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Structural Health Monitoring of Two Signature Movable Bridges: Five Year Review and Lessons Learned

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Introduction

The use of Structural Health Monitoring (SHM) systems to provide information related to the state of bridge performance or situational awareness is becoming more widespread across the United States, Europe and Asia, especially in the construction of new signature structures. A second major type of bridge that serves as an ideal candidate for SHM systems is movable structures. To date, the major type of instrumentation work seen on movable structures tends to focus on balancing efforts of the movement mechanisms and load testing to support capacity evaluation of the structure or of a specific design detail, neither of which is often captured in an integrated SHM system. What makes movable structures an attractive candidate for SHM systems is not only the complexity of the structural systems employed to carry the infrastructure but also the mechanical and movement systems that must work in harmony during a bridge opening to minimize downtime to both bridge and marine traffic. Some of the main benefits that an SHM system potentially brings to movable structures are the real-time evaluation of bridge position, seating condition, span balance, weather, and motor performance. This paper serves to document the design of such a SHM system for two signature movable spans, its implementation end evolution over time, and finally a five year review of how the system was used during key events and what lessons were learned in its overall implementation.

SHM systems were designed for two signature movable bridges in the United States and commissioned in late 2011. The systems were designed to address multiple performance limit states, namely Operations, Safety, Structural Performance, and Maintenance. Each bridge (the first including a 500'+ vertical lift span while the second included a 250' Scherzer bascule span (both shown in Figure 1)) had unique design considerations and required thorough investigations. Two approaches were taken to the system design: 1.) characterizing input-output relationships as indicators of overall structural health and 2.) risk-based design. A risk assessment of each structure was carried out to identify the most relevant hazards facing the bridge operations, the most vulnerable system components, and corresponding exposures associated with the various failure mechanisms. The risk assessment aided in the design of an efficient instrumentation deployment aimed at capturing only the most relevant and critical metrics to provide guidance to the bridge operators, managers, and engineers.

Figure 1: Vertical Lift Bridge (T) and Scherzer Bascule Bridge (B)

This paper is organized into four main sections below where more detailed documentation of the structures, the design and implementation of the SHM systems and finally a five year review of the system performance will be discussed.

Description of Structures

Vertical Lift Bridge

The vertical lift bridge was opened to traffic in 1931 and currently carries a local two lane road with approximate ADT of 25,000 vehicles. The bridge opens an average of one time per day to allow the commercial and seasonal recreational marine traffic to safely pass under the span. The overall structure is made up of a variety of structural forms, all of which are steel construction: simply supported multi-girder spans, deck truss, through truss tower spans and the through truss lift span. The structural elements are a combination of built-up riveted sections and standard wide flange and angle shapes .The lift span is opened by an operator stationed in a machine house in the middle of the span. The mechanics used to open the bridge is consistent with a span drive Waddell system where both uphaul and downhaul operating ropes extend from mid-span of the lift span to each corner of the truss. The lift span is counterbalanced by two concrete counterweights housed within the truss structure of the two adjacent tower spans. Both the lift span and the counterweights are restrained from longitudinal and transverse movement by guides mounted along the height of the towers.

Bascule Bridge

The bascule bridge was opened to traffic in 1929 to replace an existing ferry service between the two river towns. The structure carries a local three lane road with an approximate ADT of 50,000 vehicles. Similar to the vertical lift bridge, the bascule bridge opens on average around one time per day again for a mix of commercial and recreational marine traffic. Overall, the structure consists of a variety of types including multi-girder spans, continuous half-through trusses, girder-floorbeam-stringer spans, and finally a double leaf bascule span. The bascule span machinery is housed beneath the roadway and is controlled by an operator stationed in a tower extending above the roadway from one of the piers. The bascule span, as previously mentioned, is a Scherzer type where the span both translates and rotates as it rolls open on a pair of track plates. The bascule spans also have two main truss types denoted Truss A and B in Figure 2, that serve as the primary lifting truss and live load carrying truss, respectively.

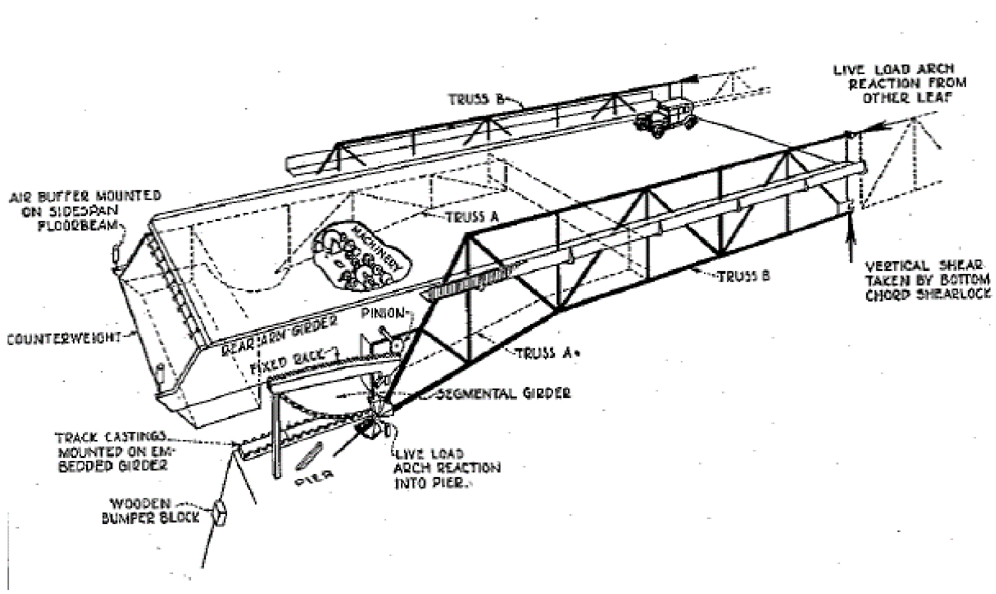

Figure 2: Schematic of bascule span lifting and live load trusses from original design.

