Implementation of a Pilot Continuous Monitoring System: Iowa Falls Arch Bridge

BRIDGE ENGINEERING CENTER

June 2015

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The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**	
InTrans Project 10-371			
4. Title		**5. Report Date**	
Implementation of a Pilot Continuous Monitoring System: Iowa Falls Arch Bridge		June 2015	
		6. Performing Organization Code	
7. Author(s)		**8. Performing Organization Report No.**	
Brent M. Phares, Justin Dahlberg, and Nick Burdine		InTrans Project 10-371	
9. Performing Organization Name and Address		**10. Work Unit No. (TRAIS)**	
Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**11. Contract or Grant No.**	
12. Sponsoring Organization Name and Address		**13. Type of Report and Period Covered**	
Iowa Department of Transportation 800 Lincoln Way Ames, Iowa 50010		Final Report	
		14. Sponsoring Agency Code	
		HR 1088	

15. Supplementary Notes

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16. Abstract

The goal of this work was to move structural health monitoring (SHM) one step closer to being ready for mainstream use by the Iowa Department of Transportation (DOT) Office of Bridges and Structures. To meet this goal, the objective of this project was to implement a pilot multi-sensor continuous monitoring system on the Iowa Falls Arch Bridge such that autonomous data analysis, storage, and retrieval can be demonstrated.

The challenge with this work was to develop the open channels for communication, coordination, and cooperation of various Iowa DOT offices that could make use of the data. In a way, the end product was to be something akin to a control system that would allow for real-time evaluation of the operational condition of a monitored bridge.

Development and finalization of general hardware and software components for a bridge SHM system were investigated and completed. This development and finalization was framed around the demonstration installation on the Iowa Falls Arch Bridge.

The hardware system focused on using off-the-shelf sensors that could be read in either "fast" or "slow" modes depending on the desired monitoring metric. As hoped, the installed system operated with very few problems.

In terms of communications—in part due to the anticipated installation on the I-74 bridge over the Mississippi River—a hardline digital subscriber line (DSL) internet connection and grid power were used. During operation, this system would transmit data to a central server location where the data would be processed and then archived for future retrieval and use.

The pilot monitoring system was developed for general performance evaluation purposes (construction, structural, environmental, etc.) such that it could be easily adapted to the Iowa DOT's bridges and other monitoring needs. The system was developed allowing easy access to near real-time data in a format usable to Iowa DOT engineers.

17. Key Words		**18. Distribution Statement**	
bridge infrastructure—continuous monitoring system—Iowa Falls bridge—multi-sensor monitoring—pilot SHM project—structural health monitoring		**No restrictions.**	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	69	NA

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

IMPLEMENTATION OF A PILOT CONTINUOUS MONITORING SYSTEM: IOWA FALLS ARCH BRIDGE

Final Report
June 2015

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Sponsored by
Iowa Department of Transportation
(InTrans Project 10-371)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement
with the Institute for Transportation

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ACKNOWLEDGMENTS

The research team would like to acknowledge the Iowa Department of Transportation (DOT) for sponsoring this research. In particular, the authors would like to acknowledge the members of the project technical advisory committee who represent the Iowa DOT offices that might benefit from the research results.

EXECUTIVE SUMMARY

With the maturity of the use of quantitative information, the next step in the evolution of bridge monitoring for the Iowa Department of Transportation (DOT) is to implement monitoring systems that not only assess targeted structural performance parameters, but systems that can also be applicable in assessing general condition (both structural and nonstructural) using multiple sensors and sensor types and to do so in near real-time.

While the bridge monitoring efforts that have taken place since the early 2000s have provided very valuable information to the Iowa DOT, it became clear that developmental work was needed to allow bridge monitoring to become part of everyday bridge condition monitoring.

Prior to the initiation of this project, the data have either been immediately used to make decisions regarding bridge condition/behavior/etc. and then provided in report format or analyzed autonomously with the outputs coming in the form of general information. The missing piece has been the creation of a mechanism to provide the autonomous data analysis coupled with means and methods for storing the data such that they could be accessed later by Iowa DOT engineers.

The challenge with this work was to develop the open channels for communication, coordination, and cooperation of various Iowa DOT offices that could make use of the data. In a way, the end product was to be something akin to a control system that would allow for real-time evaluation of the operational condition of a monitored bridge.

Development and finalization of general hardware and software components for a bridge SHM system were investigated and completed. This development and finalization was framed around the demonstration installation on the Iowa Falls Arch Bridge.

The hardware system focused on using off-the-shelf sensors that could be read in either “fast” or “slow” modes depending on the desired monitoring metric. As hoped, the installed system operated with very few problems.

In terms of communications—in part due to the anticipated installation on the I-74 bridge over the Mississippi River—a hardline digital subscriber line (DSL) internet connection and grid power were used. During operation, this system would transmit data to a central server location where the data would be processed and then archived for future retrieval and use.

Implementation Readiness

The pilot monitoring system was developed for general performance evaluation purposes (construction, structural, environmental, etc.) such that it could be easily adapted to the Iowa DOT’s bridges and other monitoring needs. The system was developed allowing easy access to near real-time data in a format usable to Iowa DOT engineers.

Through this project, it was observed that the biggest hurdle to widespread use of a system like this is storage of historical data. With data being collected at relatively high rates, a very large volume of data is collected on a daily basis. Although, from an operational perspective, this is not an insurmountable problem, there are difficulties associated with physically storing this much data.

As a result for future installations, it is recommended that the Iowa DOT develop a policy regarding how long historical data is retained.

The project team recommends that the Iowa Falls Bridge structural health monitoring (SHM) system be integrated into normal operations on a graduated trial basis to prepare for the upcoming I-74 bridge construction and SHM system installation. The motivation for this integration is to identify areas for practical improvement and to demonstrate the value added by such systems.

Integration steps were outlined and it’s expected that the process—including system testing and verification—could be completed in 18 months or less.

Implementation Benefits

Implementing a multi-sensor, continuous monitoring system in this project serves as a prototype for use on other bridges. The overall benefit from this pilot study is that the architecture of a continuous monitoring system was developed that can be implemented on any bridge type to evaluate general performance (including environmental, structural, etc.).

The monitoring system will provide data that are continuous, routinely accessible by Iowa DOT staff, and readily and directly implementable by the Iowa DOT for timely decision making. In many ways, this pilot project was intended to set the stage for the planned construction of a new bridge on I-74 over the Mississippi River.

INTRODUCTION

Background

As part of designing, constructing, and maintaining the bridge infrastructure in Iowa, the Iowa Department of Transportation (DOT) has, in recent years, focused efforts on investigating the use of new high-performance materials, new design concepts and construction methods, and various new maintenance methods. These progressive efforts are intended to increase the life span of bridges in meeting the DOT's objective of building and maintaining cost-effective and safe bridges.

Bridge testing and monitoring has been beneficial in helping with these innovative efforts, as well as providing important information to evaluate the structural performance and safety of existing bridges. The Iowa DOT testing and monitoring program, in coordination with the Bridge Engineering Center (BEC) at Iowa State University, collects performance data to compare with design-based structural parameters to determine if the structural response is appropriate. The data may also be used to "calibrate" an analytical model that may be used to provide a more detailed structural assessment (e.g., a load rating to determine safe bridge capacity).

Diagnostic testing has also been used to help identify deterioration or damage or to assess the integrity of an implemented repair or strengthening method. In cases where the Iowa DOT has investigated the use of innovative materials (high-performance steel, ultra-high-performance concrete, fiber-reinforced polymers, etc.) and design/construction methods, they have used testing as part of a program for evaluating bridge performance.

The most challenging research program cooperatively undertaken by the Iowa DOT Office of Bridges and Structures and the BEC has been related to developing a structural health monitoring (SHM) system to determine the real-time and continuous structural condition of a bridge. One example of such work aimed to develop an SHM system to identify crack development in fatigue-prone areas of structural steel bridges.

With the maturity of the use of quantitative information, the next step in the evolution of bridge monitoring for the Iowa DOT is to implement monitoring systems that not only assess targeted structural performance parameters, but systems that can also be applicable in assessing general condition (both structural and nonstructural) using multiple sensors and sensor types and to do so in near real-time.

