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Terrestrial Laser Scanning (TLS) Survey and Building Information Modeling (BIM) of The Edmund Pettus Bridge: A Case Study

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ABSTRACT:

The comprehensive digital documentation of the Edmund Pettus Bridge, a symbol of the American Civil Rights Movement located in Selma, Alabama, serves as an example of integrating Terrestrial Laser Scanning (TLS) and Building Information Modeling (BIM) technologies for the conservation of heritage infrastructure. This study aimed to employ advanced TLS and other Reality Capture (RC) techniques to generate a high-resolution, three-dimensional representation of the bridge, thereby aiding in its structural assessment and preservation. Utilizing TLS alongside 360-degree photography and UAV surveys, the project achieved detailed coverage of the bridge's architectural and structural features. The data collected was processed into a BIM model using Autodesk Revit, offering comprehensive analysis and preservation planning. The findings from this research highlighted previously undetected areas of material degradation and structural vulnerabilities, emphasizing the value of TLS and BIM in revealing critical insights into the condition of heritage structures. This project preserved the digital memory of an iconic Civil Rights landmark and set a framework for applying digital documentation technologies in heritage infrastructure conservation. The success of this methodology offers a valuable precedent for future conservation efforts, showcasing how RC technologies can enhance the preservation of historical sites and ensure their legacy is maintained for future generations.

1. INTRODUCTION

The Edmund Pettus Bridge (as shown in **Figure 1**), a national symbol of the American Civil Rights Movement, is a historically significant landmark located in Selma, Alabama, USA. Designed by Selma-born engineer Henson Stephenson (1897-1978) and constructed in 1940, this bridge has been a witness to critical events in American history, notably the 1965 Selma to Montgomery marches for the Voting Right ("Edmund Pettus Bridge," n.d.).

Figure 1. Aerial photograph of the Edmund Pettus Bridge.

The bridge's style is characteristic of its era, featuring a steel through-arch with concrete open-spandrel-arches. It stretches 1,248 feet and 6 inches long, navigating significant topographical changes along its path. The bridge's unique design, including its asymmetrical arches and decorative elements, showcases the engineering achievements of the time. However, the only substantial change since its construction has been the replacement of its original green paint with a cool gray in the early 1980s (Willkens & Liu, 2024). Despite its historical and architectural significance, the bridge faces challenges concerning its condition and the need for attention. As shown in Figure 2, the bridge's structure, while largely intact, reflects the wear of decades and the need for thorough assessment and careful conservation.

(a) Corrosion and paint maintenance needed

(b) Damaged railing plate and baluster

Figure 2. Places of the bridge needing maintenance and repairs.

The digital documentation for the Edmund Pettus Bridge, as a part of an effort to develop a Historic Structure Report (HSR) of this historically significant structure, aimed to thoroughly record and archive the bridge's existing condition to preserve its historical and architectural legacy. The primary method employed for this effort was TLS, supplemented by photogrammetry, UAVs, infrared photography, and Matterport 360-degree photography. The integration of these technologies facilitated a comprehensive and non-intrusive method of capturing the bridge's details and also ensured precision and accuracy in documentation. Furthermore, this project validated the implementation of TLS technology in effectively capturing heritage infrastructures like a bridge.

The two primary outcomes of the documentation inluded an BIM model and a set of Historic American Engineering Record (HAER) drawings (Balachowski, 2001; Lavoie & Lockett, 2016). The BIM model served multiple purposes: it aided in the preservation efforts by providing a precise representation of the bridge's current state (Abbate et al., 2022; Conti et al., 2022) and formed the basis for developing the HAER drawings. The HAER drawings provided a detailed architectural and engineering record of the bridge. Due to the page limit, this article only focuses on the context of the TLS survey and BIM model development.

2. MATERIALS AND METHODS

The digital documentation process of the Edmund Pettus Bridge involved four main stages, as shown in Figure 3. They included site assessment and project planning, on-site data acquisition, data post-processing and management, and data utilization for developing the BIM model and HAER drawings.

