UAS IMAGE-BASED POINT CLOUDS TO 3D BRIM:
3D AS-IS BRIDGE MODEL GENERATION

FINAL PROJECT REPORT

by

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Sponsorship
Pacific Northwest Transportation Consortium

for
Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

In cooperation with US Department of Transportation- Office of the Assistant Secretary for Research and Technology (OST-R)

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
	01723941	

4. Title and Subtitle	5. Report Date
UAS IMAGE-BASED POINT CLOUDS TO 3D BRIM: 3D AS-IS BRIDGE MODEL GENERATION	
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Yelda Turkan, Ph.D., Associate Professor; 0000-0002-3224-5462 Yiye Xu, Ph.D. Student	2019-S-OSU-1

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700	**11. Contract or Grant No.** 69A3551747110

12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
United States of America Department of Transportation Research and Innovative Technology Administration	**14. Sponsoring Agency Code**

15. Supplementary Notes

Report uploaded at www.pacTrans.org

16. Abstract

U.S. economic growth, as well as the mobility of people and goods across the country, are largely dependent on the health of the country's transportation systems. Unfortunately, the U.S. infrastructure is aging and has been poorly maintained for decades. Bridge Information Models (BrIM) are seen as an effective method to improve the efficiency of current bridge inspection and management practices. However, the creation of such a model remains a manual process. Because there are a large number of bridges in the U.S., manually creating BrIMs would be time-consuming, labor-intensive, and expensive. Therefore, a new framework was proposed in this study to speed the creation of BrIMs. The proposed framework was implemented on an existing bridge. The illustrative case study provides a detailed explanation of unmanned aerial system imaging, point cloud generation, and BrIM creation and placement on the basis of the generated point-cloud model. The the case study demonstrated the feasibility of rapidly generating BrIMs using the proposed framework. The proposed framework showed potential to address some of the problems associated with the current BrIM generation process in terms of cost-efficiency and effectiveness.

17. Key Words	18. Distribution Statement
	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	40	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorize**

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The authors would like to thank the Pacific Northwest Transportation Consortium (PacTrans) for funding this research. The authors would also like to thank Donghoon Ji for his help with data collection and the Oregon Department of Transportation (ODOT) for providing us with the drawings for the studied bridge used in the case study.

List of Abbreviations

AEC-FM	Architectural, engineering and construction, and facilities management
BIM	Building Information Model
BMS	Bridge Management System
BrIM	Bridge Information Model
DOT	Department of Transportation
GCP	Ground control points
GNSS	Global Navigation Satellite System
IFC	Industry Foundation Classes
LiDAR	Light detection and ranging
ORGN	Oregon’s Real Time GNSS Network
SfM	Structure from Motion
TLS	Terrestrial laser scanner
UAS	Unmanned aerial system
VPL	Visual programming language

Executive Summary

Economic growth, as well as the mobility of people and goods across the nation, are largely dependent on the health of the country's transportation systems. Unfortunately, the U.S. infrastructure is aging and has been poorly maintained for decades. Bridge Information Models (BrIM) have been acknowledged as an effective method to improve the efficiency of current bridge inspection and management practices. However, the creation of such models involves a manual and tedious process. Because there are a large number of bridges in the U.S., manually creating BrIMs for all of these bridges would be time-consuming, labor-intensive, and expensive. Therefore, a new framework was proposed in this study for speeding up the creation of BrIMs. The proposed framework was implemented on an existing bridge. The illustrative case study provides a detailed explanation of unmanned aerial system imaging, point cloud generation, and BrIM element creation and their placement in the generated point-cloud model. The case study demonstrated the feasibility of rapidly generating BrIMs using the proposed framework. The proposed framework showed potential for addressing some of the problems associated with the current BrIM generation process in terms of cost-efficiency and time effectiveness.

Chapter 1 Introduction

The mobility of people and goods is highly dependent on the health of a nation's transportation system. However, previous studies have indicated that the U.S. infrastructure is aging and has been poorly maintained for decades. The 2021 report card for America's infrastructure indicated that the average age of the U.S. bridges is 44 years, and 42 percent of them are at least 50 years old (ASCE, 2021). Even though the number of bridges that are considered structurally deficient is decreasing every year, the rate of improvement is slow because of the limited budgets available to either repair or replace these structures (ASCE, 2021). Given such circumstances, timely inspection and efficient management of bridges within the available budget are crucial to avoid any issues that may negatively affect public mobility.

However, current bridge inspection and management practices inhibit the collection and analysis of information regarding the status of bridges in an efficient and timely manner. The traditional bridge inspection mainly relies on visual observations and manual recording of defect information through pictures and note taking, which is time-consuming and dangerous for inspectors if they are required to climb to collect data. All of this information gathering increases inspection costs (Hallermann and Morgenthal 2014; Xu and Turkan, 2019). In addition, most of the nation's bridges were constructed several decades ago from two-dimensional (2D) engineering drawings. Therefore, current bridge management systems (BMS) lack digital bridge models, which could help improve the visualization of bridge condition and help link inspection data into BMSd continuously (Chan et al. 2016). This problem is further exacerbated by the large number of bridges, over 617,000, across the country that need to be inspected annually or bi-annually (ASCE 2021). Therefore, it is necessary to integrate advanced technologies into bridge inspection and management practices to improve the efficiency of the current processes.

A Bridge Information Model (BrIM) is an object-oriented database that enables storage of all bridge data, including 2D drawings and a 3D model, material specifications, inspection notes, images, and maintenance information. Recent research efforts have focused on implementing BrIMs for bridge structural condition assessment and have concluded that it is a suitable concept and technology that can be used to improve current bridge inspection and management processes (Al-Shalabi, et al. 2015; Xu and Turkan, 2019). However, several challenges will need to be overcome for its adoption into practice for bridge inspections and management tasks. These challenges include the following:

1) Manual development of 3D BrIMs for existing bridges from their 2D drawings and specifications is labor-intensive and time-consuming.
2) A 3D BrIM that is built on the basis of the original 2D drawings may not accurately reflect the as-is condition of a given bridge.
3) Departments of transportation (DOTs) do not have the resources or personnel time to develop 3D BrIMs for all the bridges they maintain and operate.

There is, therefore, an urgent need to establish an automated and cost-effective method for developing 3D BrIMs for existing bridges.

To overcome these challenges associated with the development of 3D BrIMs, this research project developed a novel data collection and analysis framework that enables rapid collection of 3D geometrical information from existing bridges in the form of 3D dense point clouds and converts them into 3D BrIMs in an automated and efficient manner. 3D point clouds were obtained by applying Structure from Motion (SfM) algorithms to the images collected by using an unmanned aerial system (UAS). In the next step, the BrIM components were reconstructed from elements in the family library created in BrIM software and were adjusted by using the point cloud data. Overall, this study developed a framework that can make it much more convenient and faster to develop and implement 3D BrIMs, which can be used to improve current bridge inspection and management practices significantly in terms of efficiency and safety, thus helping to improve public mobility.

This report is organized as follows. Chapter 2 provides a comprehensive literature review on several advanced technologies that are used for bridge inspections and management. Chapter 3 presents the research methodology by detailing the steps of the proposed framework for BrIM generation. Chapter 4 describes the study site and equipment and details the data collection procedure. Chapter 5 presents the results of the case study described in Chapter 4 and evaluates the efficiency of the proposed framework. Chapter 6 provides a discussion of the case study results, as well as the limitations of the proposed framework. Chapter 7 draws conclusions and discusses future research needs.

Chapter 2 Literature Review

As-built surveys are needed to record variations from original plans to the bridge actually built, and these changes must be reflected in the final set of drawings produced at the end of every construction project. However, over decades of use, structural deformation and defects could result in as-is condition of bridges that are different from their as-built plans. Given that most of the bridges in this country were constructed in the 1950s, 2D as-built drawings of those bridges do not reflect their as-is conditions. In addition, given the a large number of bridges in the nation, gathering information regarding their as-is conditions is extremely challenging. Therefore, technologies that can help to efficiently collect, manage, and update the as-is conditions of bridges have been explored and investigated in previous studies and are discussed in this section.

