ERA-NET Plus on Infrastructure Innovation

Infravation
An Infrastructure Innovation Programme

SeeBridge
Semantic Enrichment Engine for Bridges
Start date: 01/10/2015
Duration: 21 months

Deliverable 6.1

Project Scientific Report

Main Editor(s)	Technion – Rafael Sacks
Due Date	31/08/2017
Delivery Date	19/10/2017
Task number	6.2
Dissemination level	PU

Version 2.0, 18/10/2017

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Acknowledgment

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 31109806.0007. SeeBridge is co-funded by Funding Partners of the ERA-NET Plus Infravation and the European Commission. The Funding Partners of the Infravation 2014 Call are: Ministerie van Infrastructuur en Milieu, Rijkswaterstaat, Bundesministerium für Verkehr, Bau und Stadtentwicklung, Danish Road Directorate, Statens Vegvesen Vegdirektoratet, Trafikverket – Trv, Vegagerðin, Ministere de L'ecologie, du Developpement Durable et de L'energie, Centro para el Desarrollo Tecnologico Industrial, Anas S.P.A., Netivei Israel – National Transport Infrastructure Company Ltd, Federal Highway Administration USDOT.

Final Report

Haifa, September 2017

Executive Summary

The SeeBridge project aimed to:

- generate native BIM models of reinforced concrete highway bridges from point cloud data collected using laser-scanning and photogrammetry, 3D object recognition and BIM semantic enrichment,
- identify defects in the bridges using high resolution photography, and
- annotate the BIM models with information about cracks, spalling and other defects.

The project had five development work packages, one demonstration work package and a management work package. The project was essentially completed as of June 30th 2017, having run for 21 months since the formal start date, although demonstration activities were done in three workshops (Atlanta, Cambridge and Tel Aviv) in late September, 2017. The main achievements of the project:

1. Complete definition of the proposed SeeBridge process and tools, recorded in an Information Delivery Manual and a Model View Definition (MVD) with a binding to the IFC schema.
2. Demonstration of feasibility of data collection, through survey of fourteen bridges (three in Atlanta, ten in Cambridge and one in Haifa) with terrestrial laser scanning, photogrammetry using videos to produce point clouds, and high-resolution photography.
3. Development of 3D object recognition and reconstruction software tools, using two approaches – top-down and bottom-up.
4. Implementation of the SeeBIM 2.0 semantic enrichment tool, compilation of rule sets for girder bridges and for slab bridges, and demonstration of semantic enrichment for two girder bridges and four slab bridges, resulting in BIM models in IFC format that were shown to conform to the Model View Definition.
5. Mapping of the high-resolution photography to the BIM models, identification of defects using machine-learning algorithms, and compilation of the defect data in the BIM model files.
6. Demonstration of the use of the BIM model, complete with defect information, for inspection in virtual reality and in mixed-reality scenarios.

Considered in combination, the tools for 3D reconstruction and the semantic enrichment engine have achieved something not previously demonstrated in civil engineering – the ability to derive fully functional BIM models from point clouds. The process still requires the operator to clean up irrelevant data from the point clouds, to classify the type of structure, and to clean up errors where they occur, but the tools reduce the scope of human effort by at least one order of magnitude when compared with the effort required in current practice to model a structure in a BIM tool based on a point cloud.

Four conference papers were presented, and four journal papers were prepared, two of which have already been published. More are to follow.

The team held a kick-off meeting at the University of Cambridge in December 2015, a mid-term workshop at Georgia Tech in Atlanta in July 2016, a workshop to coordinate between the conclusion of the research at the Technion in Haifa in late March 2017, and four demonstration workshops in September 2017 (in Atlanta, Cambridge, Munich and Tel Aviv).

The SeeBridge team is grateful to the GDOT staff and to Netivei Israel for their contribution to the data collection efforts and to our scientific committee liaison, Katherine Petros of FHWA, for her support and close collaboration. We greatly appreciate the strong support we received from the Infravation management

group, not only in funding, but in coordination with the other Infravation projects, support for Technology Readiness Level assessment, publicity throughout the project, and indeed moral support!

As the project closed out, a company from NYC applied to license the IP with a view to commercial implementation of the SeeBridge approach.

Consortium Partners

Technion

Georgia Tech

University of Cambridge

Kedmor Engineers Ltd.

Pointivo, Inc.

Technische Universität München

Trimble Navigation Ltd.

Pro-bono collaborator

Georgia Department of Transportation

Subcontractor

AEC 3 Germany

Supporters

London Underground

Netivei Israel

Bundes Ministerium fur Verkehr and Digitale Infrastruktur

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1 Publishable Summary

1.1 Project Goals

Highway asset owners throughout the Infravation partner countries face two major problems with regard to the data needed for **maintenance, repair, retrofit and rebuild of their bridges** and other structures: a) **the extensive time required for data collection** by existing assessment methods, and particularly the need for lane closures, given the enormous numbers of bridges in service; and b) the gap between the **quality of data available** in Bridge Management Systems (BMS) and the information needed for reliable decision-making and subsequent design and construction work.

The need for innovative solutions for **rapid and intelligent survey and assessment methods** has led to numerous research efforts toward laser scanning and modelling of bridges. However, the models produced do not contain any semantic information. The major remaining problem with these methods is that they require lengthy, expensive and error-prone human efforts to produce object-oriented parametric bridge models (equivalent to Building Information Models, or 'BIM' models, of buildings). In the meantime, the transportation service often remains interrupted.

Motivated by these challenges, the SeeBridge team proposed an automated system that integrates the following novel technical components to provide semantically rich BIM models of bridges (challenge D.1):

- Spatial & visual raw data collection with existing rapid and non-contact survey technologies such as laser scanning, video/photogrammetry, etc. (**challenge C.2**)
- A bridge object detection and classification software tool for automated compilation of solid 3D geometry from the point cloud data. This includes two steps: a) identification of segment faces and b) compilation of distinct solid objects represented by the faces.
- A rule-processing expert system for semantic enrichment of the solid geometry model to generate a BIM model. This too has two aspects: a) identification and classification of bridge objects (piers, abutments, girders, deck etc.), and b) deduction of supplementary information concerning material types, internal component geometry, etc., based on historical expert knowledge (**challenge C.2**).
- A damage measurement tool for damage identification, classification and spatial/visual properties measurement and integration of this information with the BIM model (**challenge D.1**).

The output of the proposed system is a BIM model sufficiently semantically meaningful to provide most of the information needed for decision-making concerning the replacement, rehabilitation or repair of a bridge. The primary objective was to demonstrate the utility of the model to TRL 6 by applying resulting models to decision-making for repair or for retrofit or rebuild. The BIM model is intended to be sufficiently rich in information and geometry to serve as a central component for BMS.

Compiling this system required the research team to go beyond the state-of-the-art in three specific areas, and these were set as the key goals of the project:

- Automated compilation of geometric solid objects from bridge point clouds

- Semantic enrichment of the solid geometry to generate BIM models
- Damage mapping (cracks, spalling, etc.) based on the BIM model

1.2 Results

We call the resulting system SeeBridge, which is an acronym for "Semantic Enrichment Engine for Bridges". This name expresses the idea that some of the ways in which engineers 'see' a bridge model, with the ability to infer implicit information from the explicit shapes visible in the digital model, can be captured in the form of rules that can be processed using forward chaining inference engines. The system concept is illustrated in Figure 1. **Data collection** on the bridge is performed using laser scanning and high resolution photogrammetry. Two approaches to **reconstructing the solid 3D geometry** were developed, one using a bottom-up approach and the other using a top-down approach. Both of these detect objects by their shapes from the point cloud data. The **semantic enrichment** stage uses expert rules to identify connections, classify the bridge objects, and infer other missing information. The result is an enriched BIM model stored as an IFC file. Both the raw survey data and the enriched IFC file provide the input for the **damage detection** software module, which identifies crack, spalling, bleeding and corrosion, and adds this information to the model by mapping it directly to the enriched BIM model. Thus a complete BIM model of the bridge, with damage information is produced.

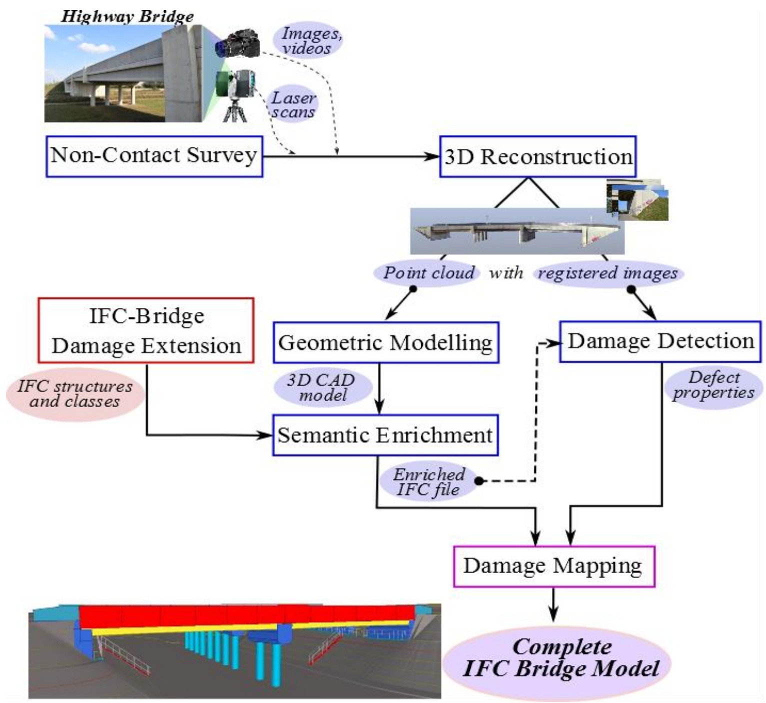


Figure 1. SeeBridge System Concept

In order to build a prototype of the proposed process, the research team had to overcome technical obstacles in each of the distinct steps highlighted in bold in the preceding paragraph. The following paragraphs detail the documents and tools prepared to define the system, the results achieved in each of these areas, and the technology readiness level that has been achieved.

1.2.1 System Definition

The Information Delivery Manual (IDM) document defines the process of bridge inspection thoroughly with full detailing of the information needed to describe a bridge, its parts, the relationships between them, the defects and their association to the bridge parts, and the metadata concerning the inspections themselves. The IDM also defines the data exchanges and the functional requirements within the suggested 'SeeBridge proposed bridge inspection process' (see Figure 3 in the IDM document – available from the SeeBridge website, http://seebridge.net.technion.ac.il, under RESULTS->Deliverables).

The process maps and the data exchanges are the primary result delivered in the IDM document. The exchanges were mapped, defined and described within the full workflow of a bridge management process and a full process map was created (see IDM Figure 5 & Appendix G in the IDM document). The developed specifications were used by all the SeeBridge working groups for developing the described tools.

A formal Model View Definition (MVD) for the SeeBridge system was developed on the basis of the IDM. The MVD is a computer-readable definition of the information concepts and constructs needed for the system, and it defines them in terms of a binding to the entities and relationships of the Industry Foundation Classes standard (ISO 16739:2013). This enables automated checks of the SeeBridge output files for syntax and content, using the open source XBIM Xplorer tool.

1.2.2 Data Acquisition

All necessary data in this project was acquired by three different techniques: laser scanning, videogrammetry, and photogrammetry. Laser scanning is an active sensing process that maps an environment based on emitting millions of laser beams and calculating the distance according to the time-of-flight principle. On the other hand, videogrammetry and photogrammetry are passive sensing techniques that map an environment by inferring 3D coordinates of points from multiple viewpoints.

The Trimble and Pointivo teams used all the above-mentioned techniques in a joint effort to scan three concrete bridges in the state of Georgia, USA. To perform the laser scanning process, the Trimble technician first inspected each site to devise a plan for stations that the laser scanner needed to be set up. Individual scans were captured at each station. These scans were then merged together in a post-processing step to generate a point cloud for each bridge. The Pointivo team performed the videogrammetry procedure using an iPhone6 as the primary sensing device. The team captured a video stream that provided multiple viewpoints for each given point on a bridge. Structure from Motion algorithms were then used to generate image-based 3D point clouds from the captured video stream. A DSLR camera was also used to capture still photographs for the photogrammetry step. Similar to videogrammetry, multiple viewpoints were captured for each given point on the bridge.

The Cambridge team used two high-density surveying technologies (laser scanning as well as photogrammetry) to generate detailed spatial raw data with registered imagery for inspection of ten slab and slab-beam bridges around Cambridge. They registered the raw scan data properly in the office and the registered results are ready to be processed for WP 3.

1.2.3 3D Reconstruction

The Cambridge team and the Georgia Tech team pursued two distinct solid model reconstruction strategies, top-down and a mixed top-down/bottom-up, respectively. Both cases involved the creation of a user interface for rapid manual pre-processing of the point cloud to remove non-bridge data (road surface, vehicular traffic, foliage, etc.). Inputting the bridge point cloud data to the top-down solution resulted in a Level of Development (LOD) 100 model of a bridge's piers, slab or girder components, and deck. Doing the same for the mixed top-down/bottom-up solution resulting in LOD 200 models of the piers, abutments, deck side elements, and the bridge's girders, box beams, or slabs. For girder bridges, additional elements include the diaphragms and soffit surfaces. The non-structural, upper portions of the deck were reconstruction at LOD 100. These elements include the road, the sidewalks, and the parapets. The output format, being an IFC model, were consistent with the input format expected by WP4.

Both approaches utilized a top-down algorithm for initial partitioning of the bridge. The partitioning served to break the bridge down into the substructure, the superstructure, and the deck. For the purely top-down approach, these sub-divisions were final and provided the bounding boxes necessary for the LOD 100 output. Classification of the components exploited the partition zone and the geometry of the points within each partition. Further processing by the mixed approach continued sub-dividing the components in order to identify surface elements, which were then fused with neighboring partitions based on a surface model similarity score. A machine learning method was employed to hypothesize both the solid model type of each surface, as well as its component category (pier , column, pier cap, abutment, diaphragm, girder, box, slab, deck side, road, parapet). The output of the machine learning algorithm provided the surface components to merge into one solid model, which after doing so, was output to an IFC file together with the component label. As interior or occluded points of a bridge cannot be scanned, simple rules were applied to certain surfaces to extrude them into volumetric elements (such as abutment faces and visible box beam faces). Components with insufficiently scanned faces and non-trivial solid model geometry were not recovered by the process (e.g., diaphragms with only lower face scanned).

1.2.4 Semantic Enrichment

The first achievement of the Technion and TUM team was to build a robust rule-processing engine. The resulting SeeBIM 2.0 system can apply rules with operators that check for the existence of a range of properties and topological, geometrical and other relationships between objects. Unlike earlier versions, it applies no restrictions in terms of the orientation or shape of the objects.

The second achievement was to develop a rigorous method to compiling enrichment rules that could guarantee completeness of the rule set for classification of any pre-determined set of bridge components. Using matrices to express the relationships between object types and a test for uniqueness of result strings, the team could encapsulate expert bridge engineers' knowledge in a formal, structured way that would ensure that all the object types could be identified.

In the development work the team used synthetic models of bridges (compiled manually from scanned point clouds using BIM software) as input, because the output models from the previous work package were not yet available. It proved possible to achieve 100% success in classification, numbering, axis reconstruction, aggregation and repair of occluded objects. For example, the team succeeded in devising rules to lengthen girders that were too short, to insert placeholders for missing objects (bearings) and to flag objects that require revision by the operator (plinths, in this case). In the final days of the project, reconstructed 3D models were obtained from GT and Cambridge. The results for semantic enrichment of these models were mixed. The Cambridge bridges were correctly enriched, as was the Atlanta Acworth bridge, but the Haifa bridge reconstructed model enrichment suffered numerous problems due to missing objects in the reconstruction.

We conclude that the enrichment engine and the process for rule compilation are robust, and that the enrichment process itself works well if the reconstructed model has all of the expected objects. The shortcomings identified in the last bridge model can be overcome in two ways: a) manual inspection and modification of the reconstructed 3D model, which should require a very small fraction of the time that would be required for manual reconstruction as done today, and b) expansion of the rule sets to include sufficient redundancy to cope with situations where some expected object types are absent.

1.2.5 Defect Detection

The Cambridge team has developed a method for detecting defects automatically for the scope of bridge inspection. This method consists of three steps. The initial step is the high resolution surface texture reconstruction based on the 3D geometry of a bridge and unregistered high-resolution imagery. Image content is back-projected onto the element geometry based on a combined approach of photogrammetry and raytracing. This results in copy which is fully textured, data-rich and an exact replica that can be used, for example, for automated defect detection. The automated defect detection identifies healthy concrete and inherently leaves potentially unhealthy surface clusters. In order to do this, we have developed a data-preparation method for splitting and merging the image textures such that high-resolution imagery can be used as classifier input without resizing the input image data by keeping small texture details. This is necessary as many of the defects, such as cracks, only fill a minor part of the surface area but are crucial for the inspection. A state of the art deep neural network is used for the binary classification. The training and evaluation dataset was assembled from real life inspection data repositories. Finally, the defect findings are integrated into a BIM model. To achieve this, we developed a novel information model that enables to integrate defect information into BIM models. This information model is based on an investigation of multiple bridge inspection manuals from different countries and continents. Industry Foundation Classes are used to demonstrate the mapping of the information model to a specific BIM implementation.

1.2.6 Technology Readiness Level

An internal assessment of the overall Technology Readiness Level (TRL) of the SeeBridge prototype system (Deliverable 6.1) determined that at the end of the project, the system had achieved TRL 6.

The TRL of the system as a whole is the minimum of the TRL values for the distinct system components, and as such is also dependent on the bridge type since some system components were only developed and tested for a single type. As can be seen in Figure 2, the system component that governs the TRL level for slab bridges is the semantic enrichment step, whereas the component that governs the TRL level for the girder bridges is 3D geometry reconstruction.

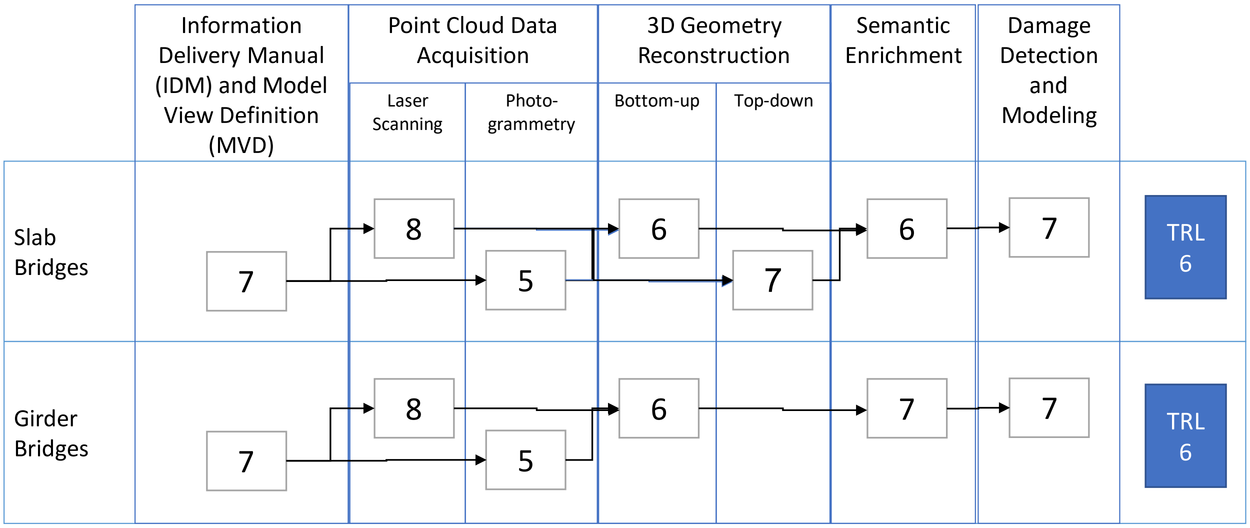


Figure 2. Technology Readiness Levels for SeeBridge components at project end (internal assessment). See Deliverable 6.1.

1.3 Challenges

The most acute challenges that the research team encountered were those where it was necessary to push the boundaries of the state-of-the-art in research and practice.

Preparation of the Information Delivery Manual (IDM), including the process maps and definition of the model exchanges, required extensive effort but use proven procedures. Likewise, compilation of the Model View Definition (MVD), and the extensions to the underlying IFC data schema to which it was bound, used the ISO standard IFC schema and commercial tools for MVD definition. This work also benefitted from the earlier work of the IfcBridge working group. Laser scanning of the fourteen bridges employed standard equipment and procedures and did not encounter any unexpected problems. Acquiring high resolution images of the surfaces of the components of the bridges was done with standard cameras and support equipment. The only challenge here was close access to the surfaces, and this was overcome with a tall tripod based mast and camera remote control (drone access to the bridges was ruled out given the regulatory prohibitions on drone flights in proximity to traffic that are in place in most jurisdictions.