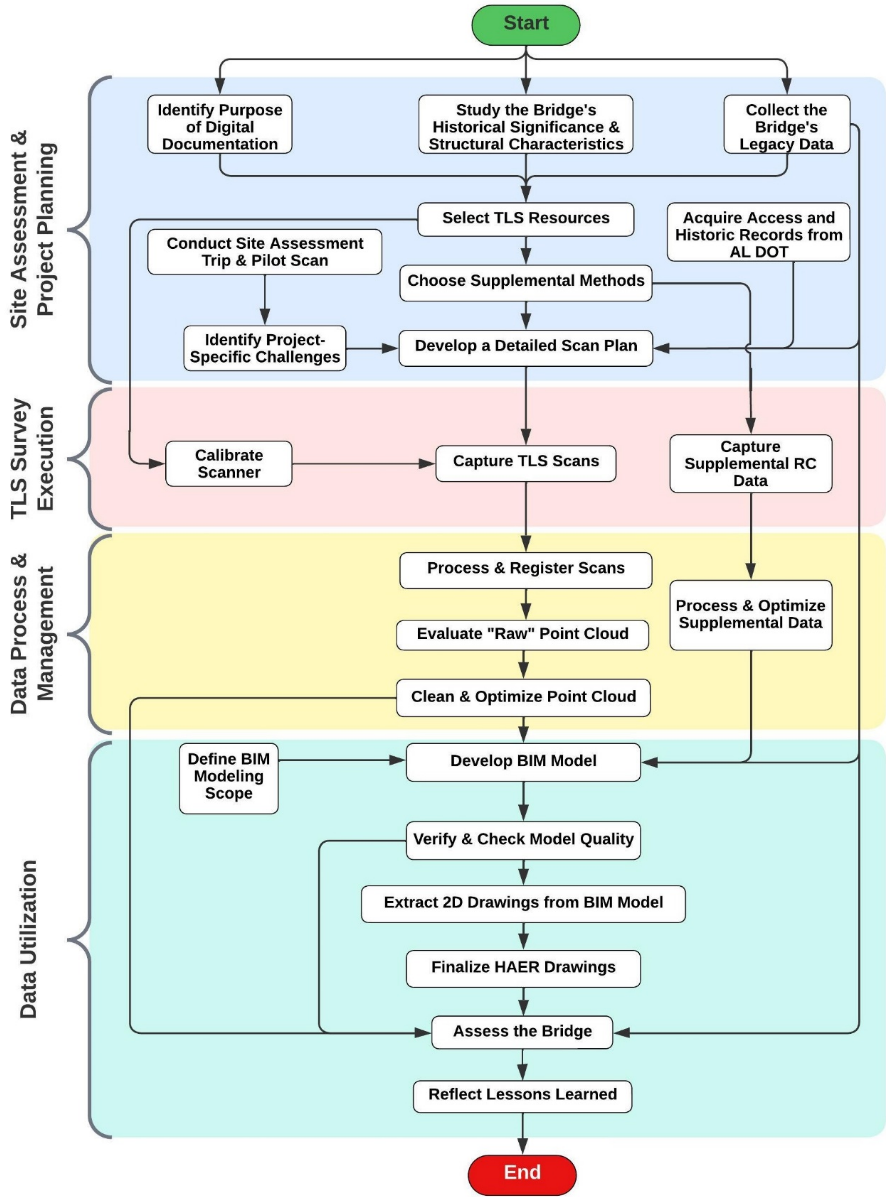


Figure 3. The Process of the Edmund Pettus Bridge digital documentation.

2.1 TLS Field Survey

2.1.1 Selection of TLS Technology: Choosing TLS as the primary technique for capturing the existing conditions of the bridge was based on several factors that made it suitable for the project (Del Duca & Machado, 2023; Gollob et al., 2020):

