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3D Laser Scanning for Quality Control and Assurance in Bridge Deck Construction

Final Report
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16. Abstract

The inspection of installations of rebar and other embedded components in bridge deck construction is a tedious task for field inspectors, requiring considerable field time for measurement and verification against code requirement. The verification of rebar and dowel locations after placement of concrete is another difficult but important task. Ground Penetrating Radar (GPR) is often used to verify the locations of dowels and rebar after the construction of bridge deck is completed. Although GPR is an effective method for this purpose, the discovery of quality problems, if there is any, associated with rebar installations is often too late to secure timely and cost efficient repair. There is a need for proactive quality control and assurance methods that can assist field inspectors to quickly inspect and monitor code compliance of installations of rebar and other embedded components before and during the placement of concrete. In this project, the utility of 3D laser scanning for quality control of bridge deck construction is investigated. We demonstrated the common workflow for field scan collection and data analysis for verifying bridge deck construction quality. We focused on a set of parameters that need to be monitored during bridge deck construction. The research results suggested that with careful planning and well designed workflow, 3D laser scanning is an effective method for controlling the quality of bridge deck construction, and state DOTs should consider incorporating 3D scanning as a proactive quality control methods.

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DESCRIPTION OF THE PROBLEM

Bridges are key elements in the transportation system. However, as of 2003, about one third of the nation's bridges were classified as structurally deficient or functionally obsolete. (ASCE, 2005). Bridges in the northern United States and Canada are more susceptible to deterioration because of their location. The continuous freeze-thaw cycle combined with chloride ingress from snow-melting agent used during winter deteriorate bridge decks. Many concrete decks that were designed to last more than 40 years are in dire need of major repair services just after 5–10 years of service and some of them may need to be replaced after 15 years. (Sherif Yehia, 2008). Some bridges even fail when they are in service, causing casualties and property losses. More than a dozen major bridges, overpasses and highways have collapsed in the United States and around the world in the last 40 years, killing dozens of motorists (Press, 2007).

Recently, there is an increasing emphasis on building bridges of durability. Keeping the bridge healthy is critical to the safety of the traveling public; a longer bridge life cycle will also produce economic and social benefits. A durable bridge relies on good construction and maintenance. On one hand, the routine inspections and timely repairs are important to keep the healthy operation of bridge. The Federal Highway Administration (FHWA) has developed guidelines for the bridge inspection process. Those guidelines require the periodic inspection of all bridges on public roadways at least once every two years (AASHTO, 1994). On the other hand, it should be noticed that, the quality control and assurance during the construction process are equally important, because the quality of the construction is the foundation of bridge's durability.

A typical concrete highway bridge in US consists of prefabricate steel girder or concrete girder and cast-in-place concrete deck. Because the bridge deck often uses cast-in-place concrete, the installation of rebar cages and placement of concrete became the key factors of construction quality and accuracy. Inspection and evaluation of rebar placement and concrete placement are important construction quality control tasks. Numerous efforts have focused on enhancing the inspection and evaluation procedures. Construction inspectors need assistance in formally developing goals for inspection and developing and searching among the range of possible inspection plans that can be implemented on site to address these goals (Chris Gordon, 2008).

Generally, in order to make reinforced concrete to working as the designer intended (DOT A. , Construction Manual Arizona DOT , 2005), the inspector and resident engineer must ensure that reinforcing steel placed in a structure is:

- The correct grade and type of steel;
- The correct size, shape and length;

• Placed in its specified location and spaced properly;

• Tied and spliced together properly;

• Clean and will get an adequate cover of concrete in all directions;

• Placed in the correct quantities

On most bridge construction site, due to site limitation, contractors usually choose ready-mixed concrete. The Quality Control of ready mixed concrete is necessary in order to combine effectively constituents subject to variation in such a way as to produce a product of consistent quality and performance (Dhir, 1976). As for the ready-mixed concrete, their slump, workability, and density are tested by supplier and checked by a resident engineer before use. For most of time, there is little problem associate with the quality of concrete itself.

When focusing on the quality problems of concrete deck. The reinforcing steel must have adequate concrete cover near any exposed surface. Cover is the single most important factor in protecting reinforcing steel from corrosion (weather, snow-melting agent etc.). Cover is also necessary to assure that the steel bonds to the concrete well enough to develop its strength (Staff, 2005). In order to achieve adequate cover and spacing, the clearance is also needed between reinforcing bars so all of the concrete mix can completely surround the bar (DOT A. , Construction Manual Arizona DOT , 2005). AASHTO (American Association of State Highway and Transportation Officials) and ACI (American Concrete Institute) have minimum clearance requirements on reinforcing steel installations.

As mentioned above, insufficient concrete cover will cause exposure of the rebar. The exposed reinforcement, not only affects road surface evenness, but also seriously shortened the service life of a bridge. And it is a common bridge deck quality problem, usually caused by inaccurate measurement and construction.

As a structural material, reinforcement steel bar in the bridge deck is designed using the same criteria as regular reinforced concrete (H.Hilton, 1990). However, reinforcement should be designed and placed to minimize interference with the placement of concrete. Reinforcement should be placed as shown on the placing drawings. There, the detailer will indicate the number of bars, bar lengths, bends, and positions (Staff, 2005). Large diameter bars are frequently used in bridge deck. Exceptional care may be needed to properly incase larger sizes of reinforcing steel in the concrete. Special anchoring devices may also be required to support and maintain the spacing of the reinforcement during the concreting operation (Institute, 2008). Evidence shows that, the anchorage/splice of reinforcing rebar is equally important as the spacing and cover of it.

The failure of anchorage may cause sudden failure of bridge deck. Poor handling and inspection will result in this kind of quality problem.

Currently, the inspection of installations of rebar and other embedded components in bridge deck construction is a tedious task for field inspectors, requiring considerable field time for measurement and verification against code requirement. The verification of rebar and dowel locations after placement of concrete is another difficult but important task. Ground Penetrating Radar (GPR) is often used to verify the locations of dowels and rebar after the construction of bridge deck is completed. Although GPR is an effective method for this purpose, the discovery of quality problems, if there is any, associated with rebar installations is often too late to secure timely and cost efficient repair. Delay in opening the bridge to public traffic is a common sequence with this sort of quality problem. Repairing a just constructed bridge deck can also raise public dissatisfaction. There is a need for proactive quality control and assurance methods that can assist field inspectors to quickly inspect and monitor code compliance of installations of rebar and other embedded components before and during the placement of concrete.

Recent studies by the Construction Industry Institute have indicated that for a typical US$100 million construction project, between US$500,000 and US$1 million are spent purely on keeping track of where things, typically thousands of items, are on the site and on monitoring the status of construction activity. Approximately 2% of all construction work is devoted to manual intensive quality control and tracking of work progress, including operations involving earthmoving and bulk materials handling. Any technology that can reduce this burden and decrease time to delivery will offer a significant competitive edge. It should be further emphasized that any technology that delivers automated and rapidly available information relating to project status and the position of components at the site would also bring further cost savings by supplying that information to automated and semi-automated systems (Geraldine S. Cheok W. C., 2000).

The development of a scanning system for bridge quality inspection will complement these efforts. The proposed scanning system has the ability to suggest adjust or modify strategies for common problems in concrete bridge decks construction, which include rebar deviation, reinforcement cover too thin or too thick, excessive settlement or lack of settlement.

APPROACH

The purpose of this research is to investigate the potential of 3D laser scanning as a proactive quality control and assurance method for bridge deck construction. Today's 3D laser scanning technology is capable of collecting millions of accurate point measurements in a very short amount of time at large distances (10-300m). The range accuracy of these point measurement is generally in the range of 0.2-4 millimeters depending on the distance to objects. Specifically, this research will validate the utility of laser scanning during bridge deck construction as a quality assurance tool. The new procedures and tools will significantly improve quality control and assurance procedures for concrete bridge deck construction.

The proposed research approach consists of four major components including literature review, design of data collection and processing work flow, a field validation study, and data analysis and discussion. A bridge construction project was used as a case study in this work.

METHODOLOGY

Literature Review

By the Federal Highway Administration's (FHWA) definition (FHWA, Recommended Framework for a Bridge Inspection QC/QA Program, 2013), quality assurance (QA) is the use of sampling and other measure to assure the adequacy of quality control procedures in order to verify or measure the quality level of the entire bridge inspection and load rating program. Quality control (QC) is procedures that are intended to maintain the quality of a bridge inspection and load rating at or above a specified level.

In FHWA's National Bridge Inspection Standards (NBIS), the Quality Control and Quality Assurance requires each state to assure that systematic Quality Control (QC) and Quality Assurance (QA) procedures are being used to maintain a high degree of quality accuracy and consistency of bridge. The accuracy and consistency of the inspection is vital because it not only impacts programming and funding appropriations, it also affects public safety. Therefore, the FHWA has developed their recommended framework for a bridge inspection QC/QA program.

In their QC/QA program, the inspection methods mainly rely on the visual inspection of the bridge. A lot of works are concentrated on the qualifications of Program Manager, Team Leader, Inspection Team Member and Load Rater. These qualifications include Years and type of experience, Training completed, and Certifications/registrations. The program also includes special skills, training, and equipment needs for specific types of inspections.

The NBIS gives several state practices example, the procedures of Pennsylvania, Oklahoma, Wisconsin, Oregon, Massachusetts, Washington State DOT address specific aspects of the "Recommended Framework" in a manner the FHWA considers commendable. But most of them are still mainly about inspecting personnel's qualification and experience.

In the FHWA's Bridge Inspector's Reference Manual, the concrete inspection requirements are stated as follow: When inspecting concrete structures, note all visible cracks, recording their type, width, length, and location. Also record any rust or efflorescence stains. Concrete scaling can occur on any exposed face of the concrete surface, so record its area, location, depth, and general characteristics. Inspect concrete surfaces for delamination or hollow zones, which are areas of incipient spalling, using a hammer or a chain drag. Carefully document any delamination using sketches showing the location and pertinent dimensions (FHWA, Bridge Inspector's Reference Manual, 2012).