The main challenges therefore were in videogrammetry, semantic enrichment, 3D reconstruction and defect detection.

1.3.1 Videogrammetry

Videogrammetry is the practice of determining 3D coordinates of points on an object using one or more video streams taken from different angles. This method is capable of producing 3D coordinates for points that are distinguishable enough to be matched in at least two different viewpoints with sufficient angle of triangulation.

According to this definition, three main challenges arose in applying this method to scan bridges. First, it proved challenging to acquire multiple viewpoints for all the important surfaces of a bridge in a video stream captured using a mobile camera. Some surfaces are not easily accessible for a person and cannot be covered from multiple angles. Second, lack of illumination under the bridge deck or in occluded corners imposes significant challenge for automatic point matching algorithms and increases the chance of failure in finding corresponding points; without this information, 3D coordinates of the point cannot be calculated. Third, some surfaces in a bridge, especially the surfaces under the deck, are poorly textured; this challenges the accuracy of the point detection and matching steps and leads to very noisy 3D points in the point clouds in those areas. The project concluded that videogrammetry was inferior to laser scanning for this part of the data acquisition.

1.3.2 3D reconstruction

The main challenge associated with full solid model reconstruction lies in the incompleteness of the point cloud data. The most complete scans were those of the Atlanta bridges, while the Cambridge and Haifa scans failed to meet the WP3 input specifications for significant portions of several to many components. An additional challenge lies in the bottom-up segmentation strategy, which first generates an over-segmentation then seeks to simplify it through segment merging. When multiple hypotheses are feasible, the segment merging process may select an incorrect merging option. The surface segments do not join across components but rather incorrectly fuse distinct faces of a single component. In doing so, there exists the possibility of misclassifying and later incorrectly recovering the object geometry.

1.3.3 Semantic enrichment

The challenges faced in this step were both inherent and procedural. Inherent: building enrichment rule operators capable of dealing with generic and unrestricted 3D geometry; compiling rule sets that were rigorous; and defining object data schema for bridge-specific concepts absent in the ISO standard IFC schema. All of these were thoroughly overcome. Procedural: delay in completion of the 3D reconstruction step meant that the development had to rely on two synthetic models, with the first full testing possible only in the last days of the project. While the rule-sets for the synthetic models could be developed to the point where 100% success in semantic enrichment could be achieved, the results for one of the four automatically reconstructed 3D models clearly showed that the rule-sets lacked the redundancy needed, in terms of relationships between object types, to cope with situations in which some object types are not reconstructed.

1.3.4 Defect detection

Two main challenges exist for the defect detection. First, reconstructing an entire bridge surface depends on correctly and exactly determining the camera degrees of freedom (position, orientation, focal length). No technology exists that can measure these values at a sufficient precision. Photogrammetry is used to estimate the camera degrees of freedom. This requires sufficient image surface coverage including high resolution imagery and robust image features for identifying points in multiple images. All these constraints are difficult to meet. Second, the training and evaluation of the machine-learning defect detection method requires a reliable set of labeled reference data. This data does is not publicly available. We have overcome this challenge by compiling a labeled dataset, but for full implementation, it will be necessary to expand this dataset.

1.4 Contributions

SeeBridge's main contributions are:

1. Complete definition of the proposed process and tools, recorded in an Information Delivery Manual and a Model View Definition (MVD) with a binding to the IFC schema.
2. Demonstration of feasibility of data collection, through survey of fourteen bridges (three in Atlanta, ten in Cambridge and one in Haifa) with terrestrial laser scanning, videogrammetry to produce point clouds, and high-resolution photography.
3. Development of 3D object recognition and reconstruction software tools, using two approaches – top-down and bottom-up.
4. Implementation of the SeeBIM 2.0 semantic enrichment tool, compilation of rule sets for girder bridges and for slab bridges, and demonstration of semantic enrichment for two girder bridges and four slab bridges, resulting in BIM models in IFC format that were shown to conform to the Model View Definition.
5. Mapping of the high-resolution photography to the BIM models, identification of defects using machine-learning algorithms, and compilation of the defect data in the BIM model files.
6. Demonstration of the use of the BIM model, complete with defect information, for inspection in virtual reality and in mixed-reality scenarios.

Considered in combination, the tools for 3D reconstruction and the semantic enrichment engine have achieved something not previously demonstrated in civil engineering – the ability to derive fully functional BIM models from point clouds. The process still requires the operator to clean up irrelevant data from the point clouds, to classify the type of structure, and to clean up errors where they occur, but the tools reduce the scope of human effort by at least one order of magnitude when compared with the effort required in current practice to model a structure in a BIM tool based on a point cloud.

The contribution of SeeBridge in principle lies not only in improving the bridge inspection process, but, more importantly, in the rich form of digital bridge documentation for asset management.

2 Project Results

2.1 Results Overview

This chapter presents the results of the SeeBridge process in all five key areas of activity in the project: system definition, point cloud data acquisition, 3D geometry reconstruction, semantic enrichment to produce BIM models, and defect detection and recording. Perhaps the most significant result of the research is the fact that the tools enable compilation of bridge BIM models with minor support from human operators, with very high dimensional accuracy and accurate and thorough reporting of defects.

For a full list of publications – journal and conference papers, popular press and presentations – please see Section 5.3, on page 46 below.

2.2 System Specification

2.2.1 Information Delivery Manual

The Information Delivery Manual (IDM) document is the first stage of the SeeBridge project where we define the process of bridge inspection and the information needed to describe a bridge, its parts, the relationships between them, the defects and their association to the bridge parts, and the metadata concerning the inspections themselves. A common traditional existing bridge inspection process was mapped (see IDM figure 1, available from the SeeBridge website, http://seebridge.net.technion.ac.il, under RESULTS->Deliverables) and then a modified process which includes SeeBridge suggested improvements to the process was created (see IDM figure 3, ibid). In this process, four novel SeeBridge technical components were integrated into the bridge inspection process in order to provide semantically rich BIM models for the inspected bridge. The new components were:

1. A bridge data collection system using remote sensing techniques such as terrestrial/mobile laser scanning and photogrammetry/videogrammetry.
2. A bridge object detection and classification software for automated compilation of 3D geometry from the remote sensing data using both parametric shape representation and boundary representation.
3. A semantic enrichment engine for converting the 3D model to a semantically rich BIM model using forward chaining rules derived from bridge engineers' knowledge.
4. A damage detection tool for damage identification, measurement, classification and integration of this information in the BIM model.

Incorporating the suggested SeeBridge technical components into an existing bridge inspection and management process was done with great care as the impact on the existing workflow and on the way the BMS is used to manage the bridge stock is significant. One of the major changes is the introduction of a BIM model as a database for the bridge inspection and management process. Three situations for incorporating BIM models into the process were defined:

a) Using the 'as-built' BIM models of bridges if and where they exist (almost nonrealistic for existing bridges to date).
b) Automatic creation of 'as-is' BIM models of bridges using the SeeBridge technical components numbered 1-3 above (activities 2.3.1, 2.3.2, and 2.3.3 in IDM Figure 3, ibid).
c) Preparation of 'as-built' BIM models of bridges manually based on drawings.

Option b) was the major solution that SeeBridge provided, since most of the existing BMS have not incorporated BIM models. The SeeBridge solution of this aspect greatly reduce the effort and costs required for BIM model integration into the BMS.

For a complete view of the suggested modified inspection process within the whole bridge management process, a detailed process map (see Figure 3 below) was created by the SeeBridge team using Business Process Modeling Notation (BPMN). Horizontal swim lanes are used for the disciplines (Actors) and vertical ones are used for the process stages, starting with pre-inspection and ending with network work planning. Although not included within the scope of the SeeBridge project, it was decided that a full bridge management process will be mapped so that one can better understand the proposed SeeBridge inspection process within the global bridge management concept.

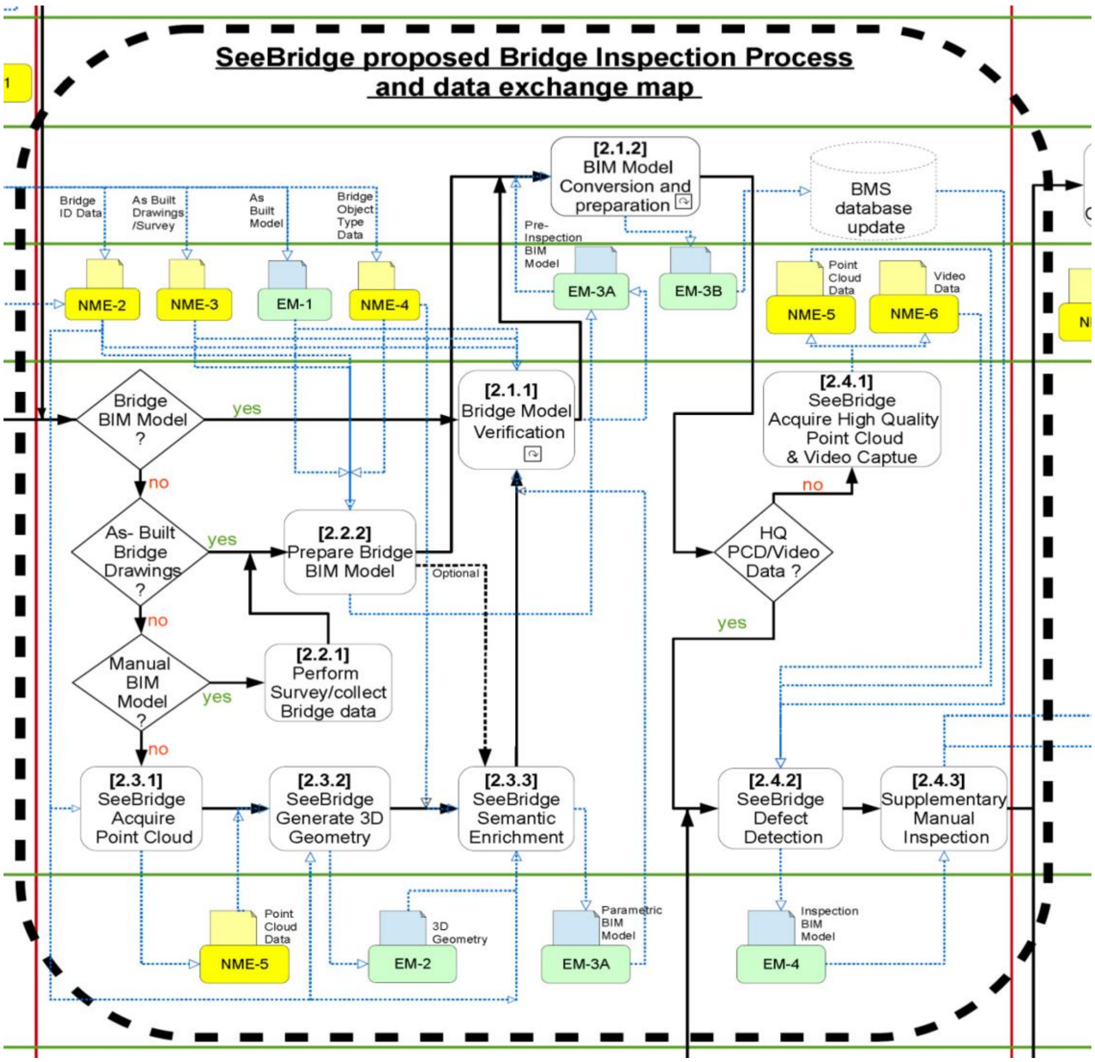


Figure 3. Partial view of the SeeBridge BMS process map.

The data exchanges are fully described in the IDM document. The exchanges were mapped, defined and described within the full workflow of the detailed process map of the bridge.

The data exchanges description and specifications define so called 'exchange models' (EM) and 'non-model exchanges' (NME). The EMs are the data contents of the BIM models that are exchanged between the different functions through the inspection process. Likewise, the NMEs are the data exchanges that do not use BIM models, i.e. they are documents, spreadsheets, or other formats. Since the inspection process is a part of a bridge management scheme and is documented in specific BMS modules, the use of NME in database format is currently unavoidable. When possible, the new Inspection BIM model will contain additional general inspection and structural information that in due time will replace part of the traditional database format. The different NME's were defined, and a specification was established for each one including the specific format per NME.

A full description for all EM's was compiled, including the following parameters: Project stage, Exchange discipline, Description, LoD and related information exchanges. The Exchange Model specification details the EM data items related with the Bridge BIM models used along the defined process. The specifications organize the information items in a hierarchy of information groups, information items, attribute sets and attributes as follows:

a) Information Group - represent the main data OBJECTS in a Bridge Model such as site, bridges, aggregation objects, main bridge elements, etc.
b) Information Items - are specific example of the main members of each information group. They are detailed based on the assumption that every information item in an information group has the same attributes.
c) Attribute Sets – are groups of properties that are used to describe an information group. The attributes are grouped in this way because sets occur in identical form across multiple information groups.
d) Attributes – are the properties that are needed to fully define the information group.

An Exchange Model specification lists all of the information groups and all of their attributes needed for enabling the exchange. For each exchange model we identify on the right columns of the table whether each attribute is required (R), optional (O) or not needed (N). The attributes were listed in the rows of the table.

Information Group	**Information Item**	**Attribute Set**	**Attributes**	**Notes**	**Model exchange (R/O/N)**					
					EM-1	**EM-2**	**EM-3A**	**EM-3B**	**EM-4**	
Site	Site	Identification	Site ID		R	R	R	R	R	
		Location	Coordinates N, E, Z (reference point)		R	R	R	R	R	
			Road No.		R	N	R	R	R	
			Linear Reference (reference point)		R	N	R	R	R	
		Topography	Digital terrain model	DTM file	O	R	R	R	R	
			Survey contours		O	O	O	O	O	

Information Group	Information Item	Attribute Set	Attributes	Notes	Model exchange (R/O/N)					
					EM-1	EM-2	EM-3A	EM-3B	EM-4	
Bridge	Bridge	Identification	Name		R	R	R	R	R	
			Number		R	R	R	R	R	

Figure 4. SeeBridge EM specification data table format (sample).

Another aspect that was taken care of in the IDM was defining the Specification for the Bridge inspection and management process tasks. The tasks were divided into Non SeeBridge tasks and SeeBridge tasks and for each one a specification was prepared including the content of the task and the input and output for the task. This enables a better understanding of the connection between the data exchanges and the actual tasks related to them.

2.2.2 Model View Definition

A Model View Definition (MVD) is a computer implementation of an IDM. It maps the information exchanges in IDM to a subset of the IFC schema, and defines the exchange requirements in a computer readable data model.

The SeeBridge MVD was developed based on IFC4 Add2 with the following goals:

- to identify the required objects, properties and relationships between objects needed to represent bridges according to the IFC schema.
- to provide a resource for the upcoming effort for the IfcBridge and other extensions
- to accelerate the quality control / quality assurance of produced IFC Models by using data validation tools

Development of IDMs and MVDs for specific exchange requirements of business processes within the construction industry is encouraged by bSI. Not only does this effort allow the assessment of the capabilities of the current schema in satisfying the industry needs, but also provides opportunities to explore possible shortcomings and specify necessary extensions for future development. Furthermore, specification of an MVD gives the project stakeholders the ability to validate the project deliverables against the exchange requirements automatically.

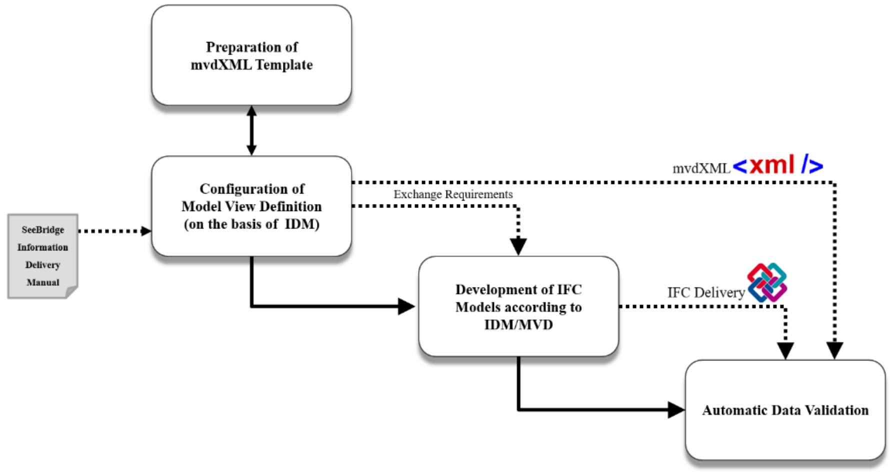


Figure 5. The workflow of the MVD development and usage

In the SeeBridge project, the online platform BIM*Q, a requirements and quality management system developed by AEC3 Germany, was applied for MVD development and generating the SeeBridge mvdXML file. For each bridge object, a mapping to existing entities of the IFC4 data model was defined. Object properties were mapped to the available IFC concepts, and additional data types for each property were defined. This enabled to formally define the exchange scenarios and their requirements described in the IDM, and provided the basis for generating a corresponding mvdXML file. This particularly includes the semantics of bridge component types and their relationships and thus allows to verify the outcome of the semantic enrichment process.

A unique feature of the SeeBridge system is its capability of incorporating the defect information in a BIM model. A Bridge can have multiple defects, each of which can be classified as structural defect or not. The bridge defect is composed of a number of element defects (ElementDefects), some of which may be associated to the same bridge element component. The MVD was composed in a way that includes the possibility to describe defects in IFC and associate them with the affected bridge components.

The open source system XBIM Xplorer was used to validate the project's IFC files of bridge models for compliance with the generated mvdXML representing the rules defined in the MVD. Doing so it was possible to check the IFC files used in the different exchange scenarios in the SeeBridge project for compliance with the requirements defined. More importantly, we could show that the process chain developed and validated in the SeeBridge projects provides a generic approach for formal quality control of bridge models handed over between the stakeholders of the inspection process – a very important pre-requisite for bringing the SeeBridge process into practice.

Figure 6. Checking an IFC bridge model for compliance with the defined MVD using XBIM Xplorer

2.3 Point Cloud Data Acquisition

The objective of WP2 was to produce detailed spatial raw data (3D point clouds) using high-density surveying technologies including laser scanning and photo/videogrammetry, and to test the suitability of each of these methods for the SeeBridge process. Data was captured for a total of 14 bridges: 10 in Cambridge, UK, 3 in Atlanta, Georgia, and one in Haifa, Israel using Lidar, Trimble MX7 (mobile mapping system), Hi-resolution images, and 1080p video. This data was processed to produce spatial raw 3D point clouds with registered imagery.

The data acquisition effort far exceeded the original SeeBridge plan in terms of the number of bridges surveyed. The research group felt that a greater variety of bridges from three different countries would enable the team to develop more robust solutions for the data processing, and would enable better validations than would have been possible with the original three bridges that were specified. The additional data acquisition was made possible by the efforts of Trimble in providing scanning tools in the US, by the generous support of Netivei Israel, and by the special efforts of PhD student Ruodan Lu at Cambridge University.

The Cambridge team used two high-density surveying technologies (laser scanning and close range high resolution photogrammetry), to generate detailed spatial raw data with registered imagery for inspection of 10 slab and slab-beam bridges around Cambridge.

Data collection of the 14 bridges was completed by the end of April 2016. All of the bridges can be reviewed on the SeeBridge project web site at http://seebridge.net.technion.ac.il/bridges.

2.3.1 Three bridges in Atlanta, GA

Pointivo, Trimble, and GDOT collaborated to capture data for three bridges (shown in Table 1) in and around Atlanta, Georgia in the US. Point cloud data and video were collected in two days. The data capture took approximately three hours per bridge. The Trimble team used the Trimble TX8 to laser scan each bridge, the Trimble MX7 mobile mapping system, and captured high-resolution imagery of specific bridge elements with the goal of approximately 10 pixels per mm. The Pointivo team used an iPhone 6s to video each bridge to generate a videogrammetric point cloud and captured high-resolution imagery to provide general overview photos of the bridges.

Table 1 Data collection of the three bridges in Atlanta, Georgia, US.