Design of SHM System

The bridges described in the previous section adopted the maintenance and rehabilitation strategies necessary for indefinite preservation after multiple attempts to replace the spans with wider fixed spans built to current code specifications were rejected for a multitude of reasons with no clear resolution. With this in mind, the owner realized the importance of gaining as much insight towards the current state of health of the structures and improving the situational awareness for the bridge operations and began to commission the design and implementation of SHM systems on the structures to aid in the objective of indefinite preservation. This section discusses two design methodologies carried out in support of the specification of sensor type and locations. While there are no formal design procedures or codes to follow for SHM systems, it is critical to always consider the ultimate system objectives when in the design phase. In this case, it was known that the ultimate objectives of the SHM system were to aid the bridge owner and engineers in support of indefinite preservation of the structures. However, a more detailed examination needed to be done to explore the most consequential hazards and vulnerabilities facing the structures.

This examination used a risk assessment to serve as the means for prioritization of the hazards and is discussed in more detail below. While the risk assessment aided in the identification of key measurements to reduce uncertainties associated with consequential risks, the system design also needed to consider unforeseen or unanticipated events. It is difficult to design for a limit state one is not aware of, however a design approach was taken to ensure that input-output relationships could be established for all structural response instrumentation. This approach will be described in further detail below.

Risk-Based Design

An informal risk assessment of each structure was carried out to guide the design of the SHM system. Risk is comprised of three elements: hazards – external factor that can damage a structure, vulnerabilities – the mode of failure given the occurrence of a specific hazard, and the exposure – the consequences associated with the hazard-vulnerability pair. The risk assessment for each structure was organized into tables listing the three components of risk as they related to specific limit states. Since it was not necessary to quantify the risk based on dollars or other metrics, the exposures were categorized by the failure mode introduced. The limit states chosen for this analysis included Operations, Safety, Structural Performance, and Maintenance. The hazards, vulnerabilities and failure modes deemed most critical by the engineers and owners of the bridge are presented in Table 1. The failure modes documented therein were used to frame a monitoring system design which could reduce the uncertainty associated with these risks.

Table 1: High Level Risk Assessment for Both Movable Structures

Limit State	Hazard	Vulnerability	Failure Mode
Operations	• Span Imbalance	• Motor Wear	• Mechanical Failure
	• Inaccurate Indicators	• Overcautious Operator	• Long Openings
Safety	• Ice on Roadway	• Unaware Motorist	• Traffic Accident
	• High Winds	• Large Trucks • Span Opening	• Traffic Accident • Structural Impact • Unsafe opening operation
	• Speeding Motorist	• Vehicle Breakdown	• Traffic Accident
Performance	• Overloaded Vehicle	• Overstressing of Component	• Structural Failure
	• Construction	• Overstressing • Connection Slip	• Structural Failure
	• Unforeseen Event	• Overstressing • Connection Slip • Bearing Unseating	• Serviceability • Structural Failure
	• Frozen Bearing	• Cracking of Support Structure	• Serviceability Failure
Maintenance	• Low Power Supply	• Motor Wear	• Mechanical Failure
	• Unlubricated Machinery	• Motor Wear	• Mechanical Failure

While the two bridges had different means of operating the movable spans, the general hazards they faced remained consistent allowing the same risk assessment framework to be applicable to both subject structures.

Input-Output Based Design

When one thinks of an SHM system, it is typically viewed as output-only data that reflects how a structure is moving, operating under load, or in general responding to other external factors. What often is neglected is the need to also quantify those external factors, or the system inputs. The quantification of an input-output relationship of a structure and external factor provides a series of response signatures that, coupled with traditional structural analysis and mechanics, serve as a means of quantifying structural performance before and after an event of interest. The post-event response signatures can be compared to the pre-event response signatures. As an example, it is well documented that for long span structures thermal loads induce some of the largest demands on primary load carrying elements. If one were to measure strain on a primary load path element (output), but not have an indication of temperature or whether there is live load on the roadway (both inputs), then the meaningful interpretation of the measured data is near impossible.

The risks identified in Table 1 above were used to identify a list of instrumentation that would reduce the uncertainty associated with the hazard, vulnerability, or both. This list was then examined to ensure that sensors were either an input or an output and that the corresponding measurement was being made to establish a relationship. The list of risks, instrumentation and input/output designations are listed below in Table 2.

Table 2: Instrumentation Approach to Address Risk Assessment and Input / Output Analysis

Limit State	Desired Measurand	Sensing Approach	Input / Output
Operations	Span Balance	Pinion Torque	Input
		Geometric Movement	Output
	Span Position	Geometric Movement	Output
		Position Camera	Output
Safety	Road Surface State	Surface Temperature	Output
		Ambient Temperature	Input
		Relative Humidity	Input
	Wind	Anemometer	Input
	Vehicle Speed	Radar	Output
	Vehicle Presence	Traffic Camera	Input
Performance	Member State of Stress	Intrinsic Strain Variation	Output
		Local Temperature	Input
		Traffic Camera	Input
		Bridge WIM	Input
	Bearing Performance	Relative Displacement	Output
		Ambient Temperature	Input
Maintenance	Power Supply	Ammeter	Input
		Voltmeter	Input
	Acoustic Signature	Microphone	Output
	Motor Output Power	Pinion Torque	Output

Specification of Sensing Type and Location

The list of sensing approaches listed above in Table 2 was used to design an instrumentation plan for each limit state per bridge. The original contract drawings, a finite element (FE) model, and interviews with bridge staff were all used to design the sensor specifications for each of the desired measurands. The important considerations to make in selection of sensor specifications included overall anticipated range, desired resolution for event detection, long term stability, accuracy and robustness for deployment in harsh environments. The determination of sensor location relied largely on sensitivity studies carried out in the FE model to determine the most influential response locations for structure-related instrumentation and on staff experience as related to operations and maintenance focused instrumentation.

Two example instrumentation plans for the Operations limit state are shown below in Figure 3 and Figure 4 for the bascule span and lift span, respectively.

