Robotic total station and BIM for quality control

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BIM to field: Robotic total station and BIM for quality control

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ABSTRACT: One of the reasons why some construction professionals are excited about BIM is because of its ability to visualize the installation of prefabricated building modules. As far as using BIM for facilitating the prefabrication process, we expect that all building components are installed correctly as indicated in the model. However, in many cases, building components such as cast-in-place concrete beams and columns are installed a little bit inaccurately because the formworks can be sagged or twisted while fresh concrete is being placed. Our research tested how effectively BIM and Robotic Total Station technology would facilitate to advance the quality control practices on field. For this investigation, we invited three Robotic Total Station technology venders to a 107,000-square-foot academic building construction project jobsite. Our test confirmed that the use Robotic Total Stations expedited the process of marking the layout points on the jobsite or collecting point data from existing facilities. Along with the results of our test, this paper also presents some lessons we learned from the field test.

1 INSTRUCTIONS

1.1 *BIM for construction*

Building Information Model (BIM), an object-based parametric three-dimensional computer model of a building combined with additional engineering or design information, has been rapidly adopted in the construction industry. According to the McGraw-Hill report published in 2009, a half of the construction firms in the U.S. already started using BIM for their projects. One of the tangible benefits that encouraged construction firms to use BIM is its capability to detect clashes between building components. Many BIM applications enable to identify the graphical objects in the 3D model that are collided against other objects, which helps construction professionals understand the spatial relationship between clashed objects and make proactive decisions to reduce reworks and change orders that could be caused by these clashes. Several BIM applications also enable to combine the objects in the 3D computer model with their construction schedule information such as start date and end date, and show the sequence of the construction process visually by getting these objects appeared on the computer screen over timeline according to its schedule information. The combination of the 3D computer model and associated schedule information, which is often called as 4D construction sequence model, facilitates construction professionals to better understand how the space on the jobsite will be occupied during construction by these equipment or temporary structures, which eventually helps them deal with the constructability issues during pre-construction coordination meetings.

1.2 *BIM and prefabricated modules*

According to the US Dept. of Commerce Bureau of Labor Statistics report, productivity in the construction industry has been declining for last 40 years. Among many solutions suggested by the industry professionals to increase productivity during construction, the use of prefabricated modules has been recently under the spotlight. Knowing that BIM made it easy to visualize the building to be built in 3D world, it is reasonable to expect that BIM should effectively visualize the prefabricated modules, which then would facilitate the construction professionals to discuss how the prefabricated modules are supposed to be installed and how these modules should be transported to the designated location on the jobsite. The ability to visually present the installation process of prefabricated modules in 3D world should enable construction professionals to use these modules during construction with more confidence, which is why BIM is expected to promote the prefabrication methods in construction.

One of the conditions we assume when using BIM for prefabrication is that all building components will be built correctly as they are presented in the 3D model. We expect that any components prefabricated using information extracted from the 3D model be perfectly aligned with other building components that are already built. However, in many cases, building components such as cast-in-place concrete beams and columns are installed a little bit inaccurately, for instance, because the formworks can be sagged or twisted while fresh concrete is being placed. Masonry structures, concrete beams and other critical construction components have tight tolerances because of other components to be built on top of them. No matter how accurately the Building Information Model is created, and no matter how many clashes are detected during the preconstruction coordination meetings, many activities that are associated with the installation of prefabricated modules on masonry structure can be messed up when masonry structural components are not built accurately. For example, any concrete beam placed half-an-inch off the designated location can affect significantly the installation of prefabricated metal components for the building façade. Crews installing these components on the jobsite may have to cut some pieces off the prefabricated modules or add additional pieces if concrete beams or columns that these components will get attached to. Time needed to cut off or add additional pieces to the prefabricated components on the jobsite before they get assembled is obviously a waste. Contractors may end up spending millions of dollars if these dimensional inaccuracies of these components are not detected on time. If we can collect the dimensional information of these masonry structures before sub-contractors start fabricating the modules, it would not be impossible to make proactive decisions to reduce their impact on the cost and schedule.

1.3 *Surveying equipment*

In many cases, contractors use tape measures to collect dimensional information of the building components, which could bear human error during measurements. As late as the 1990s, the basic tools used in planar surveying were a tape measure for determining shorter distances, a level to determine height or elevation differences, and a theodolite, set on a tripod, to measure angles (horizontal and vertical), combined with the process of triangulation. Starting from a position with known location and elevation, the distance and angles to the unknown point are measured. There is a need to improve the way measurements are taken on the field in order to increase the accuracy of the measurements. One may want to use surveyors to increase the accuracy of the measurements, but it cost contractors significantly and surveyors are not generally available when there is an immediate requirement.