Bridge ID	Location	Data Collected	Date
067-52520	Acworth	Lidar, MX7, iPhone video, Hi-res over view digital photos, selected close range photos	2/3/2016
135-01150	Gwinnett	Lidar, MX7, iPhone video, Hi-res over view digital photos, selected close range photos	2/4/2016
135-50880	Gwinnett	Lidar, iPhone video, Hi-res over view digital photos, selected close range photos	2/4/2016

Table 2 Comparison of the performance of the two data collection methods

Bridge ID	067-52520		135-01150		135-50880	
Bridge Length	140 ft		156 ft		160 ft	
Data Collection Method	Lidar	Video-grammetry	Lidar	Video-grammetry	Lidar	Video-grammetry
Collection Time	2 h 48 m	63 m	1 h 54 m	48 m	1 h 20 m	1 h 5 m
Number of Scans	27	3	21	2	47	1
Processing Time	3 h	21 Days	12 h	18 Days	8 h	20 Days
Total Point Count	2,782 M	21 M	762 M	16 M	902 M	19 M
Point Density	2 mm to 8 mm point spacing	32,750 points per sq/ft	2 mm to 8 mm point spacing	30,500 points per sq/ft	2 mm to 8 mm point spacing	29,900 points per sq/ft
Average Re-projection Error	N/A	.085	N/A	0.16	N/A	0.18
Completeness of Point Cloud	100%	100%	100%	No deck	100%	Partial Deck
Accuracy	Control	0.36%	Control	.27%	Control	.15%

An accuracy study was conducted to compare the dimensional accuracy of the methods. Lidar is assumed to be standard so the videogrammetric clouds were compared to determine error. Average error of the videogrammetric solution compared to Lidar was 0.26%. Below is an accuracy breakdown per bridge:

Table 3 Data Accuracy of Collected Data

Bridge	Bridge 067-52520	Lidar (ft)	Video-grammetry (ft)	Abs Error (ft)	Error
067-52520	Deck Length	40.26	40.24	0.021	0.05%
	Between Beams	17.10	17.04	0.061	0.36%

	Beam Width	1.22	1.21	0.008	0.68%
135-01150	Deck Length	45.97	45.93	0.038	0.08%
	Between Beams	19.42	19.37	0.049	0.26%
	Beam Width	0.898	0.90	0.004	0.48%
135-50880	Deck Length	47.22	47.10	0.119	0.25%
	Between Beams	11.37	11.37	0.006	0.05%
	Beam Width	0.75	0.74	0.016	0.15%

2.3.2 Ten bridges in Cambridge, UK

During February and March 2016, the imagery data of ten highway bridges around Cambridge were collected. These ten bridges included eight slab bridges and two girder bridges, as these two types represent the majority of bridges in the UK. The bridges are listed in Deliverable 3.1A.

One laser scanner, FARO Focus 3D X330, was used to collect point cloud data for these ten bridges. The surveyor conducted an adequate number of scans (approximately 17 scans per bridge) to ensure that every visible bridge surface is scanned. This was achieved through multiple scans from different vantage points in order to minimize occlusions and ensure a complete data set with points on all of a bridge's visible surfaces. This included scans with a user defined scan range to obtain line of sight too hard to see surfaces, such as underneath the deck. In average, each scan was taken at a Point Distance of [10mm/10m] (that is, the distance between the captured scan points in 10mm in a scan distance of 10 meters). We maintained a minimum point density of 1 point/cm2 so that the data can be used for further processing. The average on-site scanning time is 3 hours per bridge, including the setting-up time.

After the on-site scanning, the raw data was registered using FARO Scene software. It took approximately ten hours per bridge for registration.

The registration quality was fairly good. Although occlusions are inevitable in some cases due to on-site vegetation, trees and barriers, the key features, edges, and boundary points of every bridge are visible in the results and the occluded areas are very limited which are inferior to 5% of the total bridge's surface. The registration work of these ten bridge datasets was complete at the end of March.

With regard to the photogrammetry work, a camera sensor was selected to compile a representative data set. Regarding the camera, requirements were defined as followed: (1) Resolution on surface sufficient for cracks down to 0.3 mm, (2) colour-images in order to distinguish different damage indications, (3) high sensor sensitivity to adapt to difficult light conditions and (4) lens to be able to take images over two traffic lanes to avoid road closures and traffic control.

After a comprehensive comparison of a number of cameras, lenses and utilities, the Sony alpha 7RII was selected. It has a full frame sensor and a resolution of 42 MP. Hence it enables maximal physical pixel size in combination with a high resolution. A refinement of lens requirements leads to lens parameters. The specification is provided by a minimal crack width which was defined earlier as 0.3 mm. A smallest feature should be resolved with three pixels to allow robust detection. Using the lens approximation, a focal length requirement was calculated. In the assumption of taking images over two road lanes with four meters each, the required focal length is 363 mm. The Sony 70–400mm F4–5.6 G SSM II is a zoom lens with a focal length of 70 up to 400 mm. Hence, images can be taken at a distance of 8.83 meter with the desired surface resolution of 0.1 mm per pixel. Bridges are complicated structures which do not only span traffic lanes but also have high-lying areas which are difficult to inspect, such as the area between girders. To enable an inspector to also record these hidden parts of a bridge, an 8.4m tall carbon fibre tripod was acquired in combination with an Nvidia Shield tablet which serves as a remote live view and a remote control.

The team photographed all ten bridges, resulting in roughly two terabytes of image data and more than 21,000 images overall. Roughly 100 person-hours were spent for data collection on site. Detailed statistics were taken during collection to protocol times, difficulties and weather condition during the collection. The weather conditions and vegetation were identified as the most critical obstacles for data collection. It was important during data collection to not only collect image data but also to record a ground truth, i.e. if these structures actually have damage or defects and of what kind. This was needed for eventual verification of the defect identification step and to have training data for a classifier later in the process. Several defects were found such as cracks, spalling and discoloration.

2.3.3 One bridge in Haifa, Israel

The Afek road bridge above route 79 in Kiryat Bialik was scanned. This is a prestressed AASHTO girder bridge with three spans totaling 17.6m length. Built in 1993, it is owned and maintained by Netivei Israel, the national roads company.

Two types of data collection methods are used: terrestrial laser scanning using a Leica ScanStation C10 scanner and video-grammetry using GoPro Hero4 Black camera, as shown in Figure 7. In the laser scanning process, the scanner was placed in multiple stations to scan the bridge, so that the result point cloud data can cover the whole scene of the site in 360 degrees. In the video-grammetry data collection process, a GoPro Hero4 Black camera was mounted on a surveyor’s helmet, so that it can capture the bridge from different angles and positions as the surveyor walked along the site. The result point cloud data is shown in Figure 8.

(a) (b) (c)

Figure 7. (a) Leica ScanStation C10 scanner (b) GoPro Hero4 Black mounted on a helmet (c) Pier.

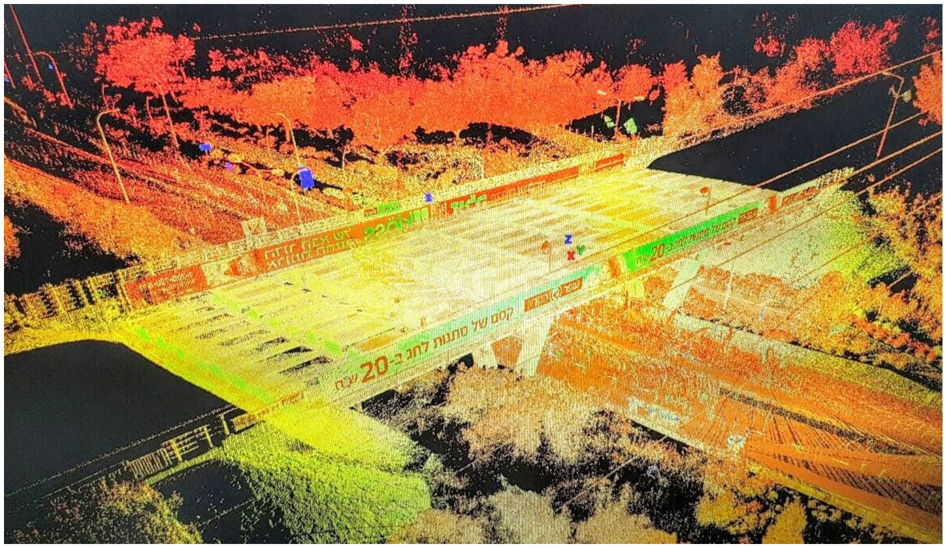


Figure 8. Point cloud data collected in a bridge in Haifa

2.4 Point Cloud to Geometry Processing – 3D Reconstruction

The primary objective of WP3 was to develop and demonstrate the capability to generate 3D parametric solid object geometry of bridge components from point clouds of bridges. As a component of the SeeBridge process, this work package takes as input a point cloud and produces as output a set of files in Industry Foundation Class (IFC) format, which as a whole represent the bridge geometry and its basic architectural components.

Two teams, one at Cambridge and one at Georgia Tech. pursued this effort. Given that noise and extraneous surface removal is an unsolved problem, both teams created user-assisted point cloud cleansing interfaces to crop rapidly the bridge from the nuisance data. Time to crop varied from 10 minutes to 30 minutes, depending on the quantity of irrelevant points scanned and the size of the input point cloud.

The Cambridge team pursued a 'top-down' approach in which the software first divides the bridge scan into zones that correspond to the major bridge assemblies: substructure, superstructure, and deck. It then attempts to match known bridge elements to the point cloud sections. Ten bridge models were compiled in BIM software from the imagery data collected in Cambridge. These models were used as the ground truth data for testing and developing the algorithms. The 'top-down' is a rapid solution for providing simple, LOD 100 models of the basic structural elements (piers, girder/slab, and deck).

The GT team adopted a mixed 'top-down/bottom-up' approach that has a processing pipeline consisting of three major components:

1. a point cloud processing engine that partitions the bridge, then segments and models the point cloud partitions using (quadratic model) surface primitives;
2. a surface primitive classification algorithm that generates hypothesized CAD labels for groups of surface primitives and also hypothesized bridge component labels; and
3. a synthesis algorithm that takes the classification information and outputs in IFC format the classification results and the solid model geometry of the fused surface primitives.

Due to the inability of the bottom-up segmentation strategy to differentiate a necessary surface from a nuisance surface or duplicate surface due to registration errors, the output of step 1 is first verified via a user interface whereby the user accepts or rejects the surface segmentation. The user time involved varies based on the number of components, ranging from 5 minutes to 25 minutes. Validation of the overall pipeline also required the creation of support code to synthesize data for evaluation purposes. The three bridges processed using the mixed approach include one from Atlanta (Acworth), from Cambridge (bridge scan #1), and from Haifa. The mixed approach is more computationally involved process, taking between 8-60 hours, for recovering LOD 200 models of the important structural bridge components, substructure and superstructure, and LOD 100 models of the remaining components, deck and above.

2.4.1 Establishing Surfaces to Reconstruct

At the kick-off meeting, the bridge components were categorized into five categories based on importance and detectability. Here, detectability refers to the visibility of the component's surface and the degree to which a sufficient quantity of the surfaces can be scanned at the target scan density. Table 4 depicts the categories based on the two criteria. Those with high importance and detectable fall into Category 1, while those that are not detectable at all fall into Category 5. Between these two extremes lie categories 2 to 4.

Table 4. Element Identification Evaluation Categories

		Element Importance				
		Very High	High	Medium	Low	-
Elementents Detectability	Detectable	Category 1	Category 2	Category 3	Category 3	Category 4
	Partially detectable	Category 2	Category 3	Category 3	Category 4	Category 4
	Non Detectable	Category 5	Category 5	Category 5	Category 5	Category 5

The `top-down` approach aimed to capture components associated to Category 1, while the mixed approach aimed to capture components in Categories 1 and 2, as well as the detectable components in Category 3. Categories 4 and 5 were excluded from consideration.

2.4.2 Top-Down Approach

The top-down approach pipeline depicted in Figure 9 captures both the pre-processing step and the five-step detection and modeling procedure. As noted earlier, the pre-processing removes irrelevant points

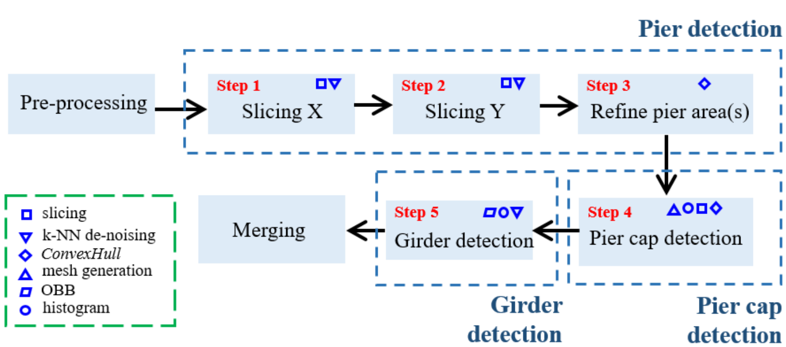


Figure 9. Workflow of Top-Down Bridge Solid Model Reconstruction

through a simple user interface. Since the emphasis was on capturing components associated to Category 1, elements that are highly detectable with very high importance, the cropped bridge PCD contains only the key structural components to recover: namely the deck assembly, piers, pier caps and girders. An additional outcome is alignment of the bridge to the coordinate axes. The span is along the x-coordinate, the transverse along the y-coordinate, and up/down along the z-coordinate. The automated steps 1 to 3 analyze transverse and span-wise cutting planes of the bridge to establish the regions with piers. Step 4 performs additional pier extraction steps. The main objective is to determine whether to decompose them further into a columns and a pier cap, or to model them as a single entity. Once the pier geometry has been established, the next step (Step 5) examines the superstructure area for existence of girders. At the conclusion of these steps, the sub-divided components are reconstructed as solid model components at LOD 100. Each identified component is modeled using the automatically extracted bounding box information. Evaluating against ground truth, the method has a 98.7% top-down partitioning accuracy and a 97% component label classification accuracy.

2.4.2.1 *Top-Down Approach: Details*

Figure 10 illustrates the input (top-left) and output (top-right) of the top-down approach with an image of the intermediate processing (top-middle). The bridge is cut into several transverse sections along the bridge span. Analysis of the cross-sectional information leads to classification of the cuts into pier containing and other classes. To improve the analysis, span-wise sections along the bridge transverse provide an alternative partitioning, with which to refine the pier containing vs other classifications. A subsequent substructure geometric analysis establishes the existence of a solid pier versus a pier with a cap and columns. Moving to the superstructure, a girder detection procedure (bottom row) determines whether the bridge model should include girders or not. Once the point cloud has been sub-divided into semantically meaningful component categories, their geometric bounding boxes inform the creation of a simplified solid model of the bridge (top-right). The color coding of the bounding boxes distinguishes the different components (red: pier columns, green: pier caps, and blue: deck).

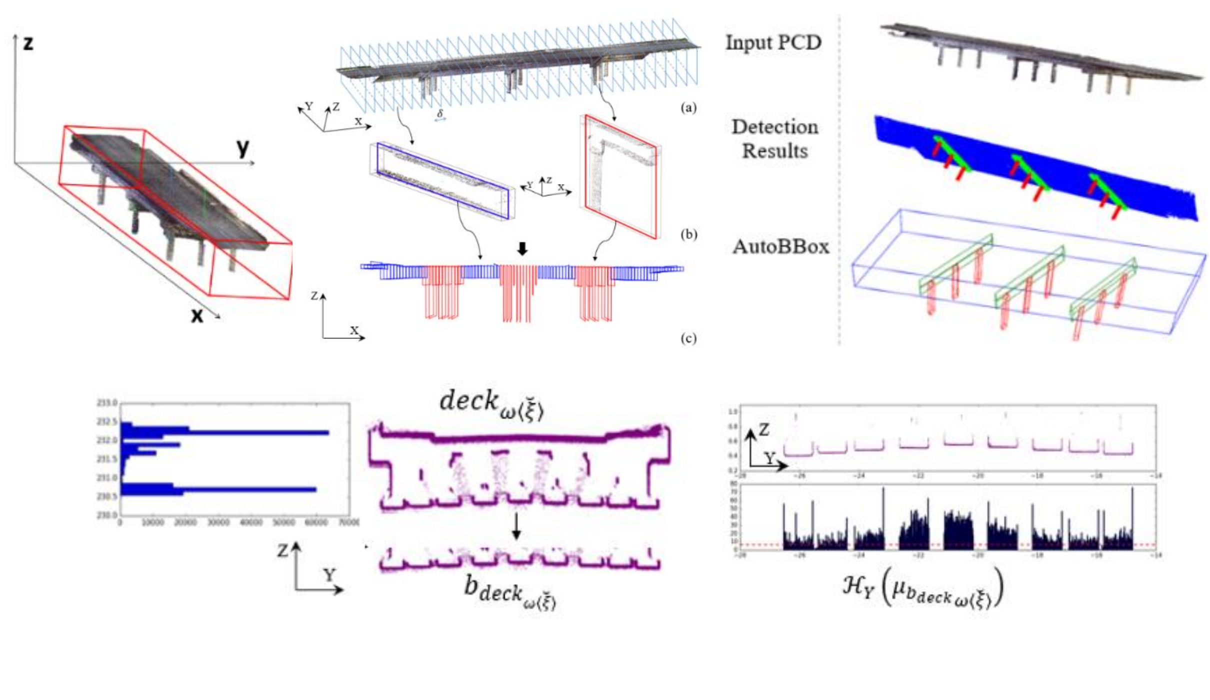


Figure 10. Depiction of the pre-processed input data (top-left), the intermediate top-down partitioning results (top-middle), and the final automatically extracted bounding box information (top-right). The bottom row depicts intermediate results associated to the girder detection and extraction procedure.

To assess the performance of the automated algorithm, Bridge Information Models (BrIM models) of ten bridges in and near Cambridge, UK, were prepared using the state-of-the-art BIM software (Autodesk Revit). The process took approximately 28 hours on average to complete a full model for one bridge at LOD 300 (with 1.5 hours per bridge on average for manual segmentation). In addition, manual segmentation of the point cloud led to ground truth outcomes for evaluation of the top-down outcomes. This manual process took approximately 90 minutes to complete, per bridge. In contrast, the automated processing took 20-30 minutes per bridge. Comparison with ground truth indicates that the top-down partitioning accuracy is 98.6% while the component-level detection accuracy is 97%. The source data for these aggregate accuracy statistics is available in Table 5 and

Table 6.

Table 5. Performance Evaluation Results of the Component-Level Point Cloud Segmentation

Bridge ID	1	2	3	4	5	6	7	8	9	10	Avg
macro-avg PRE	98.40%	99.95%	99.92%	99.86%	99.90%	99.98%	94.35%	99.97%	99.98%	99.97%	**99.15%**
macro-avg REC	99.15%	99.44%	98.86%	99.82%	99.04%	99.41%	87.81%	99.47%	99.75%	99.08%	**98.08%**
macro-avg F1	98.77%	99.69%	99.39%	99.84%	99.47%	99.69%	90.96%	99.72%	99.87%	99.52%	**98.60%**

Table 6. Performance Evaluation of the Component-Level Detection Outcomes

Bridge ID	1	2	3	4	5	6	7	8	9	10	Avg
FN	1	0	0	1	0	0	2	1	1	0	
FP	0	0	0	0	0	0	0	0	0	0	
TP	12	4	4	12	3	7	18	6	6	7	
precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	**100%**
recall	92%	100%	100%	92%	100%	100%	90%	86%	86%	100%	**95%**
F1-score	96%	100%	100%	96%	100%	100%	95%	92%	92%	100%	**97%**

2.4.3 Mixed Top-Down/Bottom-Up Approach

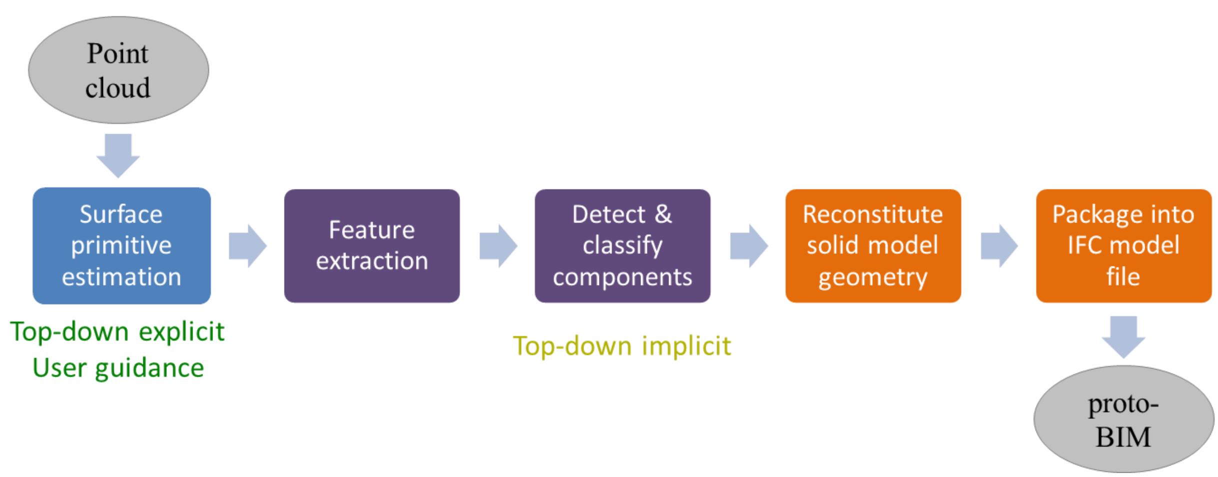


Figure 11. Pipeline of the mixed top-down/bottom-up procedure.

