Augmenting BIM with 3D Imaging Data to Control Drilling for Embeds into Reinforced Concrete Bridge Decks

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ABSTRACT

Placing embeds into reinforced concrete structures, after concrete is poured, without damaging reinforcement bars (rebar) is an industry-wide challenge encountered across the construction industry. In concrete structures such as containment vessels, bridge decks and post-tensioned concrete floors damaging rebar may compromise structural integrity and result in considerable rework. Although negative impressions for embeds can be made by placing various objects such as wooden dowels or steel rods into the rebar cage prior to pouring the concrete (and removing them once the concrete has partially or fully set), this practice is labor intensive and time consuming. A method of mapping the locations of the rebar free spaces before pouring and controlling the drilling process in real-time could have significant benefits. This paper presents research that investigated and implemented conceptual solutions for processing and incorporating point cloud data obtained from various 3D-imaging technologies into the drilling process. The 3D imaging technologies were used to map the locations of rebar within a replica of a section of a railway bridge deck. Once the point clouds were processed, zones that are safe for drilling are automatically detected and saved as a Building Information Model (BIM) that is then used to provide real-time feedback to the drill operator about whether it is safe to continue drilling based on the position and orientation of the drill. A conceptual method for providing visual feedback about the rebar-free zones to the drill operator using a laser projector was also developed. Finally, a visualization method for comparing the data obtained from the various 3D imaging technologies using the BIM is discussed.

1.   IMPORTANCE OF THE RESEARCH

1.1   Background of the Research

The construction of a railway line requires placing embeds into reinforced concrete decks along the length of the railway line. While drilling into reinforced structures, it is of utmost importance that the drill bit must avoid contacting the rebar and the utility lines. Uncertain knowledge of the locations of rebar and utility lines makes drilling into reinforced concrete decks risky for worker safety and compromises on the structural integrity of the deck. Although negative impressions (such as wooden dowels) may be placed in the rebar cage prior to pouring the concrete to create the voids for embeds, this practice is labor intensive and fraught with problems. To overcome these problems, an alternative methodology has been developed to map the locations of rebar and zones safe for drilling using 3D imaging data from laser scanning and photo reconstruction [Saidi, K., et al., 2011]. Augmenting the results of the rebar mapping and safe zone prediction algorithms based on 3D imaging data with Building Information Modeling (BIM) techniques help visualize the results from different 3D imaging technologies.   This paper presents compares and contrasts the results of the rebar mapping and safe zone prediction algorithms obtained from two specific 3D imaging technologies – laser scanning and image based photo reconstruction.   The Industry Foundation Classes (IFC) data model is used to store the geometry of the zones safe for drilling and serves as the BIM.   IFC is the open-standards product data model and file exchange format, developed by buildingSMART, that is used to facilitate interoperability between software applications in the building and construction industry. This paper also presents a feedback algorithm to control drilling for embeds into reinforced concrete decks. The feedback algorithm uses the IFC files to predict, in real-time, whether it is safe (or unsafe) to continue drilling at a certain location.

1.2   Current Methodology for Placing Embeds into Reinforced Concrete Bridge Decks

A common methodology currently used for placing embeds into reinforced concrete bridge decks involves creating negative impressions in locations where embeds are designed to be placed. Typically, wooden dowels are used as block-outs to mark embed locations in the rebar cage. The wooden dowels are screwed into the bottom of wooden planks to hold them in place and the planks are tied to chairs attached to the top layer of rebar as shown in Figure 1 [Saidi, K., et al., 2011].

Figure 1: A railway bridge deck rebar cage with the dowels and wooden planks installed [Saidi, K., et al., 2011].

The wooden planks are also used to create a recess along the length of the pavement and the top surface of the wooden planks is matched with the final grade of the concrete. After the concrete is placed and sets for a few days, the wooden planks and dowels are removed and the holes are then covered with foam plugs to prevent debris from entering and to protect them from any damage [Saidi, K., et al., 2011].