A more modern instrument is a Total Station, which is a theodolite with an Electronic Distance Measurement device (EDM). EMS measures the distance using the elapsed time required for a light wave to travel to a target and get reflected back. Since their introduction, total stations have made the technological shift from being optical-mechanical devices to being fully electronic. Recently Robotic Total Station (RTS) technology has brought an interesting attending in the construction industry because of its capability of getting the measurements integrated with the Building Information Model (BIM). In addition, unlike conventional Total Stations, the Robotic Total Station requires only one person to operate and take measurements, which may contribute to saving times and increasing accuracy in measurements.

2 ROBOTIC TOTAL STATIONS

A Robotic Total Station is the advancement to the conventional Total Station, which requires only a single person to operate and determine the location of the points surveyed. With the Robotic Total Station, the operator holds the reflector and controls the total station from the observed point with the help of a Remote Positioning Unit. Depending whether the target is static or in dynamic motion, RTS can be categorized as a passive RTS or active RTS.

A fast reflectorless measurement was also developed in 1995 (Buchmann 1996). In 1999, Leica presented the equivalent commercial version, the first commercial robotic reflectorless total station (RRTS). Scherer and Lerma (2009) noted that “the new type of reflectorless measuring TS opened new fields for practical use, above all intelligent tacheometry, which comprises the steering of the instrument via a program which is able to interpret the result of the reflectorless measurement and in consequence directs automatically the distance measuring ray of the TS to new points of interest”.

Apart from the remote operation of the total station, the integration of the GPS (Global Positioning System) to the RTS (Robotic Total Station) has been used to obtain the global coordinates from the local coordinates.

The next step of the original developments of the total station was the integration of cameras into the telescope. The origin of this synergy reminds the idea of the photo-theodolite that was developed in Italy in 1865 by Porro and in 1884 by Paganini, as well as in Germany, by Koppe, in 1896 (Luhmann et al. 2006), which is the combination of digital cameras and high-end robotic reflectorless measuring total stations. This type of Total Station (TS) is called Image Assisted Total Station (IATS).

2.1 *Applications of RTS in building construction*

Construction managers can use BIM and the Robotics Total Station technologies for accurate building practices. Site survey points generated in the Building Information Model can be uploaded to the RTS. Based on the points generated from the model, the field staff then can lay out all of the points. For instance, the accurate positioning of the hangers would ease the coordination of the MEP contractors. Furthermore, field staff can survey the components of the building with robotic total station to ensure that they are built according to the design and within acceptable tolerance range. This proactive quality control approach would prevent any subsequent conflicts. Overall, robotic total station uses the information from BIM/CAD to survey both for construction and quality control purposes. Commercially construction contractors use Robotic Total Station for building layout works to check elevations, locate column and walls, layout anchor bolts and layout utilities for each floor of the building. Some of the commercial software packages offer support to transfer the building coordinates from the model to the total station. The automatic target-locking feature of the RTS can be made use of to locate the points faster with spot on accuracy. Moreover, there will be certain points in the construction site that cannot be physically reached to hold the reflecting prism. In those cases Reflectorless distance measuring option that comes with the Robotic Total Stations can be used to get the coordinates remotely.

2.2 *4D modeling and automated surveying*

Building Information Modeling (BIM) is used to generate and manage essential building data during its life cycle. The 3D representation of the building elements together with spatial relationships, quantities and properties of the components provide several useful information for the construction and the maintenance of the buildings. One of the important aspects of BIM is the 4D simulation of the construction process, where the 3D building components are combined with line items of a construction schedule. This 4D simulation will help to visualize the construction process at any point in time, which helps to avoid any unforeseen incidents. The building production models are represented in the form of 4D models, which are created considering multiple constraints on site, such as the lifting capacity of the tower crane, construction method and activity sequence. It has been studied that 4D visualization of the building components together with automatic surveying methodologies like Robotic Total Station surveying, can be used to reflect the real-time position of the building components when they are being installed during the construction operation.

Liang et al. (2010) developed 4D PosCon to collect the 3D coordinates of the building components being installed in real time, update the 3D model of the building components, and get it compared with the as-design building model for the position offsets. This process of quantification of the deviations of the components that are being installed is expected to help to adjust operations right away.