The mixed approach, depicted in Figure 11, consists of several steps that are grossly described as (1) surface primitive segmentation and estimation, (2) surface primitive component detection and classification, and (3) model reconstruction and output. As part of the first step (blue), user guided bridge point cloud cropping occurs, followed by an automated top-down partitioning strategy. Once partitions, each partition is processed to arrive at the surface primitive over-segmentation. It is an over-segmentation in the sense that there is ideally one segment per face, which will require a sub-sequent process to establish the component level gluing of the surface elements into a single solid model object. Prior to finalizing the output, a user confirmation step preserves valid surface segmentations and rejects nuisance surfaces due to incomplete de-noising. The second step (purple) analyzes the geometric and connectivity properties of each surface element to arrive at a hypothesis for the solid model component that it generates, plus the component type it must be. The component type may be one of the following bridge component categories: pier, pier column, pier cap, abutment, diaphragm, girder, box-beam, slab, deck, road, and parapet. From the component hypotheses and classifications, the individual surfaces are appropriately merged to create solid-model objects. For components expected to have partial visibility, surface completion heuristics inform the final solid-model; for example, the abutments extrusion length is based on the longest span-wise element in the abutment region as the true volume is hidden. The solid model parametric descriptions inform the creation of an IFC output file for the bridge.

The IFC model output is at LOD 200 for the substructure and superstructure elements, and at LOD 100 for the deck elements. Based on the user surface primitive rejection steps, surface primitive segmentation accuracy varies from 2% to 10%. After the user correction step, the accuracy is 100%. However, although all surfaces that should exist do so, some surface may be represented by surface patches rather than one single surface. Having more surfaces than actual surfaces is over-segmentation. The over-segmentation rate ranged from 1-24%. In some cases, the component gets represented by multiple solid objects (Ackworth abutment), however in some cases the surfaces are correctly joined to represent the component in question, and in others some surfaces are removed but still captured when reconstructing the volumetric model. Component-level recovery from the surface primitives ranges from 97%-100%, with many of the missed components arising from incomplete components (for example, only one of three faces exist in the laser scan of a diaphragm). At this level, a component is considered recovered if at least one solid model exists for the component and that is has approximately the correct geometry. User time varied from 25 minutes to 1 hour, and scaled with the complexity of the bridge (i.e., number of components and the size of the initial point cloud with nuisance data). Likewise, processing time was variable, ranging from 8 hours to 60 hours.

2.4.3.1 Mixed Approach: Details

Figure 12 depicts the outcome of the surface primitive segmentation block for the Ackworth bridge. The left-most image contains only those surfaces associated to the pier partition zones, while the middle image includes the abutment zones plus the superstructure. Visible are the girder and the diaphragm surface elements. The right-most image adds the deck surfaces, including the roadway, the siedwalks, and the parapets. The surface primitive information is analysed by the machine learning algorithm to recover the hypothesized solid-model geometry and component-level classifications. The information supports the creation of a solid-model instantiation of the bridge and subsequent file output in the IFC format.

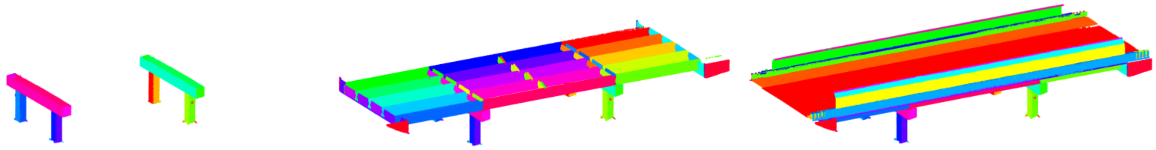


Figure 12. Surface primitive segmentation output, where each surface is given a colour. Due to the number of surface elements, some colours are similar though effort has been made to separate like colours. Left: segmentation of the piers; Middle: inclusion of the remaining substructure components (abutments) and the superstructure (girders plus diaphragms); Right: inclusion of all other components (deck side faces, road and sidewalk surfaces, plus parapets).

Sample IFC output for the entire pipeline is provided in Figure 13 for the three bridges processed. The deck components have been hidden to expose the superstructure elements. The Acworth bridge is complete, whereas the Haifa bridge has missing diaphragm components due to incomplete laser scanning. The Cambridge bridge consists of box beams, each of which was extracted. Once of the center span box beam components has been selected, hence its darker blue color relative to its neighbors. For all bridges, the pier elements are correctly extracted, as well as the abutments. Though not visible, the Acworth abutment is over-segmented. Thus, rather than a single volume, it consists of three smaller volumes. All essential surfaces with sufficient scan density have been recovered and would permit photographic texture mapping. Table 7 and Table 8 details the performance of the pipeline, with the former providing compute and user guidance time breakdowns, and the latter providing segmentation accuracy and component level detection accuracy. Missing components are mainly due to insufficiently scanned surfaces.

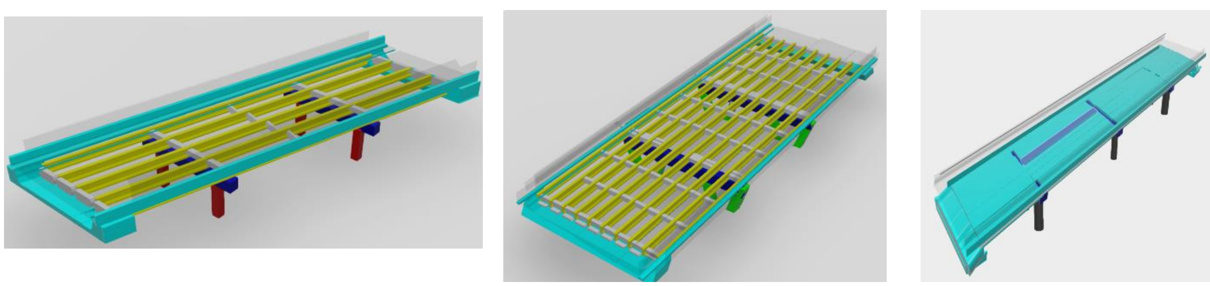


Figure 13. IFC model output for the three bridges, Acworth (left), Haifa (middle), and Cambridge (right).

Table 7. Processing time statistics broken down by step and in aggregate.

Time (hours)	Acworth	Haifa	Cambridge
Pre-processing (user)	0.3	0.5	0.3
Segmentation	8	59	14
Review & Revise	0.09	0.5	0.2
Remaining Pipeline	0.15	0.3	0.2
User	0.4	1	0.5
Algorithm	8.15	59.3	14.2

Table 8. Surface primitive segmentation error and component detection accuracy (N/C = not counted).

Accuracy	Acworth	Haifa	Cambridge
Detection Error			
Initial (Automated)	1.4% (4/286)	7% (57/807)	9.3% (11/118)
Over-segmentation	0.7% (282/280)	N/C	24% (107/86)
Component Detection Accuracy	100% (64/64)	92% (176/191)	100% (64/64)

2.5 Semantic Enrichment

Semantic enrichment refers to the automatic or semi-automatic addition of meaningful information to a digital model of a building or other structure by software that can deduce new information by processing rules. The inputs of the engine are an existing model, information about the bridge from other sources (such as a database), and a set of rules that encapsulate bridge engineers' knowledge. The rules use the existing information and evaluate the topological, spatial, geometric and other relationships between the model's objects. The output is a bridge model that incorporates the new information – new objects, property values, and/or relationships.

The objective was to build and test a software application capable of upgrading a 3D bridge model to an information model that is sufficiently rich to serve as a central component for a bridge Management System (BMS). Such an enrichment process requires input from bridge engineers. To automate this process, the semantic enrichment engine was designed to encapsulate bridge engineers' knowledge as computer readable rule sets, and to parse and update the model accordingly. The software engine was implemented as a 'software as a service' application available online, and the tool has been released as a beta version for testing. It is available to the public for testing, and can be found at http://vclab.technion.ac.il/seebridge .

2.5.1 Semantic Enrichment Engine software

The Technion and TUM teams developed the beta version of the semantic enrichment software. The software uses a run time forward chaining rule-processing engine to classify, label, aggregate and infer obscured objects in a BIM model based on the geometry and topological relationships of the components. It is provided through a web interface and is available at:

http://vclab.technion.ac.il and from the SeeBridge project web site.

The software includes functions for parsing the existing bridge model, testing for geometric and topological relationships, and for creating new objects, properties and relationships and adding them to the model. The rule-processing inference in the software is defined as IF-THEN rules using a predefined set of objects, relational and logical operators, expressed in a format comprehensible to domain experts who are not programmers. The figure below shows an example of the interface with a rule for classification of elements of a girder bridge. The rule checks for a set of conditions concerning two objects, and if they evaluate as TRUE, then the objects are classified as a Transverse Beam and a Main Girder.

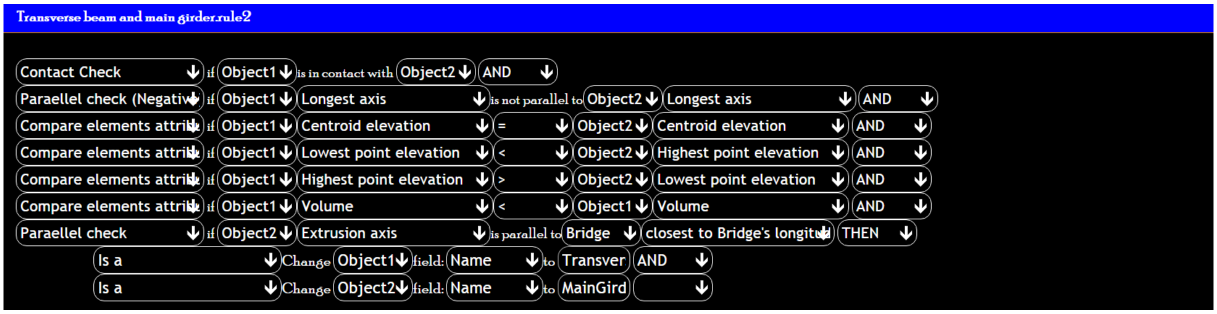


Figure 14. Sample SeeBIM rule. This rule is used to identify girders and transverse beams.

The enhancements to the alpha version include:

1. a novel and rigorous method for compilation of inference rules,
2. the ability to import alphanumeric data from a database, such as a Bridge Management System, in addition to the 3D model reconstructed from the point cloud data, to support the inference process,
3. additional operators for identification of shape features and spatial relationships that are common in geometrically complex facilities like bridges.

These enhancements removed the restrictions imposed by the alpha version's axis-aligned bounding box representation of the geometry by using a minimal volume bounding box (MVBB) representation, in the first instance, and implementation of more sophisticated spatial and topological operators to account for explicit and potentially concave geometry representation, in the second instance. The operators were based on those defined in the QL4BIM query language. The 3D geometry is processed as triangulated boundary representation, and operators evaluate correctly with convex and non-convex shapes.

For imperfect datasets, the support of user-defined tolerances in the processing of directional and topological predicates is needed. This is especially the case if geometry is reconstructed from a laser-scanned point cloud. Besides numerical discrepancies, parts of the objects' surfaces may be obscured in these data sets. This too was provided successfully in the software, and users can specify tolerances for the operators in the SeeBIM interface.

Full details of these enhancements can be found in publication #4 listed in Section 5.3.2 on page 46 below.

2.5.2 SeeBridge rule sets for Girder and Slab bridges

The rules for enrichment were developed in the following steps:

1) A basic set of spatial and topological relationships that may exist between pairs of element types (e.g., objects of type A are always below objects of type B) that are most apparently relevant for object identification is defined in consultation with domain experts.
2) The experts were asked to express their knowledge in the form of a set of matrices, one for each of the relationships. Each matrix represents a single pairwise relationship. The values in the cells are the logical results of the relationship. By design, the result values include the direction of the relationship, so that the cells below the diagonal are not needed.

3) The values for each given cell in the resulting set of matrices are strung together to generate a string in each corresponding cell of a composite pairwise spatial/topological relationship matrix. This is an NxN matrix (where N is the number of possible object types) but it has N(N+1)/2 values.
4) Each string is then compared with all others. Any string that is unique implies that if the set of relationship result values it represents is found to hold for any pair of object instances in a BIM model that is being enriched, then the identity of both of the objects can be ascertained.
5) If any object type does not have at least one unique string, then additional pairwise relationships or singular feature rules (e.g. ranges of volume, dimensions, etc.) must be added, repeating the process from step 2. This is done repeatedly if necessary, until all object types have at least one unique string.
6) Next, each string is checked to determine whether it can be shortened and remain unique, to derive a set of 'minimally unique' string codes.
7) Finally, a SeeBIM rule is compiled directly from each minimally unique string.

The rule-sets for girder bridges and for slab bridges are provided in Deliverable 4.2, version 2.0, 30th June 2017. They perform classification, numbering, axis reconstruction, aggregation and repair occlusions.

2.5.3 Test results

The system was validated using full-scale 3D models of concrete highway bridges:

- One synthetic model of a bridge above route 79 in Haifa, modeled manually in Revit from point cloud data.
- Three models from GT, generated automatically from point clouds using 3D reconstruction with the bottom-up approach: Haifa route 79 bridge and Atlanta Acworth bridge (both girder bridges but with different scopes of component objects) and Cambridge bridge #1 (slab bridge).
- 10 models from UCAM, generated automatically from point clouds using 3D reconstruction with the top-down approach: Cambridge bridges #4, #6, #8 and #9 (slab bridges) were used for testing.

All the bridge models were aligned in such a way that the longitudinal axis of the bridge lay along the X axis, the Z axis was vertical, and the origin was placed at the top face of the center of the deck. Semantic enrichment rules were applied using SeeBIM 2.0 to classify the bridge objects, to number them, to reconstruct the grids of axes, to aggregate them into bridge systems, and to repair occlusions. In Table 9 below we summarize the results of these aspects of the enrichment for all of the bridges tested.

The rule sets tested were developed using the Haifa girder bridge and Cambridge slab bridge #8. Whereas the slab bridge rules proved to be sufficiently generic to work with all selected slab bridges (selection has been made by choosing bridges with the same object types), the girder bridge rules proved to be sensitive to the existence or lack of specific object types. This clearly indicates the need for additional rules, i.e. for rule sets to be sufficiently redundant to cope with imperfect 3D reconstructions where objects required in paired relationships may be missing. Although time did not allow expansion of the rule sets for girder bridges, we are confident that this is a technical matter of extending the rule sets using the procedures developed, and does not require any fundamental research or new procedures.

Table 9. Test results for semantic enrichment. The percentage number is the degree of precision (i.e. number of correct results / number of candidate objects)

Bridge	**Haifa Bridge on Route 79**		**Atlanta Acworth**	**Cambridge 8**	**Cambridge bridges 4, 6, 8 and 9**
	Manually created model	**Automatically generated model (bottom-up)**	**Automatically generated model (bottom-up)**	**Automatically generated model (bottom-up)**	**Automatically generated model (top-down)**
Classification	100% All objects classified correctly with no false positives (columns, capping beams, plinths, transverse beams, abutments, girders, shear keys, slab and light posts).	27%[1] 8/30 primary girders were recognized. 8 transverse beams were classified as slabs and 8 plinths as primary girders.	34%[1] All of the columns, capping beams, deck slabs and 6/20 girders classified correctly. No transverse beams or abutments were classified.	96% Most objects classified correctly with no false positives. Abutments were not recognized due to wrong reconstruction of the width of the abutment.	100% All objects classified correctly, with no false positives. Object types included: abutments, columns, deck slabs, railings.
Numbering	100% All objects numbered, no numbers were repeated or omitted.	- Numbering was not tested due to small number of classified objects.	100% / 34% All classified objects were correctly numbered, but these were 34% of the objects.	100% / 96% All objects except abutments were numbered. No numbers were repeated or omitted.	100% All objects numbered, no numbers were repeated or omitted.
Grid reconstruction	100% All axes reconstructed correctly.[2]	- Grid reconstruction was not tested due to small number of classified objects.	100% / 44% 4/9 axes were reconstructed correctly.[3]	100% All lateral axes except those beneath the abutments were reconstructed.	NA Only lateral axes beneath the abutments were reconstructed. There are no capping beams and no objects to define longitudinal axes.
Aggregations	100% Objects were correctly aggregated to systems. No inadequate aggregation or objects not aggregated. [4]	- Aggregation was not tested due to small number of classified objects.	100% / 34% All objects that were classified correctly were correctly aggregated to systems. [4]	100% / 96% All objects that were classified correctly were correctly aggregated to systems. [4]	100% All objects were correctly aggregated to systems. No inadequate aggregation or objects not aggregated. [4]
Occlusions	100%[5]	Not tested.	No occluded objects.	No occluded objects.	No occluded objects.

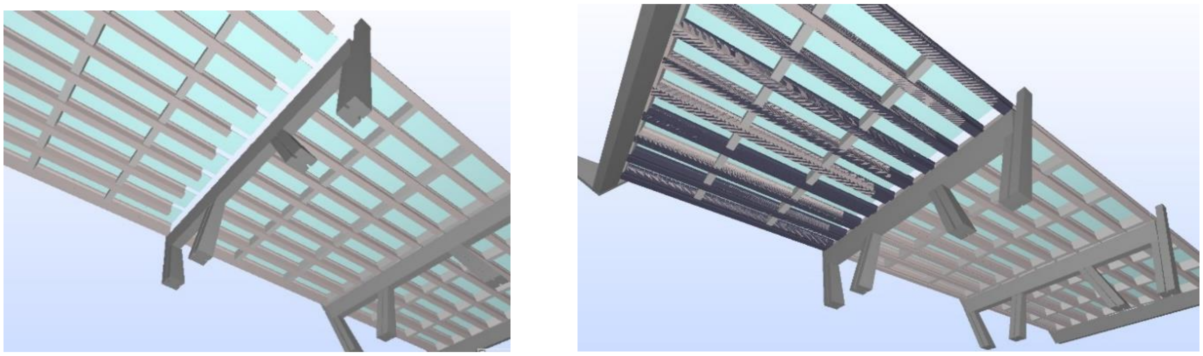
[1] Classification of the objects is dependent on the quality of the geometric model. See discussion below.

[2] Axes are on the centreline of the projection to XY plane of the following objects: abutments and capping beams (for lateral axes) and main girders (for longitudinal axes).

[3] Axes were not reconstructed for 3/5 of the main girders and 2/2 of the abutments as they were not classified.

[4] Systems compiled: substructure, superstructure, deck and spans. For the Haifa bridge, the lighting system was also aggregated.

[5] Shortening and lengthening of the main girders was successful (see Figure 15).



(a) (b)

Figure 15. (a) Girders modelled too short due to occlusion; (b) addition of full length girders to the model. Note that the original girder geometry is retained for review if need be.

Classification of the objects is dependent on the quality of the geometric model. The automatically generated models of the slab bridges, prepared using both bottom-up and top-down procedures, were good and allowed for successful classification. The bottom-up reconstruction of the girder bridges (Haifa and Acworth) was less successful in terms of generating objects that could be classified. The model of Haifa bridge suffered from features such as objects that overlap in large proportion (columns overlapping with capping beams), adjacent objects with very large gaps between them (girders and the transverse beams), missing objects, segregated objects, and objects there were not initially in the scope but modelled nevertheless (e.g. advertising billboards). Some of these can be corrected for by increasing dimensional tolerances in the rule set, but this could not be tested due to late delivery of the reconstructed models.

For the bottom-up reconstructed Atlanta Acworth girder bridge, numbering and aggregation precision was low because the classification step only managed to classify 34% of the objects. This is a result of the minor but important differences in scope and arrangement between the two girder bridges: e.g. Haifa bridge has plinths on the capping beams, Acworth bridge does not. The relevant rules, compiled with knowledge of the Haifa bridge, assumed the existence of plinths, so that the system could not classify objects whose rules included pairwise relationships with plinths, in this case capping beams. Similarly, the rules for girder classification assumed the presence of slab objects: the reconstructed model had slab objects at its edges only, thus only the edge girders were classified correctly. These problems are technical in nature, and can be resolved by adding additional rules to cater for these situations. The primary lesson learned is that the rule sets must be redundant, i.e. including rules that cover multiple situations. Compiling rule sets for each sub-type of bridge (by scope of object types in the bridge) can also be a useful practice.

We conclude that if the set of objects expected to be found in a bridge is known, then the rules can be compiled to achieve a very high degree of reliability for classification, and thus also for numbering and aggregating objects and for reconstructing grids of axes. Rule sets can incorporate a degree of redundancy to make them robust in situations where some objects expected are absent from the reconstruction. Thus, rule sets must be specific for bridge sub-types (e.g. girder bridges with/without capping beams). This will require more work than the presumed preparation of one rule set for each major bridge type of the four defined in the IDM, but it does allow for a still relatively small set of rule sets, each of which must be compiled and tested just once, according to the approach developed in SeeBridge.

