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Real-time drill monitoring and control using building information models augmented with 3D imaging data

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ABSTRACT

The problem of placing embeds into existing reinforced concrete structures without damaging reinforcement bars is an industry-wide challenge for the construction industry. This paper presents research that investigated real-time monitoring approaches for hazardous engineering processes. A conceptual solution for processing and incorporating point cloud data obtained from 3D imaging technologies[1] into the drilling process in was developed. The 3D imaging technologies were used to map the locations of rebar within a section of a railway bridge deck. Once the point clouds were processed, zones which are safe for drilling were automatically detected and saved as a Building Information Model (BIM). The BIM was 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. The results showed the feasibility of real-time feedback for improving the safety, productivity, and quality of engineering processes by helping avoid the time and cost of rework.

1. Introduction

The ability to perceive, comprehend, and analyze the spatial context of their work environment is imperative for construction workers, civil engineering personnel, and industrial workers to complete their tasks competently, efficiently, and safely. Construction worksites are dynamic, unstructured, and continuously evolving workspaces that result in unique characteristics compared to semi-structured workspaces such as industrial, manufacturing, and assembly line worksites [19]. Civil engineering projects, especially in urban areas, are characterized by narrow, constrained workspaces leading to limited visibility of resources resulting in an increase in the probability of collisions between equipment, workers, materials, and infrastructure [7,21].

Projects involving excavation and drilling increase the risk of collisions among equipment and worksite resources due to the occluded vision of operating personnel [16]. Moreover, large equipment operators are faced with the additional challenge of overcoming blind spots on equipment and haul roads [20]. Additionally, certain projects, such as two cranes working in tandem to lift heavy objects, inherently pose constraints on the operators' ability to comprehend their spatial context and challenge their ability to analyze their work environment in order to achieve their objectives [23].

Workers, performing drilling operations to place embeds into reinforced concrete decks, are faced with the risk of striking rebar and buried utility lines. As mentioned above, another example of occlusion hampering operator visibility, and therefore operation efficiency, is the case of excavation. Excavation operations in the presence of underground utility lines are faced with the constant risk of striking buried utilities resulting in significant damage to property, injuries, and fatalities. In the absence of equipment and infrastructure tracking, operators must rely on planning, judgment, and experience to estimate the areas safe for drilling and excavation. Therefore, applications that provide the operators with information regarding their spatial context would enhance their decision making accuracy and can help perform the operations safely with increased levels of efficiency.

Such context-aware computing applications periodically examine and react to changing context. Environmental variables that are typically used to communicate contextual information typically include, but are not limited to, location (where), identity (who), time (when), and activity (what) [5]. Context-aware computing applications are implemented using a mobile, distributed computing system — a collection of mobile

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and stationary sensing and computing devices that cooperate and communicate on the targeted user's behalf [17].

In this paper, the authors present a framework to develop real-time monitoring systems for civil engineering applications. The authors then present a motivating scenario and the technical approach, based on the developed framework, towards solving the scenario specific problems. The authors then present methodologies used to develop context-aware applications that address the scenario. The research that investigated and evaluated the performance of the developed methodologies in comparison with ground truth is also presented.

2. Importance of the research

The construction industry continues to have a high number of accidents and a poor record of safety compared to other industries, despite significant recent efforts to improve safety. The U.S. Bureau of Labor Statistics estimated that the construction industry historically has had the highest total number of fatalities in all industries as shown in Table 1 [4].

Furthermore, the rate of fatality in the construction industry is also relatively high. In 2010, the fatality rate for the construction industry was 9.8 per 100,000 employees — the fourth highest across all industry sectors as shown in Fig. 1 [4].

These fatalities have been ascribed to several contributing factors in order to better understand the factors contributing to these fatalities and to effectively implement safety management practices. The National Institute for Occupational Safety and Health (NIOSH) classifies the contributing factors into the following categories: lack of hazard recognition, lack of coordination of work tasks, worker inexperience, deviation from standard operating procedure, fast-track scheduling, and employers' lack of written task-specific work procedures [14]. Real-time monitoring systems usually address mistakes caused due to a lack of hazard recognition by using context-aware computing techniques.

Lack of hazard recognition occurs either due to the failure to perceive a potential hazardous scenario or due to the failure in interpreting the perceived scenario as hazardous. As mentioned previously, urban construction projects are characterized by narrow, constrained workspaces leading to limited visibility of resources [7,21] resulting in an increase in the probability of failing to perceive and identify hazardous scenarios as such.

A significant percentage of highway construction takes place during night time when the traffic flow is minimal [2,11]. In such projects, the lack of visibility becomes a major contributing factor for workplace accidents. Poor visibility and lack of lighting were found to be a leading cause for accidents involving workers colliding with traffic and construction equipment [2]. Blind spots and obstructions were found to account for nearly 75% of visibility related fatalities in construction [11].

Certain projects, that involve concealed or buried infrastructure, are inherently fraught with problems concerning limited visibility and occlusion. Drilling, excavation, and trenching operations result in frequent accidents when equipment strikes the concealed infrastructure and account for a significant amount of contingency cost, to compensate injured personnel and damaged property, on such projects. Context-sensing technology and/or computer vision techniques are employed

Table 1
Historic chart for number of fatalities per occupation.

	Construction	Protective services	Farming, fishing and forestry	Manufacturing
2010	780	261	276	363
2009	838	244	239	326
2008	977	306	286	354
2007	1172	346	258	380
2006	1273	284	297	423

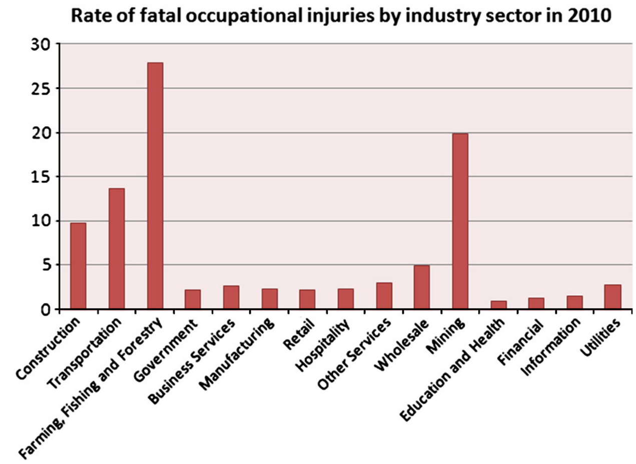

Fig. 1. Fatality rates by occupation in the year 2010 per 100,000 employees.

to obtain environmental variables that complement and enhance personnel perception in order to identify hazards.

Localization and tracking technologies have been used to capture changing worksite information to develop real-time monitoring systems to warn workers of danger [1,6,8,15,20–22]. Real-time monitoring systems track the resource's (worker, equipment, objects) spatial-context variables, such as location and orientation, in real-time using localization and tracking technologies and automatically compare the identified spatial-context with predefined scenarios identified as being dangerous. Such monitoring systems help prevent accidents by alerting personnel to potential dangers.

3. Real-time monitoring

By their nature, projects in the civil infrastructure domain consist of mission critical tasks whose failure will result in the failure of operations. In order to avoid operational failure, it is highly desirable to have decision-making support in real-time or near real-time. Real-time systems are defined as systems whose operational effectiveness depends on both the logical correctness and the performance time. Real-time systems and their performance time deadlines are classified based on the consequences of failing to meet their deadlines, as shown below [12].

1) Hard real-time: Systems where missing a deadline leads to a total system failure.
2) Firm real-time: Systems where missing occasional deadlines is tolerable but where the usefulness of a result is zero after its deadline.
3) Soft real-time: Systems where the usefulness of a result degrades after its deadline thus degrading the quality of service.

A system is required to adhere to hard real-time standards if the operation it supports requires events to occur within strict deadlines. Such strong standards are usually required of systems for which not reacting within a certain deadline would result in a great loss to life or property. For example, consider a drill control system used to warn drill operators when they are about to strike rebar or utility lines while drilling for embeds into reinforced concrete decks. Striking rebar might lead to a loss of structural integrity, and striking utility lines might result in injuries, casualties, disruption in service, and loss of property. The drill control must be designed such that the time required for the operator to react to the warning (or for the drill to shut down) is less than the time period after which the drill is expected to strike rebar or utility lines. It is integral that the drill control system is designed with adherence to hard real-time standards, as failure to meet deadlines would result in a total system failure.