2.3 *Deflection measurement and oscillation frequencies of engineering structure*

Robotic Total Station has the capability to automatically record the changing coordinates of a moving target. The accuracy of the RTS is in millimeters, which will further be helpful in measuring the small movements very precisely. The RTS is installed at a known location and its location is calibrated by sighting at least two control points. The prisms that are attached to the structure are sighted under neutral conditions, which will be the reference position with no load. Once the target is locked, desired load is applied to the structure and RTS will track the prism, which will be moving under the influence of the imposed load. The modified coordinates of the prisms are calculated and by comparing the initial and final coordinates the deflection value can be calculated.

Robotic Total Station has another important practical application in calculating the oscillation frequency of the engineering structures. RTS has been used to monitor static targets and very slow displacements in the past. The limitation in the earlier versions of the total station was the sampling rate (Less than 2 Hz) and non-constant, noisy outcome in higher frequencies (Panos et al. 2007). The new generation RTS has an average sampling rate of 10 Hz. Recent studies prove that they can be used to measure smaller oscillating frequencies with high accuracy and the accuracy will be reduced as the measuring frequency increases. This application of RTS can be dynamically used to check the oscillating frequencies of bridges under different loading conditions (Vehicular, Wind etc.), which could be used to check the stability of those structures. The structures can also be checked for loading conditions that would lead to the oscillation of the structures under resonance frequency, which could be disastrous and impending threat to them could be averted.

Some of the other common applications of Robotic Total Stations for construction are as follows:

- Checking or tying into property boundaries
- Layout of excavation lines
- Setting up of control points for laying out concrete forms and anchor bolts
- As-built checks
- Laying of control lines on concrete pad for subcontractor use
- Topographical measurements for cut/fill balance

3 FIELD TEST

3.1 *Objectives*

The main purpose of the study is to increase the knowledge base about the use of Robotic Total Station (RTS) in the construction industry from the Construction Manager's perspective. Two main technology vendors participated in this investigation and their Robotic Total Stations are used for the field tests. This study is hoping to give more clarity for construction managers to make use of this technology for their QA/QC purposes, as currently there are not much sophisticated tools available. QA/QC tasks are performed to check the as-built dimensional accuracy with the as-designed Building Information Model. The use of RTS is expected to identify the potential problems that could cause schedule delays well ahead of time, resulting in the savings of time and money.

The field investigation process involving the RTS of the two vendors demanded some standard procedures in order to establish a standard platform for comparison purposes. The research team at Texas A&M University together with participating general contractor devised a protocol to be followed for measuring some of the critical components in the field. Some building components to be measured are identified from the lessons learned in the past, which were creating some negative cost and the schedule impacts.

3.2 *Test protocol*

Three different methods have been proposed to measure the beam sides. Each of the proposed method will then be compared based on the time taken, accuracy and ease of measurement to establish the best suitable method for measuring beam sides. All the three proposed methods below will involve shooting of points that will have the X, Y and Z coordinate information (3D).

Points Along Edges – In this method, series of points along the four edges of the beam face will be shot by the RTS and those point data could be taken back to the CAD/BIM software to locate the as-built position of that corresponding beam face. The number of points required on each face can be decided based on the length of the face and the site conditions and the points to be shot are selected manually by looking through the eye piece.

Corners Only – All the four corners of the rectangular beam face are shot and those four point data with the X, Y and Z coordinate (3D) information could be used to retrace the actual position of the beam face in CAD/BIM software.

Automatic points shooting mode – Since the RTS has a unique feature to automatically shoot some series of points between two specified points, the two corner points are specified and a series of points are then shot along each of the edges for a beam face.

Steel Embeds Location – The location of the steel embeds on the beam faces should be located by shooting all the four corners of the steel embeds (3D coordinates). There could be some cases where all the corners of steel embed may not be visible as it could be buried under the concrete (Figure 9). In those cases all the four visible corners of embeds are shot along with its rough center. All the steel embeds located between two columns needs to be shot.

Column Location – The location of the columns in 2D needs to be determined by measuring the all the four corners of the column in the plan. Since the columns considered for this case study are chamfered, the exact location of the corners cannot be determined directly. In order to achieve this process, any two (or more) points are shot on each face of the column and the lines drawn connecting the points on all the four faces could reveal the actual location of the column in a CAD/BIM software. In order to shoot all the four corners of a column, multiple setup may be required to establish a line of sight with all the four faces. Using an offset prism, which doesn't require a direct line of sight to the face of the column that needs to be shot, could reduce the number of setups.