The safety and serviceability of a structure or a structural member can also be assessed by monitoring both the deformed shape and the maximum values of displacements using digital cameras and employing imaging and photogrammetry techniques (H. S. Park, 2007). The Illinois DOT provided a construction inspector's checklist for bridge superstructures; this checklist has been prepared to provide the field inspector a summary of easy-to-read step-by-step requirements relative to the proper construction of all cast-in-place concrete bridge decks (DOT I. , 2009). Although the checklist elaborates on each inspection item and the specification that should meet, unfortunately, conventional method still depends on the inspector's personal skill to determine the quality of bridge. And, it is labor intensive, sometimes subject to negotiation, and often driven by arcane rules (Turkan, 2013). An automated or semi-automated device-based bridge construction inspection system is needed.

Figure 1 An example of manual inspection, Photo courtesy of MSDOT

Lasers have long been used to measure distance. Some examples include airborne scanning lasers for terrain mapping and 3D scanning lasers for recording as-built construction details (Russell Walters, 2008). Terrestrial laser scanning (TLS) is a measurement technology that enables rapid and reasonably accurate representation, in the form of a point cloud, of the 3D surface of an object at distances ranging from tens to hundreds of meters depending on the type and technical characteristics of the scanner used. It has become a new alternative to the monitoring of structures incorporating novelty approaches (Diego González-Aguilera, 2008). This technology is currently applied in various fields, including heritage documentation, geology, as-built surveys, monitoring techniques, deformation analyses, and dimensional control (Argüelles-Fraga, 2012). In addition to the conventional stationary scanner, mobile scanners are also widely used. The kinematic GPS provided the necessary centimeter level positioning accuracy required for high performance laser scanning. The systems required ultra-accurate clocks for timing the return and Inertial Measurement Units (IMU) for capturing the orientation of the scanner (Ahmed F. Elaksher, 2002).

Figure 2 An example of TLS, Photo courtesy of AAM group

Current construction industry heavily relies on a human labor force; hence it is extremely prone to errors and deviations, causing quality problems. Laser scanning technology is an extremely powerful tool that is increasingly being integrated into civil engineering and architecture. Using laser scanning, digital 3D renderings of as-built conditions can be produced easily and relatively fast allowing for the detection of differences between what was designed and how it's being translated into reality, help engineers and management personnel to identify and mitigate the quality problems.

Further laser scanning applications in construction involve utilizing formal records and visualizations of site activity over time will likely lead to improved planning for future projects. Scans can also improve in-process inspections, which beyond impacting quality control will impact scheduling assessments, meaning that planned activities can be compared to actual progress in the field. It can help create a frequent, complete and accurate assessment of onsite conditions, which contributes to positively changing and monitoring safety conditions on site. Furthermore terrestrial laser scans have proved useful in calculating the volume of materials and assessing adjacent ground movements (Randall, 2011).

Deviations can be detected by overlapping the as-designed model with the 3D point cloud, but such comparisons are computationally too cumbersome a representation to allow for high-level reasoning about defects and their early detection (Gordon et al. 2003) Software exists for the comparison of two 3D models and can be used to conduct clash analyses so as to detect true deviations from the as-designed schematic. The most important thing that factors into this stage of the process is the interoperability of the software coordinate systems. Interoperability is a key component to the successful completion of a clash analysis. Poor interoperability could lead to the misrepresentation of certain data when transferred from one system to another. The establishment of base coordinate systems and interoperability between programs should be a key part of planning when considering the implementation of such technology on a construction site.

There are several widespread quality problems in the field of bridge deck construction, including rebar tying deviation, insufficient anchorage length, and insufficient concrete cover. The current inspection still mainly rely on inspector’s skill and experience, it’s not accurate enough to determine the quality of the construction. The traditional methods also rely on control points to evaluate the construction. All of these present complex situations where traditional metrology techniques are ineffective, due to massive quantities of data needed to describe the environment (Geraldine S. Cheok W. C., 2001).

When using 3D laser scanning, the construction site need to be scanned at different times to generate data, which can then be used to measure the work performed within the time interval considered between two successive scans (El-Omari & Moselhi, 2008) . This is because TLS is a line of sight technology, multiple scans must be merged together to form a complete image. The alignment may be performed by both direct and indirect geo-referencing methods. Direct geo-referencing methods (Scaioni, 2005) use objects as targets that have known coordinates to align the scans together or survey the control points where the scanner is set up. These coordinates are obtained through global positioning systems (GPS), Total Station, or other survey devices. Indirect alignment through software registration determines the optimal alignment of a scan based on similar features in neighboring scans to merge the scans together (Olsen, 2010). The scanning position was tied to survey targets with known coordinates. The scan data can be quickly processed to produce accurate 3D models of the scanned objects. Inspectors can use the model to verify compliance of installations of rebar and other embedded components. In general, measurements taken from the "cloud" can be used to conduct interference detection and constructability studies (Jaselskis, 2005). If discrepancies were detected, necessary changes to installations can be made.

Design of Data Collection and Analysis Workflow

The overall workflow for a typical bridge deck scanning project is shown in Figure 3. The activities in the workflow can be broadly divided into two categories: data collection and data processing. In the following sections, we explain in detail these steps.

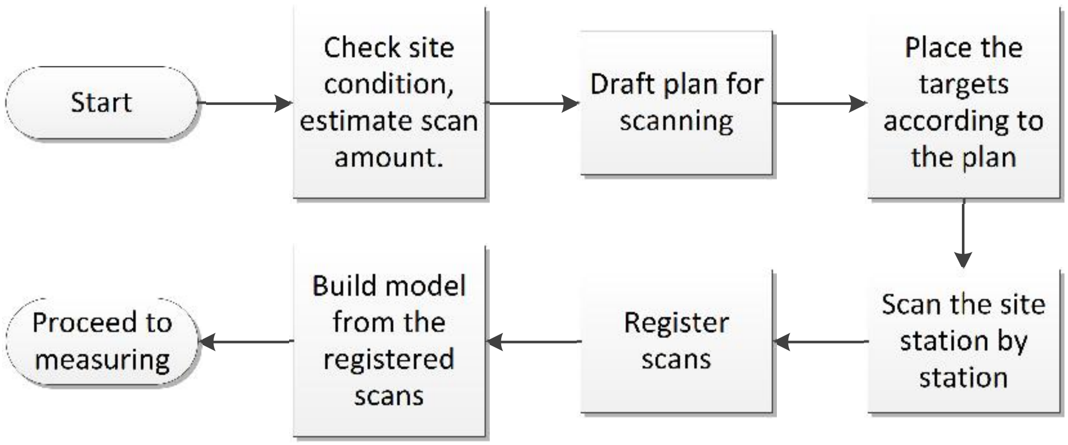


Figure 3 Typical Bridge Deck Scanning Workflow

Data Collection

The measurement requirement of bridge deck during construction is mainly about whether the site condition can meet the performance requirements and hardware requirements of a laser scanner. The first requirement is about the applicable range. There are two different types of scanners that are commonly used in 3D laser scanning. Phase based scanners utilize a constant beam of laser energy that is emitted from the scanner. The change of the phase of the laser light is measured to allow the scanner to calculate distances. Phase-based scanners are typically used in industrial applications or interior architectural spaces to populate detailed building information models of existing facilities. The advantage of this technology is the significant speed of data capture. It can capture hundreds of thousands to millions of 3D points per second, which is approximately ten times faster than most time-of-flight scanning systems (Chengyi Zhang, 2013). The 3D laser scanner which research team is using is the Faro Focus 3D which has a maximum 70m scanning radius. In order to ensure accuracy, for each two neighboring scan, they need about 5m overlapping. In this way, for a bridge no wider than 40m, the laser scanner can be set up at one end and continually conduct laser scanning to the other end with an interval of 30-40m. If the bridge is wider than the range of the scanner, double or multiple line of scan will be need.

After the scanning, the scans need to be registered together. Theoretically, two neighboring scans need at least 3 common points to register them together. Targets, such as checkerboard or spheres are needed to be place on site or around the site. The more targets (if placed properly), the more accurate the registration of scans will be. So, there should be enough space on bridge to put the targets, and the targets cannot be moved during the scanning process. Static object near bridge can also be used as targets for registering, as long as they can be detected and recorded by the scanner.

The scanner is placed on a tripod, and it has dual axis compensator that can levels each scan with an accuracy of 0.015° and an allowable vertical angle range of ±5, this requires the site to be horizontal or tilt with the adjustable range of the tripod (Faro, 2014). The scanner is designed to be used in an environment with 5° - 40°C ambient temperature and non-condensing humidity. So weather is also a restraint for scanning activities. In summary, the bridge construction site and weather condition should be checked to make sure that it meets the laser scan requirement.

The Faro Focus 3D laser scanner is a highly integrated electronic system. The scanner emits a laser beam from a rotating mirror out towards the area being scanned. Then the unit distributes the laser beam at a vertical range of 305° and a horizontal range of 360°.The laser beam is then reflected back to the scanner by objects in its path. The distance to the objects defining an area is calculated as well as their relative vertical and horizontal angles. After collecting location data of the object, the scanner will take a series of panoramic photo of surrounding environment with its built-in camera. All these data will be stored in the scanner's SD card memory. Each scan will be put into one folder under the project folder.

Bridge Scan Data Processing

The scan data collected from the laser scanner include both spatial location data and graphic data of all the points that unobstructed from the viewpoint of the scanner with its range. The location information is stored in the point cloud and the graphic information is in the photos taken by scanner's built-in panoramic camera. Each scan has its own center, i.e. the location of the center of scanner. In order to get the desirable data for our research, the scans should be combined together and put into a universal coordinate system. Each scan also has some redundancy or noise, such as points that are too far away or image of people walking through the site. All these problems can be solved through the scan data processing. The overall workflow for scan data processing can be summarized in Figure 4.