- High Accuracy and Precision: TLS is renowned for its high level of accuracy and precision in capturing detailed measurements. For historic structures like the Edmund Pettus Bridge, where every detail is critical, the ability of TLS to produce highly accurate representations of complex geometries and intricate details is invaluable.
- Comprehensive Data Collection: TLS enables the collection of comprehensive, three-dimensional data that covers all visible surfaces of the bridge. This thoroughness is crucial for historic structures. Traditional surveying methods might miss fine details or require multiple surveys to achieve comparable coverage, whereas TLS can capture the complete picture in a single pass.
- Non-Intrusive and Non-Destructive: As a non-contact surveying method, TLS is ideal for historic preservation. It eliminates the risk of damaging the structure, which is a concern with potentially fragile historic bridges. This non-intrusive nature ensured that the structural integrity and historical authenticity of the bridge were maintained throughout the surveying process.
- Efficiency and Time-Saving: Compared to traditional surveying methods, TLS can significantly reduce the time required to survey a large and complex structure like the Edmund Pettus Bridge.
- Versatility and Adaptability: TLS technology is highly adaptable to various environments and conditions. This versatility is crucial when dealing with outdoor historic structures, which may present challenging survey conditions such as difficult-to-reach areas, varying light conditions, and environmental factors. TLS can reliably operate under most of these conditions.
- Integration with Other Technologies: TLS data can be integrated with technologies such as BIM and CAD, to provide a holistic understanding of the structure.

Several limitations inherent to the TLS technology and the specific context of the Edmund Pettus Bridge were also anticipated. These limitations were essential to consider for effective project planning and execution:

- Safety Constraints: Challenges in safely positioning equipment on or near a busy roadway and issues accessing certain areas.
- Live Traffic: Safety concerns and the impact of vibrations from passing vehicles on scan accuracy.
- Limited Access above the Alabama River: Challenges in scanning sections of the bridge over the river due to difficult access.
- Complex Geometries: Difficulty in accurately capturing intricate details, such as the arched concrete stringers and concrete arches.
- Physical Obstructions: Obstructions like dense vegetation and passing vehicles or pedestrians causing gaps in data.
- Environmental and Weather Conditions: Potential interference from rain, fog, or extreme brightness affecting scan accuracy. And changes in temperature influencing material behavior.
- Calibration and Equipment Limitations: Potential inaccuracies due to equipment drifting or extended scanner range and resolution limitations.
- Data Processing and Management: Handling and processing large volumes of scanned data.
- Scan Registration Challenges: Difficulties in aligning multiple scans accurately due to the bridge's large size, linear shape, dense surrounding vegetation, and lack of nearby permanent structures to use as reference points.
- Time and Resource Constraints: Balancing the thoroughness of the scan with the project's time and resource limitations.

2.1.2 Other RC Technologies Supplemented to TLS for Data Acquisition: Several other RC technologies were utilized to complement TLS. These techniques included photogrammetry, Matterport 360-degree photography, UAVs, and infrared photography:

- Photogrammetry: This technique was essential for capturing visual details, especially information on color and materials. Given the bridge's historical significance and unique design features, photogrammetry provided high-resolution imagery and complemented the geometric data captured by TLS. It was especially useful for areas that were hard to reach for the TLS scanner or where the bridge's surface textures needed to be documented.
- Matterport 360-degree Photography: The use of this technology was beneficial for the project due to its ability to create interactive, high-resolution, and detailed panoramic views. It provided supplemental information that the TLS point cloud lacked and allowed the researcher to visualize the details of the bridge's surface areas during the development of the BIM model.
- UAVs: Drones were useful for documenting the bridge's expansive span and challenging topography. They provided aerial views and access to difficult-to-reach areas, such as the top of the main arch and spans above the Alabama River, to ensure a comprehensive data acquisition.
- UAV-Based Infrared Photography: Given the bridge's age and weather exposure, infrared photography became a valuable tool for identifying structural vulnerabilities that were not immediately visible. It helped in detecting issues like moisture intrusion or material degradation.

2.1.3 TLS Equipment and Software: A FARO Focus3D X-330 HDR (FARO X330) scanner was employed to carry out the TLS survey. At the time of the project, the FARO X330 scanner was extensively used in documenting the built environment due to its high precision, outstanding efficiency, and superior mobility. Its cost-effectiveness further contributed to its widespread popularity in commercial laser scanning applications. Several software programs were also utilized for data acquisition, processing, and developing BIM. Each piece of software was chosen for its specific capabilities and compatibility with the project's goals. Table 1 summarizes the roles and rationales for each software program in the project workflow, from processing the TLS scan data to developing the final BIM model and CAD drawings.

