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# Innovative Monitoring Strategies for Lift Bridge Performance

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# Abstract
This paper discusses innovative monitoring strategies implemented on the Danziger Lift Bridge, a vertical lift bridge with electro-mechanical tower drive systems, to address operational issues including the movable span not seating properly and span skew problems. Inspections also revealed deterioration in three of the eight trunnion bearings, necessitating further investigation and monitoring. To address these issues, the team implemented several innovative monitoring strategies, including:

- Multi-system distributed wireless data acquisition systems.
- Lasers and ultrasonics movement sensors utilized for span, skew, roadway joint, and seating monitoring.
- Predictive vibration monitoring of trunnion bearings to monitor wear degradation.

This paper will explore the performance of these systems and the lessons learned through this multi-year monitoring project.

# Introduction

## Background and Motivation

The Danziger Lift Bridge, an electro-mechanical tower drive vertical lift bridge, spans the Inner Harbor Navigation Canal (Industrial Canal) in New Orleans. Since its construction in the mid-1980s, the bridge has encountered several operational challenges and was considered a problem structure by the Louisiana Department and Transportation and Development (LADOTD). The following are the issues identified by LADOTD that prompted the engagement of Wiss, Janney, Elstner Associates, Inc. (WJE):

Figure 1: Danziger lift bridge in New Orleans, Louisiana.

1. There has been a long history of seating issues. This includes difficulty with getting the four corners of the lift span to seat firmly at the corners during normal bridge operation, as well as reports of the southwest corner "popping up" under traffic during hot weather.
2. During hot weather, the bridge would not fit between the approach spans on either end of the lift span. Prestressed concrete I-girders of the approach spans were encroaching into the expansion joint openings at both the east and west ends of the lift span resulting in contact (Figure 2) and damage between the approach span girder ends and the lift span end floor beams.
3. The orthotropic steel deck latex modified concrete overlay was failing, resulting in poor ride quality and requiring frequent repairs and patching.
4. Reports of isolated occurrences of extreme skew during operation of the lift span.

WJE was tasked with performing an inspection of the structure and installing a monitoring system as a means to gain a deeper understanding of bridge behavior under various conditions and to resolve the operational issues of the structure. The failing LMC overlay is not discussed herein as its performance was not directly related to the monitoring systems.

# Initial Inspection Findings

WJE performed a structural, mechanical, and electrical inspection as well as operational testing at the bridge in October 2019 with additional testing performed in February and November 2020. Operational testing included strain gage recordings, shaft rotation recordings, and measurements taken at the live load supports to assess the problematic seating behavior, operational skew behavior, and overall balance of the lift span. In addition to verifying the previously reported issues, there were several additional major findings that impacted the scope of the instrumentation and monitoring work:

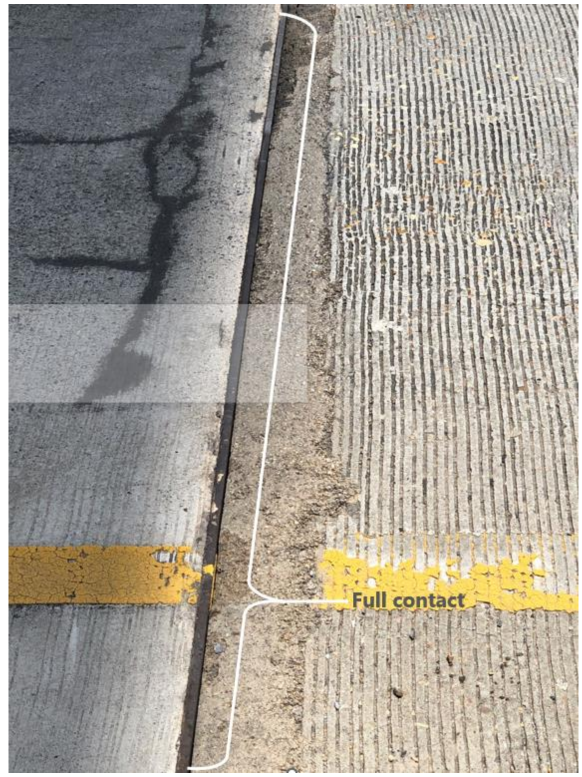


Figure 2: Joint in contact created bridge seating issues.