The step-by-step procedure to setup and use the RTS for measuring points in field is as follows. The procedure is same for the equipment from both the vendors.

- Clean the CAD drawing by removing the x-refs and bring all the points in the single file
- Place the required points to be staked out in any of the CAD software available together with the control points (Trimble LM80/AUTOCAD)
- Transfer the CAD file to the handheld collector through the standard SD card/USB port or with the help of a data cable depends on the type of data collector used.
- Check the scale of the drawing before importing it to the data collector and make sure it is in 1:1 scale.
- Assemble the prism to the prism pole and fix the instrument over the tripod.
- The tribarch screws and the fish eye level on the robot are used to level the instrument to certain level of accuracy.
- Connection is established between the instrument and the hand-held controller by setting them in a common radio frequency channel.
- The instrument is more accurately leveled by seeing the digital level of the instrument shown on the hand-held controller using the tribarch screws in a similar fashion.
- The instrument can be stationed over a known location and can verify its position by shooting another control point or it can be placed over an unknown location and its location can be found by resection after sighting minimum 2 (2D) or 3(3D) control points. For more accuracy the instrument is setup over a known point as there could be some inaccuracies due to round-offs in resection.
- The prism pole is placed over the points of interest once the control points are shot. This method can be used when the as built dimension are needed to be recorded, where the actual points to be measured are already staked out.
- In order to stake out points for layout purposes, the point to be staked out is selected in the hand-held controller and the prism pole is moved towards the designated point. The prism pole is moved in accordance to the direction shown in the controller and zeroed in as accurately as possible.
- When placing the prism pole over a point, it should be made sure that it is always vertical by using the level bubble on the pole. For higher accuracies the prism should be as close to the ground as possible.
- During the measurement process if the RTS loses the target due to some obstructions in the site, the power search mode can be used to search for the target in a specified window and can be found. If the controller is beyond the power search mode range, the robot can be manually rotated with the joystick in the controller and can be made to find the target.
- Once the points required are shot, the hand-held controller is connected back to the computer in a similar fashion and the data can be imported back. The controller has the ability to import the point data in several data formats like DXF, CSV, ASCII etc. These as-built point data can be placed over the as-designed drawings and can be checked for deviations for QA/QC purposes.

3.3 *Test outcomes*

The protocol formulated was put to use by the robots from the two vendors and the time required for each

Table 1. Test results.

Parameter	Vendor A	Vendor B
Initial setup	About 10 min.	About 10 min.
Beam Sides (3D)		
- 4 corners	2 min.	5 min.
- Series of points along segments	3 min.	3 min.
- Automatic points measurement	N/A	6 min.
Embeds (3D)	1.3 ea./min.	1.25 ea./min.
Columns (2D)	22 min.	25 min.

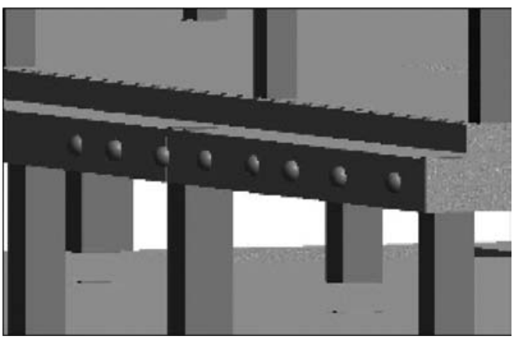

Figure 1. Imported points represented as sphere.

separate process was recorded and are tabulated in Table 1. The table shows that the time does not necessarily indicate the efficiency of the RTS from two vendors. The field conditions were different for both the cases and they were made to shoot two different datasets. The result gave a good idea about the average time taken to accomplish the tasks specified in the protocol.

3.4 *Importing point data to BIM*

The as-built point data collected from the robotic total station can be imported back to the Revit model using this application. To import the point data, save the data in x, y, z format along in a txt or csv file format and use the 'Import Pts' option in the application. While importing, the application will give options to upload the new points as a new instance or it will ask to move the existing points that are having the same point ID as the new points to the modified location. When these points are tied in to the elements, as-built models can be generated on the fly from the point data measured as the application will automatically move the existing as-designed points based on the as-built dimensions.