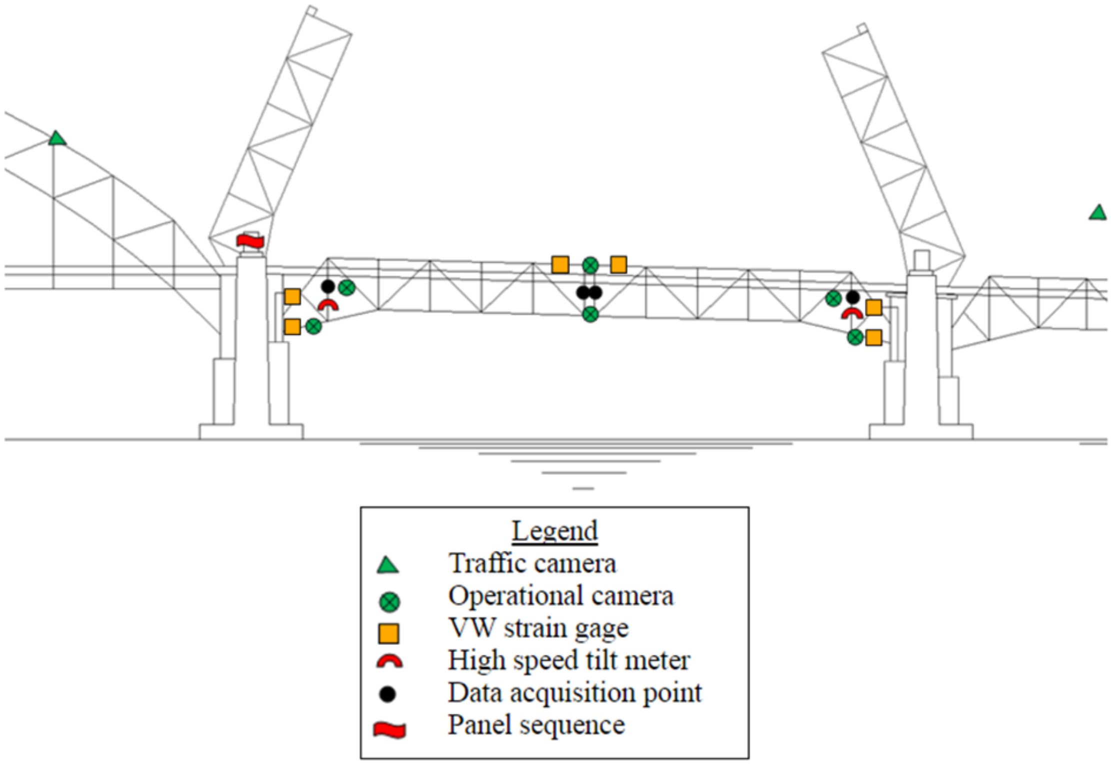

Figure 3: Example Instrumentation Plan from the Bascule Span Related to Bridge Operations

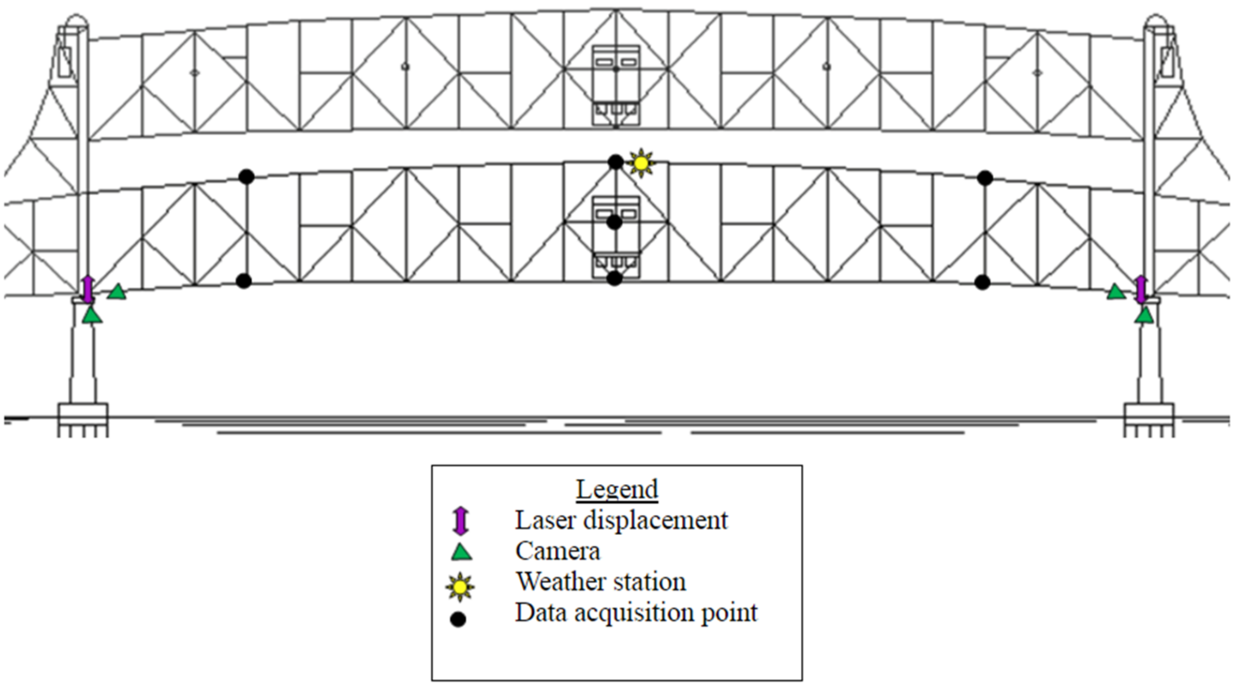

Figure 4: Example Instrumentation Plan from the Lift Span Related to Bridge Operations

Specification of Data Acquisition and Storage

A SHM system requires a robust and reliable data acquisition system to ensure that key measurements are available to staff when they are needed. The owner of the subject bridges recognized the importance of providing reliable high speed communication on their structures and in a contract separate from the SHM system development, installed a fiber optic based communications network on both of the structures. As part of this communication network, a series of data acquisition points were specified to provide for incorporation of hardware needed for the SHM system. Each data acquisition point consisted of a large stainless steel enclosure with power receptacles, circuit breaker and connectivity to the fiber optic network integrated inside the enclosure. It was not originally intended to immediately fill all of these data acquisition points with hardware, however it provided an excellent opportunity for future expansion and it allowed for the proper design and construction of the overall fiber communications network.