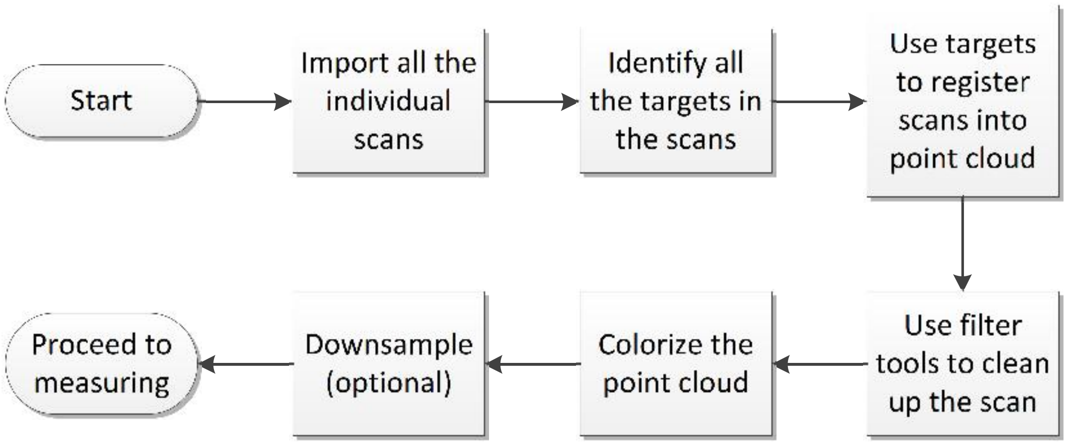


Figure 4 Bridge scans processing workflow

The scan data processing software research team are using is the scanner's bundled software, the Faro Scene 5.1.

The initial data processing steps include registration, editing, alignment, and merging. In ideal conditions, with the help of sphere or checkerboard, the software is capable of performing these tasks automatically. In other cases, if the target is out of range or if the targets can be recognized in the scan data, manual processing would be needed for these tasks. The raw scans can also be combined together into one point cloud. During the data processing, filters can be applied to remove noise and redundancy, sometimes cleaning and optimization. Then, by projecting color from the panoramic picture to each point, the point clouds can be colorized to enhance the visual effects. Once the entire point cloud data set is generated, a potential problem is that the entire point cloud dataset could be too large to be processed efficiently. This causes considerable difficulties to subsequent studies. Thus, an optional step is to use the function of "down-sampling" or sometimes called "decimate" to reduce the dataset to an acceptable resolution and reasonable file size. The final point clouds can be exported into various file formats to meet the requirement of other processing software, two common file formats are .PTS and .LAS.

Bridge Deck Measurement

After the processing of scan data, several kinds of bridge deck measurement tasks can be performed. They include measurement of rebar spacing, change detection to reveal settlements, measurement of bridge cross slope, and derivation of bridge deck concrete cover thickness. Most of these measurement tasks are straightforward except for the last task. Herein, we provide a quick derivation of the last task to highlight what needs to be done in order to get an accurate estimate of the bridge deck concrete cover thickness.

Derivation of Bridge Deck Thickness Measurement

For a typical bridge section under construction, the concrete cover thickness often cannot be measured directly.

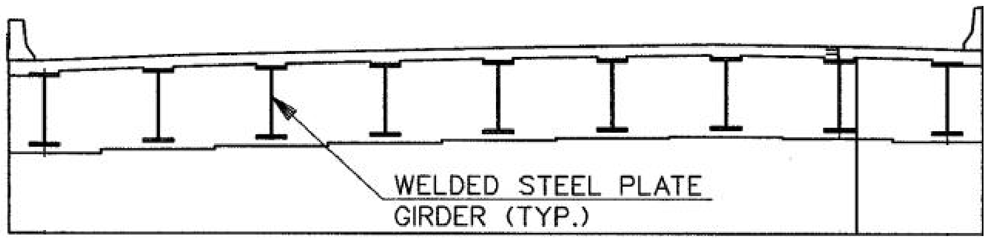


Figure 5 Typical bridge section

The first step, scan the bridge deck before pouring concrete, register the scans and measure the height h1 and h2.

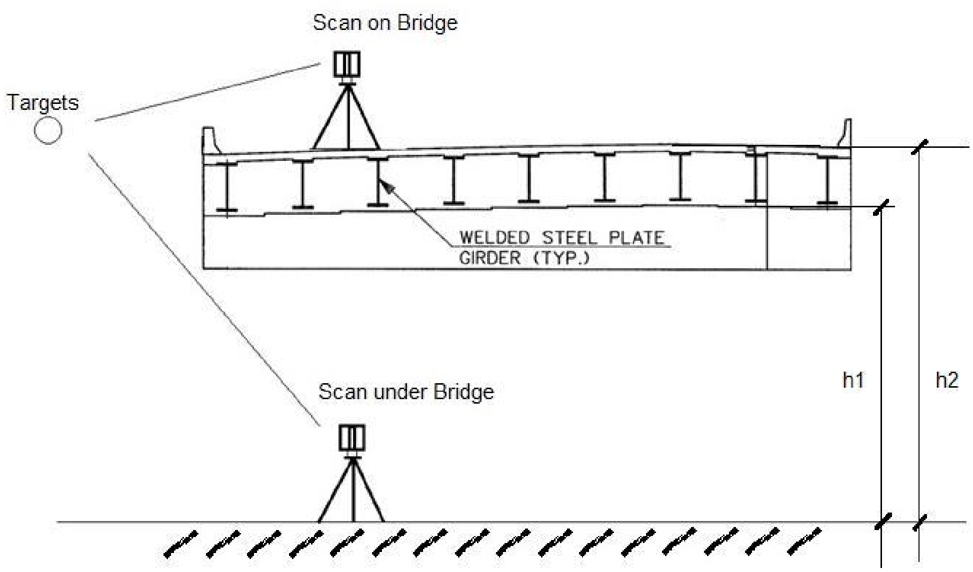


Figure 6 Measure a typical bridge section 1

The second step, scan the bridge deck after pouring the concrete, register the scans and measure the height h1’ and h2’.

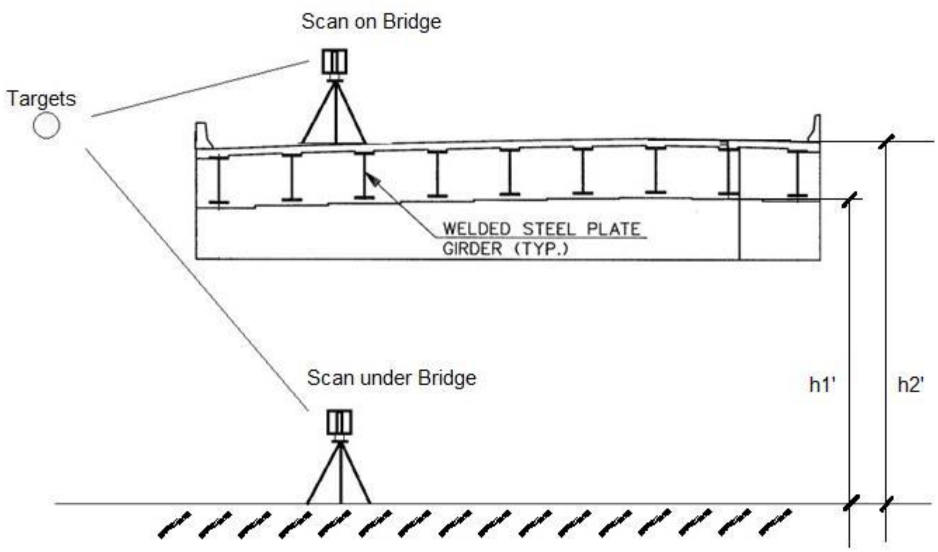


Figure 7 Typical bridge section 2

In the same location of the bridge deck section plane, the concrete cover thickness should be

T=(h2'-h1')-(h2-h1)

Then, T value can be compared with design files.

Field Validation Study

Background

The bridge we used as a validation study is a concrete deck bridge which was constructed above a rail line. In this case study, we chose the west bound of the bridge (marked with red parallelogram) as our study object. The whole old bridge in the picture was demolished; the east bound has already been replaced by a new one and the west bound is under construction. Prior to conducting the field investigations, the as-built drawings, Structural Inventory and Appraisal Sheets for the sample bridge deck were provided to the researchers and were reviewed. Comprehensive computer aided design (CAD) drawings of the sample bridge deck and plan blue prints were also provided. Also, all 1237 pages of design files were collected by researchers from the Bid Express website for reference.

The research team was interested in comparing the deviation between the rebar surface before contractor cast the concrete and the deck surface after the concrete is cured. This research involves a series work of measuring, modeling and comparing. Instead of using traditional total station, the research team chose the Focus 3D laser scanner made by FARO Company. The FARO Focus3D is a high-speed Terrestrial Laser Scanner (TLS) offering the most efficient method for 3D measurement and 3D image documentation. In only a few minutes, this 3D laser scanner produces dense point clouds containing millions of points that provide extremely detailed 3D color images of large scale geometries. Because the bridge deck area is bigger than the range of laser scanner, multiple scans are needed to cover the whole bridge. By using the FARO Scene software, multiple scans from different positions can then be automatically placed to create a cohesive point cloud, resembling an exact measureable copy of the structures.

Figure 8 An Aerial View of A Bridge under Construction

More specifically, the following data collection work was performed on this bridge.

- A thorough visual investigation of the top surface of the bridge deck (rebar surface).
- The plan of the marks on the bridge construction site.
- Collections of LiDAR scan data of the unfinished bridge deck (rebar surface).
- Collections of LiDAR scan data of the constructed bridge deck (concrete surface).