2.1 Data Acquisition Technologies

There are various reality capture technologies to collect 3D data representing the as-is status of bridges in the form of point clouds. Terrestrial laser scanners (TLS) is one of the most popular technologies for rapidly obtaining accurate 3D information from structures' surfaces and presenting this information in the form of high-density point clouds. Both researchers and practitioners have used TLS to collect the as-is geometry of infrastructure assets. For example, Tang et al. (2007) used TLS to collect the as-is geometry of a bridge and compared this method to traditional data collection methods in terms of accuracy and speed. They concluded that the accuracy of TLS data is very high, and the method presents other advantages, such as being able to "revisit" the site virtually and the ease of data collection, which are important for bridge inspection. Park et al. (2007) used TLS to develop the point cloud model of a steel beam for monitoring its displacements. Truong-Hong et al. (2016) developed a framework that utilized

TLS technology to inspect deformation and damage in bridges. Their study concluded that the data captured using a TLS is sufficient for bridge condition assessment. Besides bridge assessment, previous studies have also used TLS to assist with bridge monitoring and maintenance (Artese and Zinno, 2020; Arbi and Ide, 2015; Gawronek et al., 2019; Mohammadi et al., 2021). These studies concluded that traffic flow interruption, which is considered to be costly and time-consuming in traditional bridge inspection practices, can be greatly reduced. However, despite the high-resolution and accurate output that TLS can provide, the high price of the equipment, large file sizes, and long data processing times are considered to be primary barriers to its wider adoption in the architectural, engineering and construction, and facilities management (AEC-FM) industries (Valenca et al., 2017). Ravanel and Curtaz (2011) compared TLS and photogrammetry technologies and concluded that the cost of TLS without annual maintenance fees tended to be approximately six times or more expensive than using photogrammetry.

Photogrammetry coupled with computer vision is another technique that is being used to collect the as-is geometry of bridges. It is a technique that enables the generation of point clouds from 2D digital images. With the increasing interest in using unmanned aerial systems (UAS), more mature computer vision-based techniques, including Structure from Motion (SfM), were developed and widely used in studies to generate dense point clouds. Perry et al. (2020) used SfM to create point clouds of a bridge to visualize the condition of its surface and geometry information. UAS can be equipped with a variety of sensors, including LiDAR (light detection and ranging), which enable it to collect 3D point cloud data directly instead of creating them from digital images with the SfM technique. Roca et al. (2014) captured point clouds of various buildings using a UAS equipped with LiDAR, with the goal of generating building models and performing energy analysis. Previous studies have indicated that UAS equipped with LiDAR can be a great advantage for autonomous navigation and inspections (Lovelace and Zink, 2015; Bolourian et at., 2017).

2.2 Bridge Data Management Techniques

In current bridge management and inspection practice, typically a bridge inspector evaluates all elements and documents the data in standard inspection reports. After data collection, the inspector uploads all the data to a Bridge Management System (BMS). These reports are then compared to previous inspection reports to identify any repair/ rehabilitation/ maintenance needs. However, current BMSs can be inefficient for several reasons. First, current BMSs contain mainly bridge inventory and inspection data, but they do not provide enough information for subsequent bridge repair/ rehabilitation/ maintenance work. However, additional information, such as design and as-built information, is also needed to support better decision making, given the need for coordinated management among different phases of the bridge life cycle (Sacks et al., 2018). Second, current BMSs lack direct representation or visualization of the data (Chan et al., 2016). Third, current BMSs are primarily designed for decision-making at the system level rather than the component level, which may hinder understanding of the behavior of individual components (Chan et al., 2016; Lu and Brilakis, 2019).

As an alternative method, Bridge Information Models (BrIMs) were introduced to manage bridge information at the element level. BrIM is a term for a Building Information Model (BIM) when it is used for bridge projects. BrIM is a spatial, object-oriented database and contains not only 3D geometry but also attributes such as inspection reports and other construction documents that are directly associated with the corresponding components of the model (Eastman et al., 2011; Azhar, 2011; Azhar et al., 2015). The development of the Industry

Foundation Classes (IFC), a neutral file format that helps to improve interoperability among different applications used in different phases, enhances team collaboration and communication throughout the entire project life (Eastman et al., 2011; Tanaka et al., 2016). DiBernardo (2012) proposed a framework that integrated inspection data with 3D BrIM. Building on this study, Al-Shalabi et al. (2015) proposed a 3D BrIM-based inspection framework that integrated BrIM, data from mobile devices, and cloud computing. In the next step, the proposed framework was tested by Iowa DOT inspectors, and its potential benefits, including accuracy, speed, and ease of data collection, were confirmed.

2.3 Knowledge Gaps

The technologies that are available for as-is data collection and management of bridges are well studied, and the benefits of using these technologies, namely, point clouds and BrIM, are well understood. However, as acknowledged in previous studies, converting point clouds into BrIM is not easy, as it is a manual process that is time-consuming, labor-intensive, and costly (Lu and Brilakis, 2019). Although several algorithms have been developed to detect components of a structure by extracting planar patches or other characteristics, a few studies have demonstrated a practical method that can rapidly generate 3D, as-is BrIMs from large size point cloud data. Accordingly, this study proposed a BrIM development framework that enables the conversion of image-based point clouds (developed via SfM algorithms) to BrIM components automatically. Detailed steps are presented in the next section.

Chapter 3 Methodology

The main objective of this study was to develop a framework that enables the conversion of image-based point clouds to a BrIM in an efficient manner. Figure 3.1 provides an overview of the proposed framework, which consists of three main phases: (1) development of 3D point clouds using SfM in Agisoft Metashape software, (2) creation of BrIM component families by specifying parameters and relationships in the BrIM software, and (3) placement of BrIM components in the point cloud scene and adjustment of their geometry.