However, the process of installing the dowels and removing them is labor intensive and therefore expensive. Sometimes, the wooden planks are covered by concrete and additional time and labor is spent in locating these hidden planks. Additionally, the process also creates congestion in the rebar mats and could adversely affect the quality of the concrete by creating honeycombs and voids while restricting the access and movement of the workers placing, vibrating, and finishing the concrete [Saidi, K., et al., 2011]. The methodology also complicates processes, such as retrofitting, rehabilitation and drilling for additional railway tracks after the bridge deck is built, which require drilling into the bridge deck at locations not marked by the dowel block-outs.

2.   DIGITAL MAPPING AND STORAGE OF REBAR CAGE DATA

2.1   Acquiring Digital Data as Point Clouds
An alternative methodology has been developed to map the locations of rebar and zones safe for drilling using 3D imaging data from laser scanning and photo reconstruction [Saidi, K., et al., 2011]. A mock up model of a rebar cage with pipes representing utility lines, shown in Figure 2 (a) was used as a testbed. The laser scanner, which had a manufacturer specified measurement accuracy of ±5 mm, was used to develop a point cloud dataset, shown in Figure 2 (b) that was registered to a common coordinate frame. A second dataset was produced by using image based 3D reconstruction to develop a dense point cloud [Golparvar-Fard et al., 2010], shown in Figure 2 (c). To establish a ground truth, another point cloud dataset was developed using a Coherent Laser Radar (CLR) scan with a point spacing of 3 mm [Saidi, K., et al., 2011].
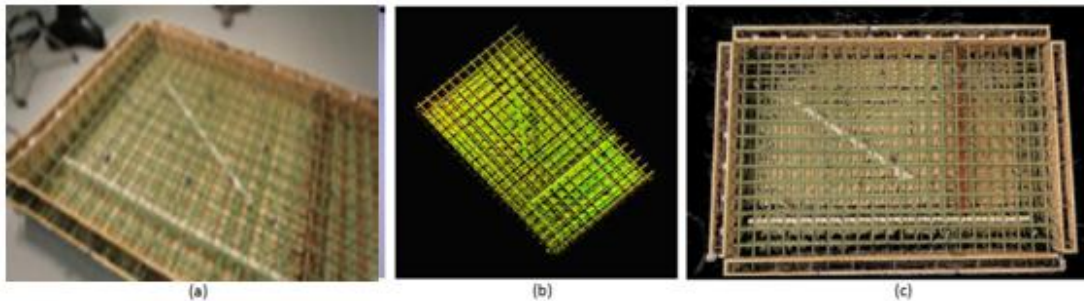

Figure 2: The point cloud models of (a) the rebar cage as developed from (b) laser scanning and (c) image based 3D reconstruction [Saidi, K., et al., 2011].

2.2   Mapping Point Cloud Data to Rebar Cage Cells
The point cloud data from the laser scanning and image based 3D reconstruction are then processed though the rebar mapping algorithm to extract the rebar intersections and the safe drilling depth within the rebar cells (the space between rebar where it might be safe to drill). The algorithm involves fitting

cylinders, of unfixed radii, to determine the intersection points of the rebar. Rebar frequently bends and deflects under its own weight and other loads. To account for this curvature, the rebar points are divided into shorter lengths so that they can be modeled accurately as straight cylinders. The intersections of these cylinders are determined and are projected onto a single plane parallel to the rebar layers. The rebar intersections are merged together and ordered to form a 2D grid on the aforementioned plane. Quadrilateral cells are then created on the plane with offsets equal to the radii of the cylinders modeled to fitting the corresponding rebar as shown in Figure 3.
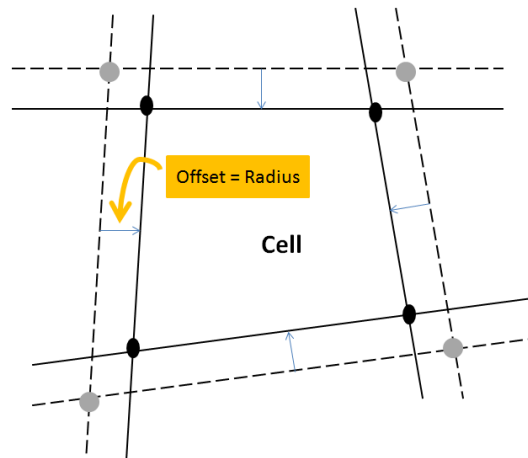

Figure 3: Extracting the quadrilateral cells in the rebar mapping algorithm. The dashed lines represent the projections of the center lines of the cylinder and the solid lines are the offsets equal to the corresponding radii.