1. During the October test operations, it was determined that the B2-SE roller bearing had failed (a roller in the bearing fractured). This failure resulted in an operational outage of the bridge. The cause of the failure was internal corrosion caused by water infiltration into the bearing.
2. Grease samples were taken from all eight-trunnion roller bearing housings. At some locations, water contamination and poor grease quality were visually apparent at the time of sampling. The samples were tested, and the results of the lubricant analyses showed varying amounts of contamination. Water content was very high at several locations; at these locations the iron content was also high indicating internal corrosion.
3. The overall balance of the lift span was approximately 27,000 lbs span heavy in the seated position, with the imbalance significantly higher at the west end of the span. As such, the existing balance condition was much higher than the design balance condition. The balance condition was also heavier than existed in 2012 when the last balance testing was done and a total imbalance of approximately 16,000 lbs was calculated. LADOTD personnel indicated that the span imbalance was increased to help mitigate the seating issues.

# Instrumentation Objective and Scope

The primary objective of this paper is to explore the deployment of distributed instrumentation systems and various sensing technologies. With the increasing complexity of modern infrastructure, there is a growing need for innovative monitoring techniques that provide real-time data on the structural health of bridges. This paper seeks to address this need by examining the effectiveness and versatility of advanced instrumentation systems in capturing critical aspects of bridge performance. Key to this discussion is the focus on several innovative technologies implemented on the project:

### Wireless Instrumentation Systems

Wireless systems offer significant flexibility and reduce the logistical challenges associated with wired connections. This paper delves into the application of wireless systems on a moveable lift bridge structure, highlighting their installation, maintenance, and data transmission performance.

### Low-Cost Microcontrollers for Sensing

The use of low-cost microcontrollers, such as Raspberry Pi and Arduino, has revolutionized monitoring by providing affordable yet powerful solutions. When combined with a variety of sensors, these devices enable the creation of distributed networks that monitor multiple parameters simultaneously. This paper explores how these microcontrollers can be utilized to develop cost-effective monitoring systems without compromising accuracy or reliability.

### Machine Condition Monitoring for Predictive Maintenance

Predictive maintenance is a critical aspect of modern infrastructure management. The application of machine condition monitoring techniques has proven highly effective in this regard. By analyzing data trends and identifying early signs of wear or failure, these techniques enable proactive maintenance strategies that can prevent costly repairs and extend the lifespan of bridge components. This paper discusses how these techniques are applied to bridge structures, providing insights into their benefits and challenges.

In summary, this paper provides a comprehensive overview of the various innovative techniques employed to monitor the challenging behavior of a moveable bridge. By focusing on wireless systems, low-cost microcontrollers, and machine condition monitoring, the paper highlights through examples the potential of these technologies to enhance our understanding of bridge performance and contribute to more effective maintenance practices.

## Innovative Monitoring Strategies

To address the various operational issues, an extensive instrumentation system was developed and deployed. This system included the following monitoring systems:

- Distance (lasers, ultrasonics, LVDTs)
- Strain sensors
- Tilt
- Thermocouples
- Amp meters
- GPS position
- Weather
- Video
- Accelerometers

In this paper, the authors will review the following key aspects of this instrument installation.

## Multi-System Distributed Wireless Data Acquisition

The multi-system distributed wireless data acquisition setup was a cornerstone of the monitoring strategy, designed to collect real-time data from various parts of the Danziger Lift Bridge. The system utilized an array of data loggers, each connected through a remote central server via cellular modems. This configuration enabled seamless and continuous data transmission, even in the challenging operational environment of a lift bridge.

The system employed Campbell Scientific data loggers, known for their reliability and precision in capturing environmental and structural data. While the Campbell Scientific data loggers are not in and of themselves innovative, WJE utilized a distributed layout between opposite spans, as well as deployed data loggers at the lift tower roof and operator house. These loggers were connected via Campbell Scientific radios and cellular modems. Radios were utilized for communication between loggers to minimize the need for cellular modems. Cellular modems were utilized to transmit data back to a centralized cloud server for further processing.

## Wireless Tiltmeters and Strain Sensors

To evaluate possible pier movement, wireless tiltmeters were deployed. These devices were integrated into the data acquisition system using RST's RSTAR connectivity, allowing the tiltmeters to communicate wirelessly with one of the field Campbell data loggers. This setup provided real-time updates on the bridge's alignment and any deviations that could signal operational issues. Additionally, wireless strain sensors were installed on the main pinon shafts to identify conditions where the bridge was not properly seated. These Wireless Resensys Senspot™ strain sensors measured torsional stresses and were combined with a Resensys gateway. Lift and daily measurement data was collected from Resensys servers and integrated into the authors' centralized data cloud server.