While the bridge monitoring efforts that have taken place since the early 2000s have provided very valuable information to the Iowa DOT, it became clear that developmental work was needed to allow bridge monitoring to become part of everyday bridge condition monitoring.

Prior to the initiation of this project, the data have either been immediately used to make decisions regarding bridge condition/behavior/etc., and then provided in report format, or analyzed autonomously with the outputs coming in the form of general information. The missing piece has been the creation of a mechanism to provide the autonomous data analysis coupled with means and methods for storing the data such that they can be accessed later by Iowa DOT engineers.

Objectives and Scope

The objective of this work is to implement a pilot multi-sensor continuous monitoring system on the Iowa Falls Arch Bridge such that autonomous data analysis, storage, and retrieval can be demonstrated. The pilot monitoring system was to be developed for general performance evaluation purposes (construction, structural, environmental, etc.) such that it could be easily adapted to the Iowa DOT's bridges and other monitoring needs. The system was to be developed allowing easy access to near real-time data in a format usable to Iowa DOT engineers.

In many ways, this pilot project was intended to set the stage for the planned construction of a new bridge on I-74 over the Mississippi River. As such, the instrumentation and other systems described in this report serve as possible sensors that could be installed on the I-74 bridge. However, the researchers emphatically emphasize that the sensor systems used in this project can be used on multiple bridge types without difficulty.

The challenge with this work was to develop the open channels for communication, coordination, and cooperation of various DOT offices that could make use of the data. In a way, the end product was to be something akin to a control system that would allow for real-time evaluation of the operational condition of a monitored bridge.

Report Content

This report is divided into five chapters. A brief literature review is presented in the second chapter with a principal focus on long-term monitoring systems and applications. The third chapter describes the prototype hardware of the bridge monitoring system. The fourth and fifth chapters summarize the data analysis and presentation means and methods. Finally, the last chapter provides a brief summary of the entire developmental project.

TECHNICAL INFORMATION REVIEW

SHM systems can vary in size, instrumentation, and specific application. Commonly, systems employ multiple wired gages strategically located on a bridge structure to measure the response to live loads. The measured response is collected and interpreted using algorithms developed for the respective project. Generally, one aims to observe any signs of damage occurring on the bridge structure, and, for this, methods of damage detection have been developed and employed. This brief review touches on some of the long-term health monitoring projects being conducted in the US and also some methods of damage detection.

Additionally, the use of roadway weather information systems (RWIS) has gained popularity over the recent years. These systems are capable of providing real-time road conditions as they pertain to the weather and safety (e.g., surface temperature). Their incorporation into a structural health monitoring system by utilizing equipment already in place can provide benefits to roadway safety decision makers. A brief review of some of the RWIS systems and their benefits also follows.

Long-Term Health Monitoring

Chakraborty and DeWolf (2006) developed and implemented a long-term strain monitoring system on a three-span, multi-steel girder bridge located on the Interstate system in Connecticut. The work was a continuation of a multi-year, multi-project endeavor in which the team aimed to identify the behavior characteristics of varying bridge types. With this information, long-term monitoring systems were developed and implemented. In this case, the bridge was made up of single-span beams and a continuous composite deck.

Using strain gages at 20 different locations, data were continuously collected at rates no faster than 50 Hz. Data collection, storage, and communication with the central computer at the University of Connecticut was completed using an onsite computer. The strain distribution in the girders was calculated for a vehicle event, and the number of trucks and their relative sizes were calculated. Comparison of the data with finite element analysis and AASHTO specifications was completed in addition to validation through live load tests.

It was concluded that measuring the actual strain behavior of the bridge along with developing a supportive finite element model showed that the stress levels are typically well below those used in the design process.

Cardini and DeWolf (2009), as a continuation of the previously discussed study (same bridge), presented an approach to use strain data from a multi-girder, composite steel bridge for long-term structural health monitoring. The goal was to identify any significant changes in the structural behavior over time that might indicate a change in the structural integrity; these changes might be caused by cracks, corrosion, or deck degradation.

An envelope of maximum distribution factors, peak strains, and location of the neutral axis was developed. Deviations from the envelope values would potentially indicate a structural change. Data validation was completed through finite element modeling and live load bridge tests. The proposed SHM approach would require the continual evaluation of the distribution factors for the girders, the peak strain values of the girders, and the neutral axis location.

Farhey (2006) investigated the long-term durability of a structural health monitoring system on a continuously monitored bridge in Ohio and discussed the suitability of the various sensor arrays and data acquisition system. The uniquely designed bridge (made entirely of high-tech fiber-reinforced polymeric materials) was instrumented with numerous sensor types to provide real-time structural data on ambient and other life-cycle effects. Some of the gage types included strain sensors (vibrating wire and fiber optic), crackmeters, tiltmeters, thermistors, and hygrometers.

A major emphasis of the results was the effect of temperature and humidity. Though humidity was determined to have little effect, distinct variations were seen in the strain data with respect to temperature. A long-term investigation of the temperature sensitivity of the instrumentation system with all its components was recommended. Also, it was recommended that fiber optic sensors not be employed for long-term monitoring applications due to their high cost and requirement for annual recalibration.

The validation of a statistical-based, damage detection approach was conducted in a study completed by Phares et al. (2011). This study was in succession of two other studies (Wipf et al. 2007 and Lu 2008), where an autonomous structural health monitoring system was developed to be incorporated into an active bridge management system that tracks usage and structural changes, helping owners to identify damage and deterioration.

The statistical-based, damage detection approach first introduced by Lu (2008) focused on mathematically defining the difference between the behavior of a normal (healthy) structure and that of a damaged structure. Control chart analysis was conducted over specific damage indicators. A one-to-one model direct evaluation method was selected as the damaged detection method because of its sensitivity to damage and ability to locate damage. The actual bridge behavior was compared to the predicted bridge behavior, which was derived from a statistics-based model trained with field data from the undamaged bridge. It is the differences between actual and predicted responses (residuals) that are used to construct control charts. The validation of this method was completed by simulating damage to the bridge by attaching sacrificial specimens. The damage detection algorithm did well in identifying damage, though several false positives were found. Efforts to correct the algorithm were completed, which improved the overall damage detection system.

Phares et al. (2013) continued to improve the previously described structural health monitoring system through the introduction of a statistical f-test. Additionally, the SHM hardware system was improved (more reliable strain gages and communication technology). A partial software package was developed and includes multiple automated damage detection processes. Also, the damage detection ability was improved through the use of redundant systems including (1) one-truck event, (2) truck events grouped by 10, (3) cross-prediction, and (4) the F_{shm} method.

Roadway Weather Information Systems

Roadway weather information systems include historic and current climatological data to develop road and weather information. According to the Aurora Program, whose objectives include the facilitation of advanced road condition and weather monitoring and forecasting capabilities for efficient highway maintenance and real-time information to travelers, the three main elements of RWIS are (1) environmental sensor system technology to collect data, (2) models and other advanced processing systems to develop forecasts and tailor the information into an easily understood format, and (3) dissemination platforms on which to display the tailored information.

Within Iowa, nearly 60 RWIS sites have been installed. RWIS sites generally consist of several atmospheric sensors and pavement sensors embedded in the pavement to measure surface temperature. Some of the newer surface pavement sensors are also able to determine the depth of precipitation on the pavement surface and the chemical concentration of the chloride solution on the roadway. It is common that an anemometer is also included at RWIS sites for the measurement of wind speed. When combined, these sensors can provide a real-time depiction of the roadway conditions, which can assist decision makers regarding any road maintenance action that might be required.

BRIDGE MONITORING SYSTEM

The SHM system includes not only the hardware required to monitor the structural behavior, but also the hardware to monitor environmental conditions and bridge security. This chapter describes the hardware used and its particular application.

Structural Monitoring – Substructure

Corrosion Monitoring

Corrosion wire from Vetek Systems was used to monitor the corrosion potential at various locations including the micropile foundations, abutment backwall, and tie-back rods. Examples of the locations are shown in Figure 1, Figure 2, and Figure 3.