The algorithm then checks each cell for its safe drilling depth i.e., the depth from the top of the concrete surface up to which drilling can be done without hitting any utility lines. The algorithm breaks the space corresponding to each rebar cell into bins, separated at discrete depth levels, and counts the number of points in each bin. If the number of points in a bin exceeds a threshold limit, then the bin is considered unsafe for drilling as shown in Figure 4. The number of consecutive bins deemed safe for drilling from the top of the deck determines the safe drilling depth of the cell. The rebar-mapping algorithm exports a list of cells, each cell identified by the four points that make up the quadrilateral and a safe drilling depth.
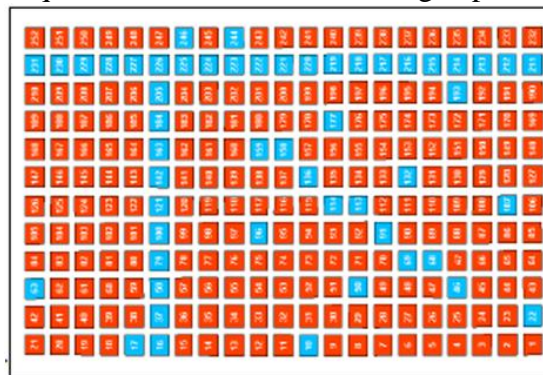

Figure 4: Predicted cell status for a particular bin where red and blue cells denote safe and unsafe status respectively.

To establish the ground truth data, the CLR point cloud is used to determine the coordinates of the rebar intersection. This is done as a manual process and is performed for each cell individually. The process involved fitting cylinders, where the radii of the cylinders are not fixed, to the point cloud of the rebar. For a given cell, only the points around that given cell are used to fit the cylinders. The safe drilling depth of the cells is determined by measuring the locations of the utility pipes in the rebar cage mock up in the testbed.

2.3 Storing Cell Information as IFC Files

The results of the rebar-mapping algorithm are processed to generate the volume of the safe drilling cells in an IFC file and are visualized as a BIM. The IFC representation of the rebar and bridge models is used, rather than commercial BIM software, to simplify the visualization of the models and associated safe drilling zones. The IFC files are also used as input files for the feedback algorithm used for controlled drilling and laser projector based guidance for drilling.

3 CONTROLLED DRILLING FOR EMBEDS

3.1 Drilling Feedback Control Algorithm

The drilling feedback application, as demonstrated in the testbed, determines, in real time, whether it is safe or unsafe for a drill to continue drilling at a particular location in the concrete deck using the Indoor Global Positioning System[1] (iGPS) to track the position of the drill bit tip. The drill in the demonstration was fitted with a pair of iGPS receivers, as shown in Figure 5, which were tracked by the iGPS system.
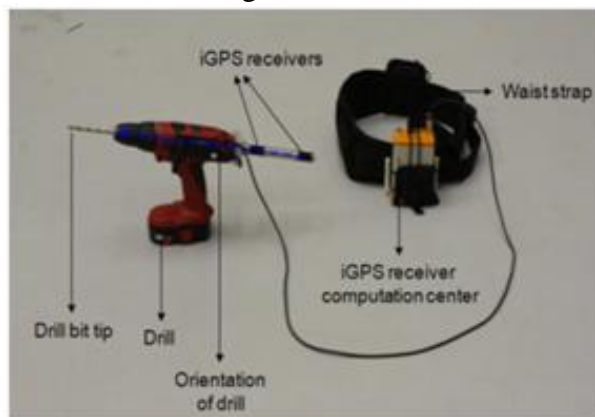

Figure 5: Modified drill set up with the iGPS receivers attached to the drill.