The implementation of real-time monitoring systems based on context-aware computing [5,17] transcends the reality–virtuality continuum as shown in Fig. 2. Immutable environment variables, such as fixed infrastructure, and constraints, such as hazard scenarios, are captured and stored as pre-processed data. Dynamic environmental variables and characteristics are continuously captured in real-time through appropriate sensing technologies and are processed and interpreted in the virtual environment. The relevant pre-processed and real-time data are then passed onto the hazard detection algorithm which determines whether the captured scenario is hazardous or not. The results, including any potential warnings, are communicated to the appropriate personnel through audio-visual methodologies that can fall anywhere on the reality–virtuality continuum. Based on any potential warnings communicated, the operator makes the decision whether to continue with the scenario or seek an alternative.

The monitoring system must be designed such that the appropriate data are captured, processed, analyzed, and warnings are issued to the personnel, if necessary, within the duration in which the current scenario could transform into the potentially hazardous scenario that has been identified. The monitoring system is designed to be "real-time" by ensuring that the context-aware computing algorithms allow for appropriate safety factors and tolerance variables. The remainder of this paper explains how the developed framework can be utilized to design and implement real-time warning systems based on context-aware computing for a particular motivating scenario which is described in the following section.

4. Motivating scenario

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 avoids contacting the rebar and the utility lines in order to mitigate potential damage to workers and property. Uncertain knowledge of the locations of rebar and utility lines makes drilling into reinforced concrete decks risky for worker safety and compromises the structural integrity of the deck.

4.1. Currently employed methods

One of the current methods 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 rebar chairs attached to the top layer of rebar as shown in Fig. 3 [16].

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 as shown in Fig. 4 [16].

4.2. Shortcomings of currently employed methods

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 [16].

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. These shortcomings can be addressed by developing context-aware real-time monitoring systems that guide

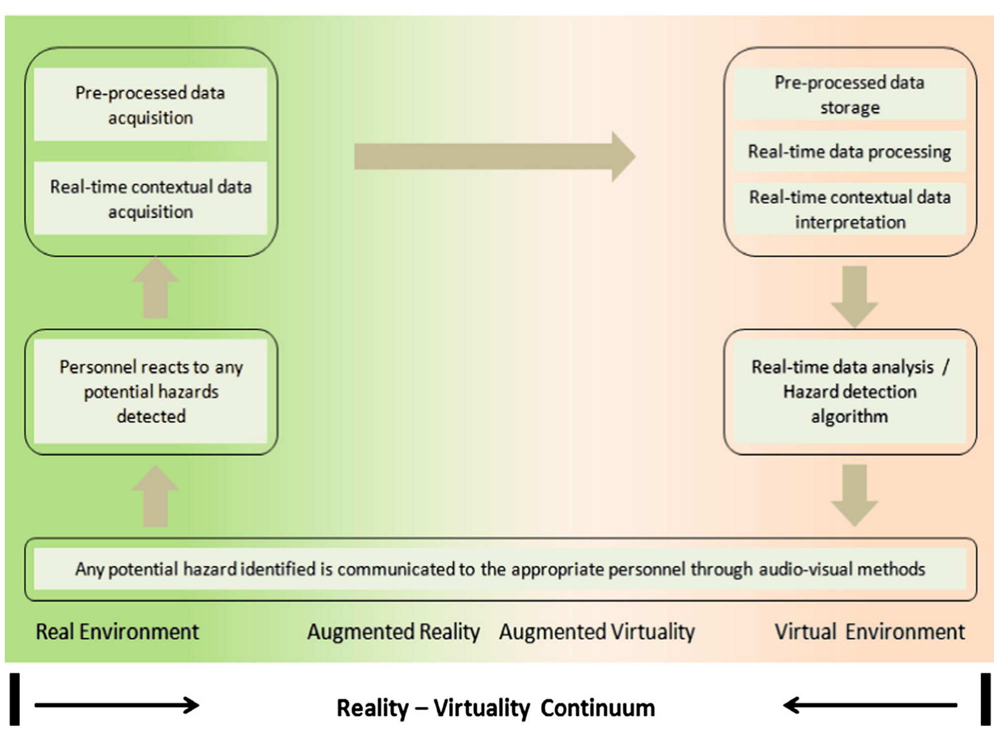

Fig. 2. Real-time monitoring systems within the reality–virtuality continuum.

Fig. 3. A railway bridge deck with dowels and wooden planks installed.

drilling personnel while drilling for embeds into reinforced concrete decks. The remainder of this paper deals chiefly with the design and implementation of two such real-time context-aware systems.

5. Technical approach

5.1. Proposed methodology

Based on the aforementioned framework, the authors present two potential approaches to control drilling for embeds into a reinforced concrete deck in order to prevent the drill from striking any rebar or utility lines and in order to preserve the structural integrity and utility services, respectively. The first approach is based on developing a feedback algorithm that warns the drilling personnel when a rebar or a utility line is about to be struck as shown in Fig. 5.

3D imaging data are captured as a point cloud, before the concrete is poured, and is pre-processed to map the locations of the rebar and the zones safe for drilling. The position and orientation of the drill bit tip are monitored continuously in real-time and the context-aware monitoring system determines whether the drill bit tip is about to strike the rebar or utility lines by using collision detection algorithms. If the collision detection algorithm determines that the captured information could lead to the drilling personnel striking concealed infrastructure, a warning is issued.

The second approach is based on providing the drilling personnel with a visual representation of the locations of the rebar and the utility lines as shown in Fig. 6. The locations of the rebar and utility pipes are captured by 3D imaging technologies similar to the first approach. The position and orientation of a movable laser projector are determined in real-time and the appropriate region of interest is determined. The locations of the rebar and utility lines within the region of interest are retrieved and projected onto the concrete surface to provide the drilling personnel with visual guidelines regarding the locations of the same.

Fig. 4. Embedment holes with block-outs removed and foam plugs inserted.

Based on these visual guidelines, the drilling personnel complete the objectives in the region of interest and adjust the laser projector so that it points to the next region of interest. The approaches described above were implemented and evaluated using the Intelligent and Automated Construction Job Site (IACJS) test bed at the National Institute of Standards and Technology (NIST) using the setup described below.

5.2. Experimental setup

The experimental setup for the research presented in this paper consisted of a reconfigurable rebar cage which is a mockup of the types of rebar cages found in a railway bridge deck and is shown in Fig. 7 along with its conceptual model and pictures of similar rebar cages from an actual construction site. The reinforcement rebar cage is designed and fabricated to enable various rebar configurations. The rebar is held rigidly within the cage using clamps in order to establish a reliable ground truth. The intent of the experiment was to determine the feasibility of the concept. Therefore, the rebar cages were "clean," i.e., without any rebar ties and other items that are typical of rebar cages in actual construction.

The as-built configuration of the rebar cage uses #6 epoxy-coated rebar (i.e., 1.9 cm diameter). Two layers of rebar are separated by approximately 30.5 cm (12 in.) with each layer consisting of thirteen 3.66 m (12 ft) long rebar laid on top of twenty-two 2.44 m (8 ft) long rebar. The rebars are spaced at 15.2 cm (6 in.) apart within each layer and the bottom layer of rebar is also separated from the rebar cage's floor (the plywood) by 15.2 cm (6 in.). The first step towards implementing and evaluating the real-time monitoring systems, proposed in the previous sections, is to acquire the digital data as point clouds. The following section describes the methods implemented to acquire the required data.

5.3. Acquiring digital data as point clouds

As mentioned previously, a 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 [16]. A 3D imaging system, with a manufacturer-specified measurement accuracy of $\pm$ 5 mm, was used to obtain the point cloud of the rebar cage configuration, shown in Fig. 8(a). The point cloud was then registered to a common coordinate frame and was segmented as shown in Fig. 8(b).

A second point cloud dataset was produced by using D4AR image-based 3D reconstruction [9,10]. The point cloud was developed using 380 images of the rebar cage in which the subjects were mainly the reinforcement bars and their configurations. The spatial resolution of these images was synthetically reduced to two megapixels to test the robustness of the proposed method to low-resolution images and to minimize the computational time. The outcome of the image-based 3D reconstruction algorithm is shown in Fig. 9 [16].

The point cloud data to establish a ground truth was obtained using a Coherent Laser Radar (CLR) scanner instrument with a manufacturer stated uncertainty of $\pm$100 μm and a point spacing of 3 mm [16]. The point clouds were registered to a common coordinate frame. All of the point clouds were then processed through the same custom developed rebar mapping algorithm, discussed in the following section, in order to detect the spaces between the rebar where it is safe to drill after the concrete is poured.

5.4. Mapping point cloud data to rebar cage cells

The rebar mapping algorithm involves fitting cylinders, of unfixed radii, in order to determine the intersection points of the rebar. Rebar frequently bends and deflects under its own weight and other loads.