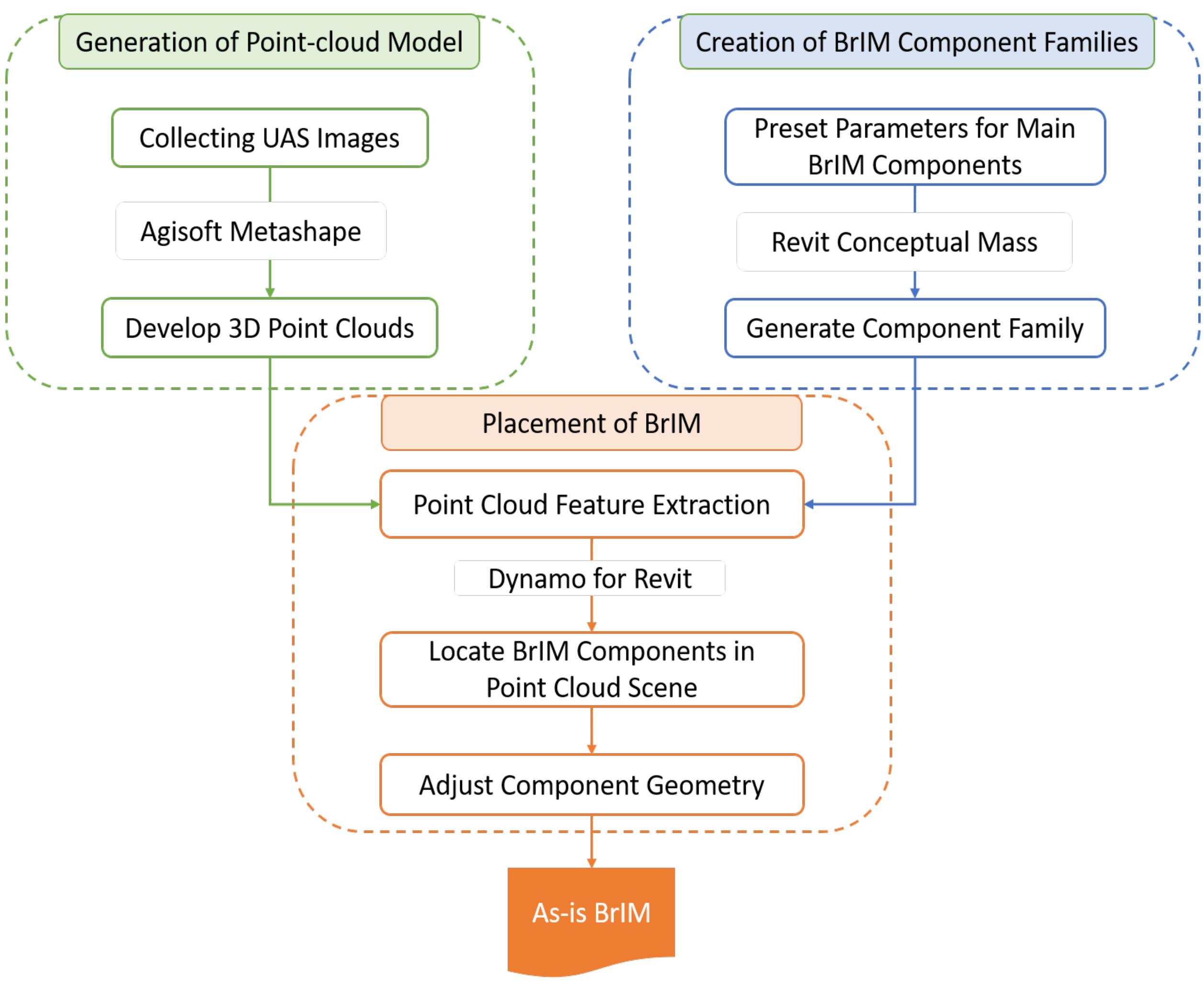

Figure 3.1. Proposed BrIM generation framework**.**

3.1 Generation of the Point Cloud Model

This phase is divided into three stages, which are (1) the site control survey, (2) UAS flight planning and imaging, and (3) point cloud generation.

3.1.1 Site Control Survey

To reference the generated point clouds in the world coordinate system accurately, a site control survey is necessary. For an efficient and optimal control survey, a survey plan is necessary to determine the location(s) for GPS control points, total station set-ups, and visual targets on the bridge. GPS control points should be distributed as evenly as possible on the study site, and they should cover the boundaries of the study site. The location(s) for the total station should be able to capture as many control points and targets as possible on the bridge, ideally all of them. Multiple set-up locations are recommended to minimize residual errors. The visual targets should be attached to as many facets as possible on the bridge so that they can be easily detected by the total station and the UAS later. The GPS device and total station can collect data on the planned locations once the survey planning has been completed. First, the GPS device needs to collect the world coordinates for each of the control points. In the next step, the total station needs to be placed at predetermined location(s) to collect data for all visible control points as well as the targets on the bridge. Finally, the world coordinates for all locations, including control points, total station, and visual targets, can be obtained by performing the registration process in the Leica Cyclone software.

3.1.2 UAS Flight Planning and Imaging

To generate a high-quality point-cloud model based on images, capturing images with high side and end overlap is very important. Therefore, it is necessary to first formulate a comprehensive imaging plan, which basically includes the design of control location(s) and the plan for the flight route. Control locations are takeoff points, as well as the place where the pilot stands, while flight routes are the paths that the UAS needs to follow. In designing control locations and flight routes, the battery capacity of the UAS, the shape and size of the bridge, the weather condition, and the pilot's skill and comfort level are all factors to consider. After appropriate control locations and flight routes have been chosen, images are acquired along the flight routes for all faces (top, two sides, and bottom) of the bridge. The manual UAS imaging process used auto-capture mode and slow-speed mode to enable sufficient overlap between images.

3.1.3 Point Cloud Generation

This study generated a point-cloud model by using the Agisoft Metashape software. Agisoft Metashape is a stand-alone software that can perform photogrammetric processing of digital images and generate 3D spatial data in the form of dense point clouds. Automated alignment of images was used to create sparse point clouds, and dense point clouds were generated after the positions of targets in images had been manually digitized. The noise-points that did not belong to any of the bridge elements—in the generated model was filtered out on the basis of the level of confidence.

3.2 Creation of BrIM Component Families

Because of its availability to the research team, Revit was used to create the BrIM in this study. Revit is widely used in the industry because of its capabilities to create custom element families as well as set user-defined parameters. Because the bridge elements were not available in Revit’s predefined library, the research team needed to create customized specific element families. The bridge model elements were divided into major group types, such as deck, superstructure, and substructure, which followed the sequence of the traditional construction process. Then, the 3D BrIM families of the above-mentioned elements were developed at the element level based on the information extracted from 2D drawings. In the Revit model, a unique identification (ID) number was assigned for each element, and other properties such as materials could be customized for each element as well.

3.3 Placement of the BrIM

To automatically generate the BrIM from 3D point clouds, Dynamo was used to extract features from the point clouds as well as to place and connect previously created elements on the basis of those features. Dynamo is an open-source plug-in for Autodesk Revit, which provides a visual programming language (VPL) built on a stream interface. First, the generated point cloud was imported into Dynamo and converted to the project coordinate system. Next, different elements had to be created on the basis of their locations and cross-section parameters. A slicing plane was then generated to filter the cross-section of each bridge element, and the 2D ConcaveHull α-shape (Moreira and Santos. 2006) was implemented to describe the shape of the filtered cross-section. Next, the created BrIM families were placed in the identified cross-section and adjusted to fit the described shape. In the end, the BrIM elements could be developed by using the cross-sections of different elements, and their height and length could be extracted from the point clouds.

Chapter 4 Study Site/Data

To demonstrate the feasibility and efficiency of the proposed framework, an illustrative case study was conducted using the data collected from a concrete girder bridge located in Corvallis, Oregon. The primary objective of this case study was to evaluate whether the proposed framework can help to improve the 3D BrIM development process by automatically creating a model from the image-generated point cloud data. This section describes the study site, equipment, and the data collection procedure in detail.

4.1 Study Site

The bridge selected for this study was located at the intersection of Corvallis-Newport Highway and the I-34 Highway, near Eric Scott McKinley State Park in Benton County, Oregon. It was a concrete girder bridge that was constructed in 1992, with a full length of 1257.5 ft. However, this case study focused only on three spans of the bridge (see figure 4.1) for three reasons:

(1) The curved shape of the three spans of the bridge made it a good candidate for testing the reliability of the proposed framework on a structure with a certain degree of complexity.

(2) There was enough room for flying the UAS under it to collect information from the bottom of the bridge.

(3) The surrounding area of the study site was relatively clear (no power lines, fewer trees and bushes, and less traffic and people), which was considered good for setting the control points on the ground and for comfortably operating the UAS around it.

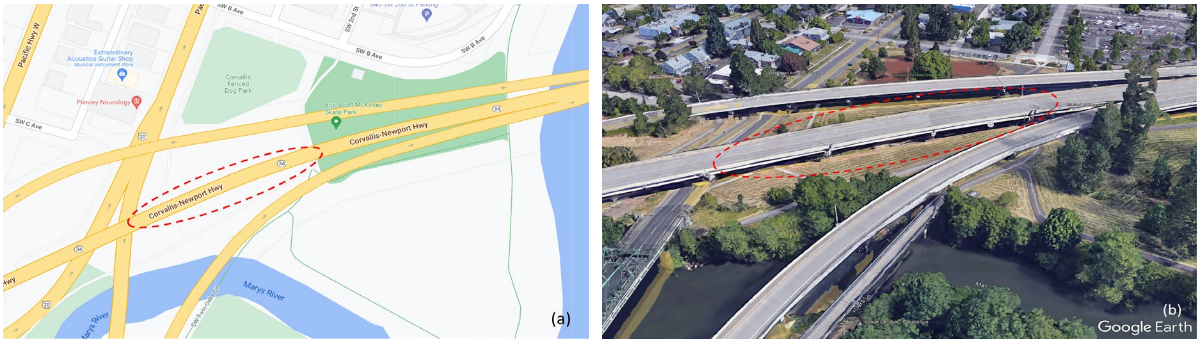

Figure 4.1. The location of the case study site in Corvallis, Oregon. (a) The bridge location on Google Maps; (b) 3D scene of the bridge on Google Earth.