The specific data acquisition used on both structures was specified based upon the nature of the sensor, however all hardware utilized came from the Campbell Scientific ecosystem of dataloggers and communication peripherals. The bulk of the dataloggers designed for this project tended to be CR1000 and CR3000 devices. This hardware was selected for a variety of reasons, but the most pertinent are listed below:

- Proven durability in harsh environments
- Ability to read vibrating wire sensors at both slow and fast rates of speed
- Ease of communications between dataloggers
- Ability to read an extensive catalog of sensor types
- Ease of networking all devices into a single data management platform

The last point mentioned in the list above was critical for the SHM system success. By using Campbell Scientific's LoggerNet software suite, it was possible to network all devices into a single data management platform. Each unit could be programmed independently of one another to allow for variable sampling rates, and independent data recording schemas. Also housed within the LoggerNet suite of software is LNDB, Campbell Scientific's interface with SQL database storage. A SQL server was designated for this project and was configured to house all data stored from the sensors and also push the data to web interfaces where needed.

It is important to note that not all data is recorded at all times in this system. In some cases, sensors have to be sampled at high rates of speed (greater than 20Hz) in order to characterize the response of the structure to live load inputs. This places large demands on data storage facilities and analysis processes, and while data storage is cheap data analysis is not. By paring down the data collection to store only events of interest, it eases the burden on data storage and analysis efforts. Some sensors are also sampled and recorded continuously for the long term, however these tend to be sampled at slow rates of speed (once per 20 minutes or more) and typically quantify environmental effects and long term variation in intrinsic forces or global movements of the structure. The final data storage specifications were finalized after implementation of the SHM system where data storage rates and recording schemas could be adjusted to ensure realistic data storage requirements. A flowchart depicting how information flowed from the sensors to the end user platforms is shown below in Figure 5.

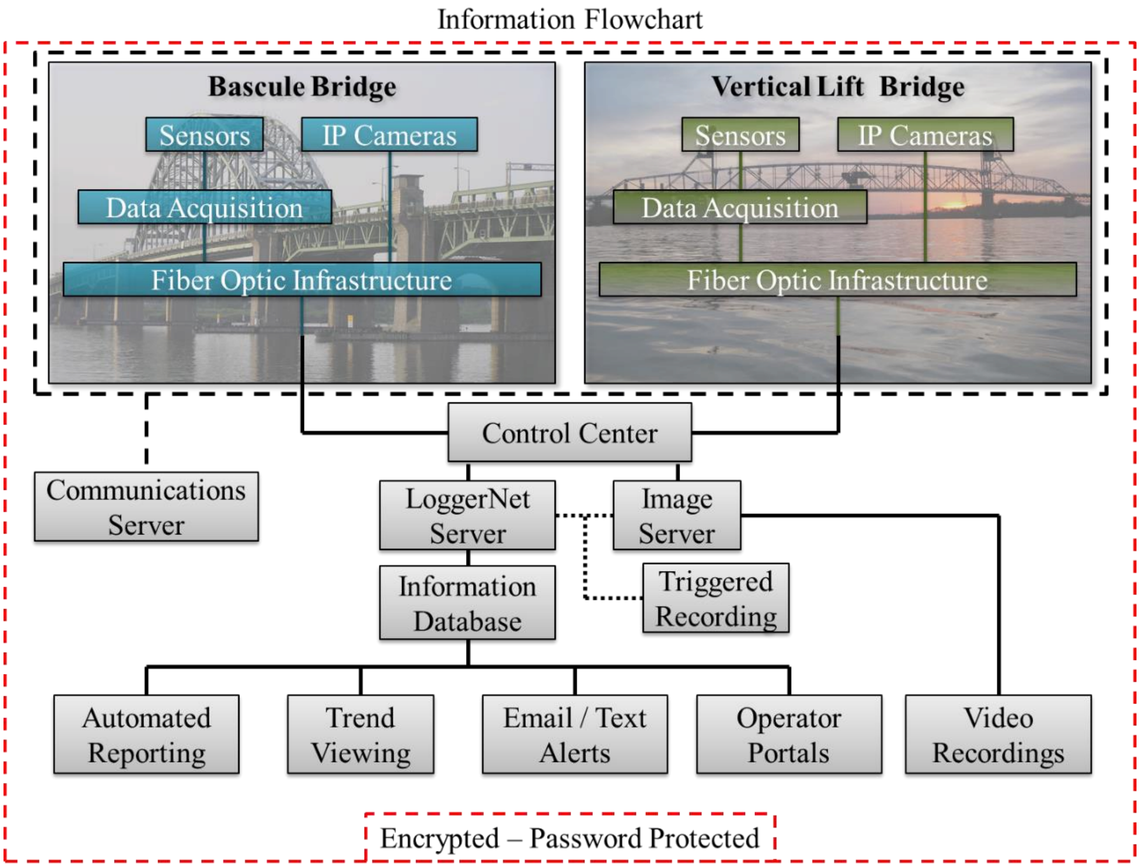

Figure 5: Information Flowchart for the Two Movable Bridges from Sensors to End-User Platforms

Implementation of SHM System

The SHM system was installed over a period of four years as project funding became available and as specific subsystems became critical to the operations of the bridge owner. The sensors were installed according to manufacturer recommendations and data acquisition systems were deployed within the pre-installed enclosures previously discussed. A central control center for storing and pushing data out to visualization platforms was created within the bridge owner's IT infrastructure system. Specific challenges of this phase of the project were the development and implementation of on-the-fly analysis and alerting capabilities and visualization of the system through a series of web portals.

Development of On-the-Fly Analysis and Alerting

Commonly asked during a SHM system deployment is the question 'Who is watching this data 24 hours a day so that we know if something happens?' Obviously, no SHM system would be sustainable if it required personnel to observe the sensor readings around the clock. The success of the system relies heavily on automated data analysis and alerting of events to streamline the amount of time spent interacting with the system directly. For the two bridges discussed herein, there were multiple challenges faced for real time alerting. The first was separating short term events from long term events, which is not as straight forward as it seems considering the two events are superimposed on one another. The second challenge was understanding that thresholds cannot simply be applied to individual sensor readings for exceedance alarms. In many instances, different responses are correlated with each other and temperature changes, requiring the development of algorithms to detect when a signature response has changed from its defined state.