2.1.4 TLS Survey Planning: An initial assessment for the TLS survey of the Edmund Pettus Bridge was conducted in November 2019. It involved several critical steps:

- Preliminary Site Visit and Pilot Scans: This site visit focused on the north approach ramp and Span-1 on the City of Selma side of the bridge. Pilot scans using the FARO X330 laser scanner were also performed to evaluate the equipment's effectiveness in the bridge's environment and validate scanning strategies.
- Photographic Surveys and Coordination with ALDOT. Photographic surveys were conducted to document the existing conditions and assist in planning the scanning process. A meeting with the Alabama Department of Transportation (ALDOT) was held to discuss the project scope, operational, safety, logistical aspects, and access to the bridge's historical and maintenance records.

The project team discovered several challenges and notable features of the site through the project assessment visit and pilot scans. They included:

- Traffic Conditions: The bridge experienced traffic at high speeds, often exceeding the official limit of 20MPH. Observations indicated that traffic speed could reach up to 45MPH, causing significant vibration that potentially affected scanning accuracy.
- Optimal Timing for Field Survey: The lightest traffic, identified as early Sunday mornings, was considered the feasible time for field surveys.
- Environmental Factors: The dense vegetation south of the Alabama River, high humidity levels, potential for high winds, and significant temperature-induced bridge expansion were noted. These factors required equipment stability and data accuracy considerations, especially since the survey was anticipated to span several months.
- Access Limitations: Restricted access was recognized in areas under the bridge, particularly over spans 1, 2, and 3 above the Alabama River and on the medians. This limitation required strategic planning for scanner placement and data capture with alternative methods.

Software	Use in Project	Justification
FARO SCENE	Processing and registering TLS scan data.	Compatible with FARO scanners; efficient in processing and registering a large amount of TLS scans.
Autodesk ReCap Pro	Cleaning and preparing point cloud for BIM/CAD use.	Advanced editing tools; integrates well with Autodesk products.
Autodesk Revit 2020	Developing the BIM model of the bridge.	Industry-standard for BIM; supports point cloud data.
AutoCAD 2020	Creating CAD drawings of the bridge.	Precision drafting; widely accepted in professional fields.

Table 1. Software programs used for the Edmund Pettus Bridge project.

2.1.5 TLS Survey Execution: The TLS survey started in November 2019. However, due to the COVID-19 pandemic outbreak, the project experienced a temporary halt, resumed in summer 2020 and concluded in July 2020. To capture all of the 72 scans, the bridge was divided into four sections for a systematic approach (as shown in Figure 4). Scanner locations (as shown in Figure 5) were strategically chosen for optimal coverage, with attention to elevated areas, complex elements, and the scanner's range (Che et al., 2019; Del Duca & Machado, 2023).

A targetless approach was used due to the project's time and resource constraints. For a comprehensive TLS survey of a large and complex structure like the Edmund Pettus Bridge, choosing an optimal scanner setting was crucial to balance detail, coverage, and efficiency. The project team used the same settings of the FARO X330 for all 72 project scans of the project, including ½ Resolution, 2x Quality, Color turned on, and an unlimited Range. Counting setting up the scanner, taking scan, and capturing panoramic photos, each scan took about 17 minutes to complete.

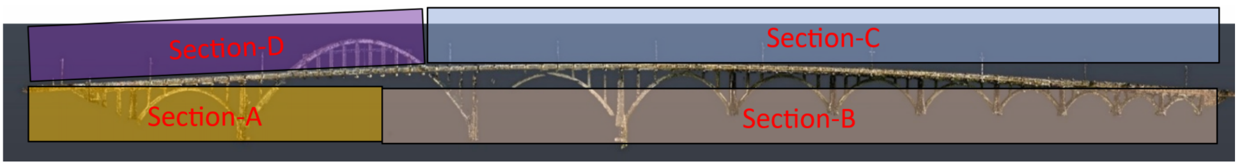


Figure 4. TLS survey phasing plan.

Figure 5. Planned scanner locations on the deck of the bridge.