Figure 1. Corrosion monitoring of micropile foundation

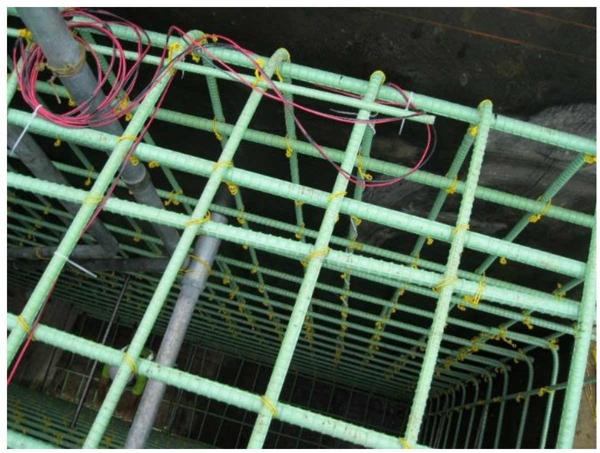


Figure 2. Corrosion monitoring of abutment reinforcement

Figure 3. Corrosion monitoring of tie-back rod

Vetek's V2000 system is made up of silver wire placed inside a plastic braid. The wire is wrapped around the element of interest (e.g., tie-back rod), and another wire is connected to an exposed area of the element; each wire is then routed to the data logger. Once the element is in place and encapsulated with grout or concrete, the pour water of the grout acts as an electrolyte, and the electric potential between the anchor and electrode can be measured. In the event of corrosion activity, the corrosion electrochemical activity registers on the electrode as increased voltage and current. Typically, readings less than 300 mV DC indicate that no corrosion activity is present. Readings from 300 mV to 400 mV DC indicate that corrosion has begun. Readings above 400 mV DC indicate that corrosion is fully active on the anchor steel.

Abutment Relative Movement Monitoring

The relative movement between north and south abutments is measured by the Micro-Epsilon optoNCDT ILR 1182-30 housed in the enclosure, shown in Figure 4 and Figure 5.

Figure 4. Measurement of relative movement

Figure 5. Relative movement laser

This optoelectronic sensor has a range of just under 500 ft using a target board and resolution of four one-thousandths of an inch; the distance between abutments at Iowa Falls is approximately 286 ft. A target board was created from lauan plywood and reflective tape. The sensor operates with a 50 Hz measuring rate and thus can be used for fast processes, though this rate of measurement would not be required for assessing relative movement between abutments.

Arch Bearing Rotation

Tiltmeters were installed at the base of each arch at the south bearings. The tiltmeters indicate rotations about the bearing hinge (if any).

Rock Bolt Strain Monitoring

Rock bolt strain is measured at six locations at the rock cut support walls, three at the north abutment and three at the south. Geokon Model 4910 Instrumented Rockbolts are made up of a vibrating wire strain gage located inside a short length of threaded rock bolt, in this case a Williams threaded bar. The threaded bar is coupled to the rock bolt, as shown in Figure 6, and together the assembly is installed as a rock bolt normally would be, as shown in Figure 7.

Figure 6. Rock bolt strain sensor attachment to rock bolt

Figure 7. Rock bolt strain sensor installed

A lead wire extends from the end of the rock bolt to the data logger to accommodate continuous measurement. Many of the substructure sensor locations are shown in Figure 8.

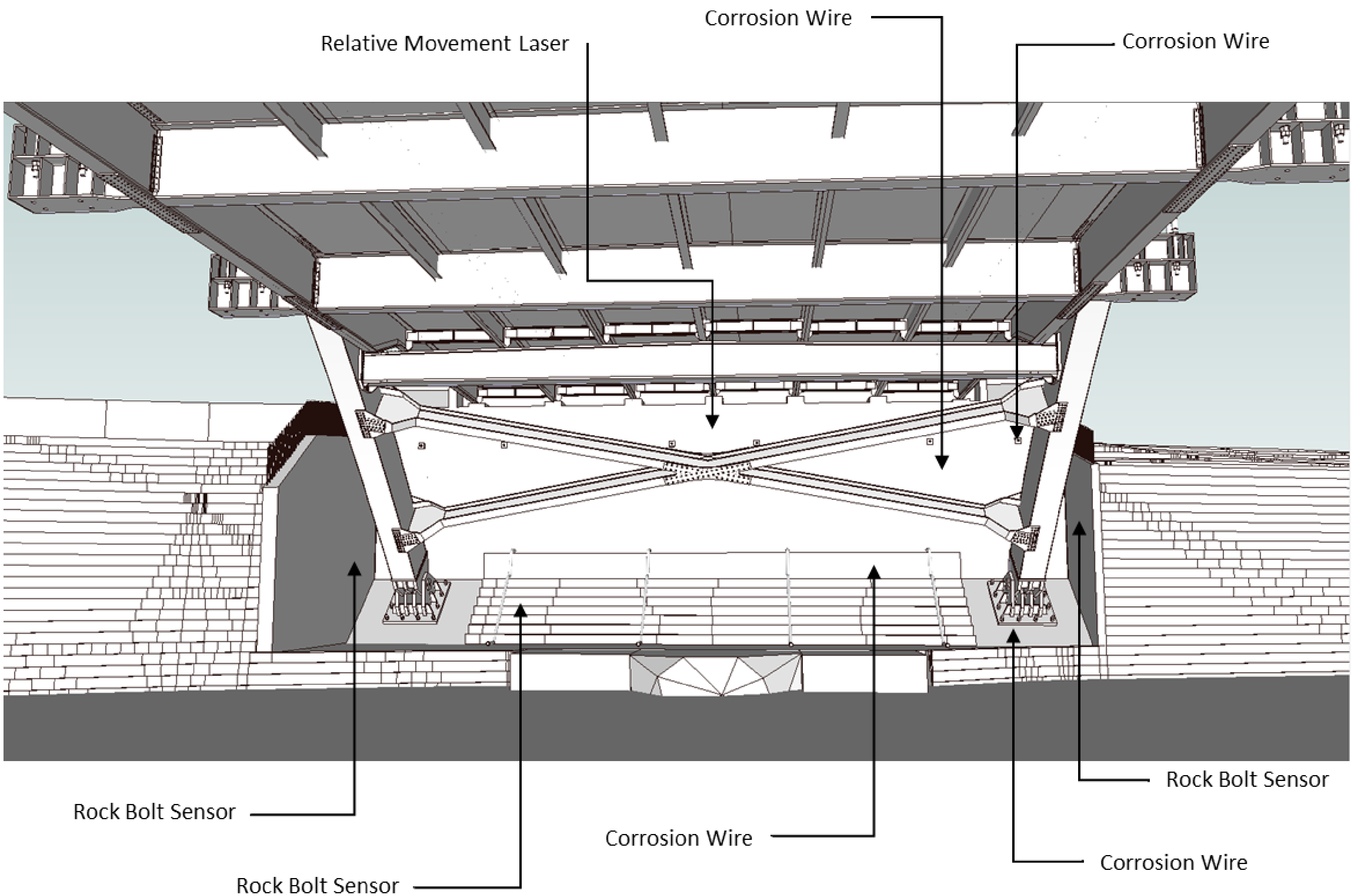


Figure 8. Substructure sensor locations

Structural Monitoring - Superstructure

Arch Rib Moisture Monitoring

Though unlikely, the possibility still exists for some moisture to accumulate at the base of the arch ribs. Such moisture accumulation could represent a long-term concern. Small drainage holes have been fabricated into the base plate to alleviate any accumulation. Even so, two methods of moisture monitoring were put into place to demonstrate the potential monitoring capabilities: direct sensing by a leaf wetness sensor from Campbell Scientific, Inc. (237-L), shown in Figure 9, and visual observation by a Panasonic HCM735A camera, shown in Figure 10.

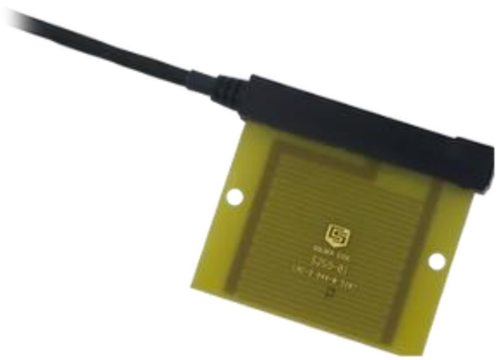


Figure 9. Campbell Scientific leaf wetness sensor

Figure 10. Panasonic HCM735 camera

The leaf wetness sensor operates by measuring the electrical resistance on the surface of the sensor. When enough moisture has accumulated on the sensor plate, the electrodes are bridged and a significantly different reading is recorded. The camera at the base of the arch provides a continuous live feed and lighting through auxiliary light-emitting diodes (LEDs), through which one can visually observe the current condition. An image from the live camera feed is shown in Figure 11.