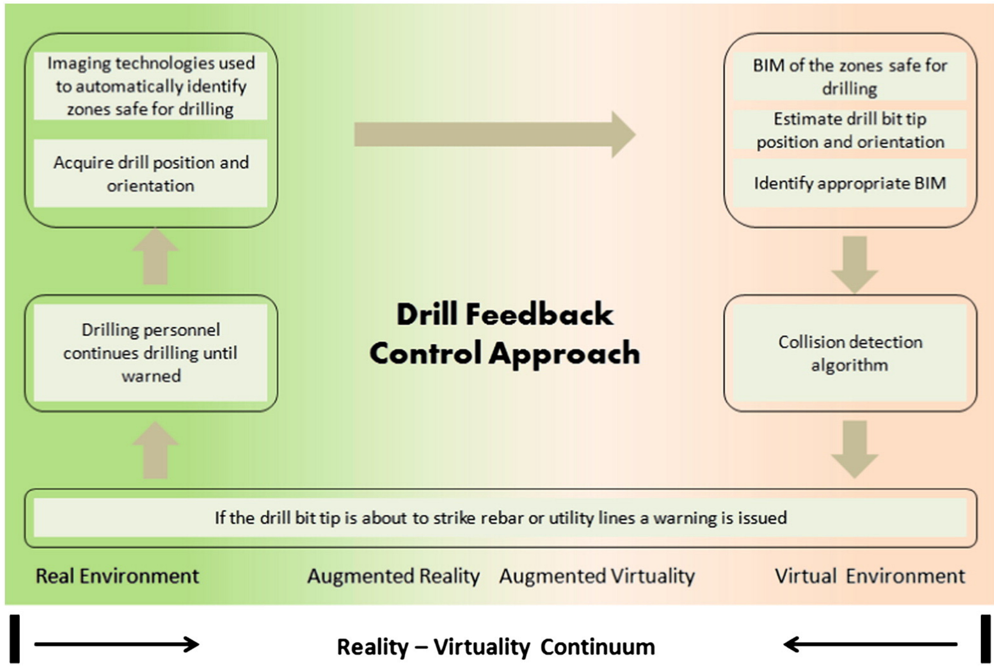

Fig. 5. Overview of the drill feedback control approach.

In order to account for this curvature, the rebar points are divided into shorter lengths, as highlighted in Fig. 10, so that they can be accurately modeled as straight cylinders.

The intersections of these cylinders are determined and then 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 fit the corresponding rebar as shown in Fig. 11.

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 rebar or utility lines. The algorithm breaks the space corresponding to each rebar cell into bins and determines the number of data points in each bin. In an idealized world without noise, an experimentally acquired 3D point cloud should contain only points which are located on a surface of real, physical objects (e.g., rebar cage or bottom surface of a slab). The presence of a single data point, for which a 2D projection falls inside the quadrilateral cell and

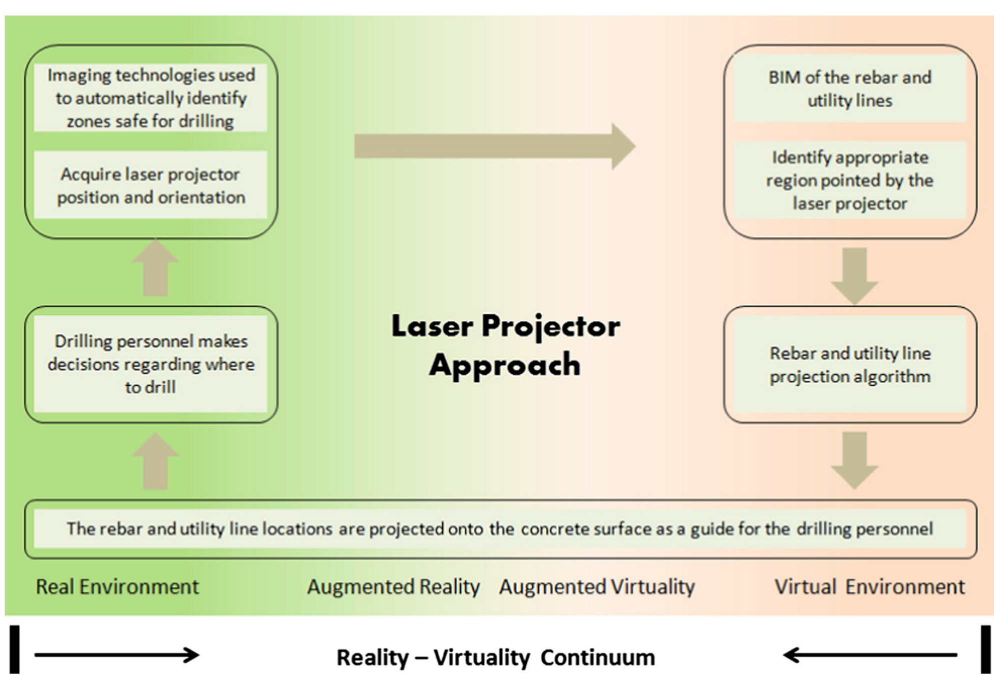

Fig. 6. Overview of the laser projector approach.

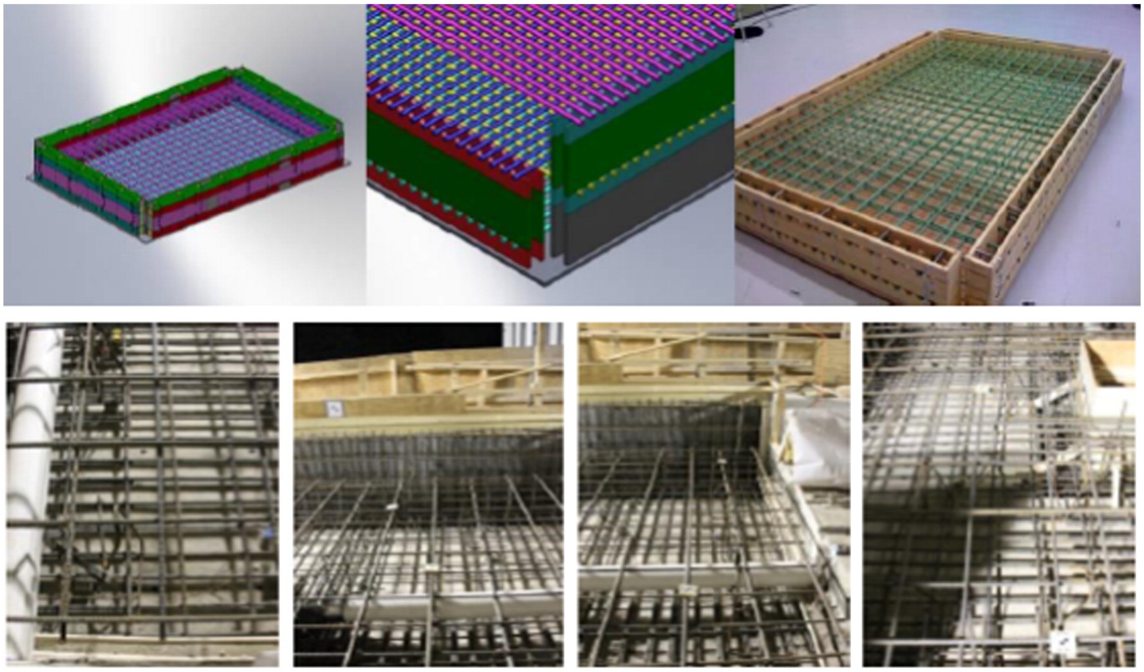

Fig. 7. The reinforcement rebar cage 3D CAD model, as-built product, and unordered pictures of a railway deck rebar cages it represents.

for which height is in one of the depth bins, would signal a presence of an obstacle. In reality, data also contain 'phantom' noisy points which are not located on the surface of a physical object and the algorithm has to filter out such points. We use a reasonable assumption that noisy points are scattered in space (more sparsely filling the depth bins along drilling direction) while real data points cluster in one or two bins corresponding to the depth at which a real obstacle is located. A linear classifier (safe/unsafe) is used with the threshold set to the average number of points in the depth bin. A bin is declared safe if a number of points in that bin is smaller than the threshold—otherwise, the bin is marked as unsafe. Fig. 12 shows the results of the rebar mapping and cell status prediction algorithms for a particular bin level. 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.

Establishing the ground truth data was a manual process and was 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 cells were then classified as either safe or unsafe for drilling by visually identifying cells in which it was safe to drill vs. cells in which it was not.