4.2 Data Collection Equipment Used

To collect the data that were needed to generate the point cloud of the target bridge, three types of equipment were used, namely, UAS, Global Navigation Satellite System (GNSS), and a total station. The UAS used in this study for collecting images of the bridge was a DJI Mavic 2, which was controlled with a smart remote controller. A Leica GS14 GNSS receiver and a Leica CS15 data collector were used to collect the real-time world 3D coordinates of each of the ground control points (GCPs). The GNSS receiver and the data collector were fixed on a 2-m-high pole with a bipod for collecting data. The total station used in this study was a Leica Nova MS50 MultiStation, which was fixed on a tripod to collect the local 3D coordinates of each of the GCPs and targets that were affixed to the bridge. A prism fixed on an adjustable pole with a bipod was needed at each GCP location during this process. Figure 4.2 presents the equipment used for data collection.

Figure 4.2. Equipment used in this study: (a) DJI Mavic 2 pro and the smart controller; (b) Leica Nova MS50 MultiStation, prism, and adjustable height pole and bipod; (c) Leica GS14 GNSS receiver, Leica CS15 data collector, fixed height pole and bipod.

<u>4.3 Data Collection</u>

The data collection was conducted over two consecutive days with good weather conditions. Before data collection, twelve black/white paper targets (see figure 4.3(a)) were attached to the four piers of the bridge. Paper targets were evenly distributed on each side of each pier so that they could be captured by the total station and UAS from a variety of locations. The first day's data collection consisted of collecting (1) world coordinates at predetermined GCPs using GNSS, and (2) local coordinates of the GCPs and paper targets on the bridge. The second day’s data collection mainly focused on obtaining the digital images of the bridge using the UAS.

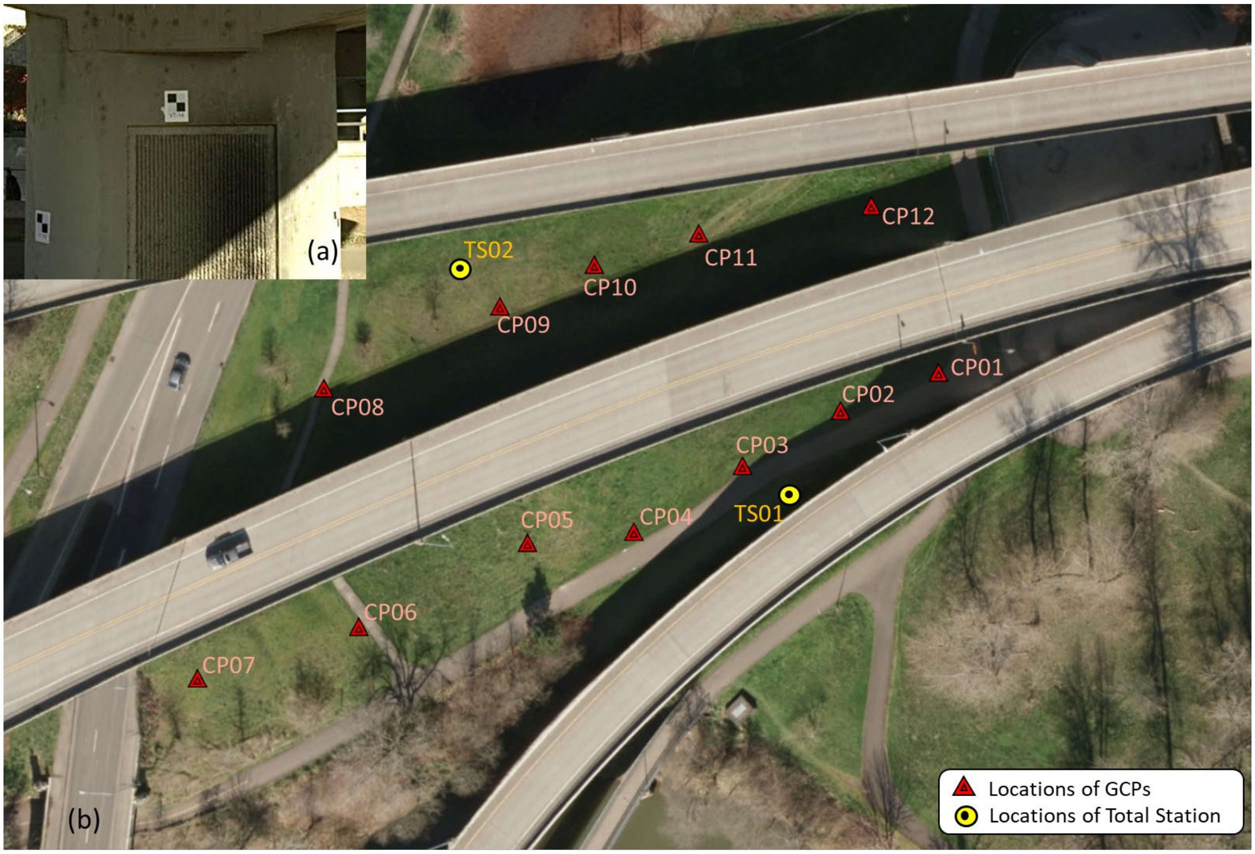

Figure 4.3. (a) An example image of the black/white target affixed to the bridge; (b) The locations of twelve GCPs and the locations of the total station in ArcGIS.

4.3.1 Data Collection - Day 1

Twelve GCP locations were pre-determined along both sides of the studied bridge and distributed evenly throughout the study field. The locations of all twelve GCPs are presented in figure 4.3(b). GCPs were marked on the ground with blue tape and pins in different colors so that they could be easily located during the data collection process. Assuming that the trees and other bridges surrounding the studied bridge could affect GNSS initialization, the GNSS receiver was turned on and initialized (3D coordinate quality was less than 0.03 m) in an open area before being slowly moved back to the study area. Then the GNSS receiver and the data collector were placed on the first GCP (CP01 in figure 4.3(b)) to measure the real-time data utilizing Oregon's

Real Time GNSS Network (ORGN). As soon as the equipment had collected data for three minutes, the positioning data for this point was saved, and the equipment was moved to the next GCP. This process was repeated until the positioning data for all twelve GCPs were obtained.

Following the GNSS data collection, two locations were identified to set up the total station to collect the local coordinates of the GCPs as well as the black/white targets on the bridge. The total station was placed at various locations since (1) it was impossible to survey all the GCPs and the targets from a single point because of blind spots caused by the piers, and (2) data collection from different locations is highly recommended to reduce residual errors. First, the total station was placed on TS01 (see figure 4.3(b)) to survey GCPs with the prism that was visible from this location. Several shots had to be taken for some of the GCPs because the prism was wobbling. Second, the total station surveyed all visible targets at TS01 using the reflectorless mode by shooting the intersection of black and white areas (center point) on the paper target. The total station was then moved to TS02, and the above-described process was repeated for all visible GCPs and targets.