Figure 11. Visual moisture monitoring in arch rib

Hanger Strain Monitoring

With the Iowa Falls Bridge, the Type A floorbeams are supported at each end by four 2 in. diameter structural strands (see Figure 12). Two of the hanger locations (eight total hangers) on the west side of the bridge were equipped with Geokon Model 4410 Strandmeters, as shown in Figure 13.

Figure 12. Cable hangers

Figure 13. Strandmeter

The strandmeter consists of a vibrating wire sensing element in line with an internal spring. As the strandmeter shortens or elongates, the tension in the spring changes and is sensed by the vibrating wire element. The change in spring tension is directly proportional to the change in gage length, thus enabling the strain within each hanger to be measured and recorded. Such measurements are then directly related to the live load force being carried by each hanger.

Arch Strain Monitoring

The arches of the Iowa Falls Bridge were monitored at six locations using electrical resistance-type strain gages from Hitec Products, Inc., model number HBW-35-125-6-GP-NT, as shown in Figure 14.

Figure 14. Electrical resistance strain gages

Four gages were located at each location, one each on the vertical surface at the top and bottom corners of the box-shaped cross-section. The gages are bonded to stainless steel shims that are attached inside the arch elements as shown in Figure 15.

Figure 15. Arch rib strut

Arch gage and strandmeter locations are shown in Figure 16.

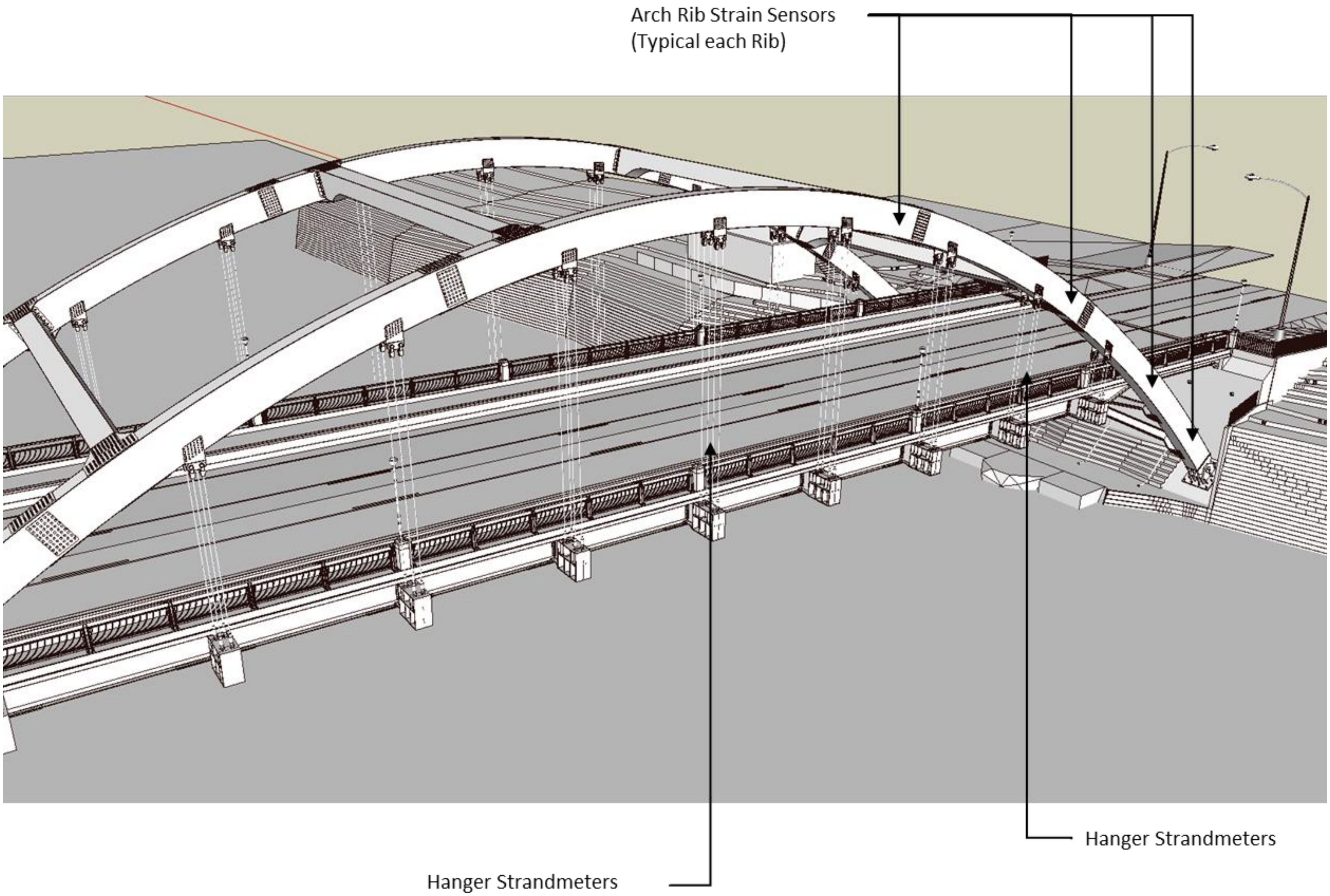


Figure 16. Arch strain monitoring

Data Collection for Rating and Heavy Load Detection

To best collect data for the purposes of superstructure rating and heavy load detection, a series of strain gages, the same as those used in the arches, were used at numerous locations on the superstructure framing and underside of the deck. The strain data from all of the gages are recorded and used to identify vehicle types and relative weights. Figure 17 and Figure 18 show the installation of strain gages on one of the Type B floor beams and stringers, respectively.

Figure 17. Strain gage installation – Type B floorbeam

Figure 18. Strain gage installation – stringers

Strain gages were also placed on the underside of the deck in several locations. In lieu of attaching the gages, as would be done on steel members, the strain gages were adhered to the deck with an epoxy resin. An example of this installation is shown in Figure 19.

Figure 19. Deck strain gage

In addition to the deck strain sensors, multiple thermistors were installed into the bottom side of the bridge deck to measure the deck's internal temperature. The sensor locations are shown in Figure 20 and Figure 21.