In addition to these field investigations, additional data process, measure and compare were conducted later. These tasks include:

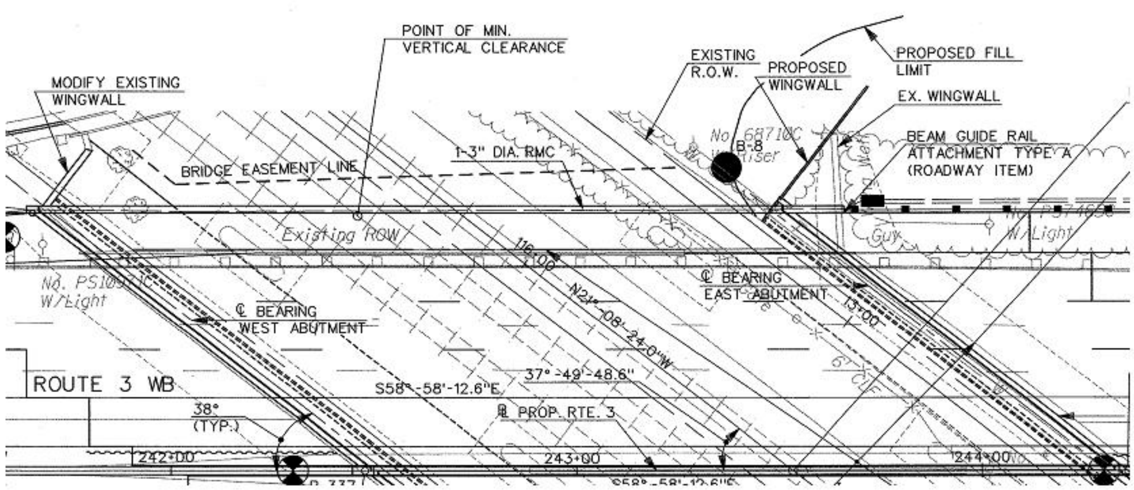
- Registration of scan point cloud (rebar surface and concrete surface).
- Overlap of the rebar surface and concrete surface.
- Measurement of rebar spacing.
- Measurement of bridge deck section slope.

Figure 9 Faro Focus 3D scanner

We used a series of software programs to process the laser scan data and conduct measurement tasks. The programs we used include FARO Scene(for registering individual scans), Cloud Compare(overlaying points clouds and measuring distance between models), and Bentley MicroStation(making model of rebar and deck surface from points clouds).

Overview of Site Conditions and Constraints

The following figures show the layout of the bridge and the cross profile of the bridge. As we can see from the above, the west bound is a typical 4-lane steel girder bridge with cast-in-place concrete deck. The bridge is about 200ft (61m) long and 65ft (20m) wide. By the time we start our study, the girders are already installed and the rebar are already tied.



West Bound Plan

Figure 10 West Bound Plan

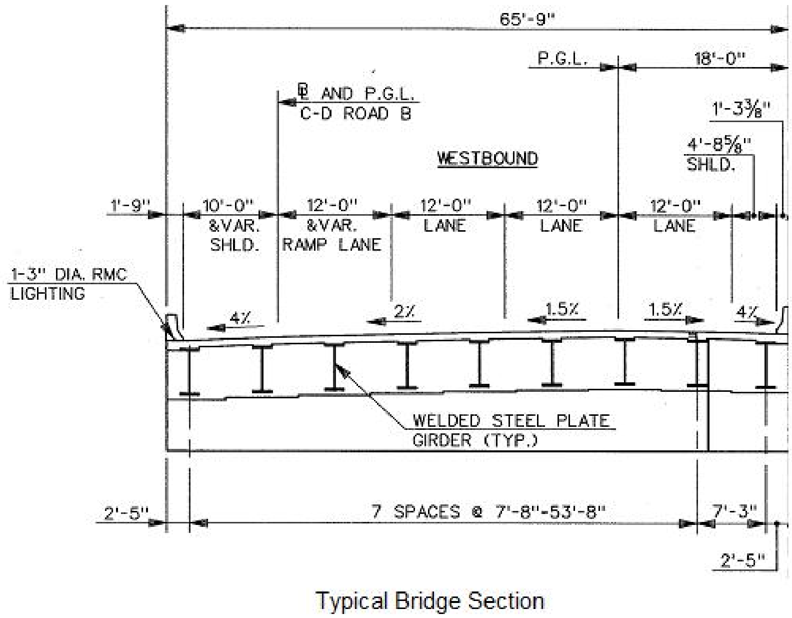


Figure 11 Typical Bridge Section

Due to the construction of the west bound, all the traffics are moved to the east bound. Underneath the bridge is the busy main train line, so we have very limited space, which restricted all the measurement work on the surface of west bound bridge.

Data Collection and Processing Workflow

Figure 12 shows a detailed workflow we employed in this validation study.

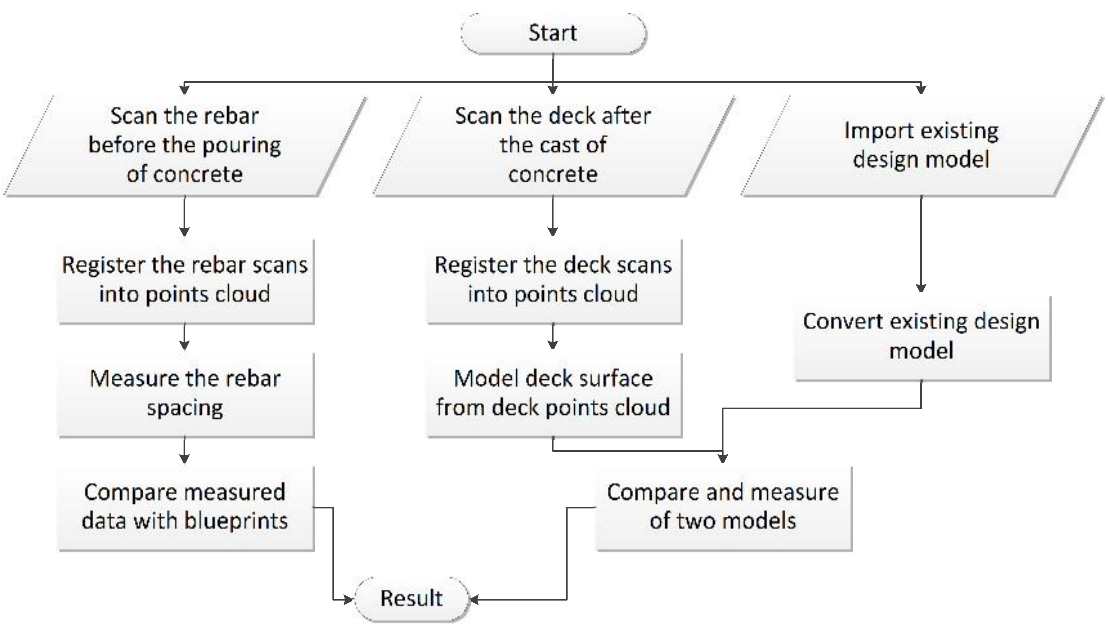


Figure 12 General workflow of bridge scan

Data Collection

As mentioned before, multiple scan are needed to form the points cloud. In the registration process, targets like spheres or checkerboards are used to locate and combine the scans. To form the points cloud, in each two adjacent scans, there should be at least three common targets.

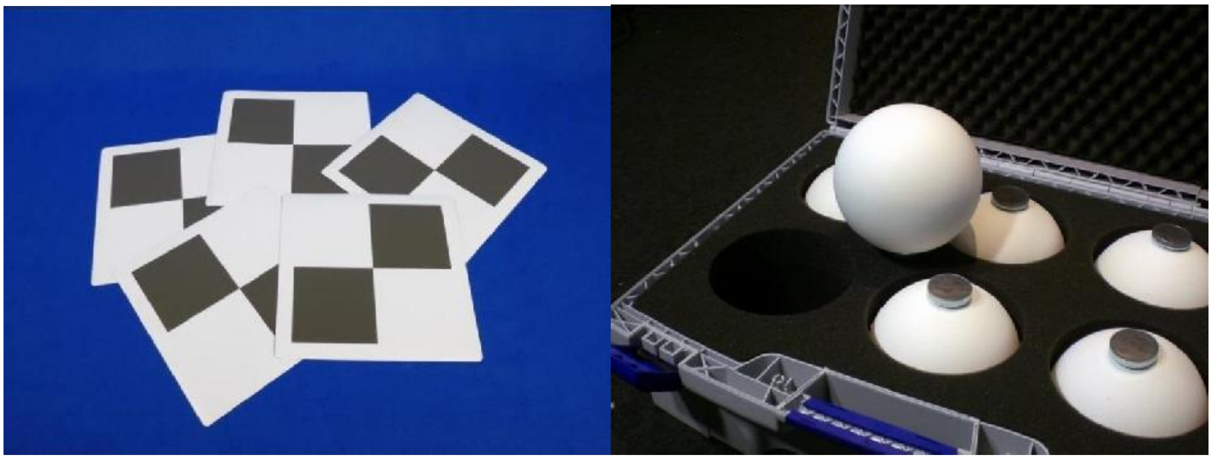


Figure 13 Spheres and checkerboards

In the rebar scans, the team chose to use checkerboards as targets, because compare to the spheres, they are easy to produce, very cheap, and easy to setup. But there are also some disadvantages of the checkerboards. For example, in order to be automatically identified by the processing software, the checkerboards need to be put as perpendicular as possible to the laser beams emitted by a scanner. This hard to achieve and reduce the effective range of the scanner. To compensate for this issue, we placed checkerboards at short distance intervals.

The first series of scans were conducted to capture the bridge deck before concrete placement but after the rebar cages are installed (Figures 14, 15, 16). The scanner was moved along the middle of the bridge. At the end, eleven scans were collected to capture the site condition. After the concrete is poured and cured, the team returned to the site to scan the deck surface (Figure 17). At this time, the bridge already has a smooth surface, so researchers decided to use the spheres as the targets. Registration based on sphere targets typically offer better accuracy than checkerboard targets. Eight scans are collected for the deck surface after the concrete has been placed. Together, these scan data provide 3D documentation for the bridge deck before and after concrete placement. If both scan data sets can be registered to a common coordinate system and tied to several common points that do not move with the bridge deck surface, the analysis of the difference between these scan data sets reveal the settlement of the bridge deck. It is expected the bridge deck will settle, but the question is on the magnitude of the settlement and how does it compare with the calculated or estimated bridge deck settlement after the concrete has been placed.