4.3.2 Data Collection - Day 2

Once the control survey had been completed, the UAS could be operated to capture digital images of the bridge. To provide optimal image coverage of the bridge, "lawnmower pattern" flights on both sides as well as the bottom of the bridge were conducted. The flight plan can be seen in figure 4.4. Manual flight mode was used because of the complexity of the surrounding environment and the pilot's comfort level. To obtain images of the bridge with sufficient end and side overlap, the automatic image capture mode was employed during data collection. For the two sides of the bridge, the pilot flew the UAS about 10 m above and 2 m to 3 m away from one end of the bridge, tilted down the camera to focus on the bridge, and flew the

UAS slowly along the side of the bridge while automatically taking images every 2 seconds. After the UAS had reached the other end of the bridge, the pilot lowered the UAS' altitude by 1 m, tilted the camera up/down to center the bridge, and flew it back using the same procedure. This process was repeated for both sides of the bridge and ended when the UAS was about 1 m above the ground. To collect images from the bottom of the bridge, the UAS was flown at approximately 1.5 m above the ground, and it slowly followed the flight path (green line in figure 4.4) for each span. The camera was tilted up 30 degrees (maximum tilt angle) during the entire data collection under the bridge and captured images every 2 seconds. The collected images were stored in the memory card in DNG (raw) format. The battery capacity of the UAS used in this study was 29 minutes per flight. Nevertheless, each flight was set to 20 minutes to reserve sufficient time for a safe return. During the data collection, six batteries were used for UAS imaging, which took about 2 hours in total.

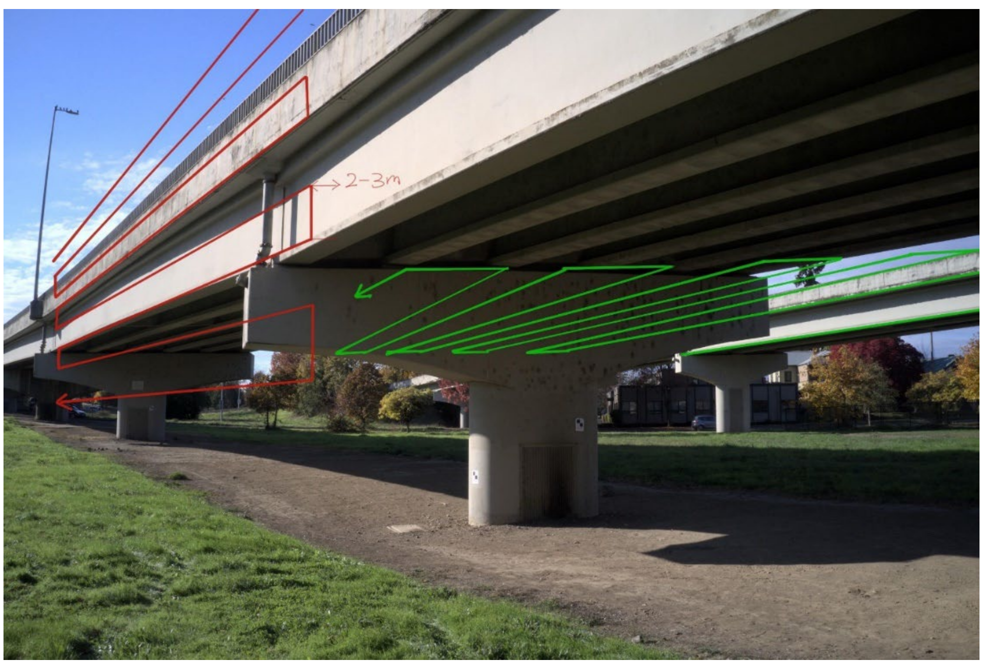

Figure 4.4. Predefined flight plan (red line for top and sides of the bridge and green line for bottom of bridge) for UAS imaging the sides and bottom of the bridge**.**