2.6 Damage Detection and Identification

2.6.1 Texture mapping

The texture mapping aims to reconstruct the complete visible surface texture of all bridge elements based on the bridge geometry and high-resolution imagery. Therefore, for each bridge surface point the corresponding images and image coordinates have to be identified. Detailed bridge geometry and high-resolution imagery exists from previous work packages. No workable solution exists that instantly provides position and orientation of the camera in a sufficient way. The only location information that can be used is the image content itself. Our method for texture reconstruction consists of four steps: (1) photogrammetry using the unregistered imagery; (2) registration of the laser-scanned point cloud and the photogrammetric point cloud; (3) image candidate extraction based on ray tracing and (4) image selection based on pixel size and surface/camera angle.

The photogrammetry is a crucial and fragile step in the process. This step extracts the camera position and orientation. Minor inaccuracies and registration errors have major impact on the reconstruction results. We tried an element-wise photogrammetry, where we only used images showing a specific element, and a global photogrammetry, where we used all images of a bridge. Element-wise photogrammetry is less error-prone and less computationally expensive, but more difficult for later registration. Global registration, instead, is computationally expensive as the search space for corresponding features grows exponentially with the number of images to search in. At the same time, the point-cloud to point-cloud registration in step 2 and 3 is easier as global correspondences can be used.

We used multiple methods for registering the photogrammetric point cloud to the laser-scanned point cloud. A first approach was to directly pick correspondences in both point clouds, out of which one can calculate the transformation to get from one 3D space to the other. Picking exact correspondences requires identification of the same unique positions in both point clouds. On round objects, such as columns, this is not possible as there are no corners, and, if done on element level, features of adjacent elements are absent. Our second attempt was to determine a picked point in the photogrammetric point cloud based on locating the same point in two images and using epi-polar geometry to calculate the corresponding 3D point. We used the iterative closest point algorithm (ICP) for refining the registration. However, this method requires constant point densities. Point clouds from photogrammetry and also from laser scanners vary considerably in density which lead to poor results of ICP. Our final method is a hybrid approach of using the global photogrammetric point cloud for point-cloud to point-cloud registration, extracting the transformation using the images used in the global and element-wise reconstruction, and using the element-wise reconstruction for the subsequent step.

The next step is to select the corresponding images and pixel positions for each geometry surface point. We used a ray-tracing approach to identify whether an image pictures a specific surface point and also to extract the corresponding pixel position. A line can be drawn between each optical center and surface point. Supposing a linear camera model, the intersection of this line and the image plane pictures the corresponding surface point. Occlusions caused by other elements can be detected by verifying whether this line intersects with other elements first. Occlusions caused by vegetation or cars cannot be detected and have to be sorted out manually.

Finally, we pick one pixel representation out of the list of pixel candidates based on the following rules:

- Image pixel size: A smaller image pixel shows greater detail. Distance, however, should not be used as it does not take zoom into account. A far away picture shot with zoom can be better than a close-up.
- Pixel position in the image: Optical non-linear effects are smaller in the image center and hence are better for texture reconstruction as the precision of the location is higher.
- Camera angle to the surface: A perpendicular orientation of the camera lens to the surface is desirable, as this way a square shaped pixel maps a square shaped region on the element surface. Having a different angle deforms the shape of the surface region mapped by a square shaped camera pixel.

A corresponding reconstruction of a column surface is shown in Figure 16.

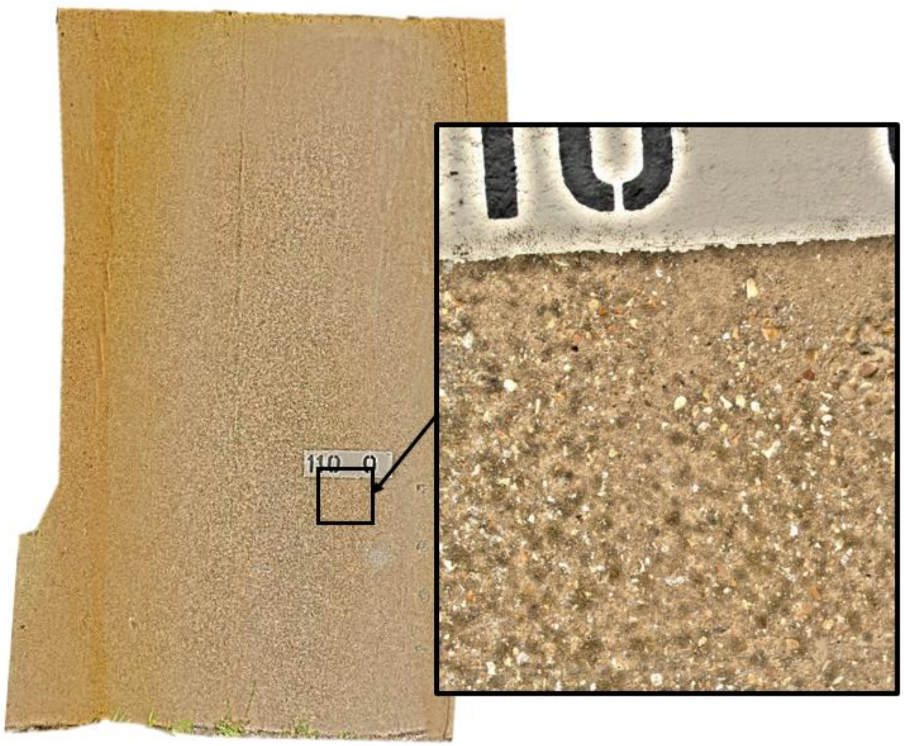


Figure 16. Reconstructed surface based on bridge geometry and high resolution imagery

Annotated dataset

The dataset consists of multiple data sources. We first collected own data as described before. This results in an enormous number of roughly 3 TB of mostly intact concrete surface, but as there is only a minor number of defects on these bridges, we identified additional data sources for defect imagery specifically.

We asked multiple Department of Transportation (DoT) agencies to make their inspection repositories available. Federal Highways Agency (FHWA), Peterborough City Council, Connecticut DoT and Georgia DoT provided 75 GB of inspection data.

Defect detection

The objective is to develop a method that localizes and classifies defects in a surface texture image. Machine learning methods are the state of the art method for localization and classification tasks in multiple fields. We have a two-stage approach to use machine learning to solve the defect detection problem. The first stage is to distinguish intact from suspicious concrete. Bridge defects can appear in a large variety. Finding samples of all possible appearances is not possible. Hence, our first stage is to detect intact concrete and reduce the element surface area only to the suspicious areas which might be a defect. To do so, we split the surface texture into little chunks and train a deep neural network to only classify these chunks as either *intact* or *suspicious*. We have used a pre-trained Inception V3 network and fine-tuned it on our own dataset. This process is still on-going, but first results are promising, as can be seen in Figure 17. In the example shown, we manually added a spall and tried to give it an inconspicuous appearance. It is successfully detected by the classifier. For the second stage, we extract the connected suspicious chunks and refeed them into a second, separately trained network. This will give us a score for each defect class. The advantage in this approach is that even if a defect is not known, the classifier will detect it as suspicious as long as its visible appearance differs from faultless concrete. These indistinct findings can be presented to a human inspector for further investigation.

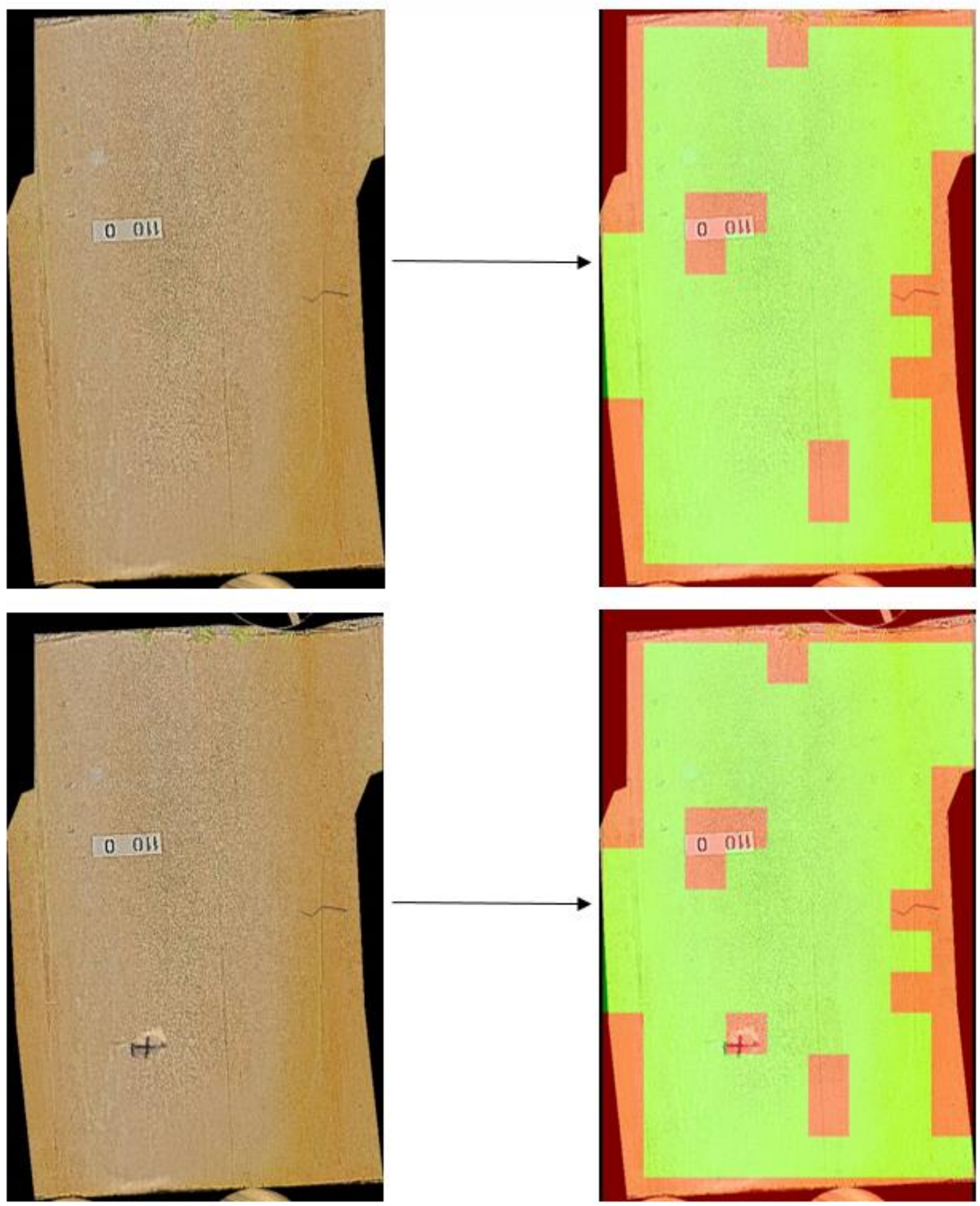


Figure 17. Classification of an element texture with and without an example spall

Integrating damage data into BIM

We have developed a novel concept for integrating RC defect information into an open and well-defined BIM model using the latest IFC standard (IFC 4 Add 2). In order to have a meaningful and significant basis for what information to include in a BMS for the purposes stated, existing bridge inspection guidelines from multiple continents were examined and requirements for defects and their properties were extracted and analyzed. We have converted this information into an object-oriented hierarchy and assigned corresponding IFC 4 entities, both structurally and content-wise. The resulting entities are presented in Figure 18 along with the relevant defect properties in Table 7. We have defined a typical inspection situation and documented findings in an example file in order to illustrate the feasibility of the concept. We have developed a prototypical viewer which is able to open and visualize the resulting model. Figure 19 shows some example defects. We found that the existing IFC 4 standard is capable of modelling bridge defects and general bridge inspection information in compliance with existing bridge inspection guidelines.

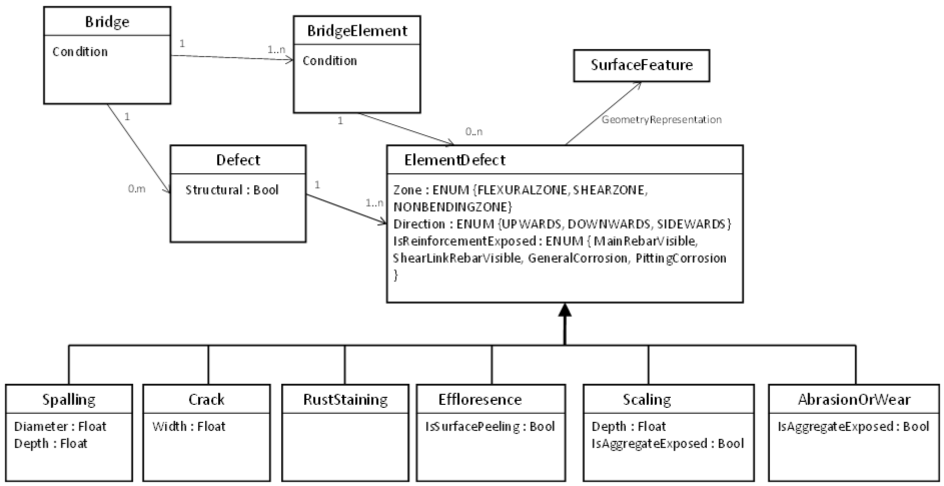


Figure 18. Information model of bridge defects

Table 7 Property sets, their properties and data types.

Surface defect	**Property**	**Data type**
Spalling	Diameter	Float
	Depth	Float
Cracks	Width	Float
Rust staining	Presence	Bool
Efflorescence	IsSurfacePeeling	Bool
Scaling	Depth	Float
	IsAggregateExposed	Bool
Abrasion / Wear	IsAggregateExposed	Bool
Exposed reinforcement	State	Enum (MainRebarVisible, ShearLinkRebarVisible, GeneralCorrosion, PittingCorrosion)
General	Zone	Enum (FlexuralZone, ShearZone, NonBendingZone)
	Direction	Enum (Upwards, Downwards, Sidewards)

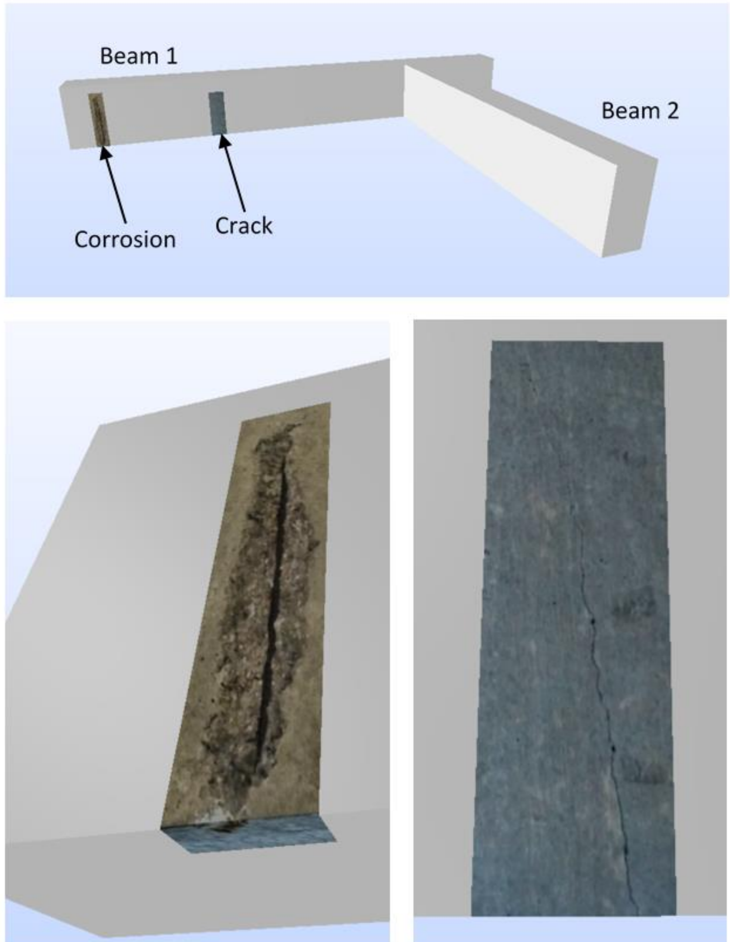


Figure 19. 3D view of IFC model including the defect location and texture. Zoomed in views show high resolution defect texture.

2.7 Internal Technology Readiness Level Assessment

The Technology Readiness Level (TRL) internal assessment report evaluates the technological maturity of SeeBridge and all its pertaining components, in an exclusive and holistic manner. This TRL assessment was conducted in collaboration and accordance of all consortium members, and numerically represents the level of maturity achieved, both at sectional level as well as at overall level. The standard used for the assessment was the TRL criteria developed and published by the US Department of Defense, which uses scores ranging from 1 to 9.

The assessment was performed for two kinds of bridges – Slab Bridges and Girder Bridges. Each kind was evaluated against the TRL criteria, both at the local/sectional and global level. The TRL for each bridge type was determined by taking the minimum score of all steps in the process. Where more than one technical solution for a step was developed, the maximum score of all pertaining solutions was taken as a representative of the TRL score for that step.

The internal assessment of the overall Technology Readiness Level (TRL) of the SeeBridge prototype system (Deliverable 6.1) determined that at the end of the project, the system had achieved TRL 6 for slab bridges and TRL 5 for girder bridges. The following figure succinctly illustrates the scores assigned to each of the sections, as well as the overall scores for both bridge types. The system component that governs the TRL level for slab bridges is the semantic enrichment step, whereas the component that governs the TRL level for the girder bridges is 3D geometry reconstruction.

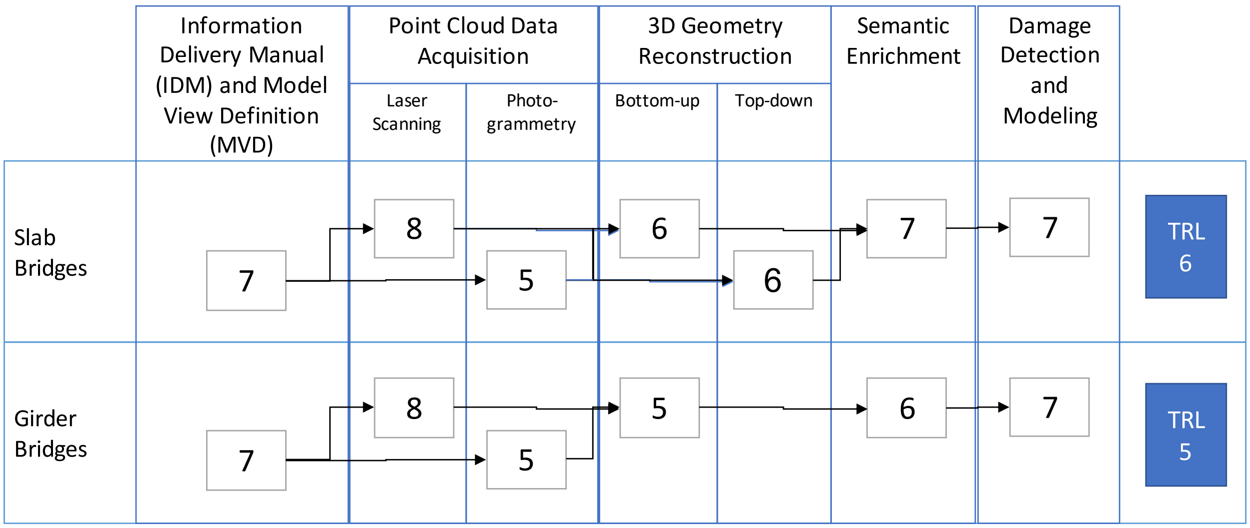


Figure 20. Technology Readiness Levels for SeeBridge components at project end (internal assessment). See Deliverable 6.1.

The TRL scores of 6 and 5 for slab bridges and girder bridges respectively suggest that the system has been tested in a relevant environment and that the system has passed all testing measures in a simulated operational environment.

A detailed analysis of the assigned scores can be found in the full TRL Internal Assessment Report (Deliverable 6.1). In addition, the set of questions and answers in the box below may help readers interpret the overall assessment.

What needs to be done to reach the next TRL?

As the overall TRL score is based on the minimum of all the part-specific scores, improving the score of the weakest stage will drastically improve the overall TRL. For both Slab and Girder bridges, the weakest link in the process was the '3D Geometry Reconstruction' phase which did not meet the automation as well as the LOD requirements. Hence, investing in and improving the reconstruction phase will drastically improve the overall performance of SeeBridge.

To what degree is the scope of the system limited? What actions are required to extend this scope to additional bridge types?

