn, on the design and implementation of intuitive and accurate quality inspection procedures as well as assisting aids by integrating laser scanning information and AR display. The visualization and automated dimension estimation processes help inspectors to identify discrepancies accurately after the manufacturing stage of the formwork and rebar arrangement. More importantly, the facilitation on the quality inspection is that the quality evaluation results generated by computers are confirmable judging by inspectors' own professional experience and personal inspection results. Such a personal inspection process can be also benefited from the AR display as long as the quality of the positioning approach is reliable. The limitations of the current study include: the AR tracking target is still needed in the experiment, more advance positioning approaches, such as SLAM-based AR can be adopted for an improvement. The shapes of the formwork design capable to be extracted in this study are regular rectangle based on the developed data processing algorithms. Further improvements are expected in the future: wearable devices, such as Mixed Reality glasses, can be integrated to help inspectors get more intuitive experience. The connection with BIM standards regarding the data exchanging of the discrepancy information can be further established. It is expected that the field tests in terms of the productivity of such a proposed inspection approach can be carried out to validate its merit in practice.

ACKNOWLEDGMENTS

The second author would like to acknowledge that this research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2016R1A6A3A03010355), the Start-up Fund (project no. 1-ZE94) by The Hong Kong Polytechnic University, and the Chinese National Engineering Research Centre for the Hong Kong Branch of the National Rail Transit Electrification and Automation Engineering Technology Research Center (grant no. 1-BBVJ).

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