Chapter 5 Results

5.1 Generation of the Point-Cloud Model

After the data collection, the GCPs that were in world coordinates, and the targets in local coordinates were registered by using Leica Cyclone software. After this process, all targets were found to have error magnitudes below 0.03 m, and their locations were translated into the same coordinates as the GCPs, which were described as Easting, Northing, and Elevation and are shown in figure 5.1. With respect to the UAS imaging process, 1,245 high-resolution images of the studied bridge were collected. Figure 5.2 shows the locations of the UAS cameras and the paper targets attached to the bridge in a plan view. Eight images out of the 1,245 collected images were either taken in poor light conditions or from a bad angle and therefore were removed before the point-cloud generation process. As a result, 1,237 images were imported into Agisoft Metashape software to create the point cloud.

```
Target,Easting,Northing,Elevation
VT11,35607.777795,24880.223191,70.945909
VT10,35608.692465,24883.357021,71.023409
VT07,35640.267954,24895.968034,70.143409
VT09,35641.131195,24898.275224,70.528409
VT21,35674.370491,24912.339067,69.848409
VT16,35675.483207,24911.16583,68.763409
VT12,35712.568996,24924.694584,68.578409
VT14,35711.372143,24925.835479,69.698409
VT13,35710.991912,24927.0086,68.608409
VT10,35608.685409,24883.3629,70.975992
VT09,35641.12573,24898.280656,70.482992
VT21,35674.364526,24912.345248,69.803992
VT20,35674.681199,24914.1092,70.253992
VT14,35711.364791,24925.846471,69.651992
VT13,35710.985923,24927.016515,68.562992
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Figure 5.1. Target locations in world coordinates**.**

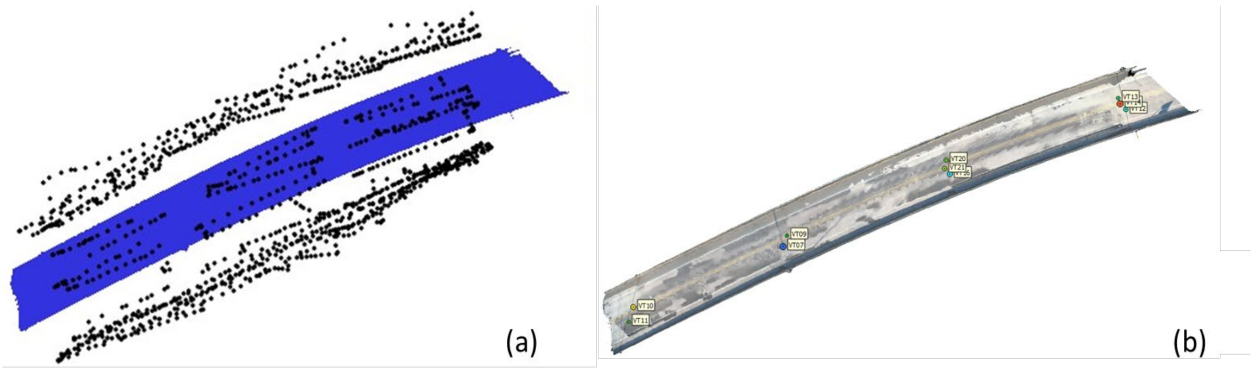

Figure 5.2. (a) Estimated camera locations and (b) black/white target locations

After the SfM algorithm had been used to automatically align images and the exact locations of paper targets in images had been digitized, the mean error estimate of the targets was 0.040873 m. A dense point cloud model consisting of 8,926,909 points was created. Figure 5.3 shows the generated dense point-cloud model and its confidence map. The confidence value of a point corresponds to the number of depth maps that were used to generate the given point. The dense points with XYZ coordinates were exported as .txt files for further use in the next steps.

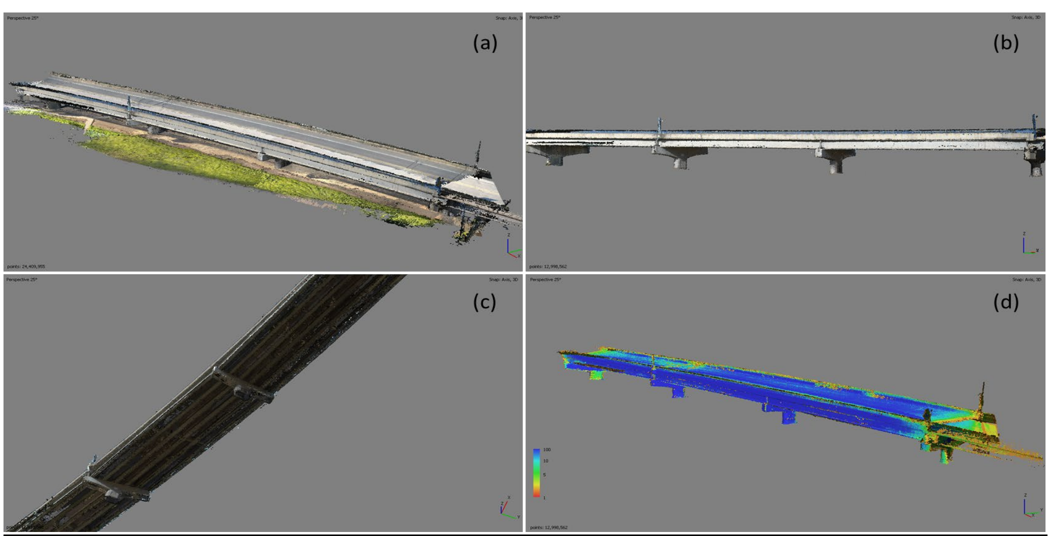

Figure 5.3. (a) Overview of the generated dense point-cloud model (ground points included); (b) side view of the point-cloud model; (c) bottom view of the point-cloud model; and (d) confidence map of the generated dense point-cloud model.

5.2 Creation of BrIM Component Families

Typically, bridges are composed of three main parts: deck, superstructure, and substructure. Each part consists of one or more elements, such as an abutment, pier, etc. In our case, piers, pier caps, and girder slabs (from bottom to top) were identified as major components. The design and parameters of the bridge elements were identified in the 2D plans provided by Oregon DOT. These parameters were then used to generate their cross-sections and create element families in Revit by using the conceptual mass plug-in. The main reason for using conceptual mass is because of its ability to create custom BrIM families on the basis of a specific set of rules. The cross-section as well as the created families of the above-mentioned elements are shown in figure 5.4.

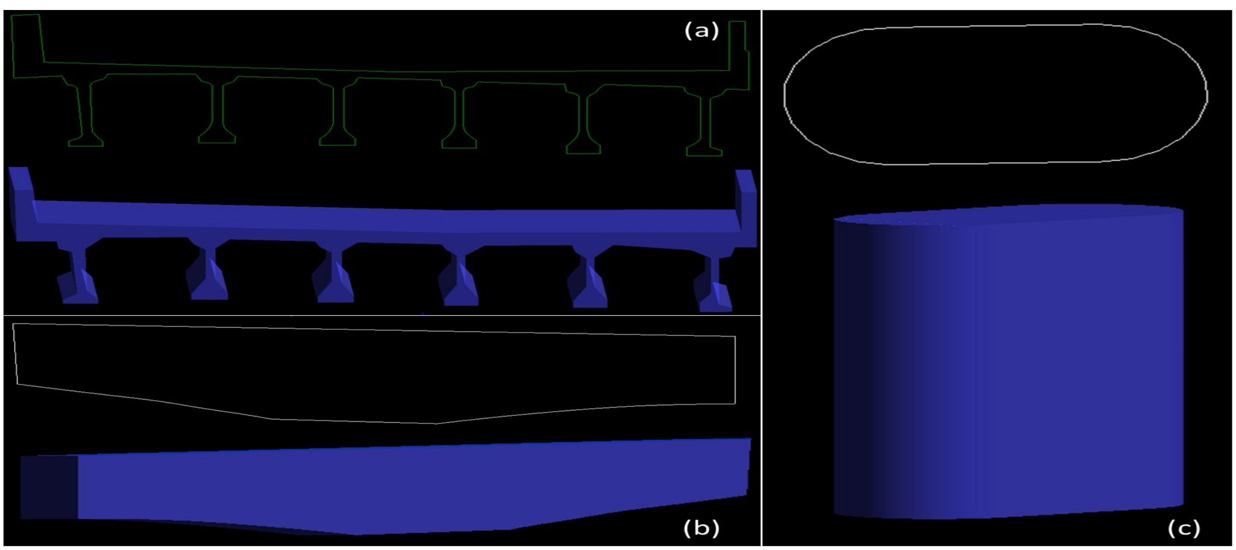

Figure 5.4. Parametric cross-section and generated BrIM of (a) girder slab; (b) pier cap; and (c) pier.

5.3 Placement of BrIM Elements in Point Clouds

To automatically generate the BrIM from the point cloud data, all points that were in world coordinates were imported into Dynamo software and then were converted into the project coordinate system (see figure 5.5). Next, piers, pier caps, and girder slabs were created separately. To generate the piers on the basis of point clouds, the points with the lowest elevation were identified, and an XY slicing plane was created starting from this point and slicing upward using Dynamo script. Once the points on the slicing plane could form a closed shape, a rectangular bounding box was constructed, and the side lengths of the bounding box were calculated. This information was then used to determine the parametric cross-section of the pier. The height of the pier was determined by using the elevation difference between the slicing plane at which the point could form a closed shape and the slicing plane at which the closed shape changed.