The scope of the overall system is currently limited to reinforced concrete slab and girder bridges. Of the four SeeBridge system steps, two are independent of the bridge type (i.e. will work for any bridge type) and two are type specific, as follows:

1) Laser scanning is generic, and will work for any type.

2) 3D reconstruction requires knowledge of the bridge components that can be expected. Top-down reconstruction steps are specific to each bridge type and must be tailored for it; bottom-up reconstruction requires a library of possible bridge components, but can work with any type if its components are defined with 3D geometry. Extension to other bridge types primarily requires addition of geometry primitives, including review of the IDM and MVD, but very little (if any) adaptation of the core software.

3) Semantic enrichment has rule sets that are specific to each bridge type. Extension therefore requires preparation of feature matrices and derivation of rule sets for classification. Rule sets are defined using the SeeBIM 2.0 interface, so that here too, no changes to the core software are needed.

4) Defect detection and registration, including close-range photogrammetry, is independent of the bridge type.

To what extent is the overall output complete?

The content of the output models is essentially complete, containing all geometry, semantic information, and defect information.

Which option for point cloud data acquisition (scanning or photogrammetry) is the most effective?

Laser scanning is effective for point cloud data acquisition. Photogrammetry is not applicable for this purpose for highway bridges, due to the drawbacks listed in section 2 of the SeeBridge report.

Is the system output useful for a BMS?

Yes. This assumes of course that the BMS is sophisticated enough to use all of the information provided, which is not the case for current BMS systems.

3 Encountered Challenges and Solutions

The SeeBridge project can be judged by measuring the degree to which the research progressed beyond the state-of-the-art in the three areas defined as its main research goals:

- Automated compilation of geometric solid objects from bridge point clouds (**3D reconstruction**)
- **Semantic enrichment** of the solid geometry to generate BIM models
- **Damage mapping** (cracks, spalling, etc.) based on the BIM model

3.1 3D Reconstruction

The development of as-is BrIM generation needs to address two challenges common to any solution approach:

a) Complex Geometry. Real-world bridges are not straight or flat and in many real cases, the cross-sections of the deck change though the length of the bridge. Even with a very basic design, bridges contain a certain degree of horizontal/vertical curvature, often in both directions. Traditional surface-based detection approaches tackle this challenge by capturing subtle changes in surfaces. However, this approach is incompatible with large-scale modifications to or high-level operations on the extracted 3D primitives if they are modeled as extruded cross-sections.

b) Missing Data. The traditional problem of object detection addressed by surface reconstruction is to recover the digital representation of a scanned object's shape. Besides noise, which is easily removed by a user-guided process, the scanned data has a second category of defects: missed point data. Missing data is attributed to (1) local variable point densities due to the distance from the surface to the scanner position; (2) poor scanning methodology and planning; and (3) clutter and occlusions.

The solution to the complex geometry problem involved partitioning and reducing the point cloud sub-components evaluated so that more permissive methods may be employed. The partitioning step restricts the algorithms from arriving at erroneous conclusions due to their permissive nature. In a partition with more components, such a strategy may incorrectly merge elements or misidentify points. Reducing the component quantity through semantically meaningful top-down partitioning prevents these types of errors.

Regarding missing data, little can be done beyond utilizing design-aware projections of data to recover component surfaces, and coordinate-wise volumetric information. The best solution would be to promote an intuitive, consistent, and formulaic set of procedures for scanning different categories of bridges. For the case of objects whose lengths can be inferred from their supports or from similar objects, such as girders or capping beams, the occlusions can be corrected in the semantic enrichment step. This was done for the case of girder bridges. Similarly, the presence objects such as bearing pads, and their thicknesses, can be inferred from the vertical gap distance between girders and capping beams, even if they are entirely occluded from the view of the scanner.

3.1.1 Specific Challenges: 'Top-down' Approach

Testing of the top-down approach was limited to slab bridges and girder bridges and to ten bridge samples. The sample size for girder bridges (2) is too limited to assert how generalizable the proposed method is.

To address the aforementioned challenges, the following solutions are proposed:

1. A slicing-based recursive segmentation algorithm is developed which transforms a large unstructured PCD into an ordered sequence of slices, bounding boxes and mid-planes. Slicing makes it possible to approximate the global topology of the bridge through multiple local configurations. This algorithm not only provides the opportunity to achieve an optimal level of detail for future model generation as per IFC standards, it also keeps full access to data detail without any information loss.
2. The proposed slicing algorithm can handle locally imperfect data efficiently through an occlusion immunity scheme that can infer and reconstruct key geometric properties based on closest sound slice.

3.1.2 Specific Challenges: Mixed 'Top-Down'/'Bottom-Up' Approach

Beyond the primary challenges, additional specific challenges included the point cloud quantity and the polynomial time nature of bottom-up methods. Our solution was to incorporate top-down processing to arrive at many low cardinality point cloud partitions, each of which has a consistent run-time. In this way, what would normally be an algorithm with quadratic time cost versus point cloud instead runs in roughly linear time. The final results do not show a strictly linear relationship versus point cloud size. Instead the complexity of the geometry and the speed with which surface elements merge into larger ones is the rate limiting factor. Employing parallel processing architectures would lower the runtime further, but would require additional machines.

3.2 Semantic Enrichment

In the development of the enrichment engine the team had to address three major challenges:

1. In most expert system development efforts, compilation of rule sets is essentially a social exercise that entails interviewing domain experts to elicit their knowledge and compile it in a computer readable format. The process depends on intuition and subjective judgment, and neither the completeness nor the precision of rule sets can be guaranteed. Since the success or failure of the approach is dependent on the robustness of the tools, a rigorous method was needed for compiling rules sets, one that allows testing for adequacy.
2. The input bridge model only provides the geometry and placement of the 3D shapes. However, alphanumeric information, such as the year of construction or a building's location, can be vital in supporting semantic enrichment, providing essential clues to support inference rule processing. Such information is often available in some other data source, such as a highway agency's Bridge Management System, and should be imported with the model.
3. The bridge engineers' inference of bridge objects and systems identification largely depends on the visual screening of the geometric and topological features of the objects and systems. To apply these rules in the enrichment process requires that the inference engine have advanced abilities in geometry and topology processing. Such processing algorithms should be integrated in the system.

To address the three challenges, the following solutions were developed:

1. A new rigorous inference rule set compilation system was developed. The key bridge elements' shape and pairwise features for inference are listed and formed in square matrices. The bridge engineers are asked to traverse and fill all the conditional feature in the matrices. More inference features may be added to the matrices until all the bridge elements can be uniquely identified by their features. These conditional feature matrices are then used to compile the rule sets for the model enrichment.

2. A subroutine for incorporating external data source has been developed in the enrichment engine. The data in BMS is exported in excel files, which are parsed and loaded to the system in the predefined data types.
3. The algorithms for checking ten types of pairwise topological relationships and four types of shape features were developed and implemented in the enrichment engine.

The process developed for rule definition results in rule sets that contain sufficient tests to identify all the possible object types in the domain. This is an important enhancement of the SeeBIM approach to semantic enrichment. Naturally, however, such a system is still subject to the quality of the input data. The objects can be completely and correctly classified only when the models have sufficiently small errors in the locations and geometry of the bridge components to allow the geometry and topological relationship operators to perform correctly with suitable tolerances. However, model deficiencies cannot be completely avoided. For example, two objects expected to be touching may be modeled as overlapped or disconnected objects; in this case the rule checking may give a false negative error. Setting large tolerance values could avoid such results, but setting the tolerance too large is likely to result in false positive errors. Notwithstanding the robustness of the rule compilation process, success of the object classification process remains dependent on the quality of the geometric model.

3.3 Damage Mapping

The major challenges have been:

1. <u>Collecting high resolution data on site</u>:
   Defect detection requires complete coverage of a bridge surface with high resolution surface imagery. While taking these images, several quality requirements have to be considered regarding exposure, surface resolution and still positioning. In contrast, a typical highway bridge environment complicates the image taking process due to the ongoing traffic which leads to suction, spray and noise, surfaces are steep and slippery which make it difficult to find a good stand for an operator and a tripod, and finally, if the weather changes quickly then lighting conditions dramatically can change dramatically. Regarding the completeness of surface coverage, vegetation was a problem as some of the surfaces where completely blocked by close and dense vegetation. To overcome these problems, protective equipment was used to improve the working conditions on site and several pre-processing steps were established to balance the different lighting conditions on each image.
2. <u>Registering the images properly on the texture surface:</u>
   In order to register the images on the surface, all degrees of freedom from the camera relatively to the structure must be known. These include the internal parameters such as focal length and distortions and the external parameters such as the position and rotation. A laser scanner takes a panoramic image along with every laser scan, and the degrees of freedom for this panoramic image are known. However, the image quality is not good enough to do damage detection directly. The idea was to extract correspondences between the panoramic image and the high resolution images to calculate the degrees of freedom for the high resolution images. This failed because differences in resolution make it extremely difficult to find a sufficient number of correspondences. To overcome this problem, an elementwise photogrammetry reconstruction is used to calculate relative camera positions per element. These are then aligned to the bridge model by picking

correspondences manually for a coarse registration followed by an automated iterative refinement to the original laser scanner point cloud.

4. Defect detection

   State of the art machine learning algorithms still work on relatively low-resolution images, and even for this low resolution, enormous computing power is needed. However, the image data we are using is extremely high to enable identification of tiny cracks on large bridge elements. We addressed this challenge by splitting large images into smaller chunks and transferring the computationally expensive tasks to the Cambridge High Performance Computing Cluster.

5. Integration of defect information into BIM

   Inspection guidelines describe what and how to generally document bridge defects and, hence, are the relevant document also for defect localization, classification and property extraction. For this reason, presented defect properties are vaguely formulated as they have been extracted from existing inspection guidelines, clarification and consolidation of these guidelines is desirable.

4 Contributions

SeeBridge addressed the following challenges from the Infravation call:

D.1 Rapid repair, maintenance, retrofitting and revamping

- Novel solutions are needed for rapid repair, maintenance, retrofitting and revamping for future traffic requirements with minimum cost and minimum traffic disruption.
- Integral process control through the application of advanced BIM (Building Information Modelling) and other advanced ICT tools and procedures, for example in combination with prefabrication and DfMA (Design for Manufacturing and Assembly) approaches.

C.2 Next generation testing and monitoring in the exploitation stage

- Application domains include the detection of geometrical and visual anomalies on bridges.
- Non-intrusive (remote or proximity) observation techniques, such as image processing, data interpretation through artificial intelligence.

The research proposal defined a process that applied non-intrusive observation and artificial intelligence tools to compile BIM models with defect identification and recording that would form the information backbone of bridge management systems, which in turn could better support rapid repair, maintenance, retrofitting and revamping of reinforced concrete highway bridges. With hindsight, the results of the project provide a convincing argument for the feasibility of the process.

The specific contributions of the research are the following:

- The IDM and the MVD are detailed specifications of the process and of the information schema needed to support it. They lay the foundation for future work practices and the software tools needed to support them.
- Laser-scanning of fourteen different bridges and videogrammetry for four of them have shown that laser-scanning is a viable, practical and effective means to survey existing bridges for compiling BIM models. Scanning using a vehicle borne system also avoids the need for lane closures and obviates exposure to safety hazards.
- The top-down and the bottom-up approaches to 3D reconstruction, although not perfect or complete, are milestone achievements in that they have illustrated the ability to automate a large part of the process of compiling 3D solid geometry models from point clouds. This is significant not only for bridges, but for much broader domains and applications in civil engineering in general.
- The semantic enrichment engine SeeBIM 2.0 is the first tool of its kind, and it can function with all geometry without restriction on shape nor on orientation.
- Considered in combination, the tools for 3D reconstruction and the semantic enrichment engine have achieved something not previously demonstrated in civil engineering – the ability to derive fully functional BIM models from point clouds. The process still requires the operator to clean up irrelevant data from the point clouds, to classify the type of structure, and to clean up errors where they occur, but the tools reduce the scope of human effort by at least one order of magnitude when compared with the effort required in current practice to model a structure in a BIM tool based on a point cloud.
- The project has convincingly demonstrated a procedure to collect close-range high-resolution photographs of the concrete surfaces of structural elements, to apply the resulting texture images

directly to the surfaces of the objects in the BIM model using the principles of photogrammetry, and to automatically identify regions with defects such as cracks and spalling using machine-learning. The work illustrated incorporation of defect data in the BIM model and the use of mixed-reality tools to support virtual inspection tours of the bridge structure.

While there is naturally much work to be done to eventually produce a commercial tool that implements the Seebridge process, there do not appear to be principle obstacles to achieving a largely automated system. Use of such a system should greatly reduce the effort required to compile as-built BIM models of existing bridges and of bridges under construction, adding a powerful new layer of information to BMS systems.

5 Published deliverables and achieved milestones

5.1 Status of deliverables

All of the Seebridge document deliverables have been uploaded to the Infravation CMT website. Deliverable online tools, datasets, etc. are referenced from documents uploaded to the CMT site. Many of the deliverables are for release to the general public. These are marked PU below, and can be found on the Seebridge web site, under menu item *RESULTS->Public Deliverables*. Items marked RE (restricted) and CO (consortium only) are only available from the CMT site.

Del. no.	Deliverable name	Deliverable Resource Publication status and Location
1.1	Information Delivery Manual (IDM) for typical information requirements for generic Bridge Management System (BMS) and for repair/rehabilitate/retrofit of highway bridges	PU Available from SeeBridge website
1.2	Criteria for evaluation of the completed SeeBridge system	PU Available from SeeBridge website
1.3[6]	Model View Definition for Bridge inspection models, bound to IFC schema.	PU Available from SeeBridge website
2.1	A complete design of experiments with performance metrics	RE
2.2	Three image-enhanced bridge point clouds generated using high-density surveying technologies including laser scanning, video/photogrammetry, etc. Deliverable 2.2A – Photogrammetry Deliverable 2.2B – Laser scanning	RE. Available on Infravation CMT, and see Appendix A. PCD Data available at: https://www.dropbox.com/sh/y3ojgy56ej8d36m/AACfLJYaaFDc4aRwILEblX88a?dl=0
2.3	Validation tools needed to automatically calculate performance for each of the proposed metrics	RE Available on Infravation CMT, and see Appendix A.
2.4	Detailed performance evaluation report	RE Available on Infravation CMT

[6] This deliverable was added to the set during the research as it became apparent that it was essential for implementation of the semantic enrichment step, i.e. to formally and rigorously define the format and content of the IFC output files.

Del. no.	Deliverable name	Deliverable Resource Publication status and Location
3.1A[7]	Data collection and data preparation including generation of ground truth models	PU Available from SeeBridge website
3.1B	Generation of training data based on IDM, and training of classification algorithm.	
3.2A	Top-down integrated processing tool for automated compilation of 3D solid bridge model objects from point clouds (w/registered imagery), including working prototype and demonstration	RE Available on Infravation CMT
3.2B	Bottom-up integrated processing tool for automated compilation of 3D solid bridge model objects from point clouds (w/registered imagery), including working prototype and demonstration	
3.3A	Top-down validation of the automated model extraction framework	PU Available from SeeBridge website
3.3B	Bottom-up validation of the automated model extraction framework	
4.1	A semantic enrichment engine	RE Available on Infravation CMT and also available at http://vclab.technion.ac.il
4.2	A series of rule-sets for inferring bridge components based on 3D geometry and topological relationship. Rule sets for girder bridges and for slab bridges.	PU Available from SeeBridge website
4.3	An expert system for semantic enrichment of bridge BIM models	RE Available on Infravation CMT
5.1	Graphical user interface and annotated dataset of images for damage detection and classification.	RE Available on Infravation CMT
5.2	An integrated system for automated damage detection and classification.	
5.3	Demonstrator of addition of defect data to BIM model.	
5.4	Results of application of the damage classification system to the three bridge models generated from WP2, WP3 and WP4, with validation against standard damage classification from photographic inspection of the bridges.	

[7] During the research, the team decided to pursue two solutions – a top-down approach and a bottom-up approach. Deliverable 3.2A details the top-down approach, developed at Cambridge University, and deliverable 3.2B details the bottom-up approach, developed at Georgia Tech.

Del. no.	Deliverable name	Deliverable Resource Publication status and Location
6.1	Case study at TRL 6: Application of the full process, including scanning of a fourth bridge, solid modelling, semantic enrichment and evaluation for rebuild/repair or rehabilitation of a bridge	PU Available from SeeBridge website
6.2	Project scientific report	PU Available from SeeBridge website
6.3	Demonstration workshop and webinars. A set of pre-recorded videos of the demonstration workshop sessions and a Seebridge demonstrator application are available at http://seebridge.net.technion.ac.il Workshops were held in Atlanta, Cambridge and Tel Aviv on 18th Sept. 2017, and in Munich on 25th Sept. 2017.	PU Available from SeeBridge website
7.1	SeeBridge Administration Guidelines for Partners. Completed and delivered in December 2015. Not publicly available.	CO Available on Infravation CMT
7.2 – 7.4	Quarterly Management Reports. Reports were delivered at ends of months 3, 6, and 12.	CO Available on Infravation CMT

5.2 Milestones achieved

5.2.1 M1: Completion of the IDM

Verification consisted of review by a panel of experts from bridge management departments (GDOT, German Ministry of Transport, Israel Roads Company, London Underground), and evaluation of 'fitness for use' through compilation of a Model View Definition, which was compiled with the assistance of AEC3 (Germany). The IDM is deliverable 1.1, and the MVD is deliverable 1.3.

5.2.2 M2: Completion of non-contact surveys of three bridges

Means of verification: Technical: successful import into GT's software tools; Content: Review by GT, Technion and UCAM teams. The technical and content aspects were reviewed and approved at the mid-term meeting. The material is provided in deliverable 2.2.

5.2.3 M3: Interim review and coordination workshop (all partners)

Presentations of progress by the leaders of the WPs were made at the interim workshop held in Atlanta. The algorithms were evaluated and the damage types for detection were selected in light of the 3D reconstruction accuracy and the photographic resolution that was achieved. The workshop was held at Georgia Tech, Atlanta, on 14th – 15th July 2016.

5.2.4 M4: Ready for start of field testing

This milestone called for installation and operation of deliverables 3.2, 4.3 and 5.3 on the test computers. Deliverable 3.2 had two components, 3.2A using the top-down approach, and 3.2B, using the bottom-up approach. Although the semantic enrichment engine (4.3) and the top-down solver (3.2A) were developed and ready for testing by the end of 2016, the bottom-up solver (3.2B) was significantly delayed, essentially only reaching operational maturity only during the last month of the project (June 2017). Thus Milestone 4 can be considered to have been achieved in large part by January 2017, but completed only in June 2017.

5.2.5 M5: Completion of field testing

As contemplated in the project definition, field testing included data acquisition experiments and testing of the information processing pipeline, although of course information processing was tested in office conditions. Field testing of laser scanning and videogrammetry (WP2) was completed and delivered early in the project, and photogrammetry for defect detection and monitoring was completed more recently. Testing of the information pipeline for the UCAM top-down approach was completed in June 2017, but testing of the GT bottom-up process continued through the end of September 2017.

5.2.6 M6: Evaluation of field testing and reporting completed; Delivery of SeeBridge prototype at TRL6; Demonstration workshop

Three SeeBridge demonstration workshops were held on September 18th, in Tel Aviv, Cambridge and Atlanta. At the time of writing, a fourth is planned for Munich. The full demonstrator configuration of the system was delivered shortly before the workshops. This report, delivered in October 2017, constitutes the last action for milestone 6.

5.3 Publications

5.3.1 Online material

The project website is at http://seebridge.net.technion.ac.il

A web application of the semantic enrichment engine is available for use at: http://vclab.technion.ac.il/seebridge

A full set of nine demonstration videos has been published and is available at: Seebridge playlist (the URL for distribution is:

https://www.youtube.com/watch?v=Z2I1tquadmY&list=PLymiA0moE_Q7CpfXPpBnosRFrxMN4Za4j

5.3.2 Refereed journal and conference papers

1. Sacks, R., Kedar, A., Borrmann, A., Ma, L., Singer, D., and Kattel, U., (2016). **“SeeBridge Information Delivery Manual (IDM) for Next Generation Bridge Inspection”**, in 33rd International Symposium on Automation and Robotics in Construction, A. Sattineni, Editor. 18th-21st July, 2016, Auburn University: Auburn, AL.
2. Huthwohl, P., Lu, R., and Brilakis, I. (2016). “**Challenges of bridge maintenance inspection**” Proceedings of the 16th International Conference on Computing in Civil and Building Engineering, 6th-8th July, 2016, Osaka, Japan, Page: 51-58

3. Kedar, A., R. Sacks, L., Ma, et al., (2016) **"SeeBridge Information Delivery Manual (IDM)"**. Kedmor Engineers, Israel.
4. Sacks, R., Ma, L., Yosef, R., Borrmann, A., Daum, S., and Kattel, U., (2017). 'Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry', Journal of Computing in Civil Engineering, Vol. 31, No. 6, pp. 4017062.
5. Sacks, R., Kedar, A., Borrmann, A., Ma, L., Daum, S., Yosef, R., Brilakis, I., Huethwohl, P., Liebich, T., Barutcu, B.E., Muhic, S. (2017). '**SeeBridge Next Generation Bridge Inspection: Overview, Information Delivery Manual and Model View Definition'**, submitted to Automation in Construction.
6. Huthwohl, P., Brilakis, I., Borrmann, A., and Sacks, R., (2017). '**Integrating RC bridge defect information into BIM models**', Journal of Computing in Civil Engineering, in press.
7. Ma, L., Sacks, R., and Kattel, U. (2017). '**Building Model Object Classification for Semantic Enrichment using Geometric Features and Pairwise Spatial Relationships**' LC3 2017: Volume I – Proceedings of the Joint Conference on Computing in Construction (JC3), Heraklion, Greece, July 4-7, 2017, pp. 373-380. DOI: https://doi.org/10.24928/JC3-2017/0044.
8. Lu R., and Brilakis I. (2017). "**Recursive Segmentation for As-Is Bridge Information Modelling**" LC3 2017: Volume I – Proceedings of the Joint Conference on Computing in Construction (JC3), July 4-7, 2017, Heraklion, Greece, pp. 209-217. DOI: https://doi.org/10.24928/JC3-2017/0020.