The results of the rebar mapping algorithm are exported as Industry Foundation Classes (IFC) files and are visualized as a BIM. IFC is an open specification object-based file format with a data model developed by buildingSMART to facilitate data exchange in the architecture, engineering, and construction industry and is a commonly used format for BIM [3]. The IFC files act as a proxy for BIM and could be imported into BIM software if desired. The IFC files of the safe/unsafe cells were generated by in-house software that read the output of the rebar mapping algorithm and the predicted cell status. The cells were represented by IfcBuildingElementProxy entities with the geometry derived from the aforementioned source. These IFC files are used as pre-processed BIM input files for the feedback and the projection algorithms used for the controlled drilling and

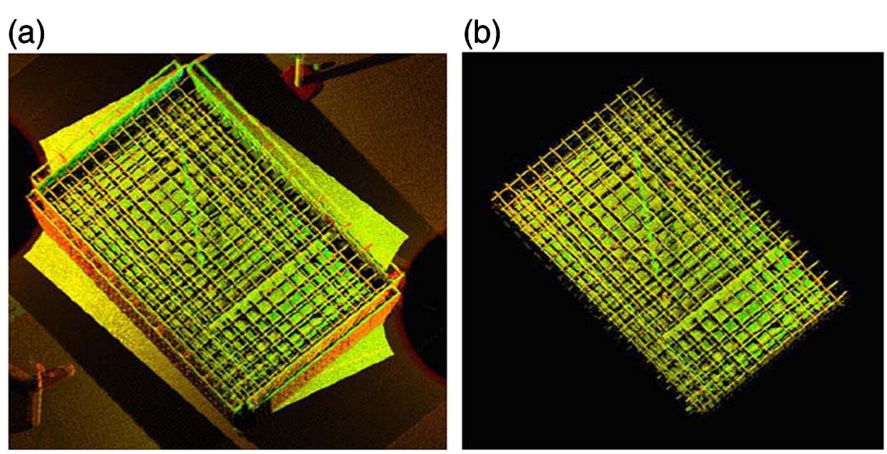

Fig. 8. (a) The points captured by the 3D imaging scanner and (b) the segmented point cloud of the rebar cage.

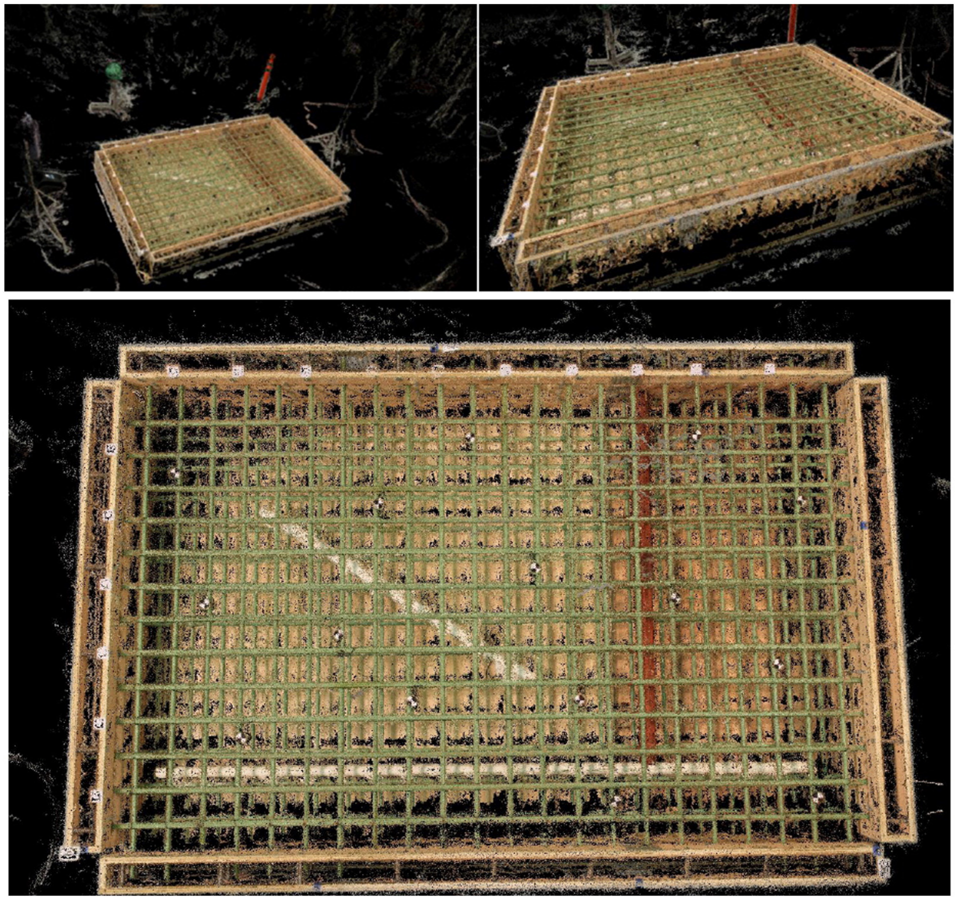

Fig. 9. The point cloud developed using D4AR image based 3D reconstruction.

laser projector based approaches. The drill feedback and the laser projection algorithms use the IFC File Analyzer toolkit to read the data encoded in the IFC files [13]. The IFC representation of the rebar and bridge models is also used, rather than commercial BIM software, to simplify the visualization of the models and associated safe drilling zones. The visualization presented in this paper was performed using the Solibri Model Checker software [18].

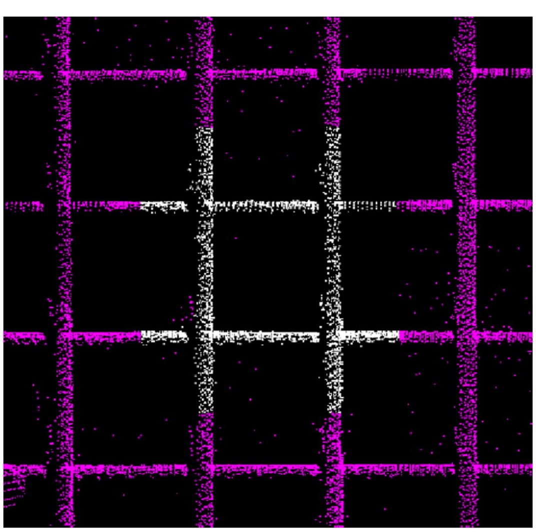

Fig. 10. The points in white are used to fit cylinders to determine the coordinates of the rebar intersections.

5.5. Indoor global positioning system

The drilling feedback control and the laser projection methods, as demonstrated in the test bed, determine, in real time, whether it is safe or unsafe for a drill to continue drilling at a particular location in the concrete deck using an Indoor (or Infrared) Global Positioning System (iGPS) to track the position and orientation of the drill bit tip and the laser projector, respectively. The iGPS, shown in Fig. 13, consists of

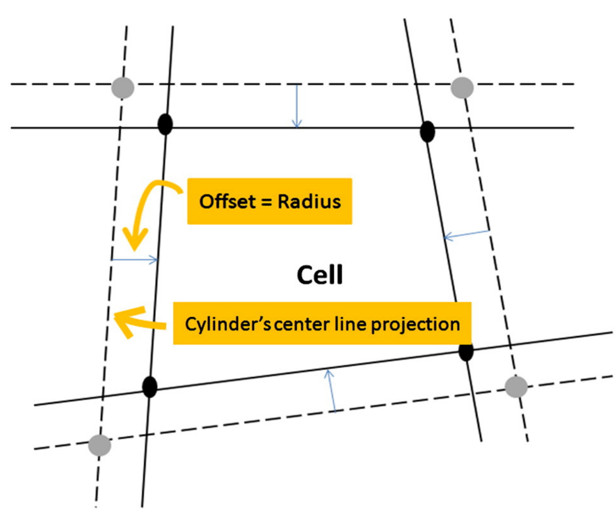

Fig. 11. Extracting the quadrilateral cells in the rebar mapping algorithm.