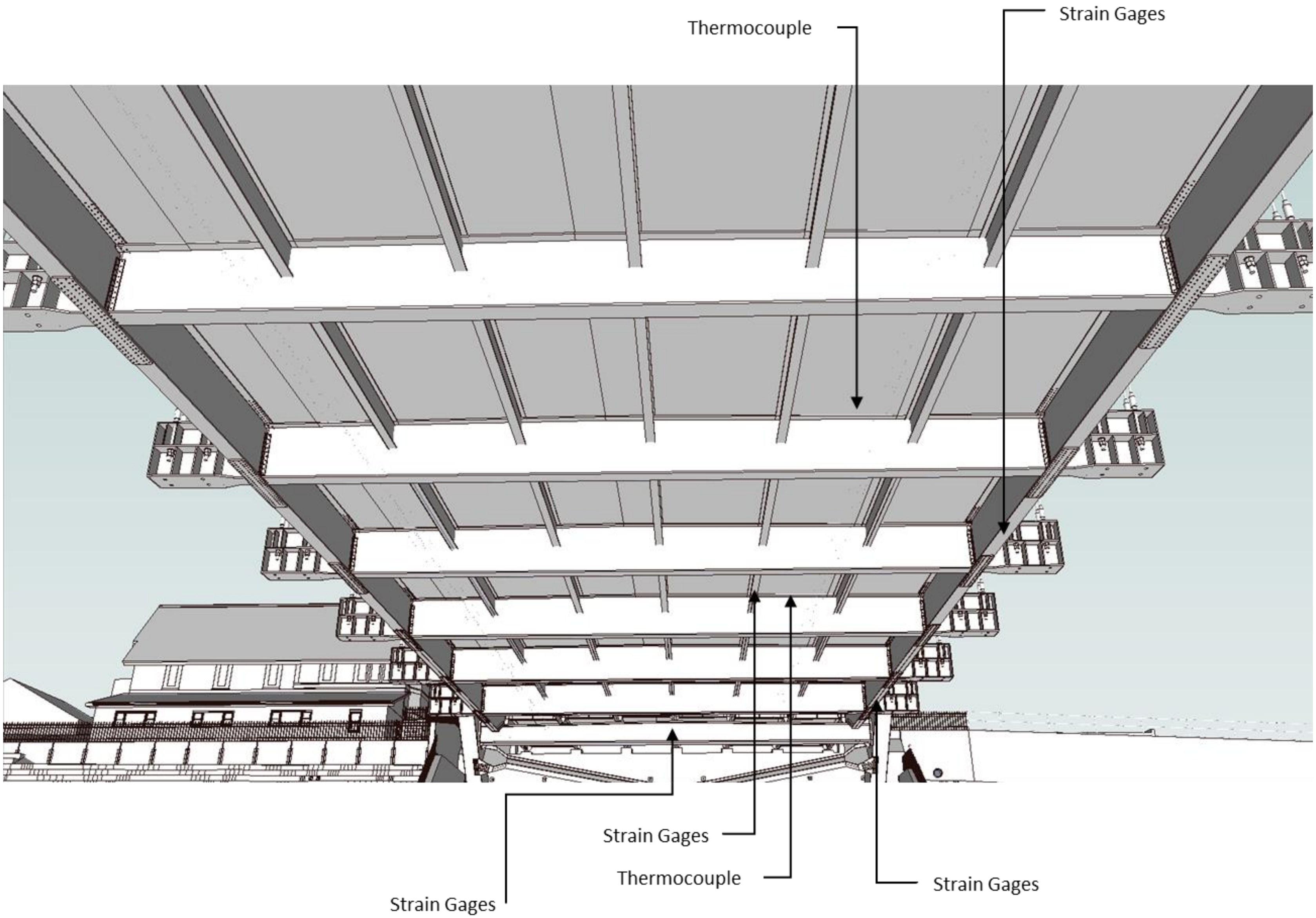


Figure 20. Superstructure instrumentation

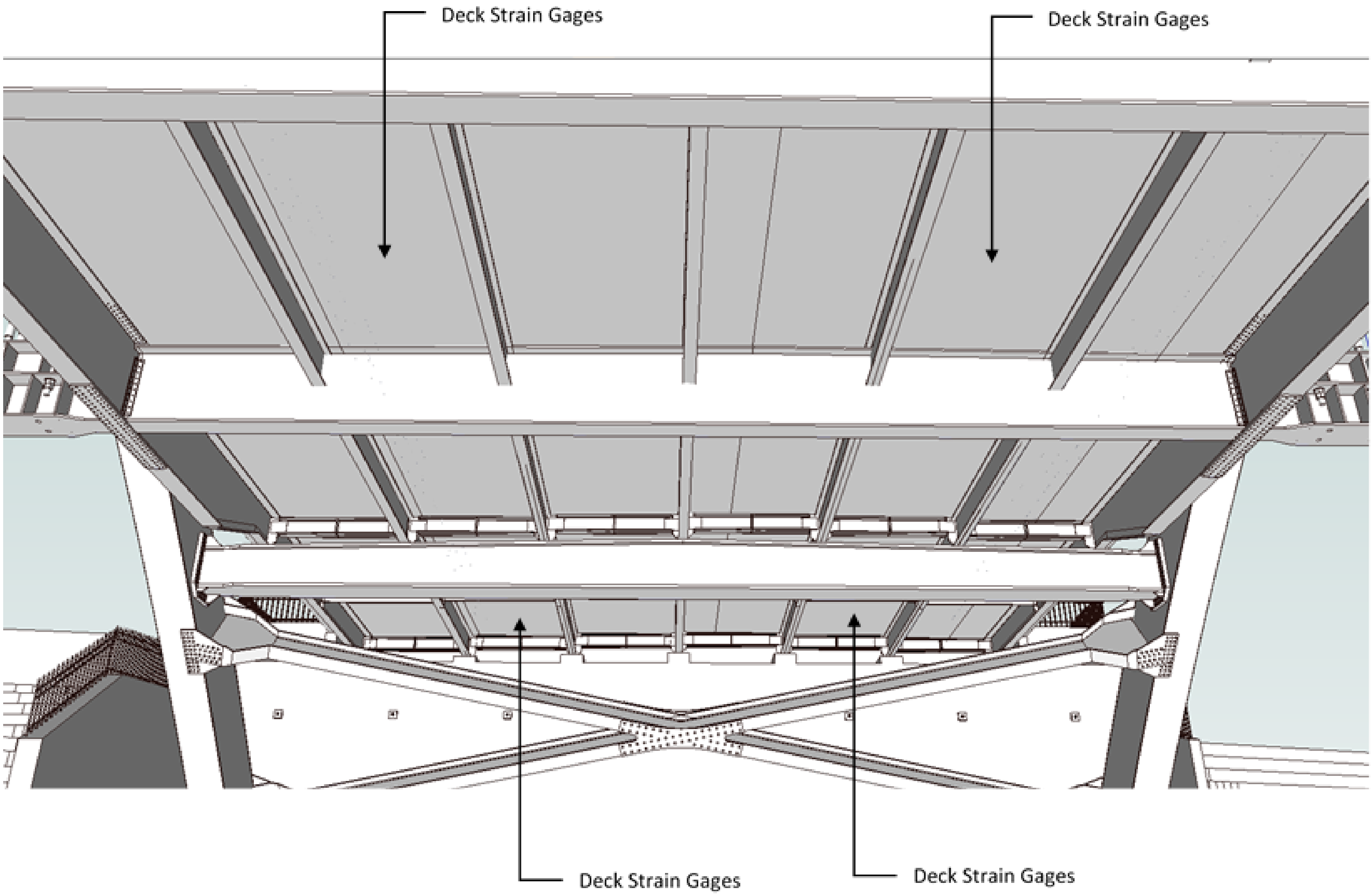


Figure 21. Deck strain gages

Data Processing

All of the gages and other sensors can be categorized into one of two groups: fast-read or slow-read. The fast-read group of gages are all of those that require rapid measurements to obtain useful data (e.g., the strain gages on the arch ribs are read at 250 Hz). The slow-read group are all of those that require measurement only occasionally (e.g., rock bolt strain, where the changes are likely to be very slow and gradual).

For each application, a separate datalogger was used. Measurements from the fast-read gages were completed using a Campbell Scientific, Inc. CR9000X datalogger, whereas measurements from the slow-read gages were completed using a Campbell Scientific CR1000 datalogger.

In addition to the loggers, other accessory pieces of equipment were needed to complete the data recording and processing. A Campbell Scientific, Inc. AVW200, 2-Channel Vibrating-Wire Interface was required for the dataloggers to collect data from vibrating wire instrumentation such as rock bolt strain sensors and tiltmeters. Also, the Campbell Scientific, Inc. AM 16/32B Relay Multiplexer was used to increase the number of sensors that could be measured by the CR1000 datalogger.

A HP Compaq 6200 Pro Microtower desktop computer and Campbell Scientific Inc.'s RTDAQ software were used on site to collect, store, and transmit the data from the dataloggers. The software is specifically intended for high-speed data acquisition.

All of the equipment plus other miscellaneous items (modem, Ethernet switch, battery backup, and power supplies) were housed in locked, waterproof cabinets mounted beneath the bridge on the south abutment wall near the southwest arch bearing; these cabinets are shown in Figure 22. Some of the data logging equipment is shown in Figure 23.