To separate long term events from short term events, when both were relying on the same sensor measurement, a dual recording strategy was developed. This scenario arose specifically in the use of vibrating wire strain gages on the bascule bridge to characterize not only the response to live loads and response during openings of the bascule (span short term events), but also the change in intrinsic forces due to ambient temperature changes (long term events). One table was set up to record the raw strain measurements from the vibrating wire sensors before any type of analysis or processing. This was used to define the long term trends of the member's intrinsic force variation. A second table was set up to record on a triggered basis the high speed sampling of the same vibrating wire strain sensor but subject to some processing. Since the events had to be defined based on a pre-determined trigger, the sensor had to be continually referenced to a zeroed response value. In other words, if no live load were on the bridge, the response should be zero when looking at the short term response component. This processing was achieved by implementing an algorithm which continuously subtracted a fifteen minute moving average from the instantaneous measurement made in real time. The fifteen minute window was determined through trial and error and is a function of the sampling rate and physics of the structure. However, this can be applied to any structure if properly calibrated. What the moving average accomplishes is the ability to subtract out the effects from variation in intrinsic force while not being influenced by the very short term (2-3 seconds) live load events.

For each of the sensors installed on the two bridges, the same type of analysis was carried out for efficient data storage and the ability to generate alerts. Overall, there are three main types of alerts defined in the SHM system: 1.) threshold exceedance, 2.) anomalous response, and 3.) sensor / communication failure. The threshold exceedance alert solely looks for values from a sensor that fall outside of a pre-determined threshold. This type of alert works best for metrics like black ice detection, wind speed, vehicle speed, and other directly interpretable measurements. The second alert focuses on those which required the definition of response signatures and uses statistics to determine whether the current reading falls within acceptable confidence intervals of the established relationship. Finally, the third alert deployed checks sensor functionality, communication status of dataloggers, local power outages at data acquisition points, and finally failures at the main server. This last set of alerts relies on the ability of the dataloggers to locally detect voltage inputs for power issues and ping communications for detecting communication outages. In general, all of these alerts are tied to email / SMS alerting, depending on end user preferences.

Visualization through Web Portals

While SHM system alerts focus on the ability to have the system autonomously scan data for abnormal readings and send alerts to users in an automated fashion, there are still times when visualization of the SHM system output is desirable. This is especially true for the movable structures focused on in this paper. Three main types of viewers were identified for the development of a series of web-based portals: 1.) bridge managers, 2.) bridge operators, and 3.) engineers. A network map of web portals was developed as a function of these three categories (Figure 6) where information which is important to each of the users was categorized and presented in displays specific to the user. As seen in this network map, the most important information relevant to bridge operators were current weather conditions, current traffic conditions (inclusive of road surface condition), and finally the operation of the movable spans. Examples of these three pages are shown in Figure 7, Figure 8, and Figure 9.