5.3.3 Awards

Ruodan Lu, Overall Winner (1st place), "Top-down Bridge Information Modelling System", Construction Innovation Competition, *Lean & Computing in Construction* (LC3), Heraklion, Crete, Greece.

6 Remaining questions and recommendations for further research

The 'bottom-up' 3D reconstruction step was the most challenging, and remains the least well-developed, of the SeeBridge project steps. While the geometry reconstruction is successful in producing 3D solid geometry, questions remain regarding the parameter values that should be used for calibrating the partitioning of segments and objects. The 'top-down' approach does not suffer the same issues, but it does require explicit knowledge and definition of the expected components, making it less generic. A hybrid method, which integrates the top-down and bottom-up approaches, would be worth exploring in depth. Top down inference is a powerful human reasoning mechanism that guides the object detection in bridge point clouds. Specifically, the top-down approach mimics an experienced engineer's process in interpreting and inferring high level semantic information about the bridge that has been scanned or processed. By contrast, bottom-up methods which have been intensively studied in computer vision and can handle more implicit geometric information in point clouds. Bottom-up models may provide essential benefits for minimizing segmentation errors. Therefore, a combination of these two approaches might increase the overall modelling robustness and efficiency.

Another way to contribute to improving robustness of the bottom-up 3D reconstruction step is to identify and classify the issues with merging or separation of solids and to explore application of sematic enrichment rules to improve the results. This would have the advantage of applying bridge-specific knowledge to manipulate the solid geometry as part of the object classification step.

Point cloud subsampling is another interesting topic for future research. Laser scanning technology can produce dense point clouds in minutes. However, efficient point cloud post-processing, storage and transmission remain challenging. It is laborious to use original point clouds for running algorithms or tests without a down-sampling procedure. Subsampling techniques that can compress the point clouds efficiently while maintaining enough key geometric features are a pressing need.

The model enrichment step still requires well-defined and domain-specific rules, in 'if-then' form, to ensure good inference results. Machine-learning techniques, on the other hand, can be trained without the need for a priori rule compilation. In SeeBridge, we did not attempt the machine-learning approach because it requires large numbers of BIM models of bridges with known object classifications. In the future, as BIM models of bridges become more common, this avenue may eliminate the need for knowledge elicitation and rule compilation.

Some technical work is also needed to expand the scope of the system before commercial applications can be considered. The first thing necessary is to expand the IDM and the information schema to cover more bridge types. The second, likewise, is to extend the rule-sets to cover the broader set of bridge types, and to test both the schema definitions and the rules sets on larger sets of bridge models.

In summary, the thrust of future research and development must be to make the methods:

- more robust, with emphasis on the 3D geometry reconstruction from point cloud data, and
- more versatile, with respect to the types of bridges that can be captured.

7 Lessons Learned

As in any research project of a 'design science' nature, as SeeBridge was, the project partners have learned a great deal through 'doing'. The attempt to define, develop and implement a full pipeline for bridge survey, 3D reconstruction, semantic enrichment and defect detection has taught us a great deal. The lessons learned are both practical and principle. Among the practical lessons learned:

- **Short lane closures** are needed for laser scanning and especially for the high-resolution photography. It is unsafe for inspectors to set up a large tripod on highway's shoulders or refuge areas, which are usually small, narrow and difficult to maneuver. We highly recommend preparing a **detailed data collection plan** including safety precautions, data requirements, equipment requirements, on-site equipment layout, and so on. The photography requires taking maximum advantage of natural daytime lighting (cloudy days are preferable). The collected data should be crosschecked before leaving the site. Special attention should be paid to the sequence of the work to minimize the time required. A **guideline document for bridge scanning** with instructions to show how scans should be done for efficiency and for maximum coverage, with detailed method statement templates, is needed. The guidelines must consider different types of bridges and bridge locations within the local environment and surroundings.
- **Manual model pre-processing work is needed both before 3D reconstruction and before semantic enrichment**. Removal of extraneous irrelevant points (e.g. vegetation, vehicles), must be done before 3D reconstruction. Orientation of the main bridge alignment axis to the global X axis, and other minor corrections can be done before or after 3D reconstruction. Although the geometry provided by 3D reconstruction is dimensionally correct, some of the objects may need to be merged or separated once the automated process has been run.
- **Semantic enrichment rule sets must not only be rigorous** (i.e. be able to recognize all bridge object types)**, they must also be redundant** (i.e. they must contain multiple rules for classifying any given bridge object type, for aggregating systems, for numbering, for reconstructing axis grids and for repairing occluded objects). The reason for this is that pairwise relationship rules will fail where any one or the other object type is absent from the specific bridge under consideration, leading in turn to failure to classify the other member of the pair. The more redundant the rule sets can be made, the more generic they will be. Thus, fewer sub-types of bridges will need to be defined, and fewer rule sets will be needed.
- The **tolerance settings for pairwise rules must be calibrated** in accordance with larger samples of reconstructed 3D bridge models.

More fundamentally, we have learned that the 3D reconstruction step is the most difficult one to automate, because generating useful volumetric objects from point clouds is more difficult than expected. An integrated top-down and bottom-up model reconstruction approach is effective for bridges which consist of clearly delineated pieces, such as precast objects with limited variations of shapes and spatial relationships, but more difficult for continuous, monolithic structures. We expect that the methods developed for 3D reconstruction will improve greatly as experience accumulates and the algorithms are improved. From the start, this was the most ambitious aspect of the project, and it is gratifying to recognize that much progress has been made in tackling it.

The major portion of the time for human effort in the SeeBridge process is spent on spatial data collection. With better protocols for survey and possibly with automation of selection of survey positions, this time can very likely be reduced. Extensive experience in the field should allow for a significant learning curve improvement of this aspect.

Finally, condition assessment, and consequently also inspection practices, differ widely across the world. A one-size-fits-all approach is hard to realize. Yet the protocols of many jurisdictions are determined with respect to the limitations imposed by the resources available. This implies that if systems like the one contemplated in the SeeBridge project can be applied, reducing the human effort required, then jurisdictions may be able to apply more rigorous bridge inspection protocols than they can under current constraints.

8 Detailed Financial Report

The detailed financial statement has been uploaded to the Infravation CMT site.

9 A PPT presentation summarizing the status and content of the project

The PPT presentation can be downloaded from this link:

https://technionmail-my.sharepoint.com/personal/cvsacks_technion_ac_il/_layouts/15/guestaccess.aspx?guestaccesstoken=aiR1IjmLnm%2f0pqm1JtgW22ktaP9CuJZP7xRKkyzWaPM%3d&docid=0134cb5285c8c42ac9e08e605b200a474&rev=1&expiration=2017-02-06T09%3a19%3a51.000Z

Appendix A: Data Collection – Atlanta, GA

Bridge Details from the US National Bridge Inventory (NBI)

Acworth: 067-52520

LTBP Bridge Portal Simple Search

Summary | NBI | Historical Data | LTBP Data | Deterioration

Latitude: 34.0647, Longitude:-84.6700
Location: IN KENNESAW CITY LIMITS

Important NBI Attributes

1-State Name	Georgia
8-Structure Number	000000006752520
Bridge Name	SOUTHSIDE DRIVE over COWAN ROAD CR-3501
26-Route Classification	19 - Urban Local
48-Length Of Largest Span	18.2
49-Total Length	42.6
52-Deck Width	12.7
34-Skew	0
22-Owner	2 - County Highway Agency
27-Year Built	2002
37-Historic Significance	5 - Bridge is not eligible for the NRHP.
31-Design Load	6 - MS 18+Mod / HS 20+Mod
45-Number Of Main Spans	3
43A-Main Span Materials	5 - Prestressed concrete *
43B-Main Span Design	2 - Stringer/Multi-beam or girder
107-Deck Type	1 - Concrete Cast-in-Place
108A-Wearing Surface	1 - Monolithic Concrete (concurrently place...

Figure B.1

Gwinnett 1: 135-01150

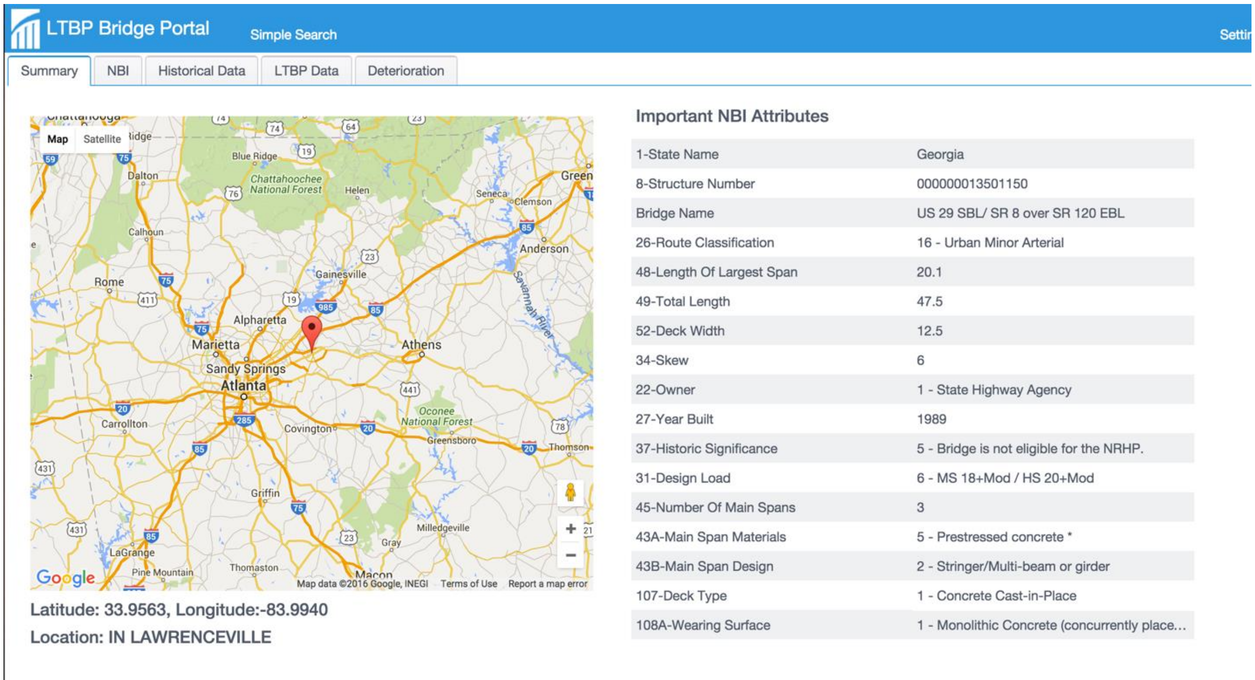
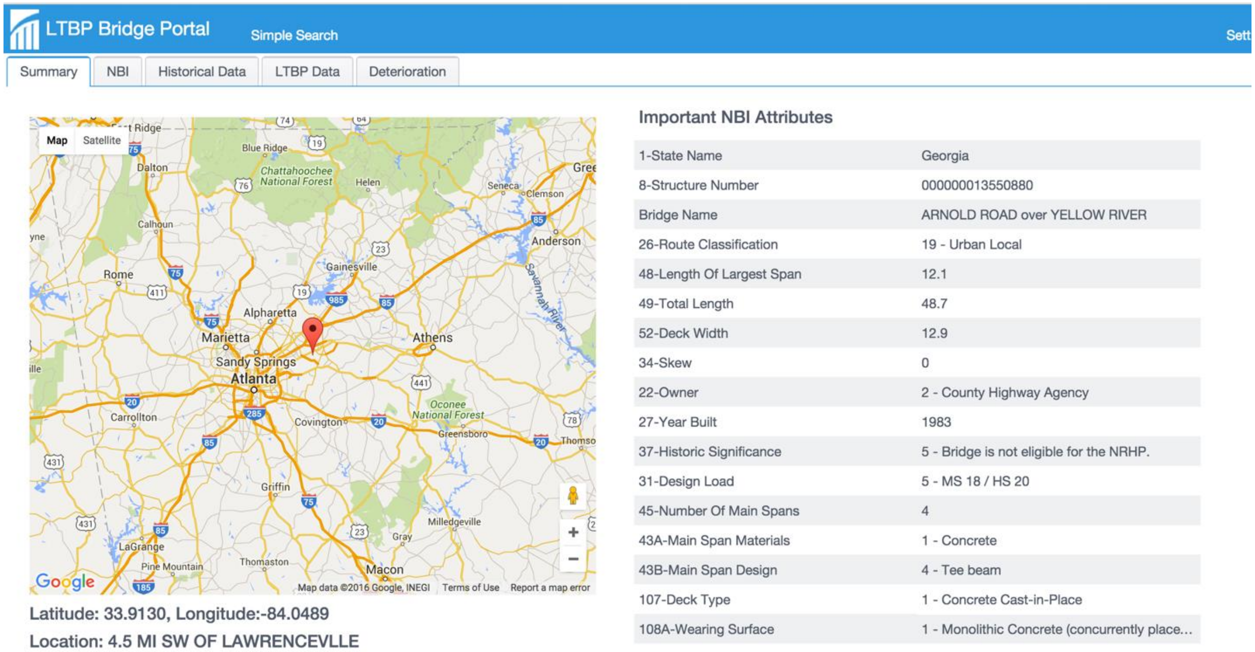


Figure 0.2

Gwinnett 2: 135-50880



1-State Name	Georgia
8-Structure Number	000000013550880
Bridge Name	ARNOLD ROAD over YELLOW RIVER
26-Route Classification	19 - Urban Local
48-Length Of Largest Span	12.1
49-Total Length	48.7
52-Deck Width	12.9
34-Skew	0
22-Owner	2 - County Highway Agency
27-Year Built	1983
37-Historic Significance	5 - Bridge is not eligible for the NRHP.
31-Design Load	5 - MS 18 / HS 20
45-Number Of Main Spans	4
43A-Main Span Materials	1 - Concrete
43B-Main Span Design	4 - Tee beam
107-Deck Type	1 - Concrete Cast-in-Place
108A-Wearing Surface	1 - Monolithic Concrete (concurrently place...

Figure B.3

Data collection tools

The tools used were the following:

LIDAR

The Trimble TX8 was used to collect laser scans at each bridge. Specifications can be found here http://www.trimble.com/3d-laser-scanning/tx8.aspx

At each bridge a series of 3-4 minute scans was acquired the number of scans depended on access, accuracy needs and conditions. The number ranged from 20-45 scans per bridge.

MX7

For two of the bridges access allowed us to drive the Trimble MX7 under and over the bridges. This vehicle-mounted system uses six 5MP (megapixel) cameras to capture spheroidal images at predefined intervals. While it may not provide the level of detail needed specifically for this project this is the type of system a DOT is more likely to own or have access to. The data provided a series of images for 2 of the 3 bridges. http://infogeospatial.trimble.com/TrimbleMX7.html

Digital Photography

A total of 2,400 photographs were captured of all 3 bridges. These fell into two categories:

1. General overview photos capturing larger portions of the bridge
2. High resolution/close up photographs of specific bridge elements. These were captured with a goal of approx.. 10 pixels per mm with substantial overlap. An attempt was made to capture locations that showed defects or failures.

iPhone Video

Hand held captured of each bridge. No specific additional equipment was used other than iPhone 6s.

Data collection procedures

Traffic Control and Lane Stoppages: Bridges were selected to remove/minimize the need for traffic control/lane stoppages. Typical bridge inspections do not use traffic control, so bridges were selected based on the ability to capture the data without closing lanes or impeding traffic. Data could be captured from the side of the road without need to interfere with traffic.

Capture Patterns: Specific capture patterns must be followed to ensure inspector safety and minimize the need for traffic control and lane stoppages.

Figure B.4 Bridge 067-52520

The Acworth Bridge was captured with the Lidar, MX7, Hi-Res imagery, and an iPhone 6s. The Lidar data was captured using 47 scans. The MX7 data was captured by passing under the bridge in a vehicle with the MX7 mounted to the roof. The videogrammetry data was captured with 3 distinct videos. As seen in the photo above, the data could be captured without impeding traffic. The data could be captured from the sides and even in the middle of the road; however, this will not always be an option and traffic control for safety of the inspectors should be considered first when capturing data.

Figure B.5 Bridge 067-52520

This Gwinnett Bridge was captured with the Lidar, MX7, Hi-Res imagery, and an iPhone 6s. The Lidar data was captured using 21 scans. The MX7 data was captured by passing under the bridge in a vehicle with the MX7 mounted to the roof. The videogrammetry data was captured with 2 distinct videos. As seen in the photo above, the data could be captured without impeding traffic. The Lidar and video could capture the center of the bridge by staying on the shoulder. Not pictured is the large yellow lighted GDOT vehicle parked on the side of the road to alert drivers of our presence.

Figure B.6 Bridge 135-50880

Another Gwinnett Bridge was captured with the Lidar, Hi-Res imagery, and an iPhone 6s. The Lidar data was captured using 27 scans. A stream running under the bridge prevented the use of the MX7. The videogrammetry data was captured with 1 video. As seen in the photo above, the data could be captured without impeding traffic. The stream, mud, and steep embankments made both laser and image capture very difficult.

In summary, all of these three bridges have been processed and reconstructed successfully. The procedure used was as follows:

The bridge inspector, depending on the bridge type and inspection criteria, selects a proper 3D scanning approach. The options are laser scanning and video/photogrammetry. In case of laser scanning, the inspector evaluates the site and designs the laser scanning set-points so that they collectively cover the entire bridge structure. The laser scanner is then set at every set-point and a 3D point cloud is captured at each set-point. The individual point clouds are then registered to each other back at the office using automated software or manually. In case of video/photogrammetry, the inspector selects a proper camera resolution based on the project criteria, distance of the camera to the bridge surfaces, and required point cloud resolution. Once the camera is selected, the inspector captures video or takes photographs from the bridge. The important point here is to cover every surface of the bridge from multiple viewpoints. The video or photographs are then input to the processing software. The software automatically estimates camera parameters and trajectory which will lead to the generation of a dense point cloud.

Input: A laser scanner or a collection of bridge photos (.jpg) or video streams (.mov or .mp4) from a high-resolution moving camera at the site.