## Laser and Ultrasonic Movement Sensors


Figure 3: Installed laser measuring vertical lift distance.

The system also included a variety of distance measurement solutions, integrating both high-end distance laser instrumentation and cost-effective ultrasonic distance measurement alternatives.

At each of the bridge corners, three measurement lasers were installed to track the X, Y, and Z movements of the span during the lifting operations. The authors utilized Dimetix lasers (Figure 3) capable of measuring over 500 meters within a stated +/-1 millimeter accuracy. Enclosure housings were rated with IP65 (dust and low water jet protection). The vertical measurements were collected relative to the pier, while the lateral measurements were made relative to the longitudinal and transverse span guide rails. Two additional lasers were installed to measure the lift span joint opening widths at the centerline of the span.

Maxbotix Sonar HRXL ultrasonic sensors (Figure 4) were also used to measure lift span joint opening widths as an economical means of obtaining additional joint opening measurements. When utilized with digital data with the serial data connectivity, the authors observed these sensors provided accurate distance measurements. The authors utilizd Arduino ESP-32 units to digitally collect measurements from the ultrasonic sensor, and data was transmitted wirelessly to a Raspberry Pi at the operator house, which in turn processed and transmitted the data to the authors' centralized data server.

Figure 4: Ultrasonic sensor measuring joint opening distance.

### Vibration Monitoring of Trunnion Bearings

The grease samples taken from the trunnion bearings during the initial inspection identified contamination and internal corrosion of the bearings as a potential concern. Subsequently, the bearings were opened for internal inspection and defects were identified in multiple bearings, with near term replacement warranted for one bearing. Because of the amount of time needed to procure and install a replacement bearing, predictive condition monitoring was proposed to extend the service life of the degraded components.


Figure 5: Accelerometers were mounted to the housing of the trunnion bearings at four equal intervals each side for predictive monitoring.

To perform predictive conditioning monitoring of the trunnion bearings, the authors utilized vibration monitoring during lifting operations. An array of four, single-axis accelerometers (PCB 352C68) was mounted around the outer perimeter of each of the eight-bearing housing (Figure 5). The accelerometers were connected to a high-speed data acquisition system comprised of a National Instruments (NI) cRIO 9042 embedded controller with NI-9234 4-channel signal conditioning modules, transmitting via a cellular modem.

## Performance Evaluation and Data Analysis

A variety of data collection and analysis methods were utilized across the installed monitoring systems on the project.

The data collection process for this monitoring project was designed to ensure accurate and reliable data acquisition, enabling comprehensive analysis of the bridge's performance. The following methods were employed to gather and manage the data:

## Data Acquisition Speeds

To optimize the monitoring process, the collected data was structured into two distinct speed states based on the operational conditions of the bridge:

**Slow-Speed State**: Data was collected at 10-minute intervals during periods of non-lift activity. This low-frequency data collection ensured continuous monitoring while minimizing data storage and processing requirements.

**High-Speed State (Lift State):** During bridge lifts or when specific conditions were met, data was collected at a higher frequency of approximately 1Hz. This high-resolution data captured critical details of the bridge's behavior during dynamic events, such as changes in load distribution, structural vibrations, and potential misalignments. The ability to switch between low and high-speed data collection allowed for efficient monitoring, ensuring that only relevant high-frequency data was gathered during key operational moments, thereby optimizing both data volume and processing time.

The transition from slow-speed to high-speed data collection was managed through a triggering mechanism that monitored specific conditions of the bridge. These included monitoring the traffic gate, lift motor amp meter and the movement of the lift span at the live load shoes. If any of the predefined thresholds (e.g., movement of a couple of inches at the live load shoes) were exceeded, the system automatically switched to a high-speed data collection state.

These data collection methods were designed to be both efficient and responsive to the varying operational states of the bridge. By leveraging centralized data aggregation, structured data states, synchronized timestamping, and intelligent triggering, WJE was able to gather a comprehensive dataset that provided deep insights into the bridge's behavior, ultimately informing the analysis and guiding maintenance strategies.