The iGPS receivers were mounted such that they were oriented along the longitudinal axis of the drill bit and were connected to a shoulder/waist strap that also holds the computer that performs the position calculations. The receivers' positions are then wirelessly transmitted to the iGPS server. The iGPS receivers' positions relative to the drill bit's tip are known and are preprogrammed into the iGPS server

[1] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

that calculates the position and orientation of the drill bit's tip. The iGPS server has the ability to handle scenarios with multiple drills in order to simulate a drilling crew working simultaneously on the bridge deck. The application uses information regarding the position and orientation of the drill bit's tip from the iGPS server and the information regarding the zones safe for drilling from the IFC data file with information regarding safe void zones (the rebar cell region where it is safe to drill) as determined by the rebar mapping algorithm.

The overall schema of the feedback application is shown in Figure 6. The entire reinforced bridge deck is divided into smaller regions such that each region has a corresponding IFC file that stores data regarding the zones safe for drilling in that region. The application determines the drill bit position and the corresponding region, and the IFC file. If the drill bit moves into a new region, corresponding to a different IFC file, the IFC geometry is extracted and cell data is stored in a local data structure. This data is used by the application until the drill bit tip moves into a new region.
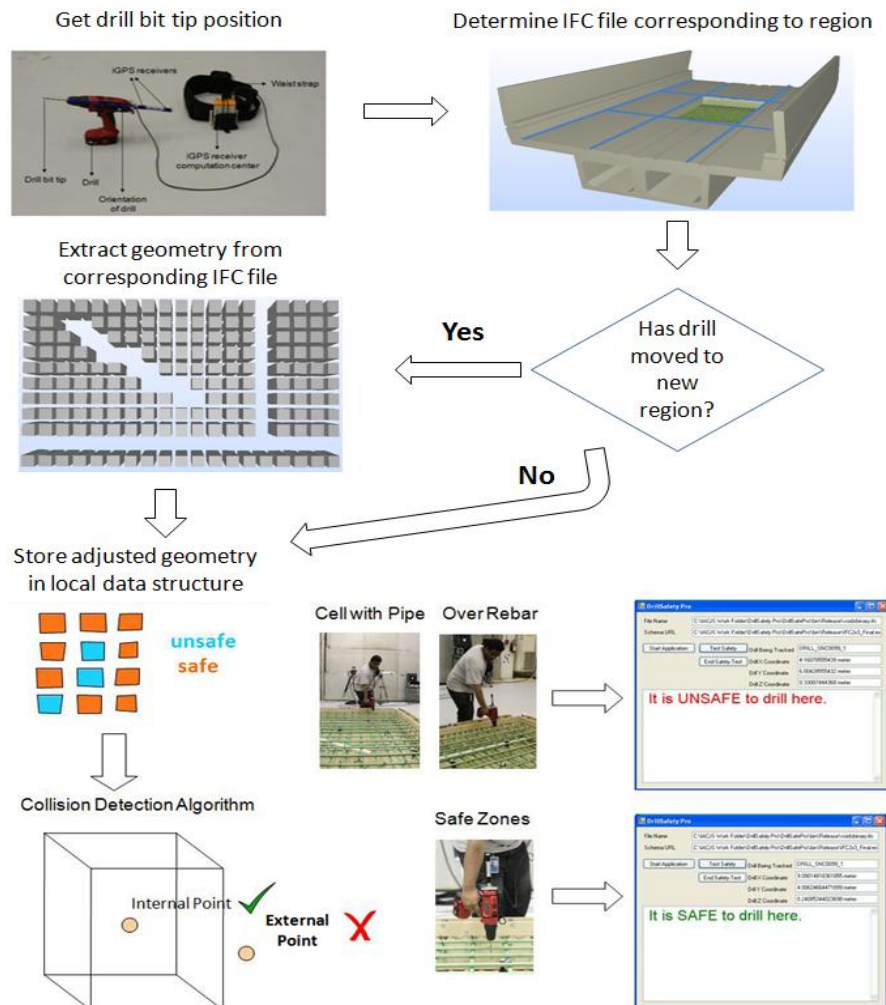

Figure 6: The overall schema of the real-time drilling feedback application that determines whether is it safe or unsafe to continue drilling at a location.