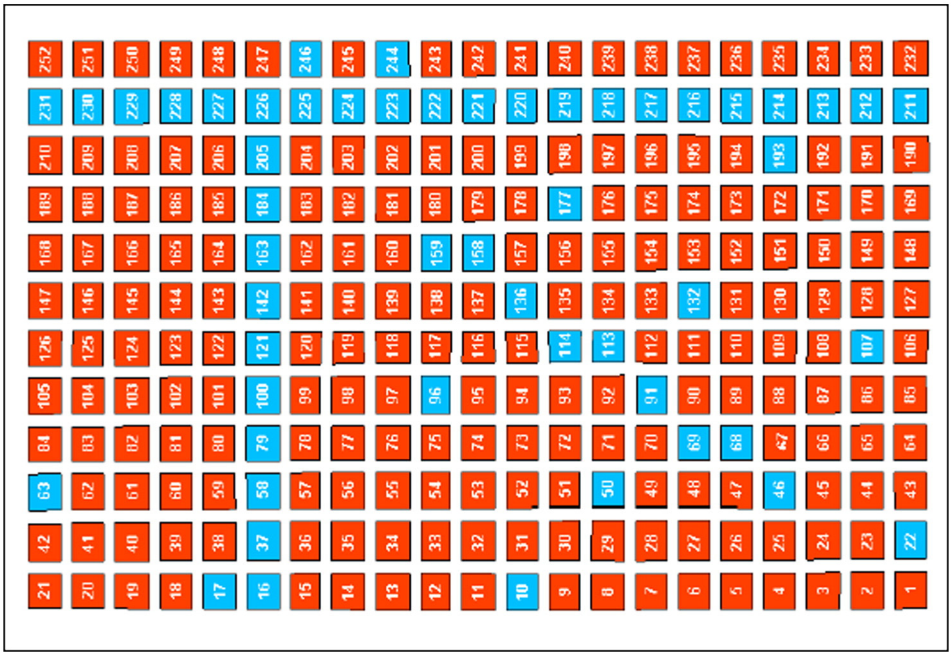

Fig. 12. Predicted cell status for a particular bin level (red = safe and blue = unsafe). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a series of tripod-mounted transmitters that emit laser signals which are picked up by the photodiodes inside the receiver module.

Using signals from multiple transmitters, the receiver can calculate its position relative to the base coordinate system defined by the transmitters. The receiver positions can be estimated as long as they have line-of-sight to two or more transmitters; however its accuracy is improved when more than two transmitters are used for the calculation. The base coordinate system of the iGPS is registered to the common coordinate system to which the point cloud data sets were previously registered. Using an iGPS vector bar (a pair of iGPS receivers fixed relative to each other by a calibrated distance), the orientation of the vector from one receiver to the other and the 3D coordinates of any point along the vector can be computed. The frequency of updates of the iGPS measurements is 40 Hz, the uncertainty of position of each iGPS receiver is ±0.250 mm, and the maximum allowable range between a receiver/transmitter pair is 40 m.

5.6. Drill feedback control approach

The drill was fitted with an iGPS vector, as shown in Fig. 14, mounted such that it was oriented along the longitudinal axis of the drill bit and was connected to a shoulder/waist strap, which holds the computer that performs the position calculations and communicates wirelessly with a central server.

The iGPS vector bar's position relative to the drill bit's tip is calibrated and preprogrammed into the iGPS server, which calculates the orientation of the drill bit and the position of its tip. The iGPS server has the ability to handle scenarios with multiple drills in order to simulate a

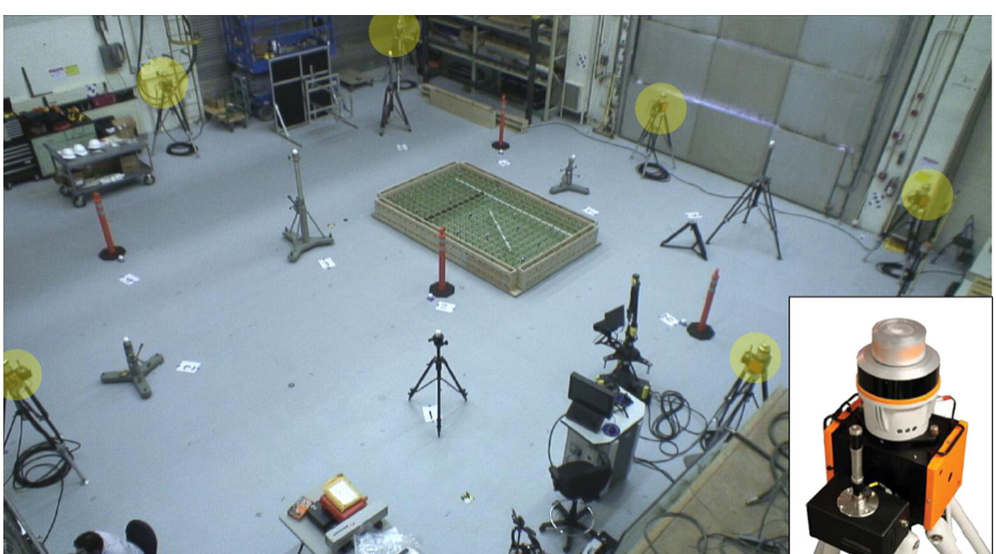

Fig. 13. Indoor GPS with transmitters, shown in the inset image, highlighted with yellow inside the IACJS test bed at NIST. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

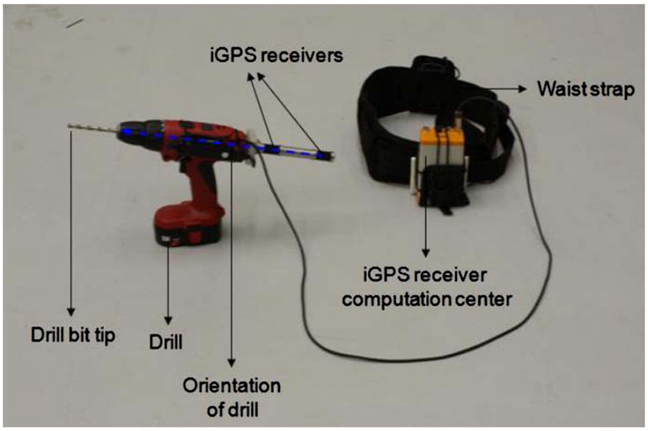

Fig. 14. Modified drill setup with the iGPS receivers attached to the drill.

drilling crew working simultaneously on the bridge deck. The context-aware computing application uses information regarding the position and orientation of the drill bit 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 as determined by the aforementioned rebar mapping algorithm.

The overall schema of the feedback application is shown in Fig. 15. 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 appropriate IFC file. If the drill bit moves into a new region, corresponding to a different IFC file, the IFC file geometry is extracted and cell data is stored in a local data structure. These data are used by the application until the drill bit tip moves into a new region.

The application interprets the IFC file data and extracts the geometry of the safe zones and stores it in a local data structure. The application interprets each safe zone as a quadrilateral prism with eight corner