Figure 14 Scanning the rebar surface

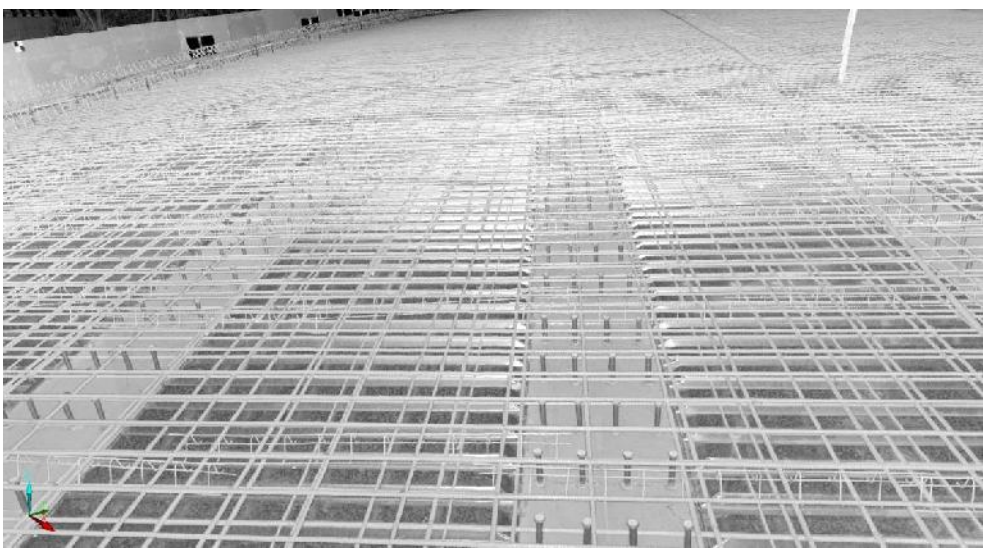


Figure 15 A Rebar 3D Image

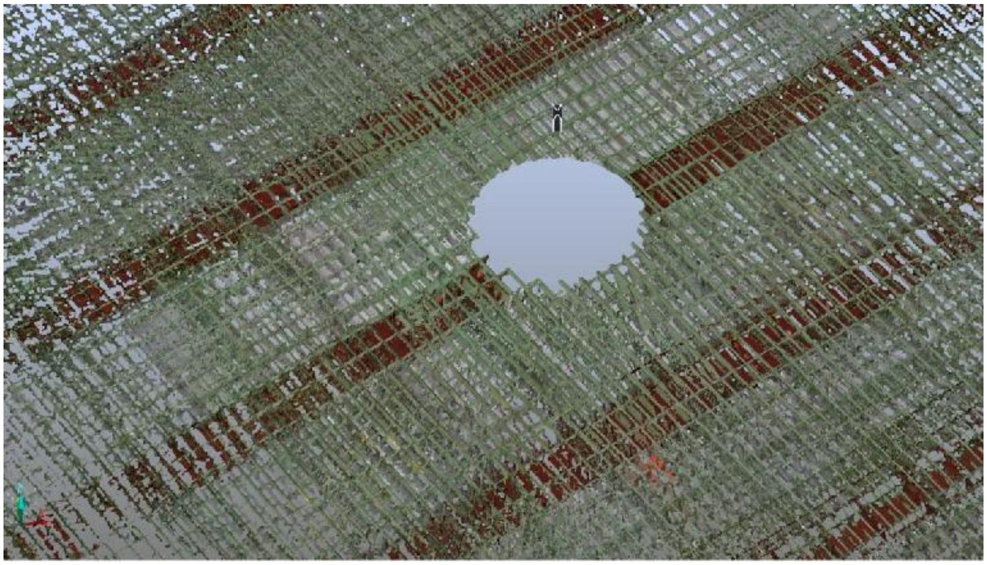


Figure 16 Colorized Point Clouds for Rebar Cages

Figure 17 Scanning the concrete surface

Data Processing

With the help of targets, two sets of point clouds for rebar surface and deck surface were generated, filtered, and processed in the FARO Scene software. Data registration presented a challenge when post-processing the data. Because there are quite a few checkerboards that cannot be automatically identified, several rebar point clouds were registered manually. Figure 18 shows the point clouds for the bridge deck prior to concrete placement, and Figure 19 shows the point clouds for the concrete bridge surfaces.

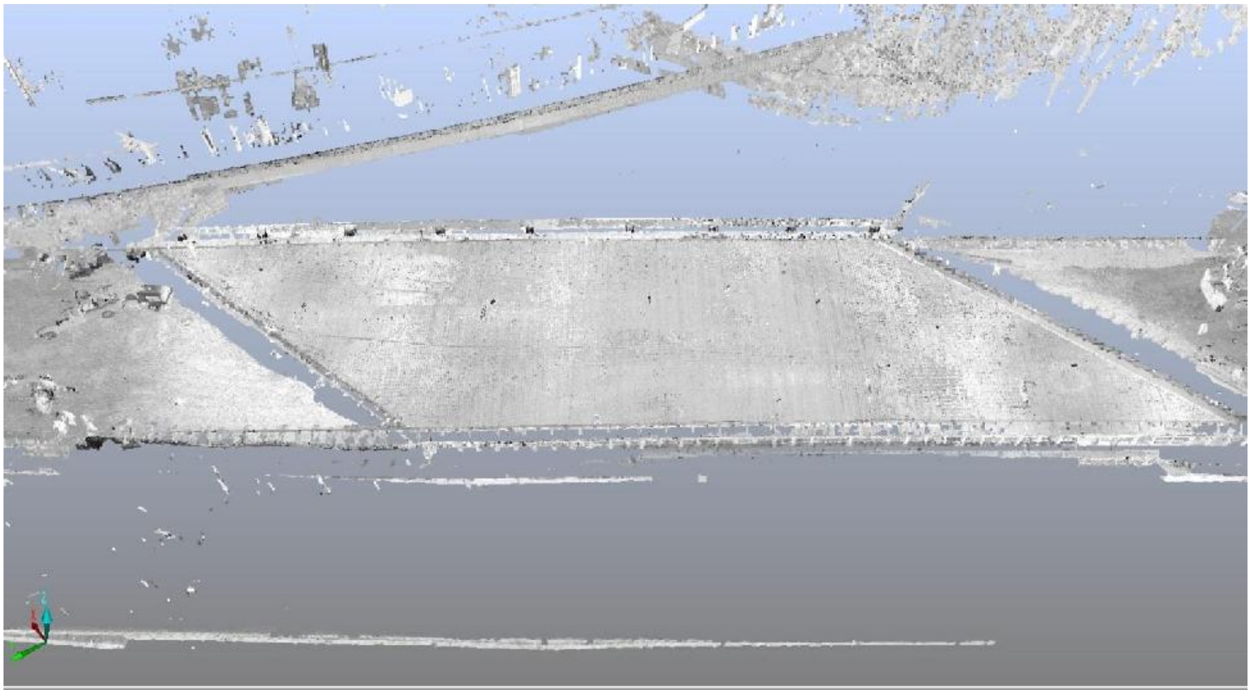


Figure 18 Point cloud for rebar surface

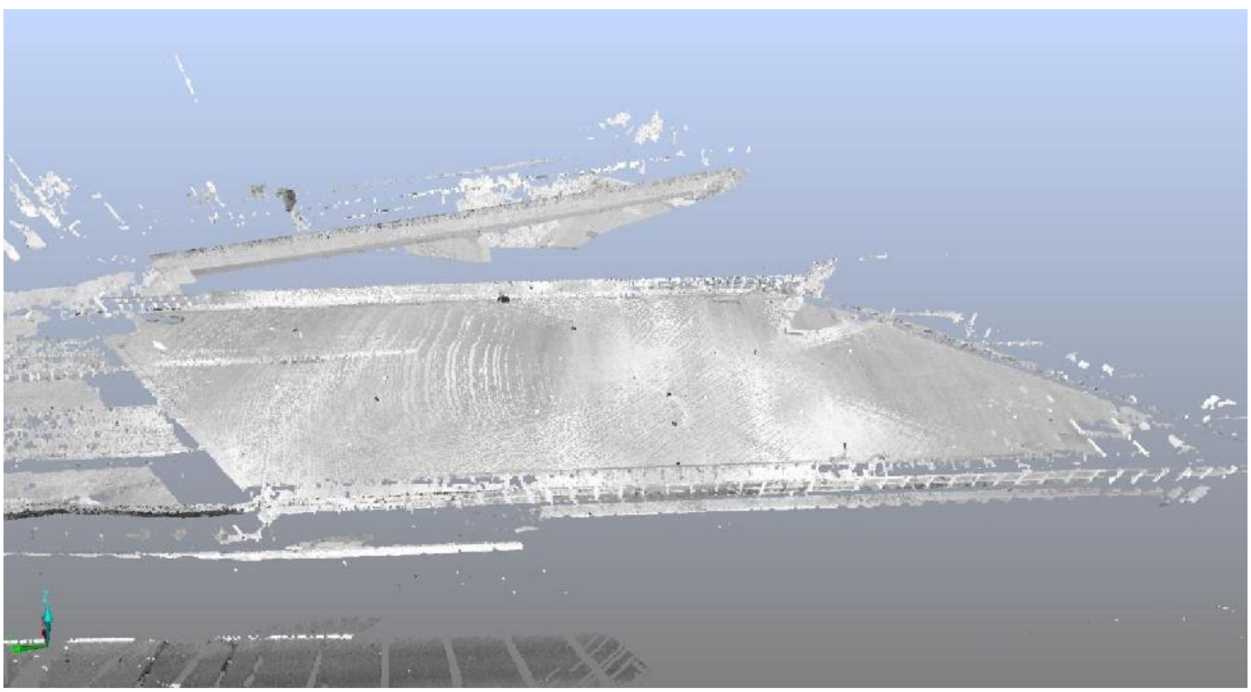


Figure 19 Point cloud for the concrete bridge surface

Bridge Deck Measurement

Several measurement tasks were performed using the processed scan data. They include rebar spacing measurement, slope measurement, and change detection among various construction phases.