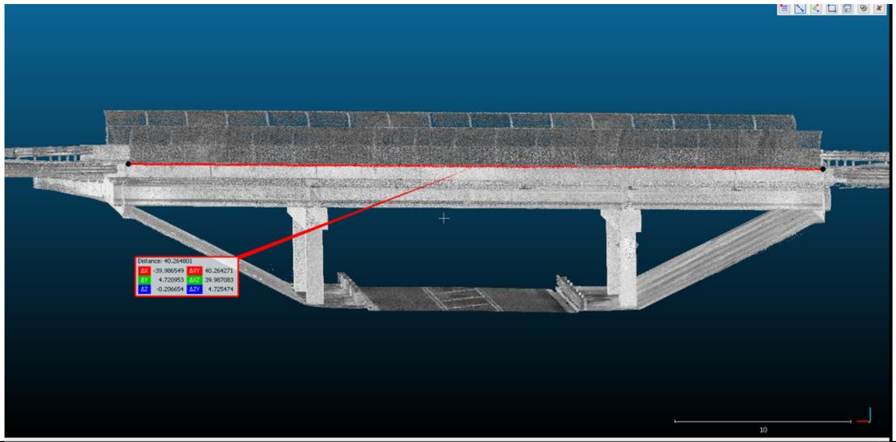
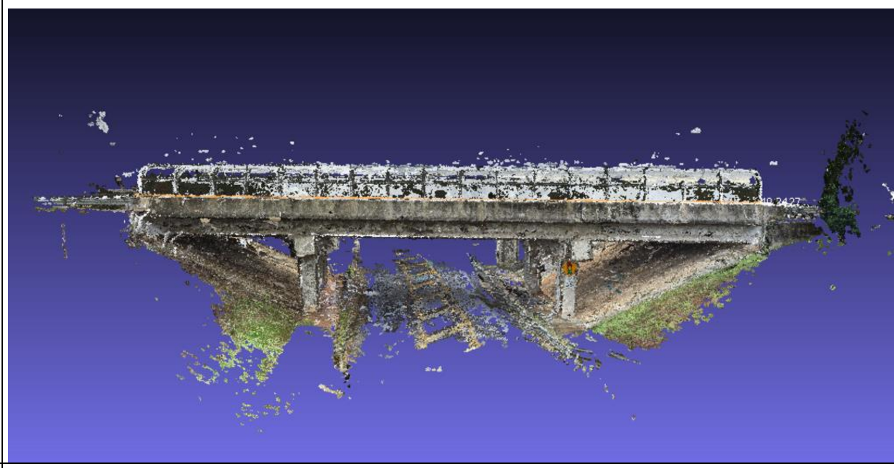
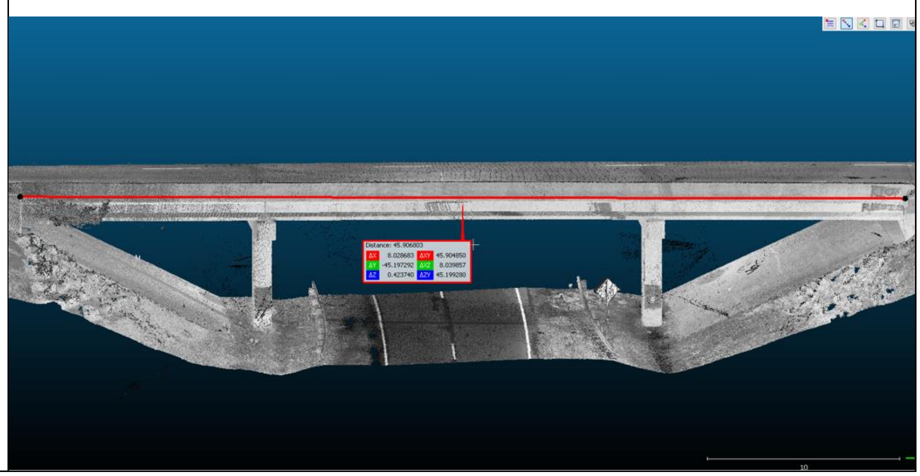
Output: Detailed spatial raw data (3D point clouds) with registered imagery (.bmp) for selected bridges.

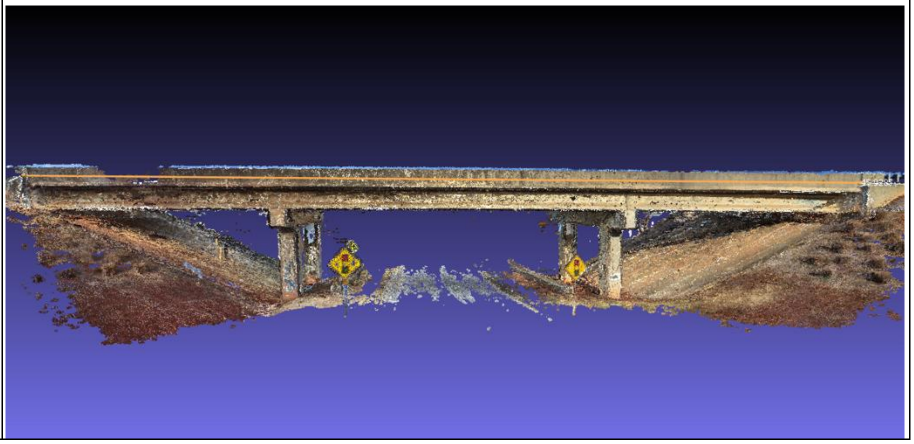
Comparison of Methods

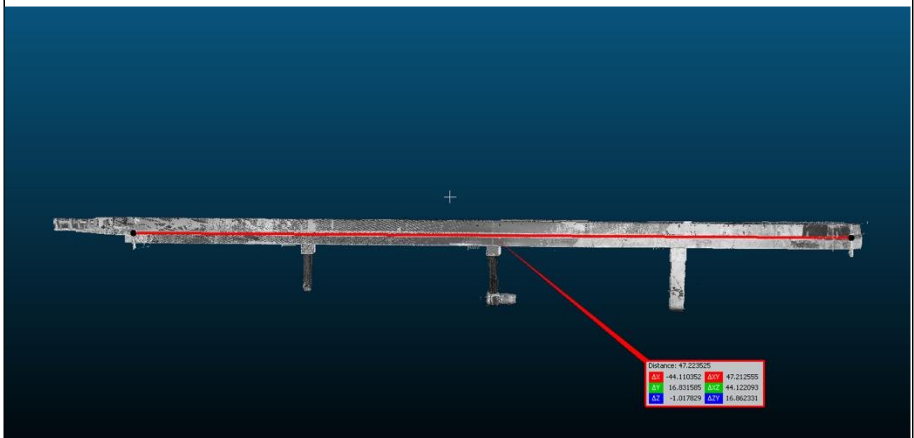
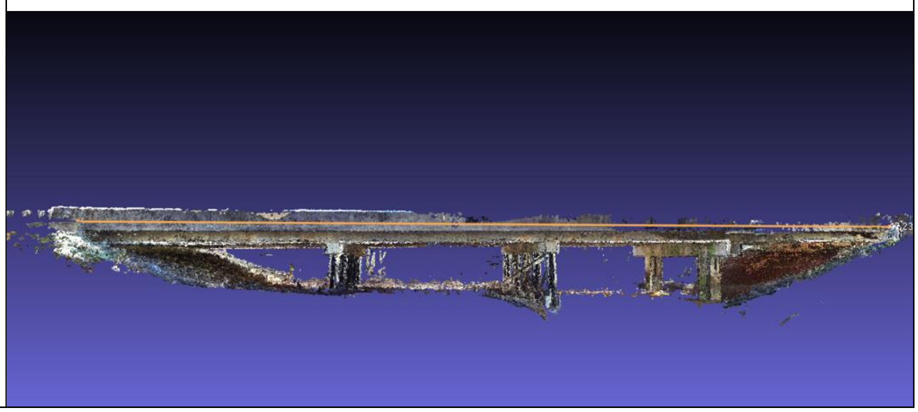
Two major types of data collection methods are compared and the data are shown in Table 10 and

Table 2.

Table 10 General comparison of data collection methods

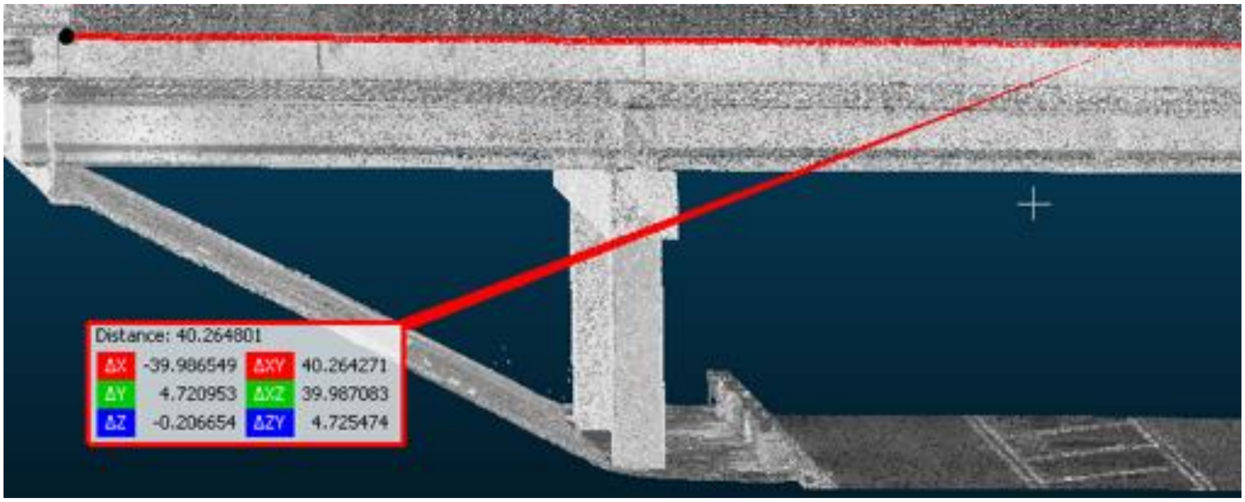
Bridge ID	Data collection method	Data preview
067-52520	Lidar	
	Video-grammetry	
135-01150	Lidar	

Bridge ID	Data collection method	Data preview
	Video-grammetry	

Bridge ID	Data collection method	Data preview
135-50880	Lidar	
	Video-grammetry	

Data collection Accuracy

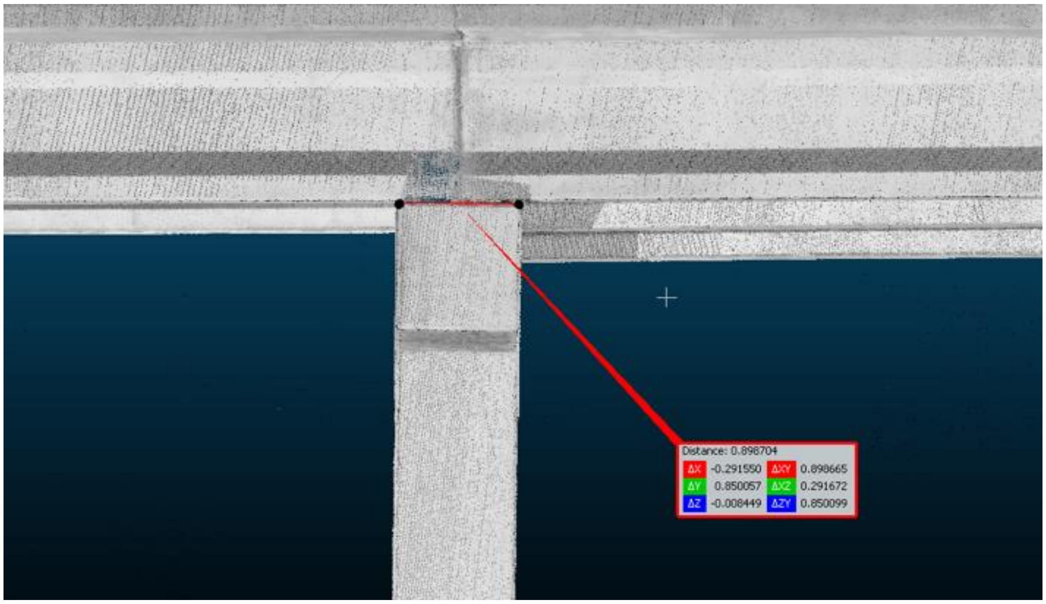
067-52520 – Acworth: Bridge Length



Lidar

Videogrammetry

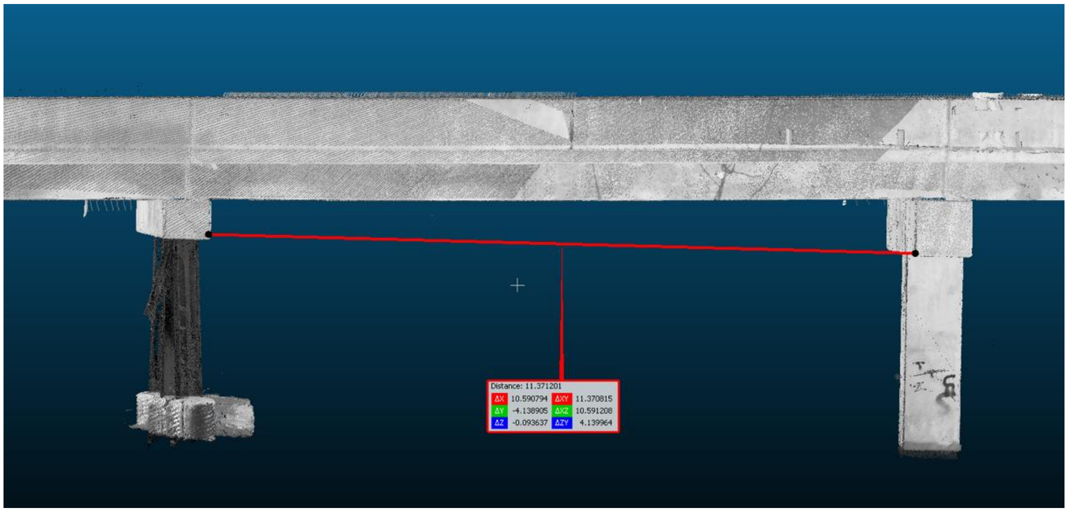
135-01150: Gwinnett 1



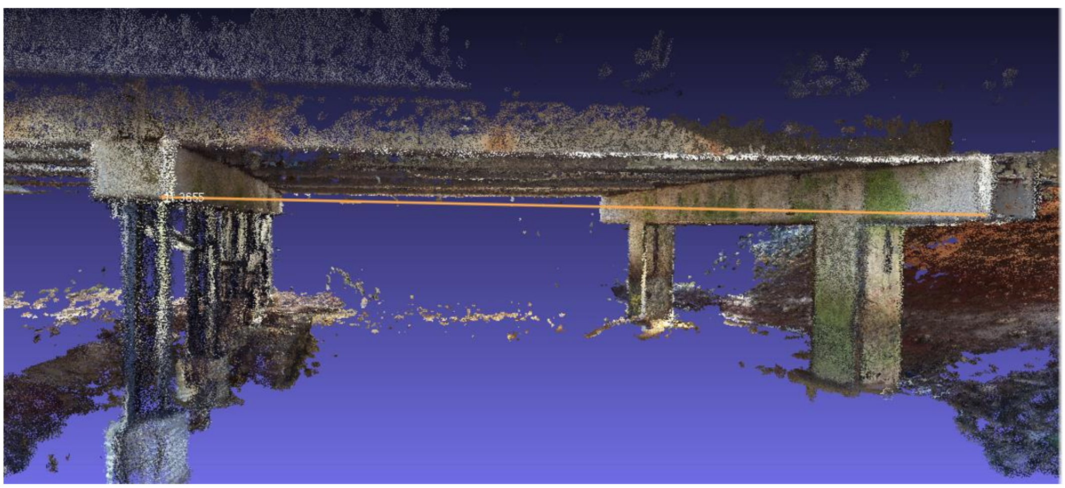
Lidar

Video-grammetry

135-50880: Gwinnett 2



Lidar



Video-grammetry

Appendix B: Current GDOT Inspection Practices

Applicability

In Georgia, there are approximately 20 inspector teams (2-3 inspectors) with four of those teams being specialists with cranes/cherry pickers and are dive-capable for inspecting piles/foundations in water deeper than 3 feet. All teams work four 10 hour days and are expected to record all data within that period as well as carry out inspections. The inspector with whom we worked (Josh) and his teammate inspect an average of 3 bridges per day. They have responsibility for the largest four counties in GA with approximately 1,500 bridges.

Current Inspection process: Unless the bridge has previous issues, the inspector expects to spend no more than 20-30 minutes at each bridge. Those bridges that have some issues might take 10 minutes longer to document and re-photograph the defect. There is a small selection of bridges (10-12) that are on a six-month inspection cycle due to significant problems. The visit to these bridges takes longer. Inspector stated that any longer than 20-30 minutes at a 'standard' bridge is too long.

Prior to bridge arrival, the inspector will have reviewed the previous inspection. On arrival, he will walk under bridge and check for obvious changes, new defects, or documents on going issues. Most measurements are qualitative grading exercises (grade 1, 2, 3, 4) and he will rarely remove his tape measure unless something has changed. The information is recorded on a standard paper form though they are trying to make use of tablets. Some inspectors are uncomfortable carrying and using a tablet; it is impractical especially when climbing through vegetation and up ladders.

The data recorded has to be then typed into their Bridge inspection software (Agile Assets). They do this at home as they have no office space. The regional supervisor has to approve all his inspections in the system then on annual basis this data is uploaded to the National Bridge Inventory. Any delay to this can cause a delay to their federal funding.

Inspection Frequency: GDOT is responsible for inspecting all 14,795 Georgia bridges, the majority of which are on the federally mandated 2-year schedule. Each year they submit inspection data to the federal database, inspecting approximately half of the bridges each year.

Historically, the federal database has not mandated the collection elemental level data but they are transitioning to inspections based on elements. However, even at this new elemental level they are not required to record defects at a precise location. For example, prior to elemental level of collection, they would define the number of girders by a total length, if there was cracking on one girder this would be recorded by defining a percentage of the total length that has at a lesser grade. Now, inspectors can define which girder has the cracking, but they still do not use any coordinate system to define the exact location along the girder.

Areas to Explore

Based on limited discussions with a small set of inspection experts (GDOT), here are areas that should be further investigated to improve understanding of market feasibility.

Bridge Selection: According to GDOT, only about 20 bridges in Georgia are precast/prestressed girders, meaning very few bridges that fall within this project show any signs of deterioration/defects. This could be due to the fact that prestressed girders are relatively new (1980s) and are often heavily over engineered since it is not cost prohibitive. This was verified on the FHWA Bridge Portal and only 16 bridges are posted that fit into project requirements. It is also mentioned that these bridges are being built to last 100 years.

Models: GDOT saw the benefit of having a rich 3D model of a bridge containing defects, especially if it could be used as a basis for stress analysis of the bridge. GDOT is also responsible for publishing the loading recommendations for each bridge and this model would be helpful, but only for the minority of bridges that have severe and ongoing issues. A data-rich 3D model may not be valuable for standard/every bridge. It may be valuable for new bridges or special situations where there could be value in spending extra time to collect data for a 3D model. If the entire collection, processing and extraction process was "easier" then it might be a practical solution, but laser scanning was never going to happen on the majority of the bridges. According to GDOT, "Inspectors just don't have time to do more than jump out of the truck for 30 minutes."

Defects: Initially there was some interest from GDOT employees for automatic identification of defects from photographs. However, as with the scanning, they could only see it being used with the bridges that need the most attention. Unless data capture can be done with less detailed photography they cannot see it being an effective way to document the cracking. The time to take photographs could be better used simply looking for/examining the cracks on site. It was mentioned if photos could be taken with a phone then it might be valuable, but carrying a DSLR was likened to carrying a tablet. (This industry has not been touched by technology, yet)

Cracking Tolerance: GDOT inspectors were surprised at the project goal of identifying and measuring cracks of 0.1 mm, which was signifcantly smaller than the guidelines in Georgia and smaller than the NCHRP, ACI, and PCI standards. The FHWA Bridge Inspectors Manual states cracks in concrete between 0.006 in - 0.012 in (0.15 mm – 0.3 mm) are considered tolerable.

According to GDOT, "concrete cracks…it's what it does" and even if a system could automatically idenitfy cracks of 0.1 mm they would not document such cracks until they reached 0.02 in or 0.5 mm – 5 times greater than our limit. The only time cracks of 0.006 in (0.15 mm) are documented is if inspectors see flexure cracks in prestressed girders. There is ONE bridge in Georgia where such girder cracks are being monitored. There are 14,000 bridges to inspect in Georgia; inspectors cannot be overwhelmed with cracks that are of little or no significance, and they cannot afford to look at every 0.1 mm crack.

Cracking Location: it is often the location of the crack more than it's size that is of importance.

Below is an example of a stepped column cap that supports the girders. There are often cracks at the step down location (A) but they are rarely signifcant and are not documented until they are considerable. Whereas, a crack or craking of any size on the cantilevered portion of the cap (B) will be considered signifcant and recorded.

Obstacles to Adoption

Minimal Bridge Selection: There appears to be a very small number of bridges for which this solution could be applicable.

Capture Difficulties: Capturing the data is not an easy task. Capture expertise on the inspection team is needed to successfully capture the data for useful results. Additionally, carrying a laser scanner or holding a phone or camera up for hours to collect data is an arduous process.

Traffic Control/Lane Stoppages: Typical bridge inspections do not require traffic control or lane stoppages. For the sake of this project, specific bridges were selected to reduce/remove the need to impede traffic. However, many of the bridges will require traffic control/lane stoppages to capture the data. Bridges along highways will require permission and coordination with NHWA.

Limited Time: As discussed in the report, bridge inspectors have very limited time to capture data (20-30 min) for the inspection. Ostensibly the initial model will take much longer to generate; but, if updating the model with only data from cracks/defects, then it is reasonable to expect the inspection time to stay roughly the same.

Technical Trust: This industry and its employees are slow to adopt new technologies, especially if they only see limited potential value. It will be challenging to build trust amongst the inspectors while the data capture remains difficult and time consuming.