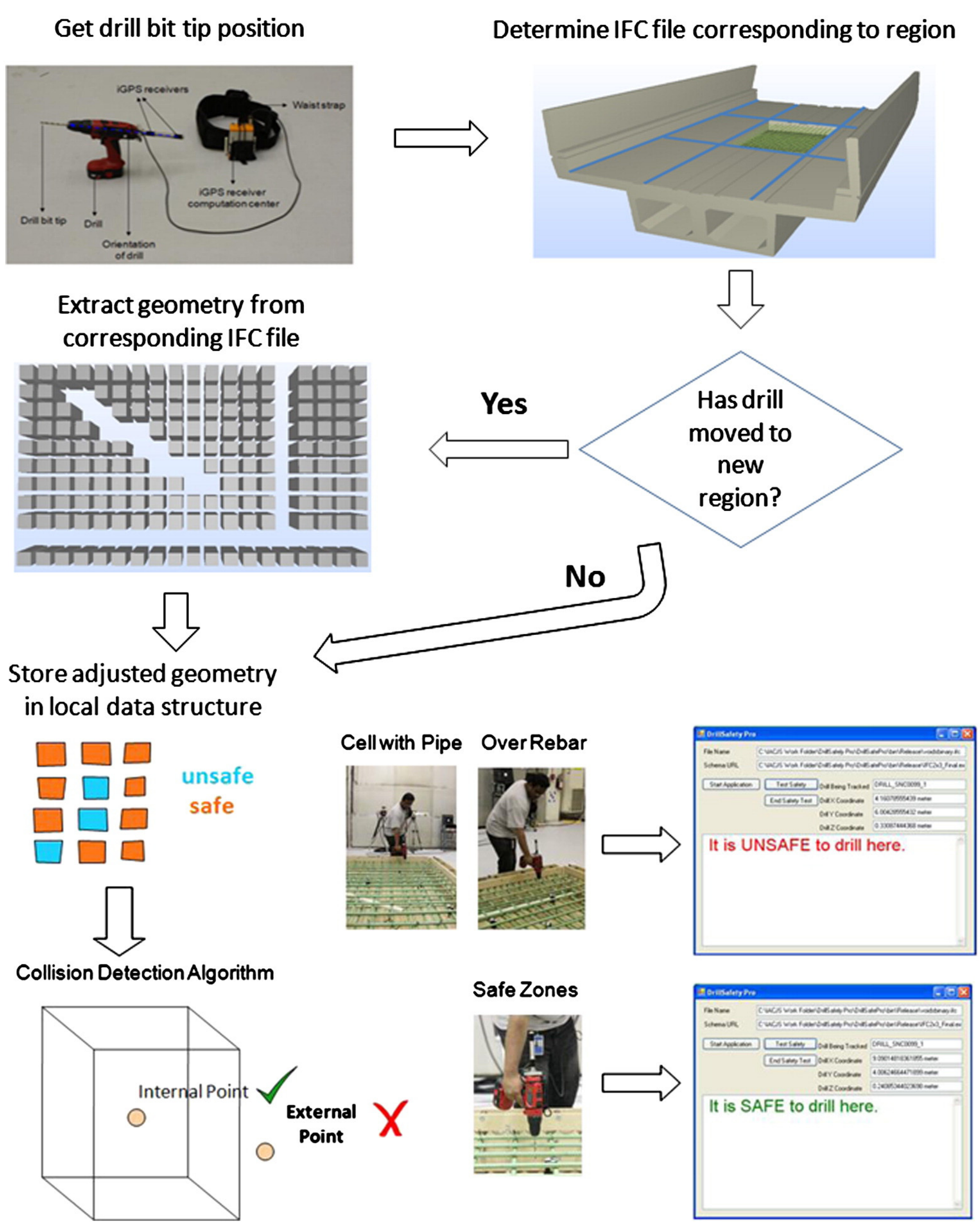

Fig. 15. The overall schema of the real-time drilling feedback application that determines whether is it safe or unsafe to continue drilling at a location.

points. The application allows for the addition of safety tolerances to the safe zone geometry which can be defined depending on how much in advance the drilling personnel wants to be warned. The application then performs containment testing between the monitored drill bit's tip and all the safe zones to determine whether the drill bit's tip is within any of the safe void zones. This is done by first geometrically defining the perpendiculars to each face of the quadrilateral prism that face towards the inside of the cell as positive. The containment is checked for by testing whether the drill bit tip position is to the same side of all six planes of the quadrilateral prism or not.

When the drill is in a safe position i.e., the position of the drill bit's tip is inside a safe 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 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 could be embedded into the drill setup to warn the drilling personnel using an audio-visual alarm. The collision detection algorithm that checks whether the drill bit tip position is in any of the safe zones within the zones (defined as such by the BIM) was found to have an update rate of over 100 Hz, making the algorithm real-time as its frequency was found to be greater than that of the input iGPS measurements.

5.7. Laser projector guidance approach

Laser projectors can be used to visualize the locations of the rebar underneath the concrete. The as-built BIM of the rebar cage, registered with the iGPS coordinate system, was used to produce rebar patterns which help guide the drilling personnel. The position and orientation of the laser projector, shown in Fig. 16(a) [16], were 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 implemented and validated in the IACJS test bed 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 Fig. 16(b). The projected pattern in Fig. 16(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.

6. Validation of the methodology

The results of the rebar mapping algorithm and the cell safety depth prediction algorithm were evaluated by the authors and are presented in this section. The goal of the validation is to qualify and/or quantify the performance of rebar mapping and cell safety depth prediction algorithms for input imaging data acquired using laser scanning, image reconstruction, and CLR methods. The rebar mapping algorithm is validated by visually comparing the BIM developed using ground truth data from CLR with the BIM developed using 3D imaging data from laser scanning and photo reconstruction. The visual comparison of the rebar mapping algorithm's performance is presented in Section 6.2 but a detailed numerical analysis is beyond the scope of this paper. The results of the cell safety depth prediction algorithm are presented in Section 6.3.

The visual comparison of the rebar mapping algorithm's performance corresponding to the ground truth, laser scanning, and photo reconstruction data was done by placing the resultant BIM inside the CAD model of the rebar cage as part of a railway bridge deck. The first step towards achieving the visualization for comparison is the development of a bridge model and its registration to the common coordinate frame.

6.1. Bridge model

A CAD model of a bridge was created to help visualize the rebar cage within the bridge structure. The cross-section of the bridge is shown in Fig. 17 [16]. The relevant bridge as-built drawings were imported into a CAD modeling software and the cross-section of the bridge was traced to form a closed poly-line. This poly-line was extended along a curve in order 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 in order 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 which was used to visualize the embedded rebar cage model as shown in Fig. 18.

6.2. Evaluation of the rebar mapping algorithm

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 point cloud data. The safe drilling

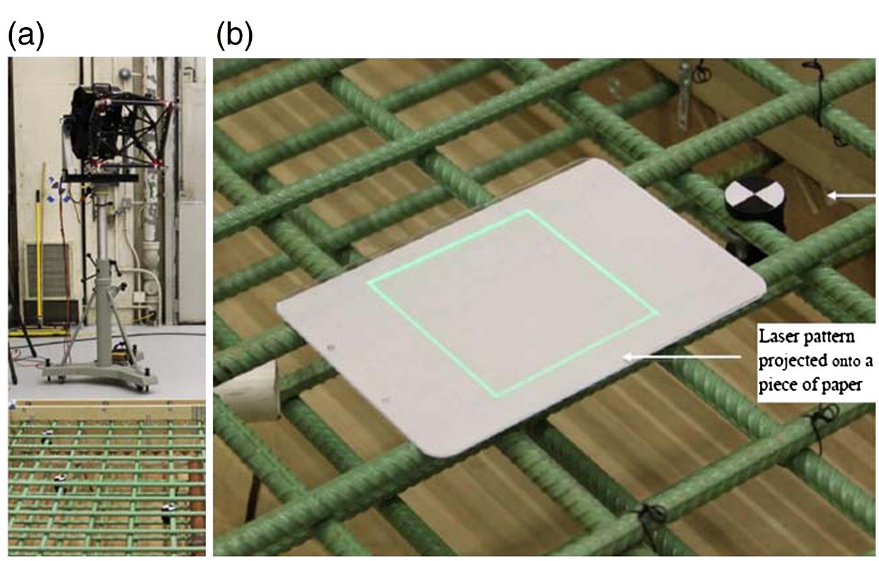

Fig. 16. (a) The laser projector used to visualize results on the actual rebar and (b) a laser pattern projected onto a piece of paper lying on top of the rebar.

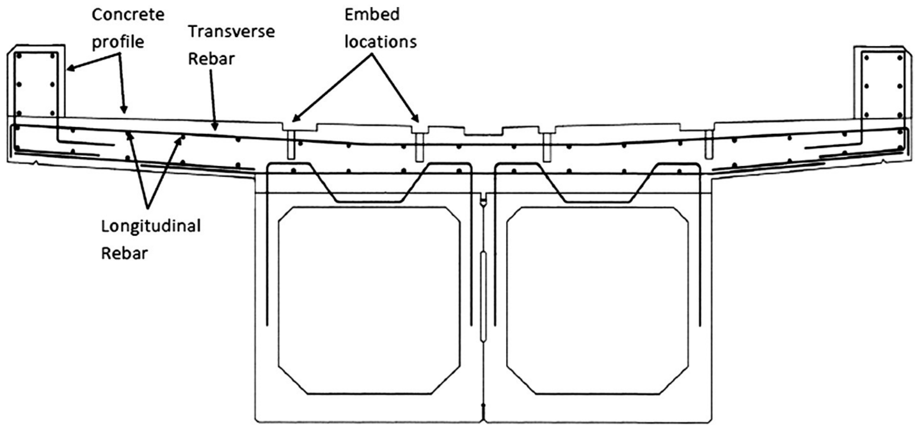

Fig. 17. A cross section of the railway bridge deck.

zones are displayed along with the ideal as-designed rebar cage model. Fig. 19 shows the perspective and overhead views of the safe drilling zones from the ground truth point cloud data.

In the figures pertaining to this paper, in order to make visualization more intuitive, the volumes in the BIM 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 Fig. 19(b) due to incompleteness of the ground truth data.

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-built rebar cage. Fig. 20 shows the close-up view of the safe drilling zones obtained from ground truth data.

Fig. 21(a) and (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 rebar targets placed in the physical rebar cage which in some cases produce unsafe drilling zones. Comparing the safe drilling zones as predicted by the image based 3D reconstruction data with the zones from the 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.