Rebar Spacing Measurement

The structural integrity of reinforced concrete bridge deck is dependent upon the following:

- Grade of steel;
- Size and spacing of the rebar; and
- Location of the rebar within the deck.

If the ironworkers do not place the rebar at the designed spacing, the final strength of the bridge deck could be compromised. Therefore, it is very important to check the rebar spacing of the bridge deck before the concrete is poured. The 3D laser scanning technology provided us a powerful tool for this purpose. For this part, we utilized the scans collected for the rebar; the spacing of the rebar is checked and compared with the blueprint data. The software we use is the VirtuSurv from Kubit. VirtuSurv is Kubit's standalone software for working with highly visual laser scan data. The program supports the import, export and display of many scan data formats and has interfaces for both CAD and Windows based programs. In this research, we are using the "Getting distance" function of VirtuServ. Figure 20 showed the Measure Mode in VirtuSurv.

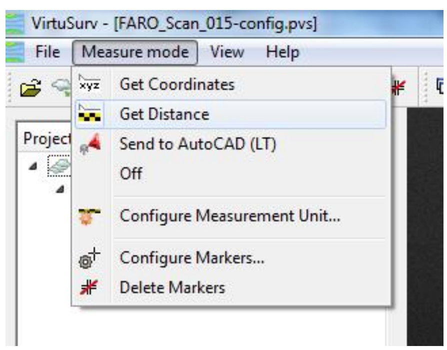


Figure 20 Measure Mode in VirtuSurv

Several steps are used to perform the rebar spacing measurement tasks. First, import the scan file into VirtuSurv, identify one kind of rebar. Second, check the blueprints and find out the required spacing of this kind of rebar. Third, measure and record the rebar's actual spacing at each location by picking points on rebar surface in the VirtuSurv. Lastly, the distance is analyzed to reveal compliances.

Figure 21 showed one part of the bridge deck rebar in 3D point cloud.

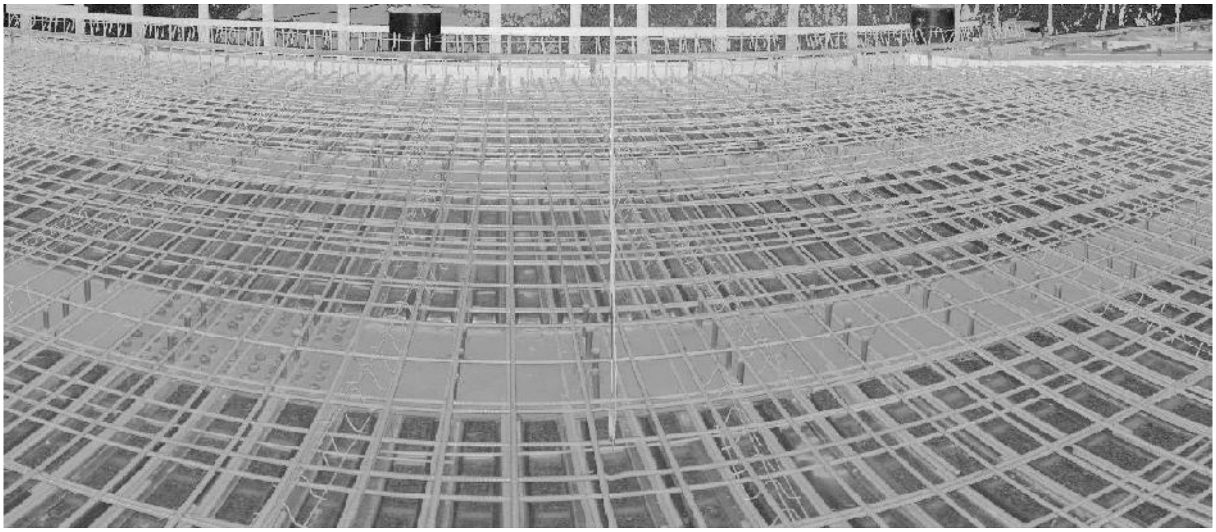


Figure 21 Bridge deck rebar in 3D point cloud

We chose the top transverse rebar to demonstrate the rebar spacing measurement and analysis. The top transverse rebar is highly visible from the scan data. The bottom rebar are often occluded by the top rebar layer, and they can be easily confused with other layers. Figure 22 showed the rebar spacing in the design file.

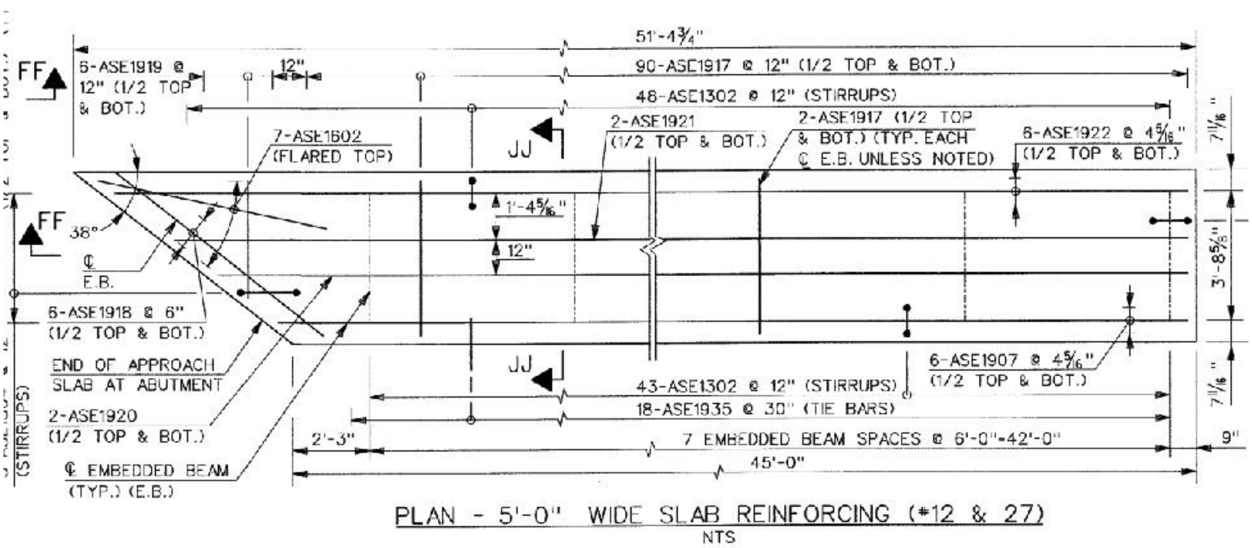


Figure 22 Rebar spacing

According to the blue prints, the bridge deck's top transverse rebar should have a spacing of 6 inch. Therefore, this task is to verify this requirement based on measurement on the 3D point clouds (Figure 23). 115 spacing data were collected and plotted in Figure 24.

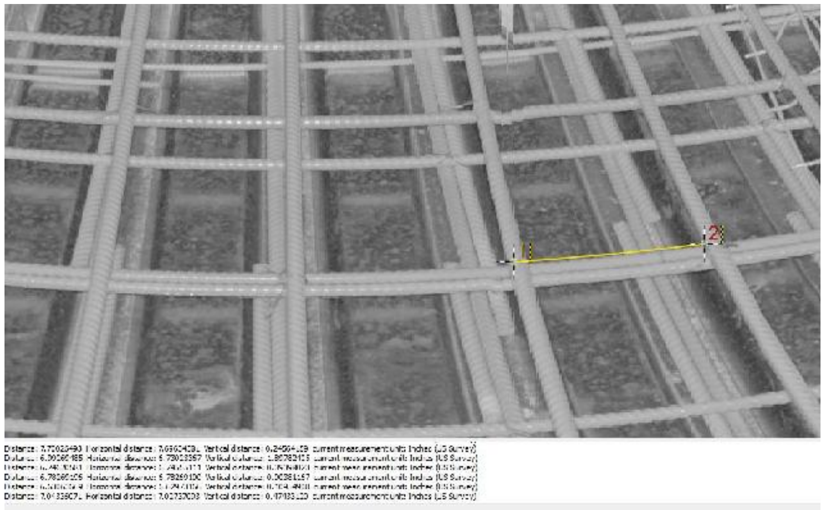


Figure 23 Spacing of top transverse rebar

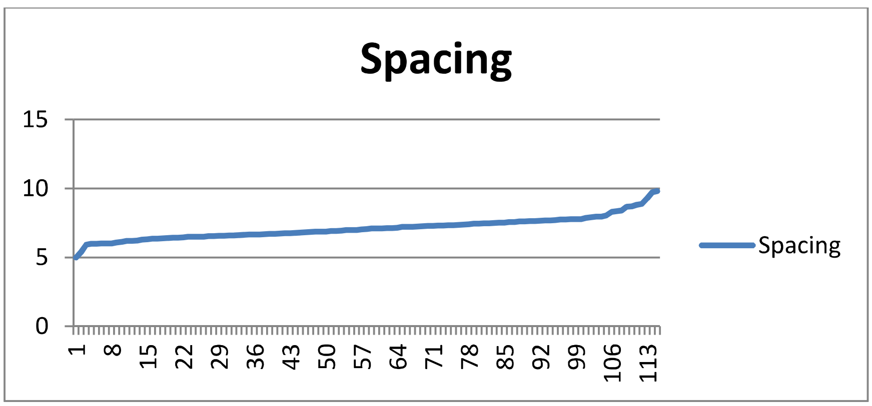


Figure 24 Spacing data 1

And below is the histogram of the spacing data.