3.5 *Issues with poles*

With the modifications made, RTS still has a standard pole. One of the modifications made is in the area of usual survey application that we have been utilizing in construction. The bipod legs, which are used, have to be balanced and leveled before taking the readings, which takes considerable time for each reading. It also takes time to adjust the pole offset from the actual point and level again to calibrate. Actual survey takes nearly 30-40 points a day, but for usual MEP projects it usually takes 400-600 points a day in the schedule. So, this process has to be hastened which is the major modification in the new RTS. One of the participating vendors came up with a solid self-leveling base-plate to replace the bipod. The pole is shortened and made to be an extendable rod pole to raise the shaft for special purposes and to take inverted levels so that the rod can be pushed to the point overhead to take readings from the prism. The top of the pole is fixed with the X-Y Positioner, which has a self-leveling laser. The prism goes on top or bottom of the self-leveling laser, which helps the subcontractor to make layout on the ground or on the overhead ceiling, which speeds up their process. This assembly of prism and self-leveling laser acts as an entity and creates no deviation from the prism to the point on the layout. This assembly does not require the base plate to be leveled. If there is a slight deviation from the layout point, the X-Y positioner can be used to minimize the slight deviation and make the laser point coincide with the actual point.

Other RTS instruments using the conventional prism poles have to be moved inch by inch to coincide with the actual point. What actually happens is, as the workers get fatigued they tend to mark points closer to the actual point, which creates deviations. The main purpose of reducing the error by using RTS is lost. This margin of error can be avoided by this RTS. There is a difference of 10–15 seconds between the readings taken by RTS and conventional survey equipment which when cumulated over 4–6 points a day saves significant time.

When the prism is put on top of the survey rod and if it is not leveled, the total station takes reading of the point away from actual point as the rod is tilted and the margin of error will be the projection of the rod on the ground. This huge deviation and variance is introduced due to the old survey rod and prism assembly, which can be avoided by the X-Y positioner, laser and prism assembly.

RC handle or the communications handle goes on top of the X-Y positioner, laser and prism assembly and fixed to the standard pole. This is a long-range blue tooth technology. The main importance of this long-range blue tooth technology is that it sends signals to total station with which it is connected. The users do not need to worry about the total station locking on to the reflective safety vests, reflections of a vehicle passing by or any other equipment. This technology also prevents it from connecting to any other RTS being used in the site as it has a committed connection. Furthermore, It also allows tracking the lost prism for which it takes only 7 seconds. Search window in the RTS is not required nor we need to see if the RTS is to the left or right. Line of sight issues are still to be resolved. Long-range Bluetooth technology enables streaming of field information to the office through the SIM card or by connecting to the Internet through wireless network. This assembly works with Monitoring Total Stations, which are extremely accurate. These are setup permanently throughout the duration of the project and it records any slight shifting in the construction activity or any adjacent building. The turning angle tolerance of RTS is 1second to 5seconds. If the project is large and expanding miles, then this slight deviation in angle diverges and becomes a large distance over a certain distance. In this case going to less tolerance RTS is preferable to minimize this error.

4 CONCLUSIONS

The main purpose of the study is to increase the knowledge about the use of Robotic Total Station in the construction industry from the Construction Manager's perspective. The study is being initiated by the Skanska USA as a part of their Innovative Research program.

Professionals representing two main Robotic Station Vendors participated in this investigation. Their Robotic Total Stations were used for the field tests. The Liberal Arts Building construction project and Olsen Field renovation project at Texas A&M University were used for the filed tests.

The protocol for fields tests were devised by the research team at Texas A&M University. The protocol formulated was about executing some tasks using the Robotic Total Station from the two vendors. The time required for each separate process was recorded. The result gave a good idea about the average time taken to accomplish the tasks specified in the protocol.

From the field tests, the research team figured out the step-by-step procedure to setup and use the RTS for measuring points in field. For the QA/QC purposes, the research team confirmed the possibility of speeding up the process of creating the as-built BIM using the point data collected from the field. It is reasonable to expect that as-built BIM would facilitate project managers to identify potential problems that could cause schedule delays well ahead of time and make proactive decisions to prevent them from taking place if the as-built BIM can be created in real time as project is moving on.

During the field investigation, crews, who were carrying out the laying out operations for the dry wall installation, found that the control point established inside the building was off by few inches. They were able to find this discrepancy using the RTS in very short time, which would have otherwise taken a long time to figure it out.

In conclusion, the research team believes that it is safe to address that the use of Robotic Total Station can expedite 1) the process of laying out the locations for dry wall, and 2) accelerate the process of collecting as-built point data and creating as-built BIM, which can be used for QA/QC in the course of construction.

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