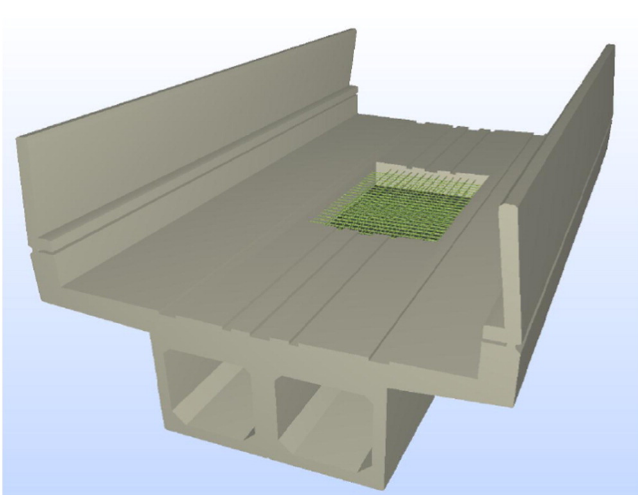

Fig. 18. The BIM of the bridge deck with the embedded rebar cage within IFC viewer.

Fig. 22 shows the safe drilling zones computed from the ground truth data as voids in the bridge deck model, i.e., the reverse of showing the safe drilling zones as volumes in the previous figures [16]. The unsafe drilling zones are shown in blue. The portions of the reinforcement bars that are visible in the top row of as-built safe drilling zones, indicates the differences between the ideal as-designed rebar cage and the position and orientation of the reinforcing bars in the as-built physical model of the rebar cage. The BIM visualized in Fig. 22 can potentially be used as an alternative input file for the laser projection approach.

Fig. 23(a) and (b) shows 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. Fig. 23(b) shows the slight difference in the safe drilling zone geometry computed from each dataset. The clashes between the green reinforcing bars with the safe drilling zones, as shown in Fig. 23(c), shows the differences between the as-designed and as-built reinforcing bar alignment.

The visualization techniques presented above can be used to compare and evaluate the results of the rebar mapping algorithm for point clouds obtained from different technologies. The authors observe that the differences in the results of the rebar mapping algorithm for the laser scanning data and the ground truth data are negligible, especially when these differences are compared to the tolerances that will be applied a priori to warn the drilling personnel.

6.3. Results of the cell safe drilling depth prediction

As mentioned previously, each cell is divided into bins of a fixed height and the cell's safe drilling depth is estimated based on the algorithm that predicts whether a particular bin is considered safe or unsafe based on the number of points that fall within the particular bin. If every bin in a cell is predicted to be safe, the cell is considered safe for drilling. Otherwise, the cell is considered to be unsafe for drilling. As with any binary (i.e., true/false) classifier, the possible results of the cell's safe/unsafe classifier algorithm are:

- Correct — A safe cell is identified as safe and an unsafe cell is identified as unsafe.
- False positive — An unsafe cell is identified as safe.
- False negative — A safe cell is identified as unsafe.

The results of the classifier algorithm implemented in this research for laser scanning and 3D image reconstruction data sets are summarized in Table 2 [16].

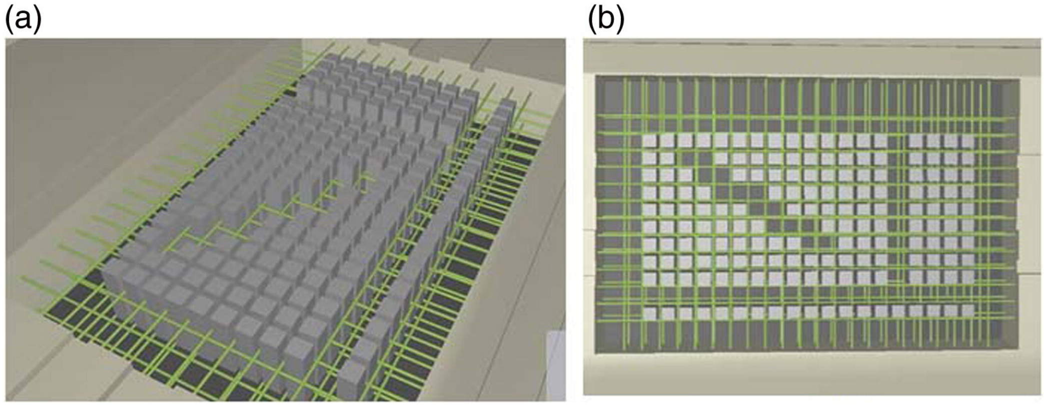

Fig. 19. The (a) perspective and (b) overhead views of safe drilling zones from ground truth data as visualized through the IFC viewer.

It is clear that the performance of the classifier depends on the quality of given point cloud data. Data with higher noise levels will contain more 'phantom' points, making the distinction between a real obstacle and a spurious object more difficult. Visual inspection of datasets acquired with two technologies, laser scanning and 3D image reconstruction, confirm that the elimination of noisy points from an acquired point cloud is critical for the improved prediction of safe cells.

6.4. Drill feedback control and laser projector approach

The accuracies of the drill feedback control and the laser projector based approach depend on the accuracies of the rebar mapping algorithm and the cell bin status classifier algorithm. Moreover, they are also dependent on the accuracies of the tracking system and the safety factors included into the algorithms to warn the drilling personnel when the drill bit tip is closer to the rebar or utility lines than what is deemed acceptable. Additional safety factors, such as any tolerances used to account for bending of the rebar due to the poured concrete and for shifting of the rebar cage, will also affect the performance of the real-time monitoring systems.

6.5. Limitations of the test bed results

The limitations of the test bed results can be classified into five main categories — data homogeneity, registration, equipment uncertainty, rebar mapping algorithm, and simulated environment limitations. These limitations are discussed below.

6.5.1. Data homogeneity

The point density for the various datasets varied greatly due to the different technologies used in capturing them. Also, within the dataset that is captured using a laser scanner, the point density is not spatially uniform since objects closer to the scanner generally include more points than those further away. In addition, the D4AR pictures were collected manually and therefore, the percent overlap between the pictures and the amount of rebar detail captured is not uniform. This leads to noise in the 3D image based reconstruction method used to develop the point cloud [9].

6.5.2. Registration

The ground truth, laser scanner, and 3D image reconstruction point clouds were registered to a common IACJS test bed coordinate frame in order to compare them with each other. The registration of the point cloud resulting from the 3D image reconstruction method to the test bed coordinate frame involved manually selecting the centers of the targets that were placed on the rebar, which resulted in random registration errors. The registration of the laser scanner data was more automated and used registration targets placed around the test bed. However, the registration algorithm relies on an initial guess and manual weighting of the targets, which also result in variations in the registration errors each time [16].

6.5.3. Equipment uncertainty

The uncertainty in the 3D position measurements from the iGPS and the ground truth laser scanner are ± 250 μm and ± 100 μm, respectively. Although the manufacturer specified a maximum point uncertainty

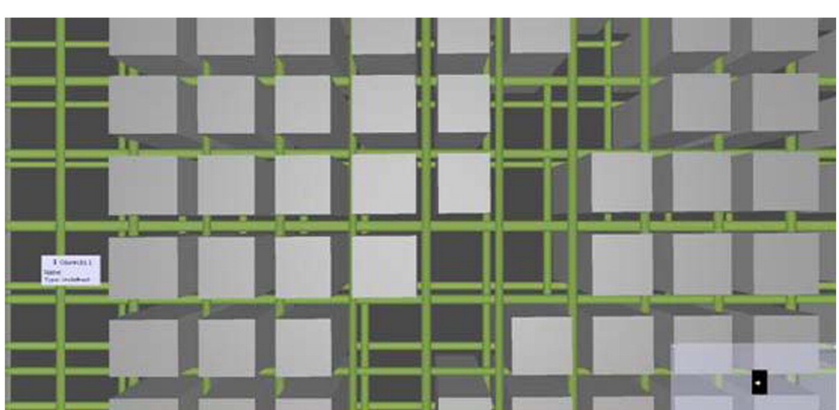

Fig. 20. Close-up view of safe zones computed from ground truth data.