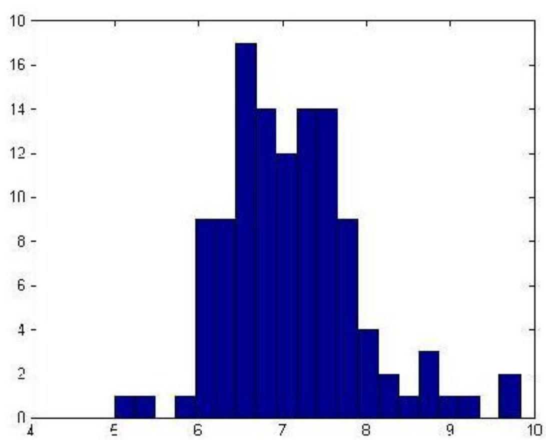


Figure 25 The Histogram of Rebar Spacing Data

The histogram shows the randomness of rebar spacing data, which very much resembles a normal distribution. It can be noted that the majority of the rebar were placed at a spacing falling into the range between 6 and 8 inch (85.2%). However, the required spacing is 6 inch, which highlights the randomness of rebar placement position quality. We also need to take the system error into consideration. Because points on the rebar surface are manually picked, and angle of view of each point is different. Even both the scan data itself and the software are accurate; there still would be human error in measurement.

Change Detection among Different Construction Phases

To conduct change detection between scan data that were captured before and after concrete placement, the bridge surface models are first converted from AutoCAD's DWG file into STL file. STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes. Figure 26 showed the DWG model of the bridge opened in MicroStation. The reason for the conversion is to convert the CAD models into a format compatible with the CloudCompare software. The rebar point clouds are converted into LAS file, which is also supported by the CloudCompare. After they are imported into the CloudCompare, they are aligned with both manual registration and Iterative Closet Point (ICP) method. More specifically, the point clouds are aligned by picking (at least 3) equivalent point pairs, which in turn provides sufficient information for computing the rigid transformation between the CAD model and the point clouds. The as-built bridge surface point cloud is selected as the reference cloud, and the design model is the aligned cloud. Figure 28 showed the aligned cloud. One thing should be mentioned here is, there are many noise points in the points cloud, they are floating above the bridge surface and invisible to us, but when the program generate the distance bar, it took those points into consideration, making the red part of the scale bar not shown in the picture.

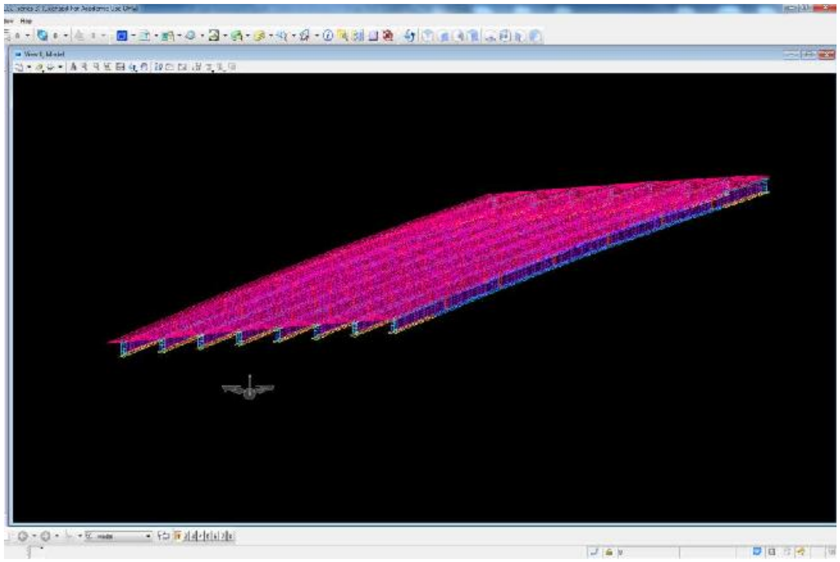


Figure 26 DWG model of the bridge opened in MicroStation

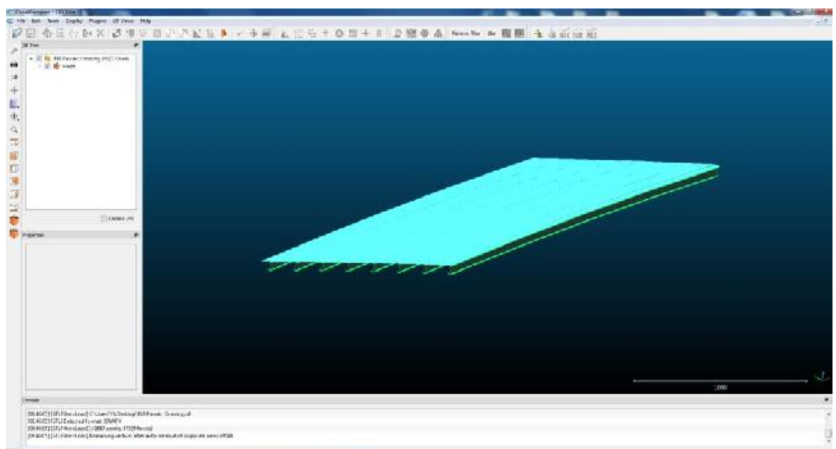


Figure 27 STL model of the bridge in CloudCompare

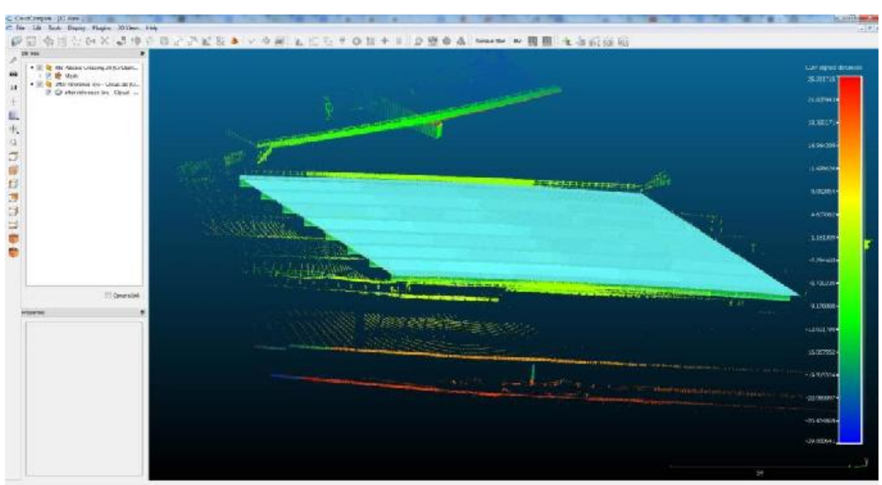


Figure 28 Difference between the aligned CAD and Point Cloud Data

The picture above shows the aligned surface model and the distance between them. As we can see from the picture, the distance between design model and as-built condition are very uniform. Although the scan we collected does not have the precise GPS and all the alignment are manually finished, the accuracy of the alignment should still be accurate. We used the adjacent bridge, which is unaffected during the construction of the new bridge, as our reference target in the manual alignment process. In future research, if reference points with precise GPS information were prepared before the scanning of the site, the precise global coordinates would be very helpful in the measurement and comparison of the bridge on larger scale.

Measure the Bridge Surface Cross-Slope

The purpose of this activity is to demonstrate how the point cloud data can be used to performance accurate measurement of the bridge deck cross-slope. We used Mircostation and its add-on software – Terrasloid to perform these tasks. Terrasolid is the de facto airborne LiDAR data processing software, and recently it has been increasingly used for mobile LiDAR data. More concretely, the points in the las format was read into Bentley MicroStation. In MicroStation, the slope of the bridge surface can be measured and compared to the design file.

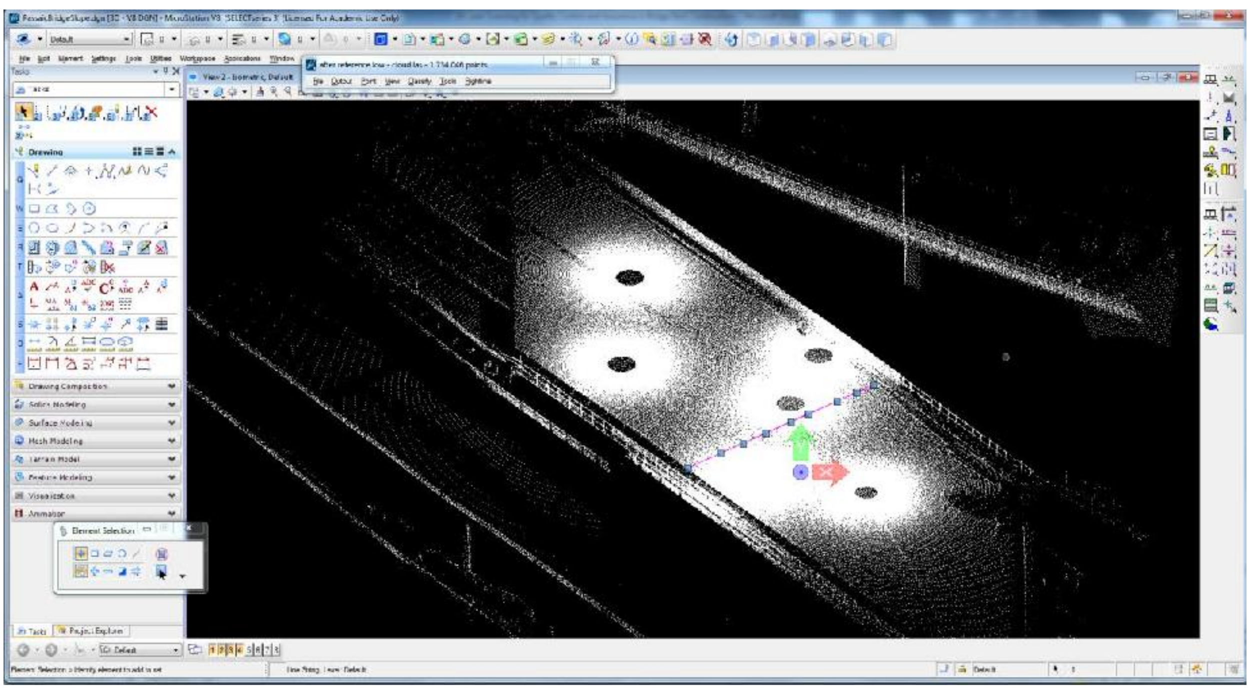


Figure 29 Measure the slope of bridge surface

The slope is calculated using the following mathematical expression:

Slope = 100 * (End z - Start z) / Horizontal length of element

Even if the element is a line string, the tool does not use the individual segments of the element. The slope is always calculated from the element's start point to its end point.