Figure 22. Data logging equipment boxes

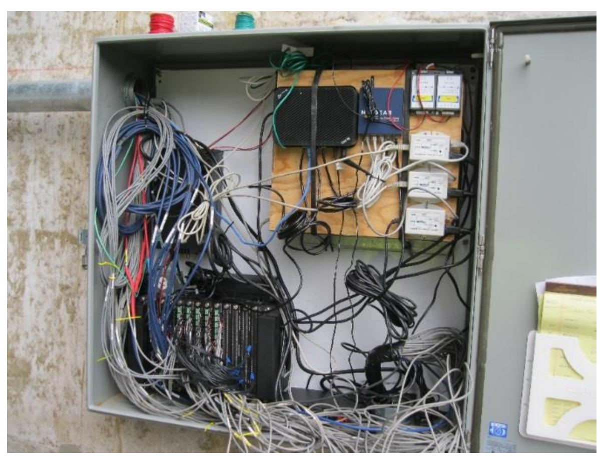


Figure 23. Data logging equipment

The gage wires were directed to the cabinets via a conduit protruding from near the southwest arch bearing and by a conduit cast into the abutment wall extending from the top of the abutment to directly behind the smaller of the two boxes. Figure 24 provides an example of the makeup of the structural monitoring equipment.

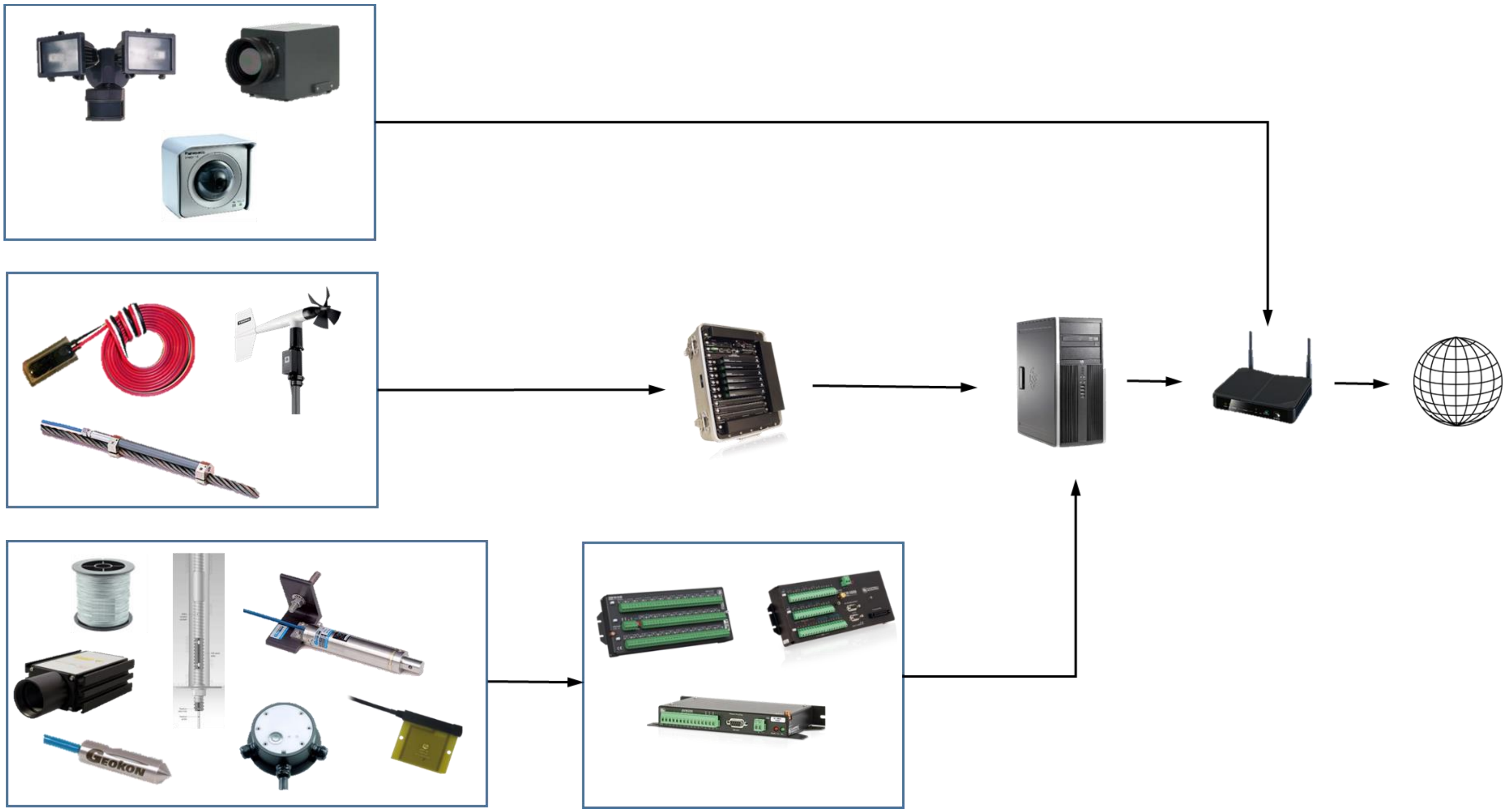


Figure 24. Structural monitoring system equipment

Environmental Monitoring

Wind Speed and Direction

The wind speed and direction are integral pieces of the overall weather information that are measured using an anemometer like that seen in Figure 25 from the R. M. Young Company.

Figure 25. Anemometer

At the Iowa Falls Bridge, the anemometer was positioned directly below one of the Type A floor beams on the west side, or upstream side, of the bridge. The anemometer is capable of measuring wind speeds up to 224 mph in any direction with an accuracy of ± 0.6 mph and in temperatures ranging from -122°F to 122°F, well within the temperature range typical of Iowa locations. The signal output consists of magnetically induced AC voltage for the wind speed and DC voltage from a conductive plastic potentiometer for wind direction.

Bridge Deck Icing

The potential for icing on the bridge deck was monitored using the IRS31-UMB Intelligent Road Sensor from Lufft. The sensor was embedded into the bridge deck surface as shown in Figure 26.

Figure 26. Intelligent road sensor

The sensor is capable of measuring the road surface temperature, water film height up to 4 mm, and the freezing temperature for different de-icing materials. The deck condition, whether it be dry, damp, wet, icy, or snowy, is also indicated. The anemometer and road sensor locations are shown in Figure 27.