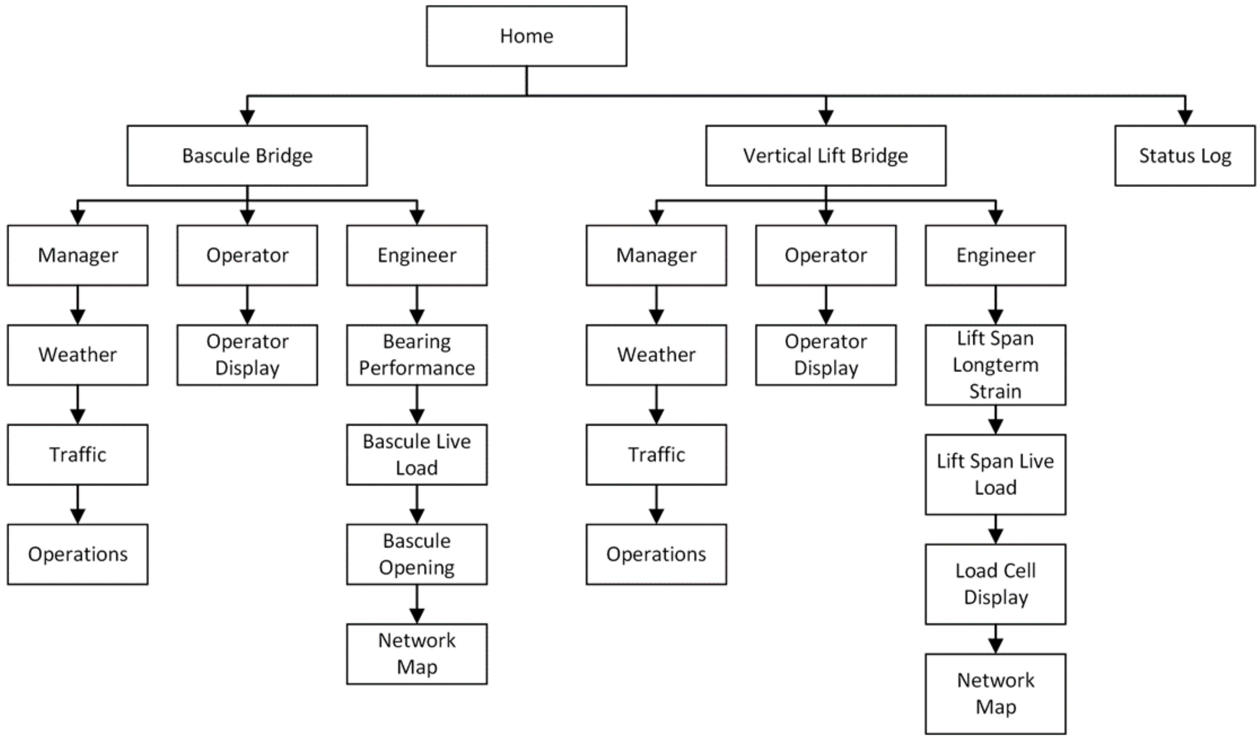

Figure 6: Framework of Web-based Portals

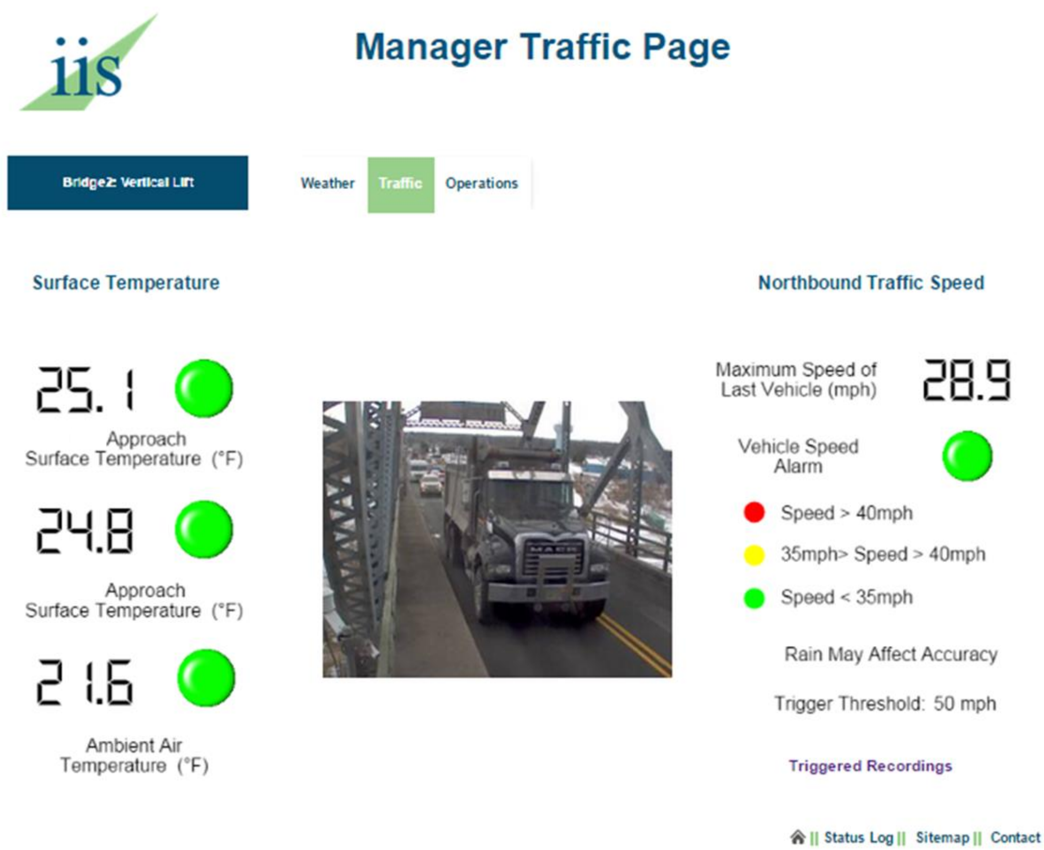

Figure 7: Example Portal for a Bridge Manager focusing on Bridge Traffic Conditions

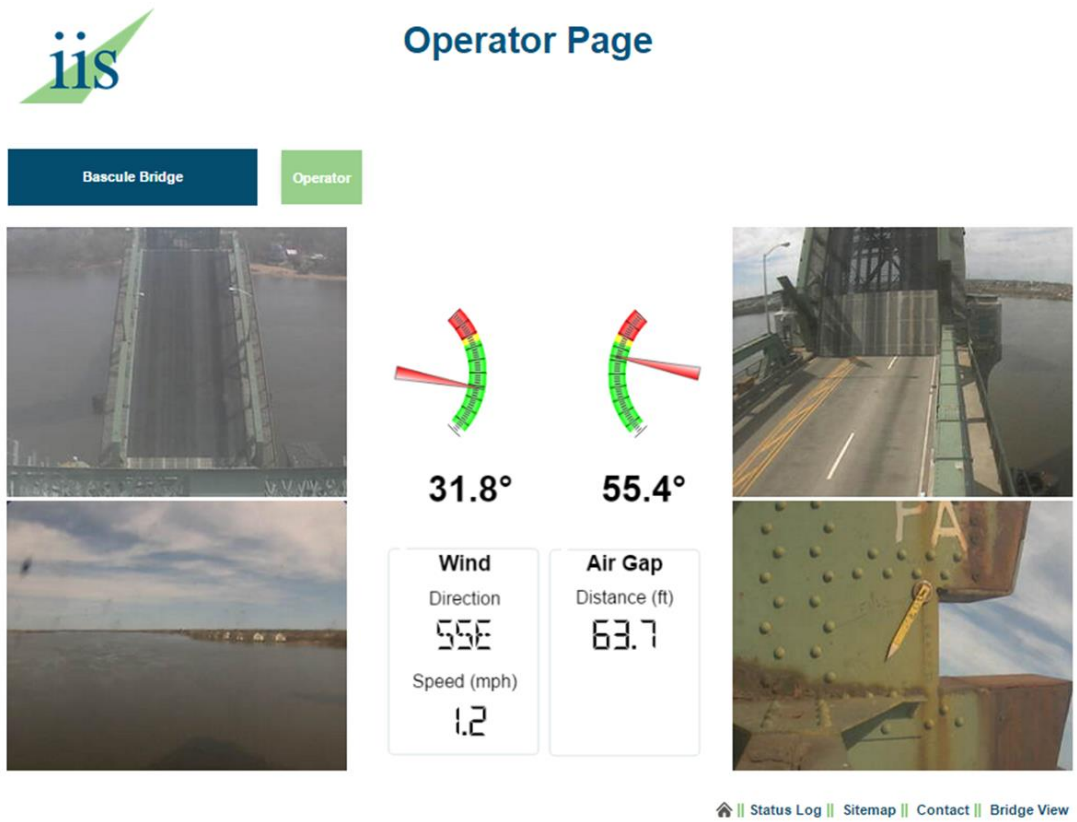

Figure 8: Example Portal for a Bridge Operator focusing on Movable Span Operations

As seen in the example web-based portals, one of the most important features is the integration of real-time cameras focused on strategic portions of the structure as related to the nature of the web page. The clearest demonstration of this is the Operator Page (Figure 8), where the most content that is displayed to the operator are real time cameras showing the navigation channel, approaches from both sides of the bascule, and the shear lock at the bottom chord of the bascule tips which must fit together precisely during the closing operations. To complement the video feeds, real time displays of bascule leaf rotations are displayed along with wind speed and direction and clear sailing distance (air gap) of the adjacent arch span. The air gap measurement was made to provide operators with the capability of routing smaller craft under the fixed span as opposed to shutting down traffic and opening the bascule span.