## Analysis of Structural Behavior

The data collected from the distance sensors, strain, tiltmeters, temperature sensors, motor amp meters, and weather monitoring systems were comprehensively analyzed to understand the structural behavior of the Danziger Lift Bridge. This analysis involved creating and reviewing time series plots that depicted the overall trends across the monitoring period. These plots provided a visual representation of how the bridge responded to various operational and environmental conditions over time.

The data evaluation also included a sensitivity analysis of the various measurement parameters. By assessing the sensitivity of each parameter, the authors were able to determine which factors had the most significant impact on the bridge's performance and behavior. This analysis was crucial for identifying potential issues and ensuring the accuracy of the monitoring system.

In addition to the long-term evaluation, the authors conducted a detailed analysis of individual lift operations. This involved creating three-dimensional movement plots (Figure 6) to visualize the bridge's movements during lifting, as well as comparing data from multiple lifts. These detailed plots allowed for a more nuanced understanding of the bridge's lift behavior and helped identify any inconsistencies or anomalies in its operation.

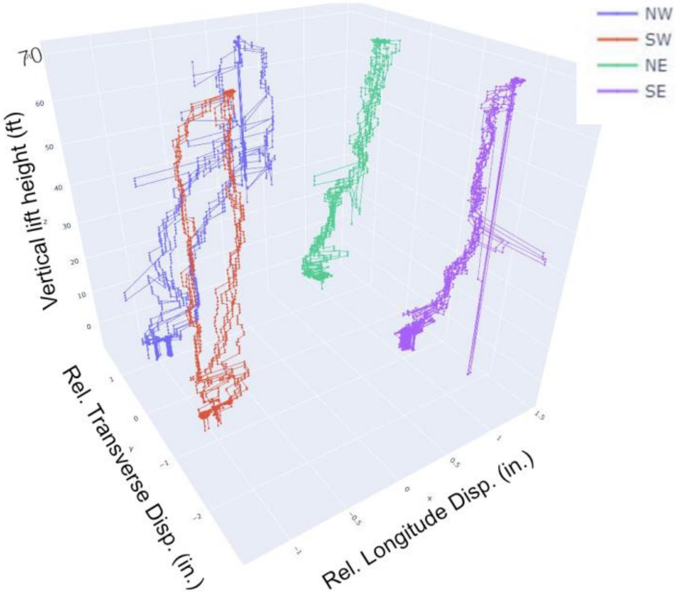


Figure 6. Plot of x,y,z displacements of lasers at the four corners during a lift.

To further refine the structural behavior analysis, the authors performed a correlation analysis between the movement data and various environmental factors. One key aspect of this analysis involved plotting bridge joint movement against temperature to evaluate seasonal performance (Figure 7). This approach provided insights into how temperature fluctuations affected the lift span's seating behavior over different seasons, revealing trends that could inform maintenance and operational decisions.

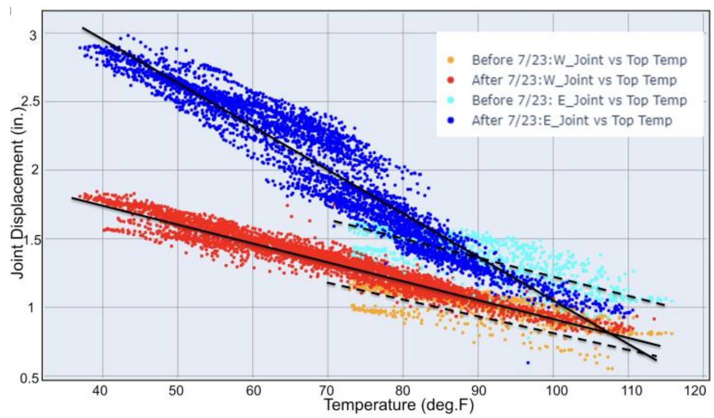


Figure 7: Plot of temperature versus joint displacement comparing performance post repair campaign.

Additionally, the structural behavior before and after the implementation of repairs was closely evaluated. By comparing data from these two periods, the authors could assess the effectiveness of the repairs and any remaining or emerging issues. This before-and-after comparison was critical in validating the repair strategies and ensuring that the bridge was operating within acceptable performance parameters.

## Spectral Analysis of Trunnion Vibrations

The system was programmed to sample and evaluate across various frequency bands identified as critical during an initial investigation. Spectral analysis was performed onboard the embedded controller and relevant waveforms stored for additional analysis as needed. Spectral analysis of selected frequency bands was assessed. Spectral plots were evaluated for comparison to baseline measurements. Notification thresholds were established based on measured differences between bearing spectral plots. As more data was collected, the thresholds were refined to eliminate spurious results.