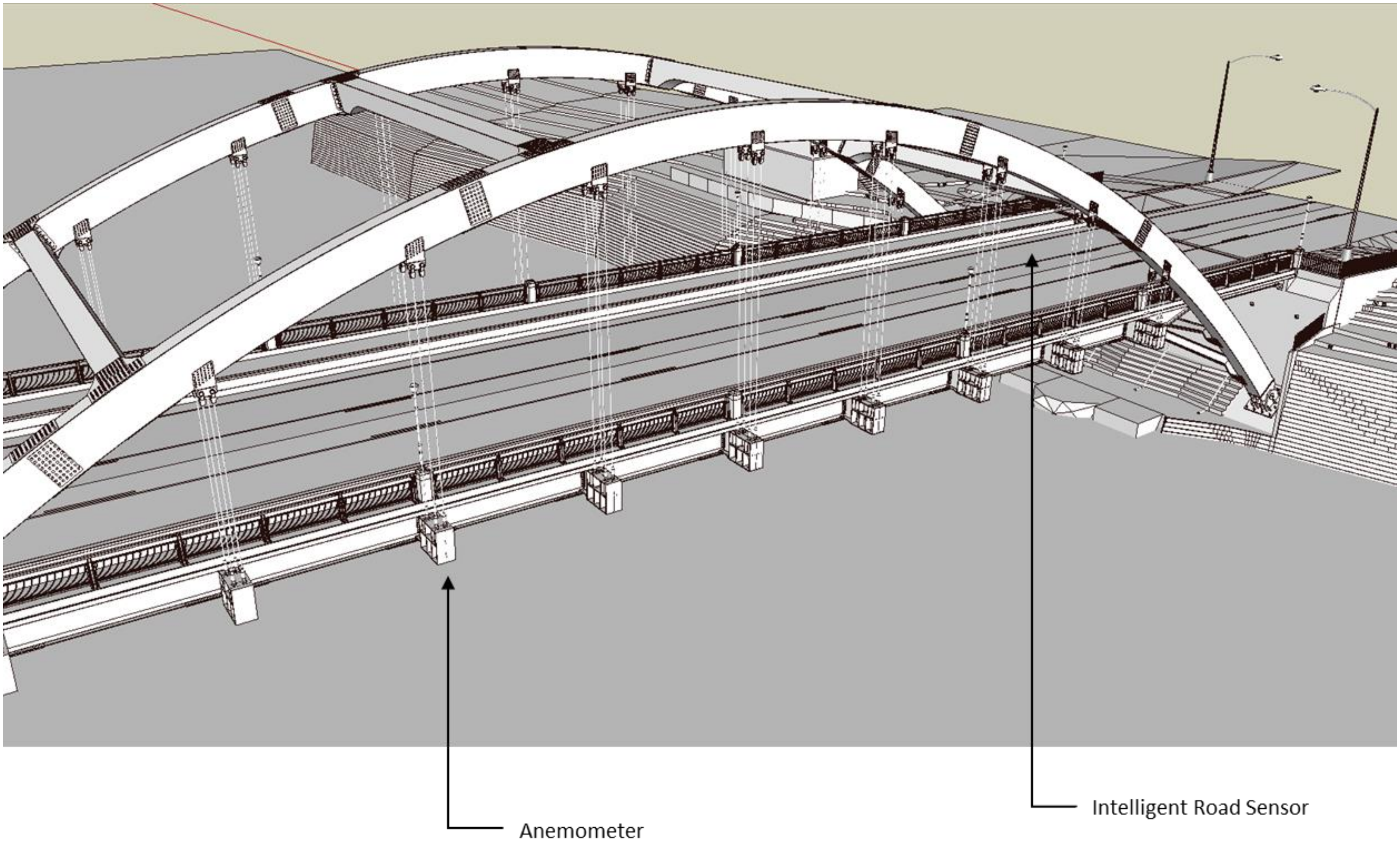


Figure 27. Environmental monitoring equipment

Security Monitoring

Infrared Camera

A JENOPTIC Optical Systems, Inc. IR-TCM 384 infrared camera was mounted beneath the bridge deck and positioned to face toward the south abutment, as shown in Figure 28.

Figure 28. Infrared camera

In the event someone would attempt to harm any of the monitoring equipment mounted on the south abutment or to cause harm to the bridge in that area, the camera would be able to pick up the heat signatures of the individual. The camera is capable of measuring temperatures between -100°F to 575°F and creating alerts indicating the camera has sensed a heated object. The camera, capable of operating in temperatures between -60°F to 125°F, a greater range than what the Iowa Falls Bridge would ever experience, was easily integrated into the structural health monitoring system. For additional security measures, a live webcam was installed adjacent to the infrared camera.

Motion Sensor Flood Light

A motion sensing flood light, shown in Figure 29, was mounted on the south abutment wall to illuminate the area where most of the structural health monitoring equipment was stored.

Figure 29. Motion sensor flood light

Without light, the area can remain quite dark and potentially promote illicit behavior such as graffiti or equipment tampering. With light, this activity is more likely deterred. The motion-activated light has a 240 degree range and uses two 150 watt halogen bulbs. The security monitoring equipment locations are shown in Figure 30.

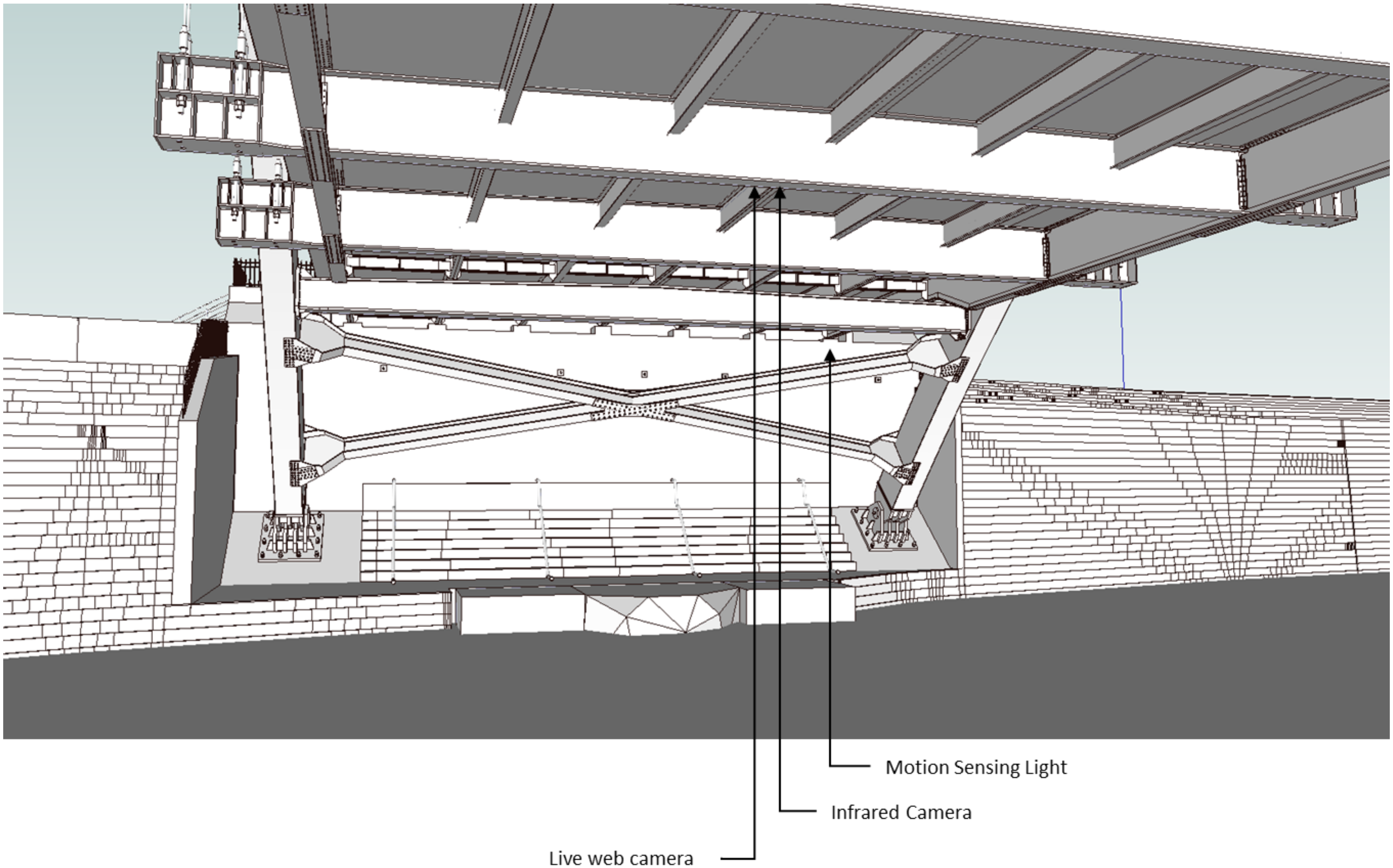


Figure 30. Security monitoring equipment

Construction Monitoring

Photography

Cameras were installed at two locations, one each at the north and south ends of the bridge. Throughout the duration of construction, the cameras provided a live view of the bridge site and also stored a still image taken every hour. These images were stitched together to form a time-lapse video of the entire construction process. An example of images captured from the south and north ends of the bridge are shown in Figure 31 and Figure 32, respectively, and the camera locations relative to the bridge are shown in Figure 33.