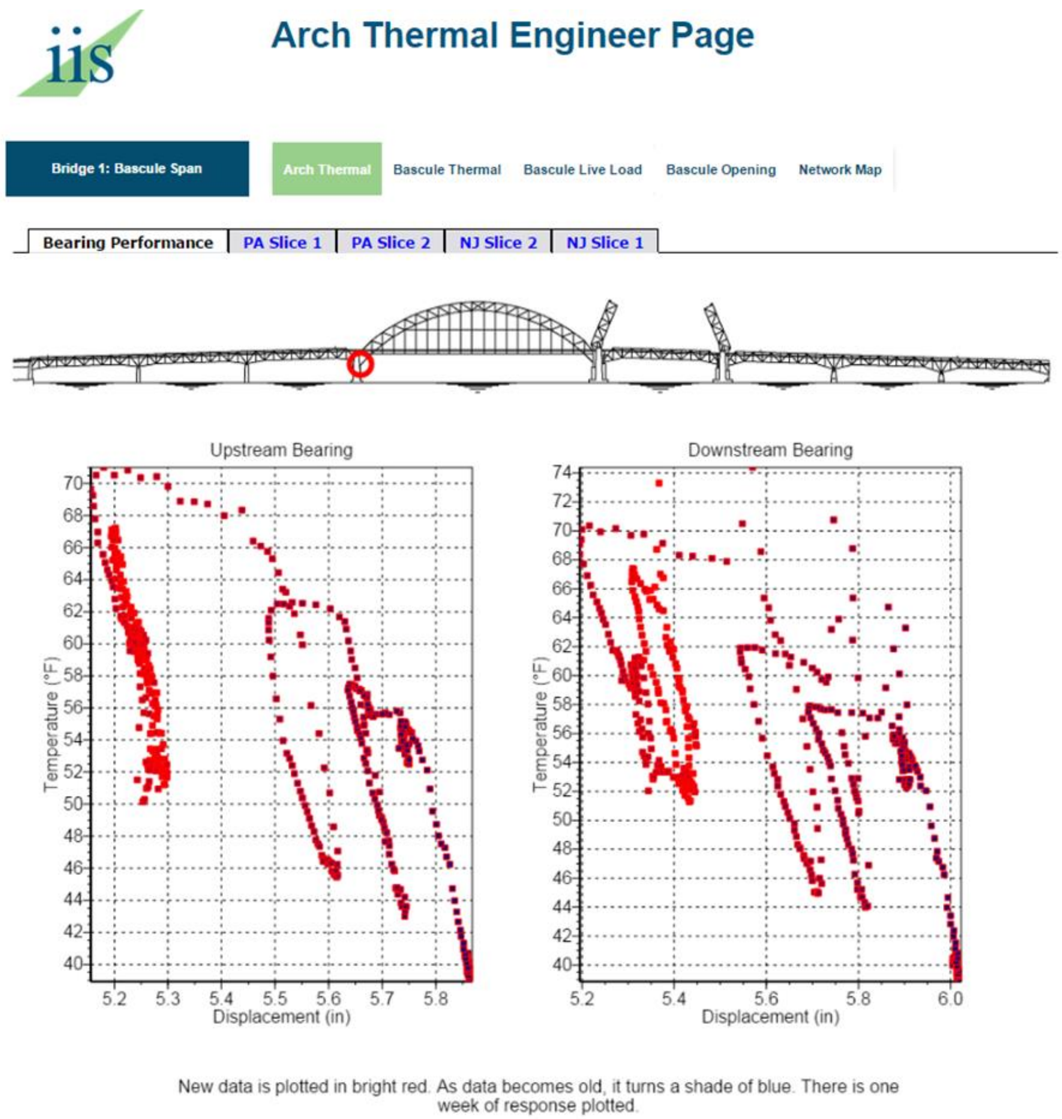

Figure 9: Example Portal for a Bridge Engineer focusing on Bridge Expansion Bearing Performance

Five Year Review of SHM System Performance and Use

A unique distinction of this SHM system is that the bulk of the sensors have been deployed for over five years and the project is at a point where we can reflect on how the system has been used and what lessons could be learned for future use of SHM implementation on other structures.

Use of SHM System during Natural Events

The SHM system for the two movable structures was used during three natural events that were never considered during the design of the system. The first was the rare earthquake in 2011 centered in the Piedmont region of Virginia. The second and third events were both hurricanes, one of which was Hurricane Sandy in 2012. These natural events present two types of unforeseen natural hazards: one which is rare but predictable (hurricane), and those which are both rare and unpredictable (earthquake). Obviously these hazards are considered rare for the Northeast United States only and is not meant to be implied for all bridges in general. In the case of the 2011 Virginia earthquake, the SHM system was used in a reactionary capacity and in conjunction with a visual inspection. The structures were primarily investigated by examining if and how the response signatures differed after the event. The signatures examined included the movable span openings and also the structural response to ambient temperature changes. For both structures, the response signatures were identical, confirming that primary load paths were not altered and the bridges were generally performing as they were before the event.

The hurricanes presented a different opportunity though, as time was available to prepare for the event. Of major concern for a hurricane is the situational awareness of wind speeds at the roadway level for determination of when to close the bridge. A special web portal was developed which documented the wind speed (both gusts and sustained) and direction for each structure. The page was used to make the determination of when to close the bridge at different levels, as shown in Figure 10 below.