### Data Processing and Fusion

The authors utilized a centralized cloud data server and analytics software to aggregate data from individual loggers deployed across the bridge. This approach facilitated seamless data collection from various points of interest, allowing for a fused dataset that could be efficiently analyzed. All measurements from the instrumentation system were available through a series of webpages and dashboards (Figure 8) using the authors' analytics custom monitoring and analysis software.

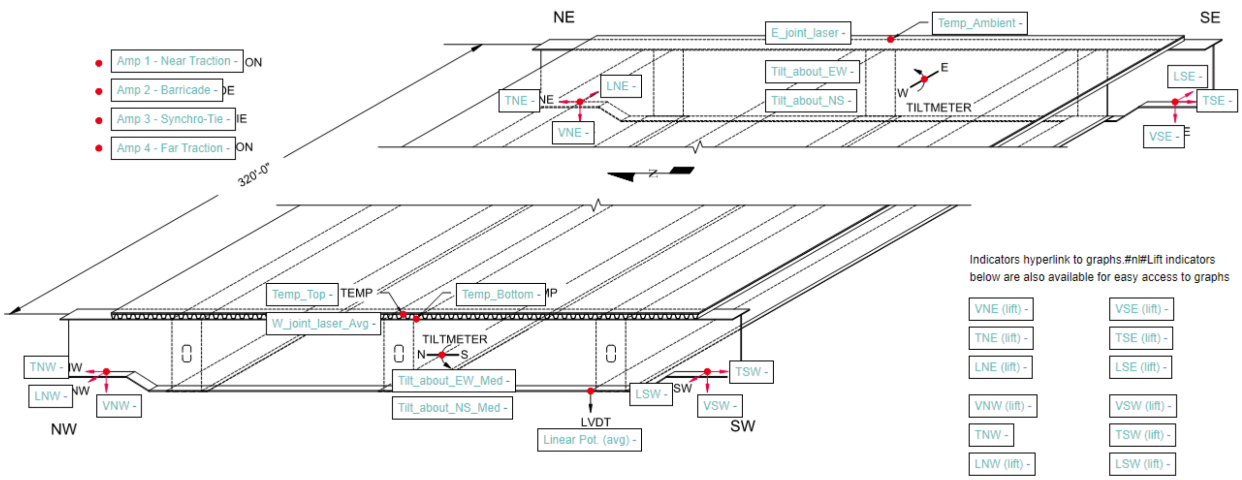


Figure 8: Digital dashboard showing the array of instrumentation for web reporting.

To maintain the integrity and usability of the data, all measurements from the individual loggers were synchronized using precise timestamping from a centralized time server. This synchronization was essential for correlating data from different sensors and loggers, ensuring that events could be accurately tracked across the entire monitoring system. The synchronized data was then stored in a centralized cloud database, facilitating further processing, analysis, and cross-referencing with historical data.

## Results Discussion

The monitoring systems and analysis strategies were successful in terms of providing the engineering team with the data needed to solve several of the long-standing issues with the structure and validate the effectiveness of repairs:

1. The inability for the lift span to fit between the approach spans during hot weather was determined to be a result of seasonal heating that caused an accumulation of thermal movements of the approach spans due to the expansion joints being filled with debris and not the result of long-term foundation movements. The short-term repair strategy was to clean out the approach span joints.
2. The uneven seating of the lift span was resolved as follows:
    a. Longitudinal and transverse balance adjustments improved the operational behavior so that the lift span would reach the nearly seated position in a level condition.
    b. Repairs to the air buffer piping and valves were implemented to mitigate the retention of pressure in the buffers that was interfering with full seating at all corners.
3. The degraded trunnion bearings remain in service, with no significant changes to vibration signatures. The LADOTD has procured a replacement bearing and has programmed repairs.

Over the multi-year monitoring period from 2020 to Present, repairs have been implemented and various instrumentation systems were employed, the authors had the opportunity to evaluate the performance of these systems and provide insights into their effectiveness.