The application interprets the IFC data, extracts the geometry of the safe zones, and stores it in a local data structure. The application interprets each safe void zone as a quadrilateral prism with eight corner points. The application allows for the addition of safety tolerances to the safe zone void geometry which can be defined depending on how advance the drilling personnel desires to be warned. The application then performs containment testing between the monitored drill bit's tip and all the safe void zones to determine whether the drill bit's tip is within any of the safe void zones.

When the drill is in a safe position i.e., the position of the drill bit's tip is inside a safe void zone, the application displays a message that it is safe to drill in that location. However, when the drill bit's tip position is outside all safe void zones (for example when the drill bit's tip is over a rebar or in a zone with utility pipes), the application displays a message that it is unsafe to continue drilling in that location. The application can be embedded into the drill set up to warn the drilling personnel using an audio-visual alarm system.

3.2   Laser Projector based Guidance for Drilling

Laser projectors can be used to visualize the locations of the rebar underneath the concrete. The as-built IFC model of the rebar cage, registered with the iGPS coordinate system, is used to produce rebar patterns that help guide the drilling personnel. The position and orientation of the laser projector is tracked by the iGPS system and the projector can be moved and pointed at the desired locations to visualize the arrangement of the rebar underneath the concrete. The proposed technology was validated in the experimental testbed by projecting patterns onto the rebar itself or onto a piece of paper that is lying flat directly on the rebar cage as shown in Figure 7.
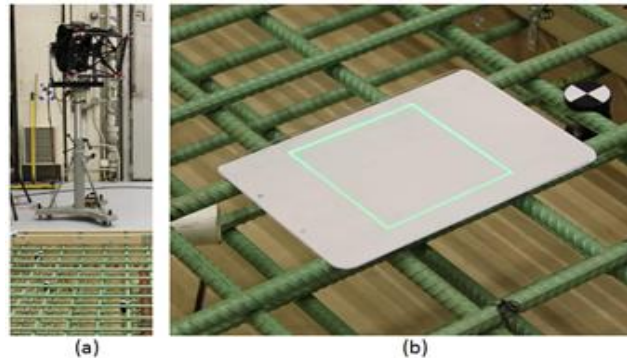

Figure 7: (a) The laser projector used to visualize results on the actual rebar and (b) a laser pattern projected onto a piece of paper.

The projected pattern in Figure 7 (b) is a square corresponding to the square formed by the centerlines of the four rebar lengths directly underneath. This technique can be used as an alternate and/or complimentary technology to help guide drilling into a reinforced concrete deck.

4. COMPARISON OF 3D IMAGING TECHNOLOGIES

4.1 Bridge Model

A BIM of a bridge was created to help visualize the rebar cage within the bridge structure. The bridge was modeled as an extrusion of its cross-section. The relevant bridge as-built drawings were imported into BIM software and the cross-section of the bridge was traced to form a closed polyline. This polyline was extended along a curve to form an extruded model of the bridge. A region of space equivalent to the usable volume of the reconfigurable rebar cage was then subtracted from the bridge deck to model an opening in the bridge with visible rebar. The bridge deck model and the rebar cage model were grouped together and registered to a common coordinate frame and were exported as an IFC file. The visualization of the IFC file of the embedded rebar cage model is shown in Figure 8.
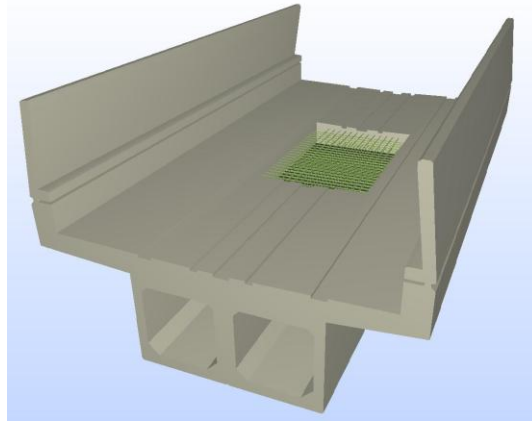

Figure 8: BIM model of the bridge deck with the embedded rebar cage (green) displayed in an IFC viewer.