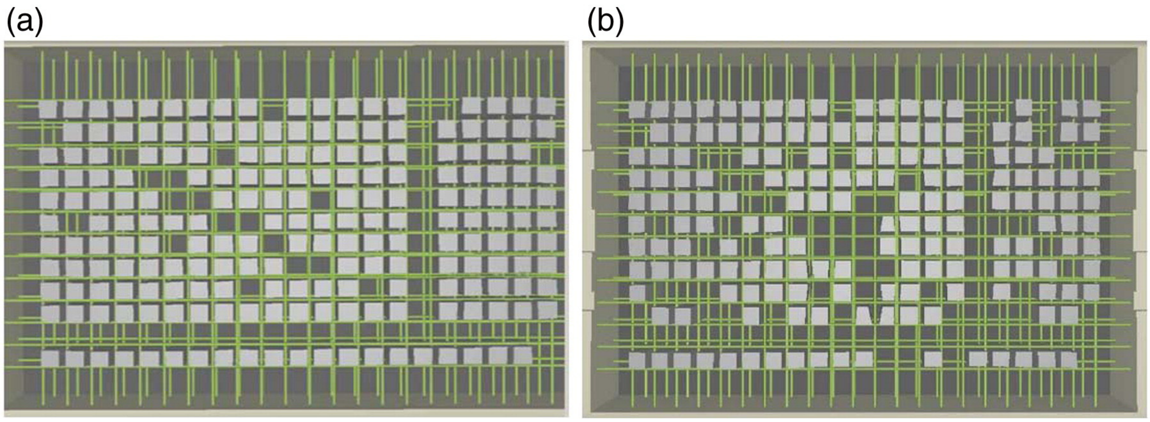

Fig. 21. The overhead views of the safe drilling zones computed from (a) laser scan and (b) 3D image reconstruction point cloud data.

of ± 5 mm for the other laser scanner used, the uncertainties in the data obtained from that laser scanner are unknown due to other sources of error such as angle-of-incidence and optical properties of the materials in the rebar cage. The uncertainties of the data obtained using the camera hardware and the D4AR software combination are also unknown. Furthermore, it is also unknown how the registration process affects the uncertainty of the data. Current methods of quantifying these errors (i.e., how registration errors propagate into all of the measured data points) are inadequate because they assume that the error in each data point in the registered point cloud is the same as the mean error around the registration targets.

6.5.4. Rebar mapping algorithm

The algorithm assumes that once the concrete is poured on top of the rebar, the resulting concrete surface will be a flat plane parallel to the floor of the rebar cage and that the process of pouring the concrete will not affect the locations of the rebar and utility lines. The algorithm would have to be extended in order to account for more complex finished concrete surfaces and appropriate safety factors and tolerances must be introduced to account for changes in the rebar and utility line locations due to bending and other side effects of the concrete pouring process.

6.5.5. Simulated environment

The results from the experiments conducted in the test bed described in the paper are also limited by the fact that all the experiments were conducted in a clean and controlled laboratory environment using a mockup of a rebar cage. However, the field conditions are often more congested and cluttered and the site is much larger than the laboratory setting leading to data occlusions due to objects (e.g., people, equipment, tools, general clutter) being in the way and limited accessibility to locations for setting up the instruments or taking photos.

Rebar cages also often contain objects or items that introduce noise to the data. Items such as rebar ties, rebar chairs, formwork, trash, and tools are often found in or on rebar cages under field conditions. Rebar hooks, bends, and splices will also add complexity. The ability to handle

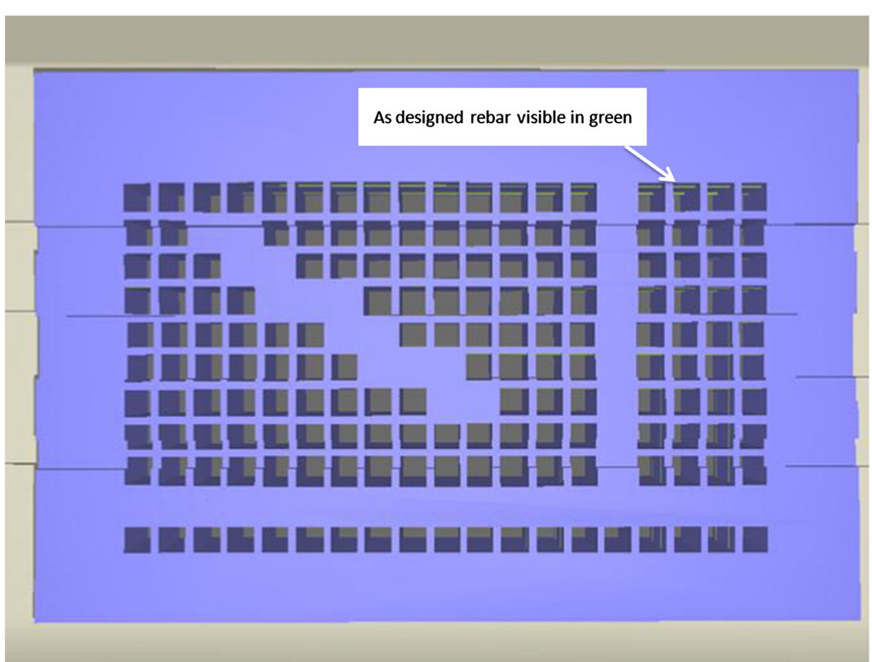

Fig. 22. Overhead view of safe drilling zones as voids computed from ground truth data. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

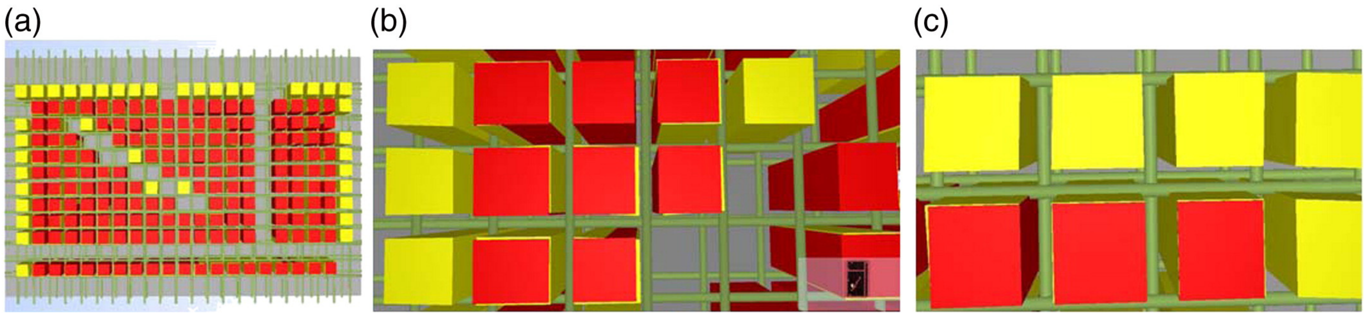

Fig. 23. The (a) overhead and (b) close up view of safe zone volumes for data from laser scanning (red) and ground truth (yellow) and a (c) close up view showing overlap with as designed rebar [16]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the added noise and complexity would require the development of a better point cloud filtering algorithm and a more sophisticated classifier algorithm.

6.5.6. Tracking system

Implementing iGPS is impractical for an actual construction worksite and certainly less so for a bridge deck. Both iGPS and laser projectors would suffer under direct sunlight due to the fact that the iGPS uses infrared signals and the projector's laser intensity may not be sufficient. Also, the dust and the less than ideal conditions of a construction site may render both systems unusable. The test bed implementation of real-time monitoring methods was a demonstration of the concept behind using such a framework and not to demonstrate how they could actually be used in construction conditions. A rugged tracking system, with the required accuracies, that works under actual field conditions and provides similar functionality to the iGPS system does not currently exist and would have to be developed. When and if better and more rugged tracking and visualization technology becomes available, these methods could be applied in the field. The cost of such a system would also have to be taken into consideration.

7. Summary and conclusions

Real-time context-aware monitoring systems have the potential to improve the efficiency of construction operations and to significantly reduce the loss of life and property in construction. In this paper, the authors present a framework for developing real-time monitoring systems based on context-aware computing techniques that identify hazardous scenarios and help construction personnel make more informed decisions.

The authors presented a motivating scenario of drilling for embeds into reinforced concrete bridge decks where monitoring systems could have a significant impact in avoiding striking concealed rebar and utility infrastructure. The authors then proposed two potential methods to address the problem of monitoring the process of drilling for embeds in real-time. The two approaches – the drill feedback control approach and the laser projector based guidance approach – were then implemented in a test bed using a rebar cage designed as a mockup of a railway bridge rebar cage.

Table 2
The results of the cell bin status classifier algorithm.

	Laser scanning	3D image reconstruction
% of false positives	1.2%	0%
% of false negatives	0.4%	30.5%
% of total false predictions	1.6%	30.5%
% of correct predictions	98.4%	69.5%

The results showed the feasibility of both approaches to provide real-time feedback for drilling into the concrete. The shortcomings of the proposed real-time monitoring methods developed in the test bed and the challenges of implementing them in the field are discussed. The methods presented 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 [16].

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