2.2 TLS Data Processing and Management:

2.2.1 Initial Scan Processing: All 72 scans were initially processed through FARO SCENE software. This step included colorizing and converting the raw data into usable point clouds, ready for further processing and analysis. Next, the "Moving Objects Filter" feature within FARO SCENE was utilized to eliminate noise, such as points of passing by vehicles and pedestrians, from the data. This feature was helpful in improving the cleanliness and clarity of the point cloud, especially given the bridge's high-traffic environment. Next, the scans were registered and integrated into a single point cloud through the following steps:

- Cluster Division: In line with the TLS survey phasing plan, all 72 scans were systematically divided into four clusters, corresponding to each designated section of the bridge.
- Automatic Registration: FARO SCENE's automatic registration feature was employed for initial alignment within each scan cluster, utilizing overlapping areas as reference points. This automatic process was also instrumental in merging the four clusters into a comprehensive whole later.
- Manual Refinement: Post-automatic registration, manual adjustments were applied to refine alignments. This step was especially useful in sections with complex geometries or where large distances spatially separated adjacent scans.
- Unified Point Cloud Creation: The culmination of this process was the integration of all registered scans into a singular point cloud. This point cloud, as shown in Figure 6, represented the entire bridge. It is worth noting that at this stage the FARO SCENE project of the bridge was over 117 GB in file size.

2.2.2 Point Cloud Data Conversion and Cleaning: After the initial processing and registration in FARO SCENE, the point cloud data underwent further refinement and preparation for 3D modeling:

- Export to Autodesk ReCap Pro (ReCap Pro): The registered point cloud was exported into a Recap project in the RCP format. This format is compatible with various Autodesk applications (e.g., Revit and AutoCAD) and is conducive to further processing.
- Quality Control and Verification: The RCP project was opened in ReCap Pro for quality control and accuracy verification. It involved a visual inspection and manual measurements of known distances in the point cloud. Such checks helped verify the accuracy and quality of the data and ensured it accurately represented the physical dimensions.
- Data Optimization for 3D Modeling: The original formation of the point cloud dataset was yet useful for modeling due to its enormous file size. The unification and subsampling of the point cloud became a critical step in reducing the overall point density. This process made the large dataset manageable and streamlined it for effective use in 3D modeling applications. Through this step, the point cloud file size was reduced from 117 GB (in FARO SCENE) to 3.4 GB (in ReCap Pro).

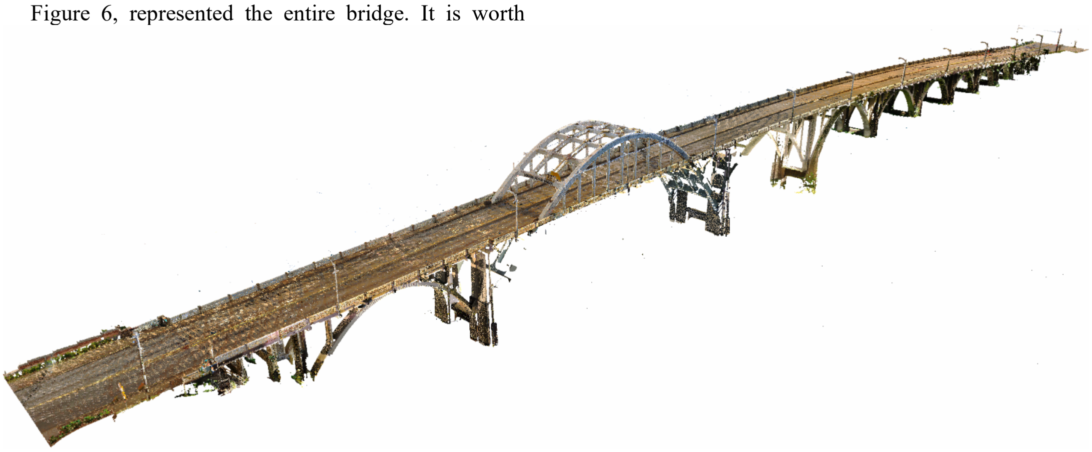


Figure 6. Registered point cloud of the whole bridge.