Safe and unsafe drilling zones computed from the rebar intersection extraction algorithm can be visualized for the ground truth, laser scan, and image based 3D reconstruction data. The safe drilling zones are displayed along with the ideal as-designed rebar cage model. In general, the rebar cage appears between the safe drilling zones, however, due to variations of the rebar placement in the as-built rebar cage, sometimes there are clashes between certain safe drilling zones and the as-designed rebar cage. Figure 9 shows the safe drilling zones from the ground truth data. The safe drilling zones are shown as grey quadrilateral prisms between the rebar and account for the three conduits placed in the rebar cage to represent utility lines.
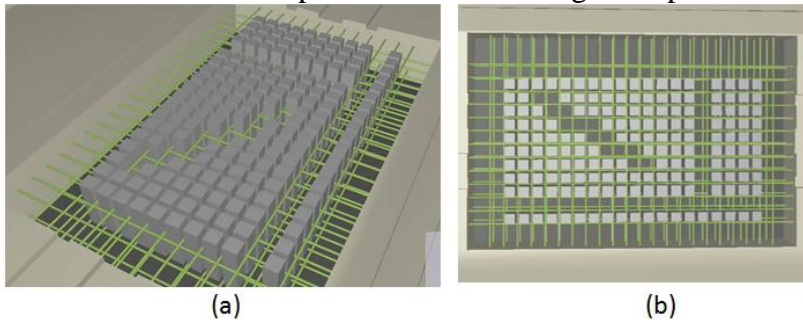

(a)   (b)

Figure 9: The (a) perspective and the (b) overhead view of safe drilling zones computed from ground truth data.

In the figures pertaining to this paper, in order to make visualization more intuitive, the volumes in the IFC files are only generated where it is permissible to drill through the entire depth of the rebar cage. Zones where it might be permissible to drill partially through the depth of the rebar cage are flagged as unsafe drilling zones and no volume is generated. Drilling zones are not computed along three sides of the rebar cage (left, right, and top sides in Figure 7 (b) due to limitations of the ground truth data).

Figure 10 (a) and 10 (b) shows the safe drilling zones computed from laser scanning and image based 3D reconstruction data respectively. Comparing the pattern of safe drilling zones from the laser scan data with the ground truth data shows some significant differences. There are differences in safe drilling zones around the position of the diagonal conduit. The other differences in the safe drilling zones are due to laser scanning targets placed in the physical rebar cage that produces unsafe drilling zones. Comparing the safe drilling zones as predicted by the image based 3D reconstruction data with the zones from laser scanning data reveals a significant variation in the pattern of safe drilling zones due to missing data in the image based 3D reconstruction point cloud data set.
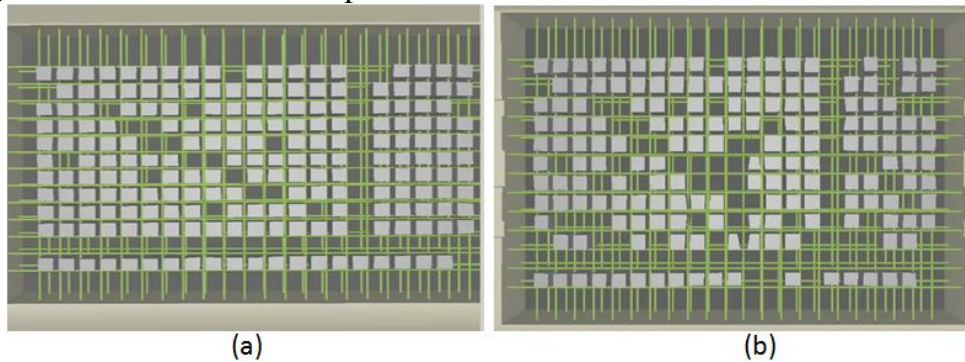

Figure 10: The overhead view of the safe zones from (a) laser scanning and (b) image based 3D reconstruction point clouds.