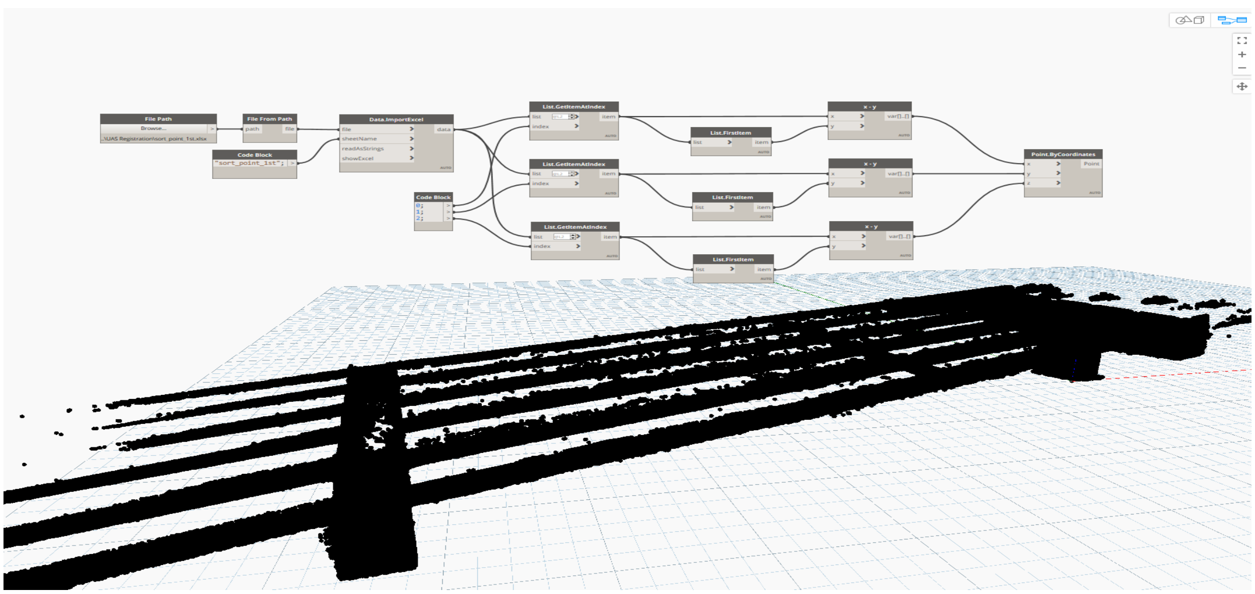

Figure 5.5. Point clouds in the project coordinate system in the Dynamo interface**.**

To generate the girder slabs on the basis of point clouds, the point clouds were projected onto the XY plane, followed by fitting a curved line to the long side of the bridge based on the points on edges (two lines for both sides). On the curve, twelve interpolated locations were identified with equal intervals, and the tangent and normal at each interpolant were calculated. Then, a vertical slicing plane was placed along the direction of the normal of each interpolated position. A 2D ConcaveHull α-shape (Moreira and Santos. 2006) was used to describe the outline of the cross-section on each slice and link it to the previously created parametric slab element. Thus, the girder slab was created by connecting the slab element at each slice position based on the curved line.

After we had successfully placed piers and girder slabs to the correct locations in the point cloud, the pier cap was placed on top of each pier and attached to the bottom of the girder slab. The direction of it was set along the long side of the pier's rectangular bounding box. The width of the pier cap was set as the same as the short side of the pier's rectangular bounding box, and the length of it was set as same as the width of the girder slab along this direction.

In the end, a BrIM was developed automatically by using the point cloud features as well as the previously created families of main elements of the bridge. Given the characteristics of the conceptual mass, the surface of each element could be dragged and adjusted in a 3D environment. This feature would be helpful for any necessary adjustment when the point clouds are overlaid with the created BrIM. The created BrIM was considered to have a level of detail (LOD) of 300, which represented the bridge model accurately in terms of size, shape, location, and orientation. Figure 5.6 presents the final BrIM developed with the proposed framework, and figure 5.7 presents the created BrIM overlaying the dense point cloud.

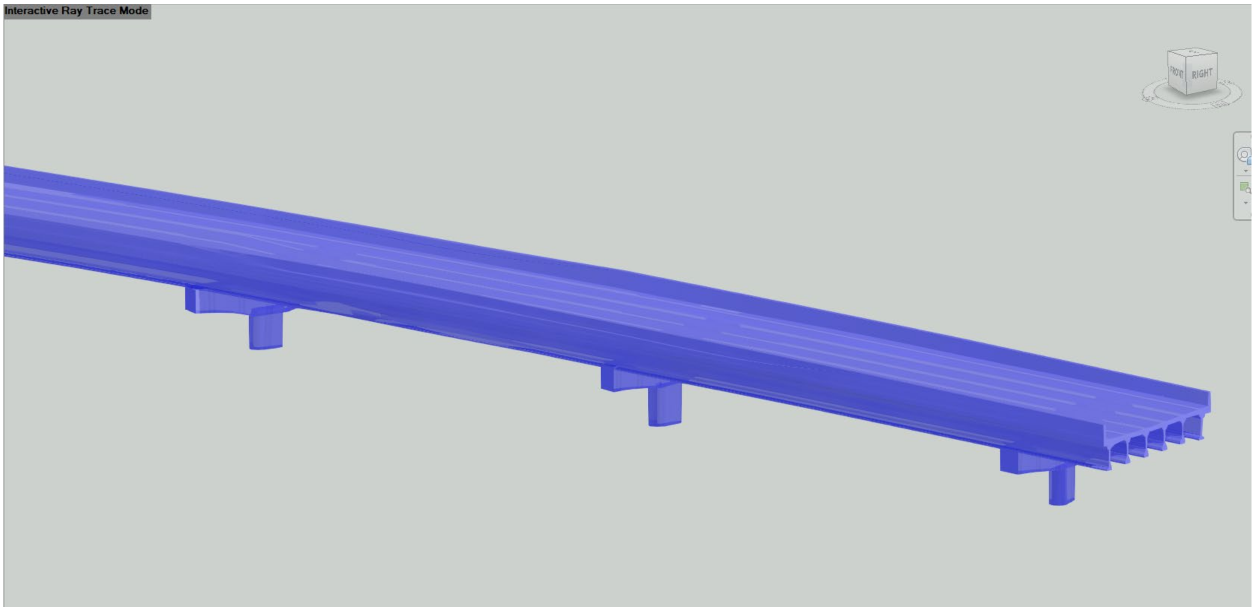

Figure 5.6. The BrIM that was developed in Revit using the proposed framework**.**

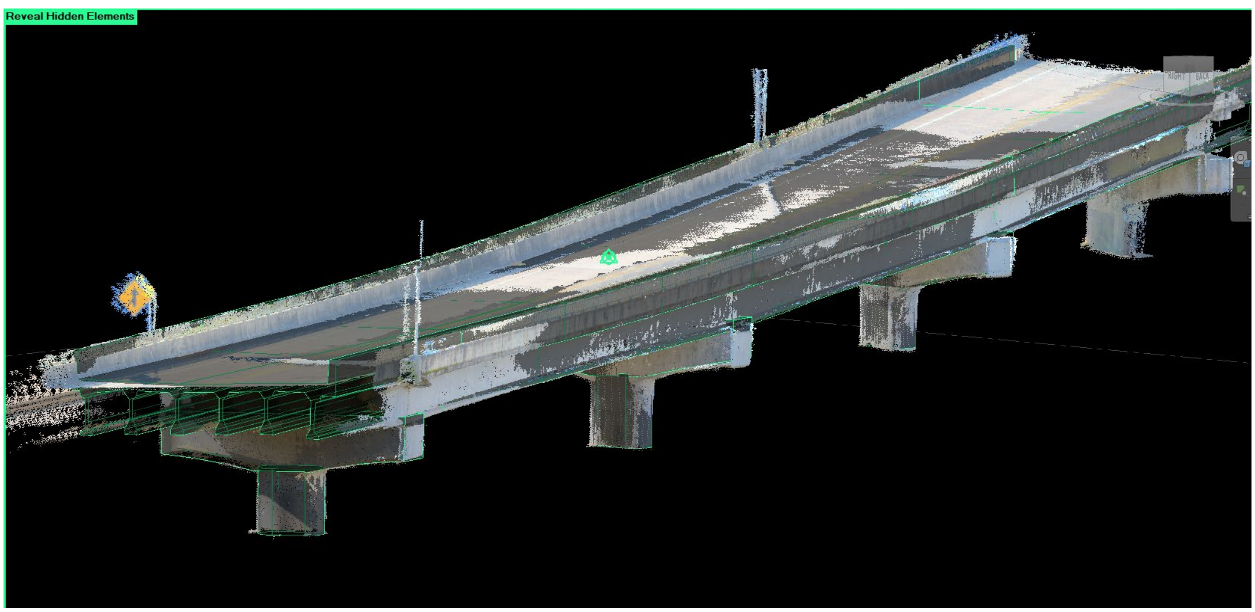

Figure 5.7.The developed BrIM overlaying the dense point cloud (the BrIM model is in green).

Chapter 6 Discussion

Even though the proposed framework, as suggested by the results presented in the previous chapter, can increase automation in developing BrIM, there are some challenges associated with its implementation. In particular, the case study identified two main challenges: accuracy of point cloud generation and accuracy of girder-slab generation.

6.1 Accuracy of Point Cloud Generation

The accuracy of the SfM algorithm, which produces point clouds from digital data, is heavily influenced by the overlap between images. In contrast to the surveying and mapping processes, which allow UASs to be flown in an auto-mode with fixed overlap percentages (sides and ends) during the flight, it is extremely difficult to ensure enough overlap in UAS imaging for 3D reconstruction. Several factors make this process difficult:

(1) Bridges are designed in various shapes and require a very detailed model in the flight planning system to pre-design the flight route in space (3D environment), which is not available in current UAS flight planning software.

(2) Most UASs that are available in the market come with a front-mounted camera, which limits their ability to tilt to collect information from the bottom of the bridge. This affects the completeness and the quality of the BrIM.

(3) The automated image capture feature embedded in UAS flight planning software can help to ensure some level of image coverage. However, the speed of UASs vary greatly, depending on the operator, and the flight speed has an impact on the quality of the images taken and therefore the quality of the point cloud produced from those images.