2.3 Development of BIM Model

2.3.1 Scan-to-BIM Approach: In the development of the BIM model for the Edmund Pettus Bridge using Autodesk Revit, the project team chose to employ the Scan-to-BIM approach. This method starts with scanning the physical structure to create a detailed point cloud, which is then used as a reference to build an accurate 3D model in a BIM software platform, such as Autodesk Revit. This approach is particularly effective for capturing the as-built conditions of existing structures, providing a precise digital representation based on real-world data (Rocha & Mateus, 2021). This methodology is feasible for the project because:

- Accuracy and Detail: Given the bridge's historical significance and complex structure, this approach is ideal for accurately capturing its details.
- Preservation and Documentation: This method is non-intrusive and perfect for historic preservation efforts, allowing for detailed documentation without physically impacting the structure.
- Efficiency and Integration: It provides an efficient workflow for integrating the scanned data into Revit, streamlining the process of converting point clouds into a usable BIM model.

2.3.2 Integration of TLS Data and Supplementary Information Sources: The primary foundation for developing the BIM model was the Autodesk ReCap RCP point cloud dataset linked to the Revit model. This point cloud provided detailed and accurate information about the bridge's measurements and current physical state. Where the point cloud data was insufficient, supplementary sources were referenced for a more comprehensive representation. These sources included the bridge's original design drawings, terrestrial and aerial photographs, an immersive virtual tour recorded using a Matterport 3D camera, and other historical records. This methodology ensured that the model was accurate to the current state of the bridge and respectful of its historical design.

2.3.3 Scope of Elements to Model: The following key elements of the bridge were included in the Revit model:

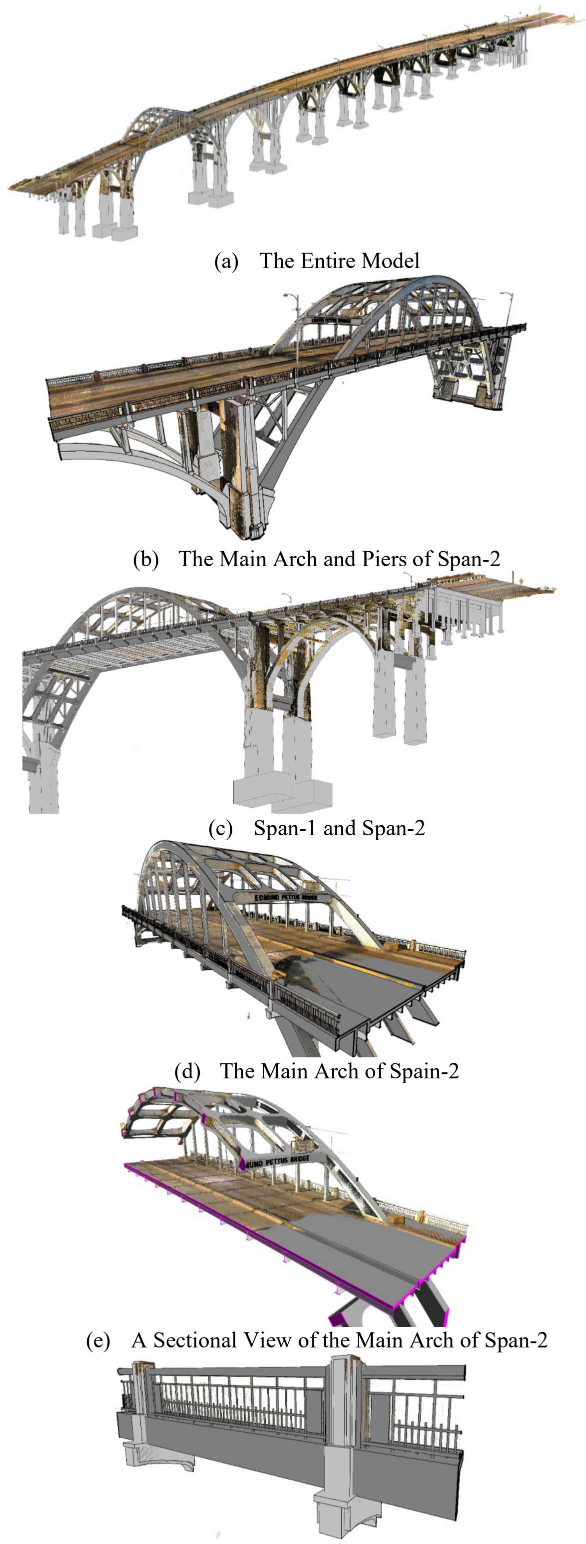
- Structural Framework: Include the primary structural components such as beams, trusses, girders, piers, footings, piles, and supports.
- Decking: The surface layer of the bridge.
- Some of the Architectural Details: Some of the unique architectural features specific to the bridge's design, such as decorative elements.
- Railings and Barriers: Details of railings, including their design, materials, and positioning.
- Expansion Joints.