Figure 11(a) and (b) show the overhead view and the close up view of the safe zone volumes for both the laser scanning (yellow) and ground truth (red) data viewed together. Figure 11 (b) shows the slight difference in the safe drilling zone geometry computed from each dataset. The clashes between the green as-designed reinforcing bars with the safe drilling zones, shown in Figure 11 (c), shows the differences between the as-designed and as-built reinforcing bar alignment.
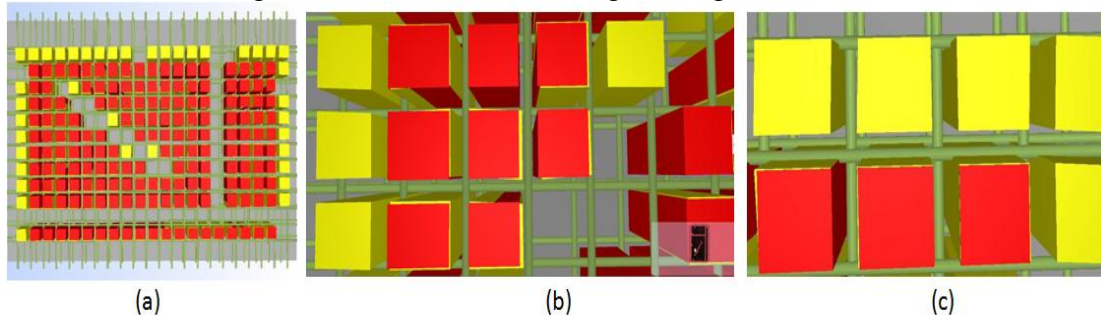

Figure 11: The (a) overhead and (b) close up view of safe zone volumes for data from laser scanning (red) and ground truth (yellow) and a (c) close up view showing overlap with as designed rebar.

Figures 10 and 11 show the visual comparison of the results of the rebar mapping algorithm for point clouds developed using laser scanning and image based 3D reconstruction techniques with the ground truth data. As with binary (safe/unsafe) classifier, the possible results of the safe/unsafe comparison between the two data sets are − correct, false positive (identified an unsafe cell as safe) and false negative (identified a safe cell as unsafe). The laser scanner data identified three false positive cells and one false negative cell compared to the ground truth data. However, the results of the rebar-mapping algorithm for the image based 3D reconstruction showed a significant discrepancy in the number of false negative cells identified by the algorithm.

SUMMARY AND CONCLUSIONS

Augmenting BIM with 3D imaging data for controlling drilling operations eliminates activities that are associated with wood block-outs in the original method. The added steps involve acquiring, processing and storing the relevant data. It would also improve access during concrete placement by eliminating obstacles to the flow of concrete. The alternative methodology [Saidi, K., et al, 2011] could significantly improve production for the concrete deck placement operation, avoiding the time and cost to place and remove dowels, and shorten the project duration. The visualization methodologies presented in this paper can be used to visualize, compare, and contrast the results of the rebar-mapping algorithm for point clouds from different technologies. The IFC files, produced from the results of the rebar intersection extraction algorithm, were used to display the safe and unsafe cells using the laser projector and were used for the drill feedback application. The accuracy of the IFC files is only as good as the results of the rebar-mapping algorithm. The details and accuracy of the rebar mapping algorithm have been documented by Saidi et al [Saidi, K., et al, 2011]. The authors are currently investigating how the proposed methodology compares to alternative methodologies, such as ground penetration radar and electro-magnetic methodologies, which identify the location, cover-depth and diameter of rebar.

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