All these issues may lead to missing information, such as discrepancies and holes, resulting in inaccurate point clouds. In the case study, even though the dense point clouds generated were satisfactory in terms of accuracy, as it can be seen in the confidence map of the dense point-cloud model (figure 6.1), substantially fewer images were collected and used to generate the dense point-cloud model (lighter colors indicate that fewer images/less information were collected at those locations). To improve the data collection, i.e., collect more detailed information, from under the bridge, a UAS equipped with a top-mounted camera would be very useful. However, a UAS with a top-mounted camera would be difficult for collecting information from the top and sides of the bridge. This issue could be addressed by using multiple UASs, but that would not be cost-effective. Also, different camera positions and sensor parameters produced as a result of using different UASs might pose problems when SfM algorithms were used to produce point clouds and then negatively impact point cloud accuracy.

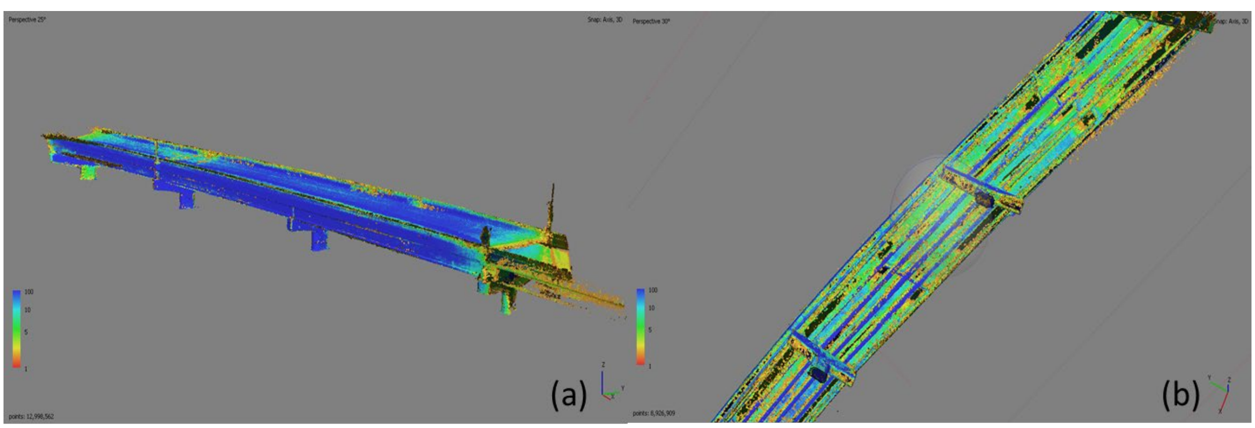

Figure 6.1. Confidence map of (a) deck sides and piers/pier caps; and (2) bridge bottom

6.2 Accuracy of Girder Slab Generation

The studied bridge in the case study had several unique features. Out of the three spans, one span had five girders while the other two spans had six girders, and the transition from five to six spans occurred where the pier cap was located (figure 6.2). Additionally, the pier cap was not perpendicular to the girders. This became an issue when the proposed method was implemented Given that the studied bridge had a curved shape, the generation of the girder slab was based on its curvature and the cross-section, which had to be perpendicular to the girders. As a result, the proposed framework needs to be improved for situations in which the support system does not run perpendicular to the girder slabs and the number of girders changes at this support location.

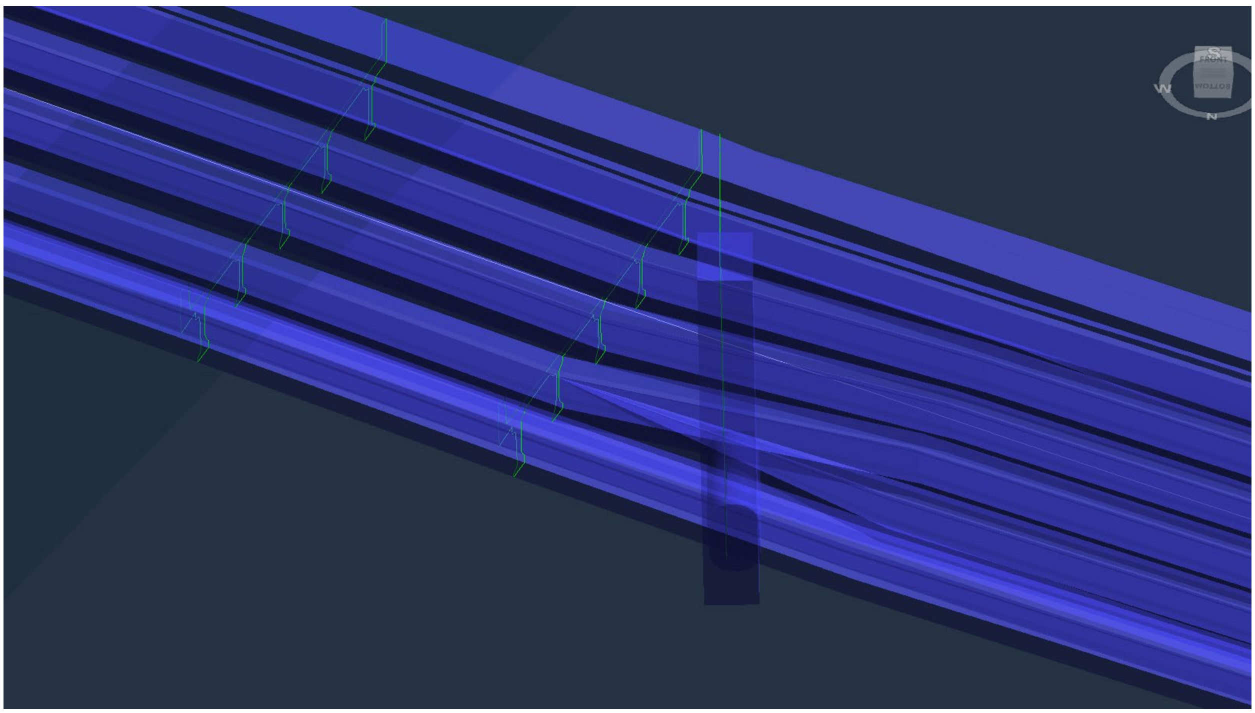

Figure 6.2. Issue identified where the support system was not perpendicular to the girders while the number of girders changed at this location**.**

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

U.S. economic growth, as well as the mobility of people and goods across the country, are largely dependent on the health of the country's transportation system. Unfortunately, the U.S. infrastructure is aging and has been poorly maintained for decades. Bridge Information Models (BrIM) are seen as an effective method to improve the efficiency of current bridge inspection and management practices. However, the creation of such models involves a time consuming and manual process. Because there are a large number of bridges in the U.S., manually creating BrIMs would be time-consuming, labor-intensive, and expensive. Therefore, a new framework was proposed in this study to speed the creation of BrIMs. The proposed framework was implemented on an existing bridge. The illustrative case study provides a detailed explanation of UAS imaging, point cloud generation, and BrIM creation and its placement in the generated point-cloud model. The case study demonstrated the feasibility of rapidly generating BrIMs using the proposed framework. The proposed framework showed potential for addressing some of the problems associated with the current BrIM generation process in terms of cost-efficiency and effectiveness.

7.2 Recommendations for Future Work

The study had a number of limitations that should be addressed in future studies. First of all, the BrIM generation process mentioned in the proposed framework was not fully automated. The parametric BrIM families of typical main elements were manually created on the basis of 2D drawings. Any bridge element that has a shape that is not already in the BrIM family library should be created and added to the BrIM family library. To automate this process, algorithms that can automatically extract cross-sections of elements and build conceptual mass should be investigated in future work. Also, the proposed framework was implemented on one concrete girder bridge. To improve the reliability of the conclusions drawn from this study, future research should apply this framework to other types of bridges, such as box girder bridges.

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