Other elements of the bridge were excluded from the Revit model, such as:

- Lighting Fixtures, Roadway Markings, Signage, Drainage Systems, and Utilities: These elements were not original or did not reflect the bridge's historical state. Including these would detract from the focus on preserving the bridge's original design.
- Environmental Surroundings: While important, the representation of the surrounding environment, such as the river, was excluded to concentrate on the structural and architectural aspects of the bridge itself.
- Other Insignificant Architectural Details: Some of the unique architectural features specific to the bridge's design, such as the steel plates of the railings.

2.3.4 BIM Modeling Process: Customized modeling was essential for this project due to the bridge's historic nature. The "Model In-Place" feature in Revit was extensively used for this purpose. This tool allowed for the creation of unique, non-standard elements that closely matched the bridge's evolved structure over the years, ensuring the historical authenticity of the model.

Developing a BIM model of the bridge involved a structured workflow that began with preparing the base model by importing and orienting the point cloud data in Revit. The next step was tracing the primary structural components like beams, girders, piers, and supports using Revit's "Model In-Place" feature directly over the point cloud. This step also involved referencing the historical design drawings to model hidden or uncaptured elements left out during the field survey. Details and decking were then modeled, focusing on unique architectural features and accurately replicating the bridge's surface details. Additional elements such as railings, barriers, and expansion joints were created next, using the point cloud data and historical drawings to guide details and positioning. Verification and adjustment was a continuous process, requiring regular cross-checking of the developing model with the point cloud and historical drawings for accuracy and making necessary adjustments for alignment with as-built conditions and historical accuracy. The final step involved reviewing the entire model for discrepancies or missing details and making final adjustments. Figure 7 illustrates visual comparisons showing how the finished Revit model aligns with the captured TLS point cloud.



(a) The Entire Model

(b) The Main Arch and Piers of Span-2

(c) Span-1 and Span-2

(d) The Main Arch of Spain-2

(e) A Sectional View of the Main Arch of Span-2

(f) Typical Railing

Figure 7. Visual comparisons of the BIM model and the point cloud.

3. RESULTS AND DISCUSSION

The documentation of the Edmund Pettus Bridge, mainly through TLS technology, was able to record and archive the

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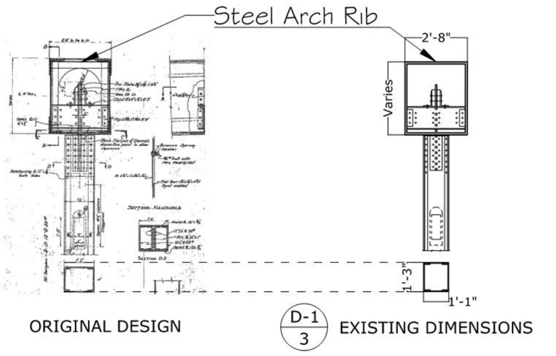
bidge’s existing conditions thoroughly. The documentation outcomes have contributed to assessing this historically and culturally significant bridge.

The TLS survey provided a detailed and precise 3D point cloud of the bridge, offering a comprehensive view of its current structural state. This high-resolution data allowed for an in-depth analysis of various structural components, including the steel arches, concrete piers, and the deck. Such detailed information is crucial for identifying areas of concern that might not be visible through traditional inspection methods.