- **Multi-System Distributed Wireless Data Acquisition**:
  The ability to distribute the data acquisition systems across various locations and assign specific tasks to each proved valuable both economically (e.g., savings on wiring costs) and in terms of reliability. The data was well synchronized with the tasks and performed comparably to centralized wired systems. Although there were additional operational costs associated with multiple cellular modems, the significant savings in installation costs outweighed these expenses.
- **Wireless Tiltmeters and Strain Sensors**:
  The wireless tiltmeters were particularly effective in extending the monitoring reach across the bridge. These sensors now serve in a long-term monitoring role as the movement concerns have now been addressed. The wireless strain sensors proved to be a robust and reliable solution. These sensors provided crucial information for evaluating seating forces. However, their recording speed and memory cache was insufficient to evaluate dynamic effects during bridge lifts for the purposes of balancing, as the storage and sampling resolution limited the application use.
- **Laser and Ultrasonic Movement Sensors**:
  The laser measurement system was found to be a valuable tool for resolving issues with joint seating and understanding longitudinal and horizontal skew behavior during lifting operations. Although the ultrasonic sensors were not initially deployed for critical project roles, over time, the authors observed that these sensors were ideal for shorter measurement ranges, such as those needed at joint openings and for lateral movement measurements at guide rails. The combination of these sensors and supporting Arduino devices provided similar accuracy to the laser system but at a fraction of the cost. In addition, they appear to be more robust than the laser measurement system as the environmental exposure below the open bridge deck joints is quite severe.
- **Vibration Monitoring of Trunnion Bearings**:
  Pre-deployment investigations and testing confirmed that trunnion bearing changes and issues could be identified using spectral evaluation, consistent with accepted practices in other industries. The vibration monitoring system remains operational and continues to provide valuable data. However, the system required additional modifications to accommodate the extreme exposure conditions involving UV degradation and high humidity.

# Challenges and Adjustments

While the instrumentation systems have proven to be valuable tools for understanding bridge behavior and evaluating the effectiveness of repairs, they have also required maintenance and occasional repair. Over the course of the project, the instrumentation systems have undergone repairs, replacements, and modifications to meet changing demands, environmental conditions, and to address issues as they arose.

A significant challenge throughout the multi-year monitoring period was the harsh environment typical of bridge settings. Bridge environments are often challenging for instrumentation due to exposure to the elements (e.g. solar and precipitation). A particularly difficult challenge was the use of high-end optical lasers near the bridge joints. Although the laser enclosures were rated IP65 (dust and low water jet), the authors experienced several failures over the years. Upon evaluation, it was determined that the placement below the bridge joints allowed significant amounts of water to pour onto the laser enclosures, particular after each of the multiple tropical storms. As the issues with joint seating were resolved, the authors ultimately opted to replace the lateral lasers with ultrasonic sensors. Additionally, vibration condition monitoring accelerometers, which are relatively unprotected from the environment, have also required replacement due to environmental exposure.

To avoid repeated travel to perform maintenance repairs, improvements were made to enhance the durability and performance of the instrumentation systems. These included adding watchdog controllers to some datalogger systems to ensure continued reliable operation and the installation of dehumidifiers to prevent component corrosion.

# Conclusion

The innovative monitoring strategies implemented on the Danziger Lift Bridge have provided valuable insights into the structural behavior and operational performance of this critical infrastructure. Through the deployment of multi-system distributed wireless data acquisition, wireless tiltmeters and strain sensors, laser and ultrasonic movement sensors, and vibration monitoring of trunnion bearings, the project successfully addressed several key operational challenges, including issues with span seating, skew alignment, and trunnion bearing degradation.

Over the multi-year monitoring period, the data collected from these systems proved instrumental in guiding maintenance and repair efforts, ultimately contributing to more reliable bridge lifting operations. The use of wireless technology and low-cost microcontrollers facilitated cost-effective and flexible monitoring solutions, while advanced data processing and spectral analysis provided a deep understanding of the bridge's dynamic behavior.

Despite the success of these systems, the project also highlighted the challenges associated with monitoring in harsh environmental conditions. The need for ongoing maintenance and the replacement of certain sensors underscored the importance of system durability and adaptability in such settings. The lessons learned from these challenges have informed adjustments to the monitoring approach, including the transition to more robust sensors and the incorporation of enhanced protective measures. The insights gained from this project not only improved the performance and maintenance of the bridge but also provide a valuable framework for future monitoring efforts on similar structures. As infrastructure continues to age and face increasing demands, the adoption of innovative and adaptable monitoring technologies will be essential to ensuring the continued safety and functionality of critical assets like the Danziger Lift Bridge.

# References

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