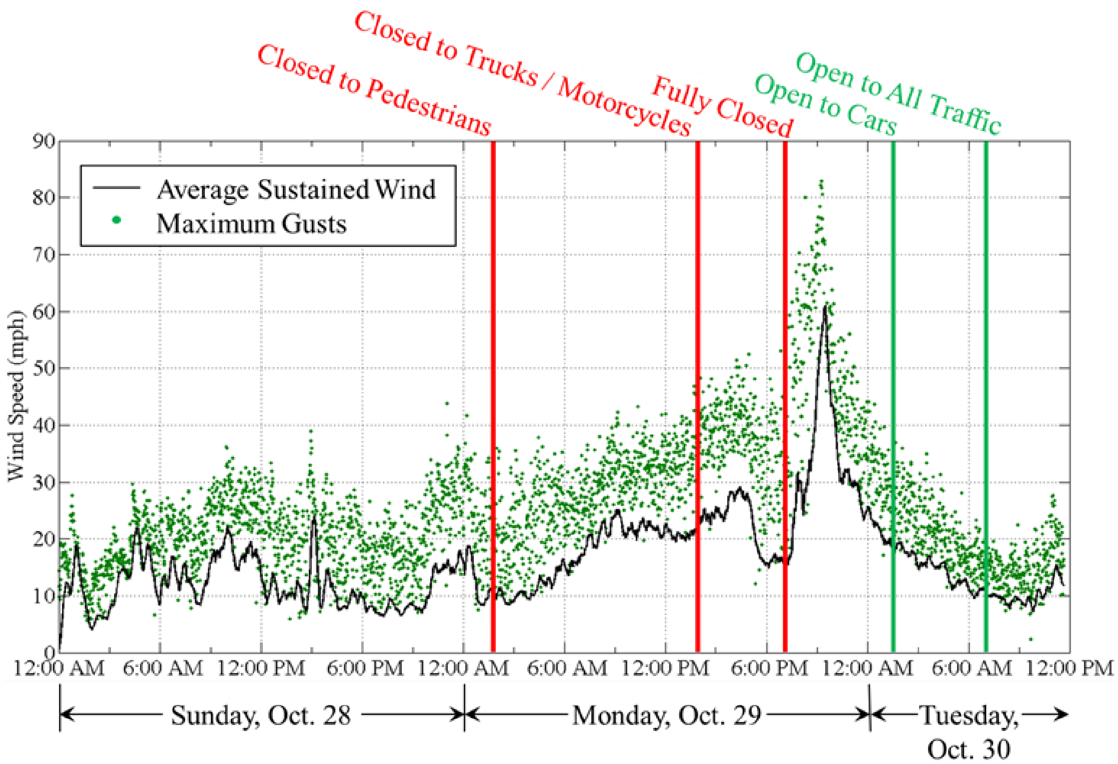

Figure 10: Time history of Wind Speeds as Compared to when Bascule Bridge was Closed to Traffic

Use of SHM System during Planned Construction

The SHM system was also used to accommodate special construction projects with certain stages where the design engineers wanted confirmation of design assumptions. By having a flexible system designed to capture global mechanisms and responses, the system generally only required a few additional sensors to make targeted measurements depending on the type of construction being carried out. For example, on the vertical lift bridge the SHM system was used to evaluate the load distribution to the truss during replacement of the operating ropes and all supporting mechanical systems through the various stages of construction with the addition of only twenty-four strain gages. The system was then able to quantify span imbalance and the effect of mass redistribution at the end posts.

Lessons Learned and Recommendations

As a conclusion to this paper, a series of lessons learned will be presented with recommendations where necessary. In general, the following remarks can be made about the deployment of SHM systems on existing structures based upon the experiences gathered during the project presented in this paper:

1. A monitoring system must be deployed in a "crawl before you run" fashion. In many cases it is even preferable to start with feasibility studies to determine whether or not the structure of interest is a candidate for SHM systems. In general, movable structures are candidates for SHM systems as they relate to the operations of the movable spans, but the extent to which other components could be monitored should be evaluated on a case by case basis – there is no canned solution for these structures.
2. The simplest solution is often the best solution. In some cases, expensive sensors can be avoided by using cheaper components or analysis to by-pass the need for the expensive sensor. However, this can lead to failures due to the reliance on subjectivity or inferior parts. One example is the use of a sensor which can detect surface conditions of a bridge deck through advanced imaging and remote sensing technologies. This sensor is quite expensive compared to an approach of making only surface temperature measurements but complementing it with ambient temperature and humidity to try and arrive at the same estimation of whether black ice is present. The time spent in developing the algorithms for the latter case more than make up the difference in the cost of the hardware – if the technology is available to make the direct measurement you need then it is worthwhile to consider.
3. Sensors should only be applied if it is understood ahead of time exactly how it will be interpreted and used to provide information to engineers and owners.

Sensors

The following lessons learned were noted as related to sensors:

1. Sensors designed for rugged outdoor applications absolutely fared the best on these structures. The sensors which suffered the most were electrical resistance strain gages that had ribbon wire leads. The wires pulled out of the sensors after roughly three years, while those which had full encapsulation and an integrated strain relief.
2. Sensors, cameras, and data acquisition systems located on the movable spans required special attention to attachment details. These spans tend to vibrate more than their fixed counterparts and thus can create excessive wear and tear on components not designed to accommodate large sustained vibrations.
3. For sensors requiring attachment to bare metal surfaces, it is best to perform the installation during a repainting project if possible. If this is not possible, then the same paint which was used on the bridge should be applied on top of the sensors after installation. It was found that commercially available paint simply did not hold up to five years of extreme exposure as well as the bridge paint did.
4. Vibrating wire sensing technology (of which tiltmeters, displacement gages, and strain gages were all used) proved to be the most reliable over the long term of this SHM deployment. 4-20mA and digital sensors also proved to be very reliable over the long term. Resistance based sensors fared the worst.

Data Acquisition and Storage

The following lessons learned were noted as related to data acquisition and storage:

1. The identification of effective zeroing routines for all sensors which are recorded at high rates and on triggered bases is of utmost importance. In addition, plan on providing redundant means of triggering events in case of a sensor failure. The accidental triggered recording of a fast sample

rate sensor over a long duration can result in the generation of large datasets which are time consuming to review and eventually discard.
2. Based on the experiences of this project, both fiberglass and stainless steel enclosures performed satisfactorily.
3. The ability to network together data acquisition with a fiber optic network is certainly desirable. However, there are still considerable costs involved with networking into the fiber optic in the future.

Web-based Portals

1. Interviews with the key personnel who will be using the portals is of utmost importance.
2. Web-based applications should be developed in the most commonly used and up to date web platforms available. When custom proprietary software is required, usage rates drop considerably.
3. Providing watchdog features on the visualization pages should also be considered. If the pages cannot be seen, then the system as a whole has failed.