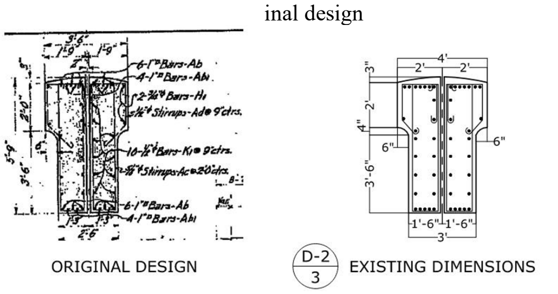
The documentation revealed several discrepancies between the bridge's original design and current condition. For example, the discovery of construction changes, such as the 90-degree distortion in the hangers of the steel arch (see Figure 8a) and variations in the dimensions of concrete struts of the piers (see Figure 8b), provide insights into the bridge's construction. Understanding these discrepancies is also critical for future restoration or maintenance work, ensuring that interventions are based on accurate actual condition information.

Furthermore, the digital documentation has established a baseline record of the bridge's condition at a specific point in time. This record is invaluable for monitoring the bridge's condition over time, allowing for the detection of new or worsening structural issues. This ongoing monitoring can also be crucial for a proactive maintenance strategy and help ensure the bridge's safety and longevity. Stakeholders can use software tools like CloudCompare (CloudCompare - Open Source Project, n.d.) to contrast point clouds from different survey periods to identify discrepancies and locate changes.

Throughout the project, the project team faced and overcame a series of technical challenges during the phases of the TLS survey, scan data processing, and development of the BIM model. Safety concerns due to traffic and vibrations on the bridge were mitigated by coordinating with ALDOT for traffic detours and scheduling scans during low-traffic periods. Adaptive scanning techniques and careful planning addressed environmental challenges like dense vegetation and variable weather. Access limitations, especially over the Alabama River, were overcome using aerial drone imaging. In TLS data processing, accurate scan registration was achieved through a combination of automatic and manual techniques in FARO SCENE software. Noise from moving objects was filtered out using automated techniques and manual cleaning, while the challenge of managing large volumes of data was met with efficient data management protocols and powerful computing resources. For BIM modeling, capturing the bridge's unique architectural details required the use of Revit's "Model In-Place" feature and referencing to historical accuracy, integrating disparate data sources involved a layered modeling approach, and maintaining historical accuracy while reflecting the current state necessitated thorough cross-referencing and validation between point cloud data, historical drawings, and recent photographs.



(a) The hangers supporting the main steel arch of Span-2 were installed with a 90-degree rotation from the original design



(b) Actual dimensions of the upper concrete strut of Pier-5 are larger than the original design

Figure 8. Discrepancies were discovered through the documentation.

4. CONCLUSION

This project has demonstrated the capabilities and effectiveness of TLS in capturing detailed and accurate representations of historic structures beyond traditional buildings, highlighting its vital role in the domain of heritage conservation. In this study, the primary goal was to record and archive the current conditions of the historic Edmund Pettus Bridge. The TLS technology played a primary role in achieving the objectives by providing a comprehensive 3D point cloud that formed the basis for further analysis and documentation. The TLS data was instrumental in developing the BIM model and HAER drawings. The models and drawings offered a level of detail and accuracy previously unattainable to the bridge. The documentation process also revealed several discrepancies between the bridge's original design and its existing condition.

Throughout the project, the advantages of TLS became evident, particularly its accuracy, non-intrusive nature, efficiency in data collection, and versatility in various environmental settings. However, the technology also encountered limitations, including challenges related to accessibility, environmental impacts on scan accuracy, and the complexities involved in managing vast datasets. These limitations highlighted the need for careful planning and execution to utilize TLS in heritage documentation.

The broader impact of this digital documentation project extends beyond the technical accomplishments. The comprehensive data collection and analysis have contributed to the structural assessment of the bridge. By establishing a detailed baseline record of the bridge's condition, the project has set the stage for ongoing monitoring and future maintenance, ensuring the longevity and preservation of this historic landmark. Additionally, the digital representation of the bridge, especially the Materport virtual space, has become a valuable tool for public engagement.

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