The slope measurement workflow is shown below (Figure 30).

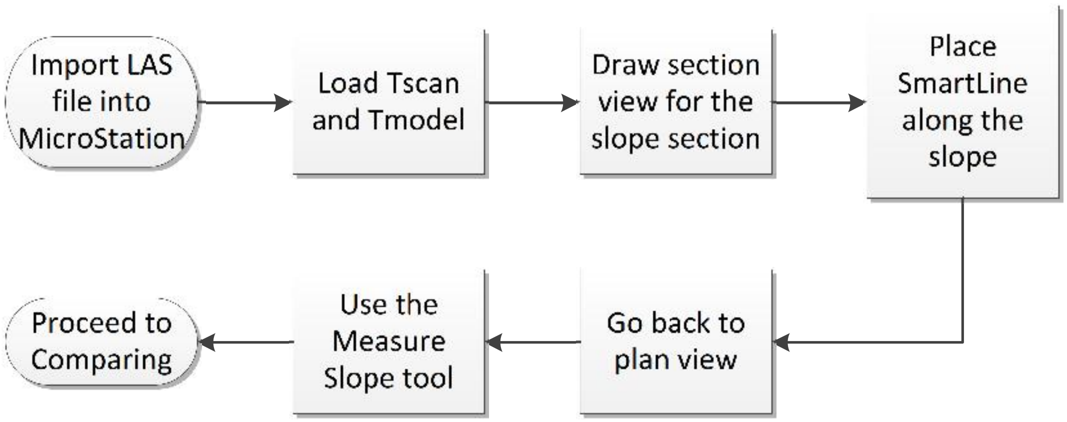


Figure 30 The slope measurement workflow

Several examples of surface cross slope measurements are shown in Figure 31. 14 section slopes samples were collected in this study. These sections are located along the west bound of the bridge. According to the design file, the section slope of the bridge deck should be 2.0%. And the average slope of these 14 sections is 1.87% (Figure 32). This result can be used to evaluate the construction quality of the bridge deck.

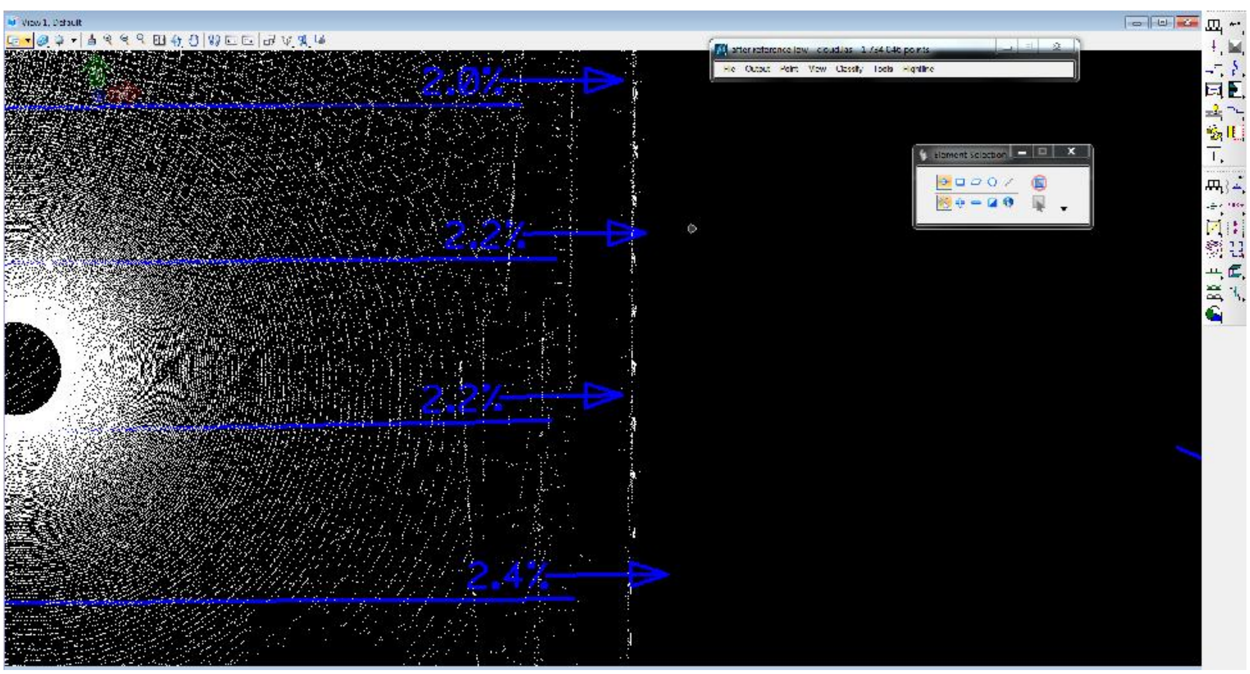


Figure 31 Several measure examples

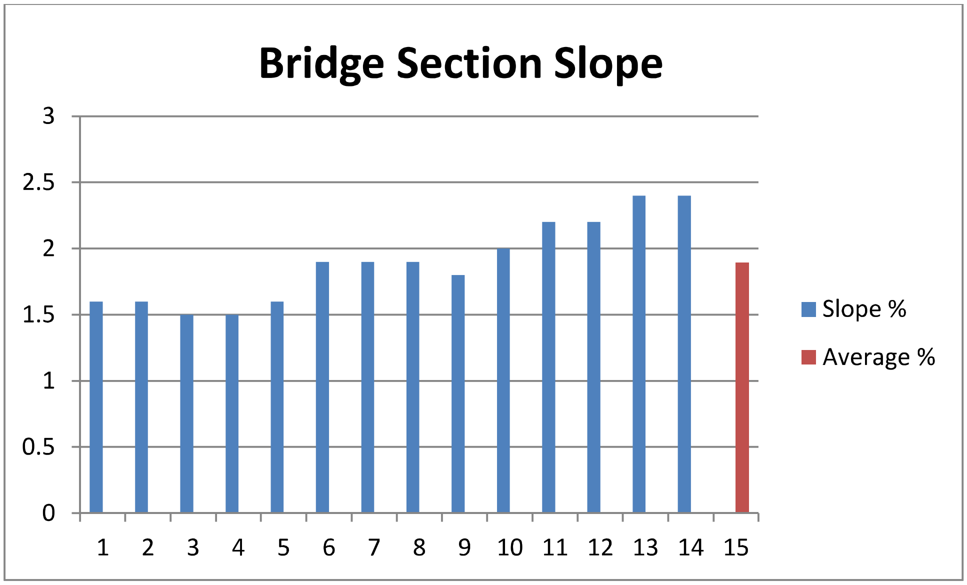


Figure 32 Bridge Section Slope

FINDINGS

The findings of this study include:

- The scan can be done in relative shorter period of time, reduce the interference with construction work.
- The whole site can be recorded, no omission of information.
- The site condition of a certain time can be recorded, and they are unable to show up again in the construction process.
- Once scans are collected, the measurement can be taken at any location.
- All measurement free of the disturbance of weather changes.

CONCLUSION

In this research, a systemic method is presented that demonstrates the feasibility of a semi-automate device-based process that measures bridge deck construction quality and accuracy by using 3D laser scanning. Three steps were taken to do this. First, the bridge deck is scanned twice to acquire the rebar data and concrete surface data. Second, point cloud data were established by merging individual 3D laser scan of the bridge, and then 3D model were computed based on the point cloud. Third, the point cloud is used to do the measurement and comparison, for example, the 3D model of concrete surface was superimposed on the design model to calculate the distance and deviation of the built bridge.

This systemic method is able to measure the distance of a simple concrete deck surface to the rebar. By measuring the distance, construction defects can be found and method to mitigate the quality problem can be provided. Compared with traditional visual inspection, this system effectively eliminates the negative influences of inspector's personal skill and experience; also it is more accurate than traditional visual inspection because point clouds establish a 3D environment to represent the construction site rather than human's eye. The most significant contribution of the system is that once the captured point cloud data are imported into the computer, the data can be measured regardless of the change of site condition.

In future research, these methods should be tested in more real construction site. Its performance in different and more complex site needs to be tested. In order to obtain more accurate data about rebar's location in the concrete deck, the system's collaborative studies with Ground Penetrating Radar (GPR) are expected. The economics of the equipment as well as the practicality and speed of the setup in a busy construction need to be assessed. A more automated workflow is also needed.

RECOMMENDATIONS

The recommendations out of this study include:

(1) While implementing 3D laser scanning technologies, detailed analysis on how the workflow of 3D scanning can be integrated into existing construction operations is needed in order to maximize benefits and minimize the disruption to site operations. Careful coordination tends to produce better scan data to support bridge deck measurement tasks.

(2) The price barrier of laser scanning technologies has dropped significantly over the past few years. The improved cost benefit ratio for wide adoption of the laser scanning technology will provide benefit to bridge deck construction quality monitoring.

(3) The 3D laser scanning technology does not replace the traditional methods such as traditional surveying and GPR. The technology works best when its results are combined with the results from these traditional technologies.

(4) The State DOTs need to consider incorporating 3D terrestrial laser scanning into their regular tool sets as it provides a quick method to document bridge construction sites for quality assurance as well as for as a permanent record to document the construction processes.

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