Figure 31. Time lapse looking north

Figure 32. Time lapse looking south

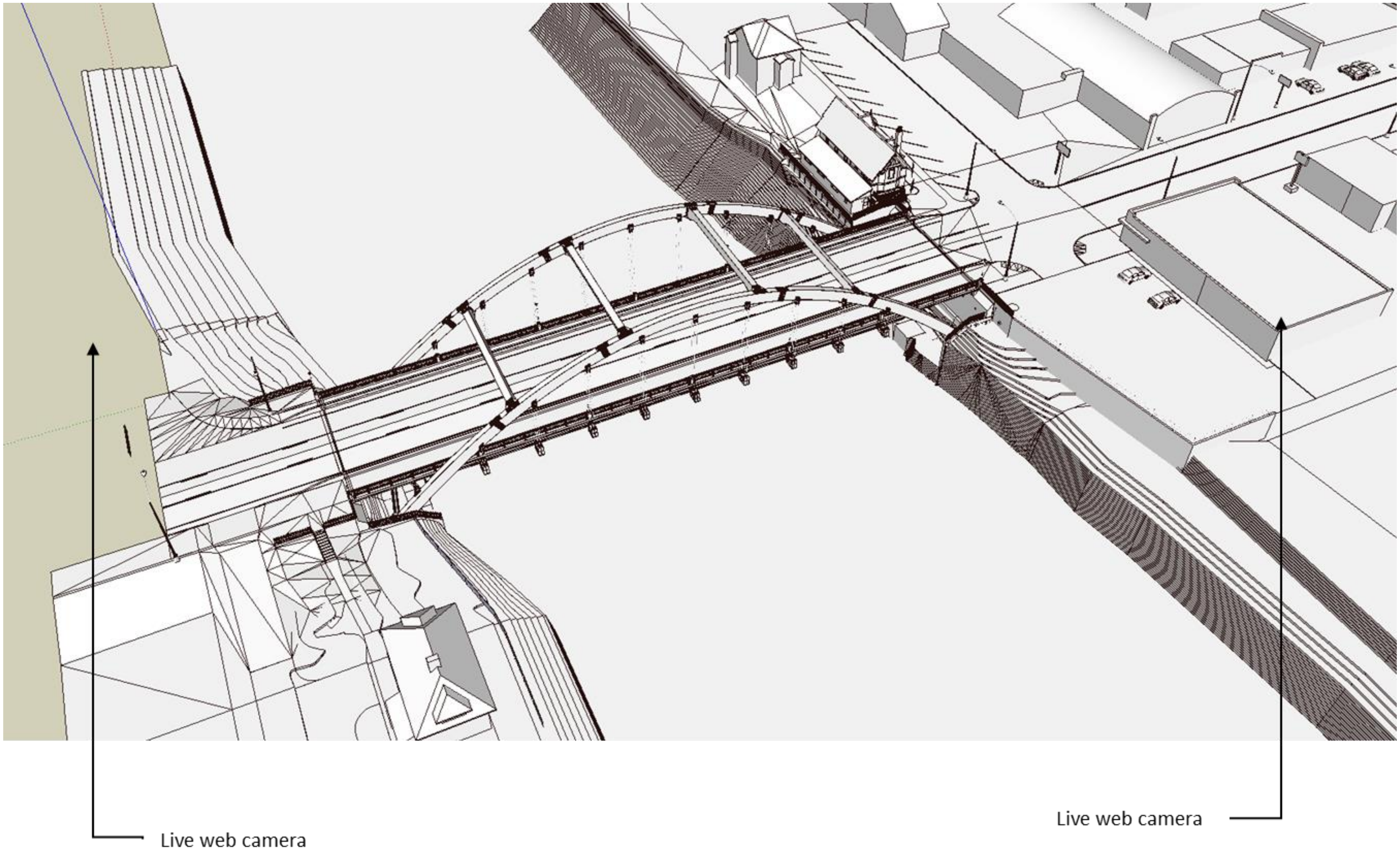


Figure 33. Construction monitoring equipment

WEB-BASED DATA VISUALIZATION AND RETRIEVAL SYSTEM

The collection of various data elements stored in an enterprise-level database opens the door to ideas of disseminating that information via a web-based system that can be utilized by engineers to view and retrieve data of interest by sensor type and timeframe. A proof of concept site was developed as a visualization component to the data collection system installed at the Iowa Falls Bridge site. This proof-of-concept site serves as the concept for how Iowa DOT engineers would interface with the bridge information on a more regular basis.

The development and design of the site was done with Microsoft Visual Studio utilizing a mixture of current web development technologies, including Microsoft ASP.NET and Microsoft Silverlight. The site is laid out into four distinct sections (Home, Sensors, Cameras, and History), which will be described in more detail in this chapter.

Home Page

The website initiates at a basic homepage where a description of the bridge, the locale, and an image of the site are given, as shown in Figure 34.

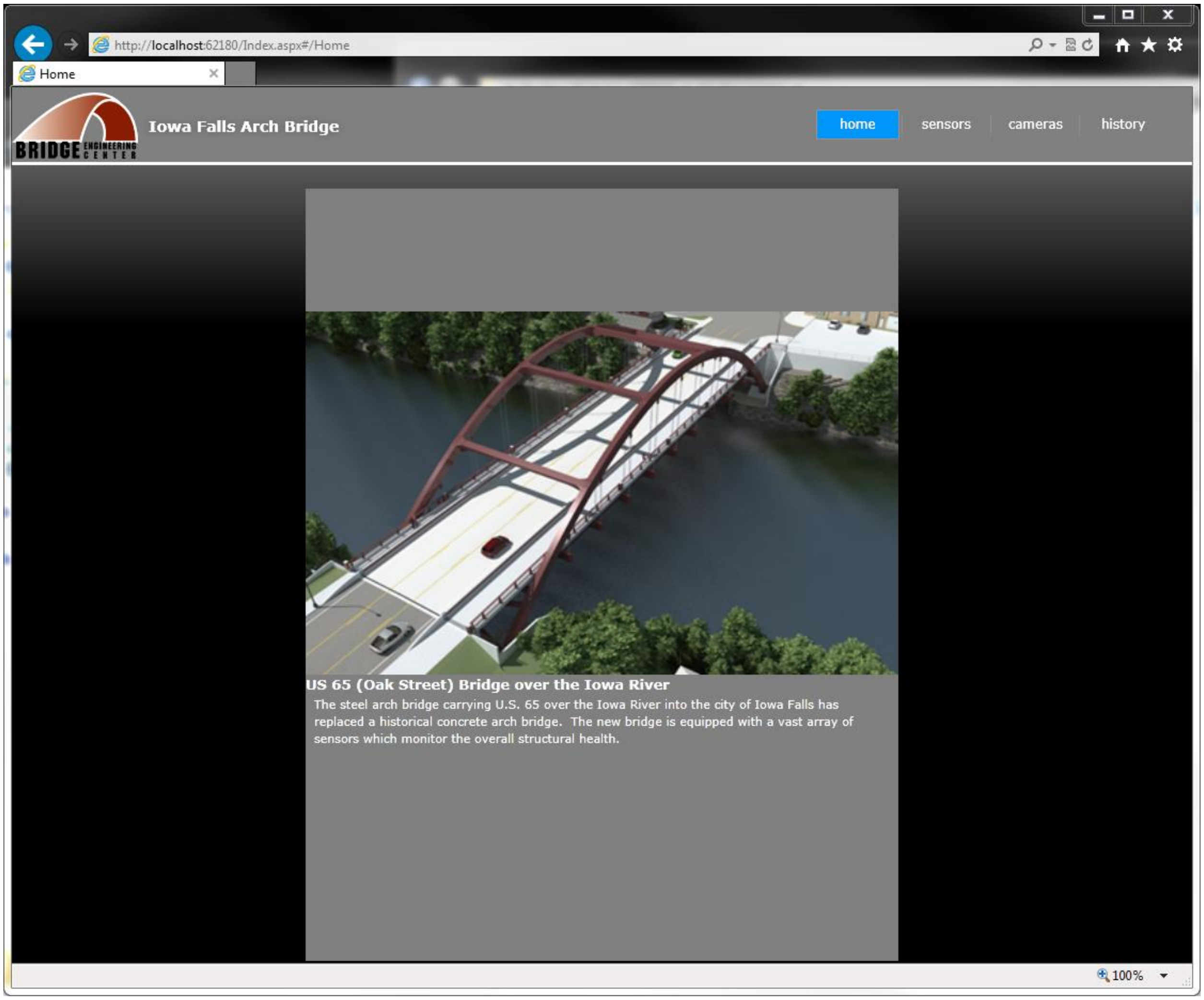


Figure 34. Iowa Falls Bridge data website homepage

The homepage serves as an entry portal to the content contained and available in the other sections. Conceptually, each bridge monitored with this type of system would have its own homepage with easily identifiable information.

Sensors Page

The Sensors section of the website gives the user a visual representation of the sensor types and locations on the bridge. For the Iowa Falls Bridge site, six views were defined as observation points for displaying these sensor types and approximate placements (Deck, East Profile, West Profile, North Abutment, South Abutment, and Lower Structure). The profile selection options can be seen in Figure 35.

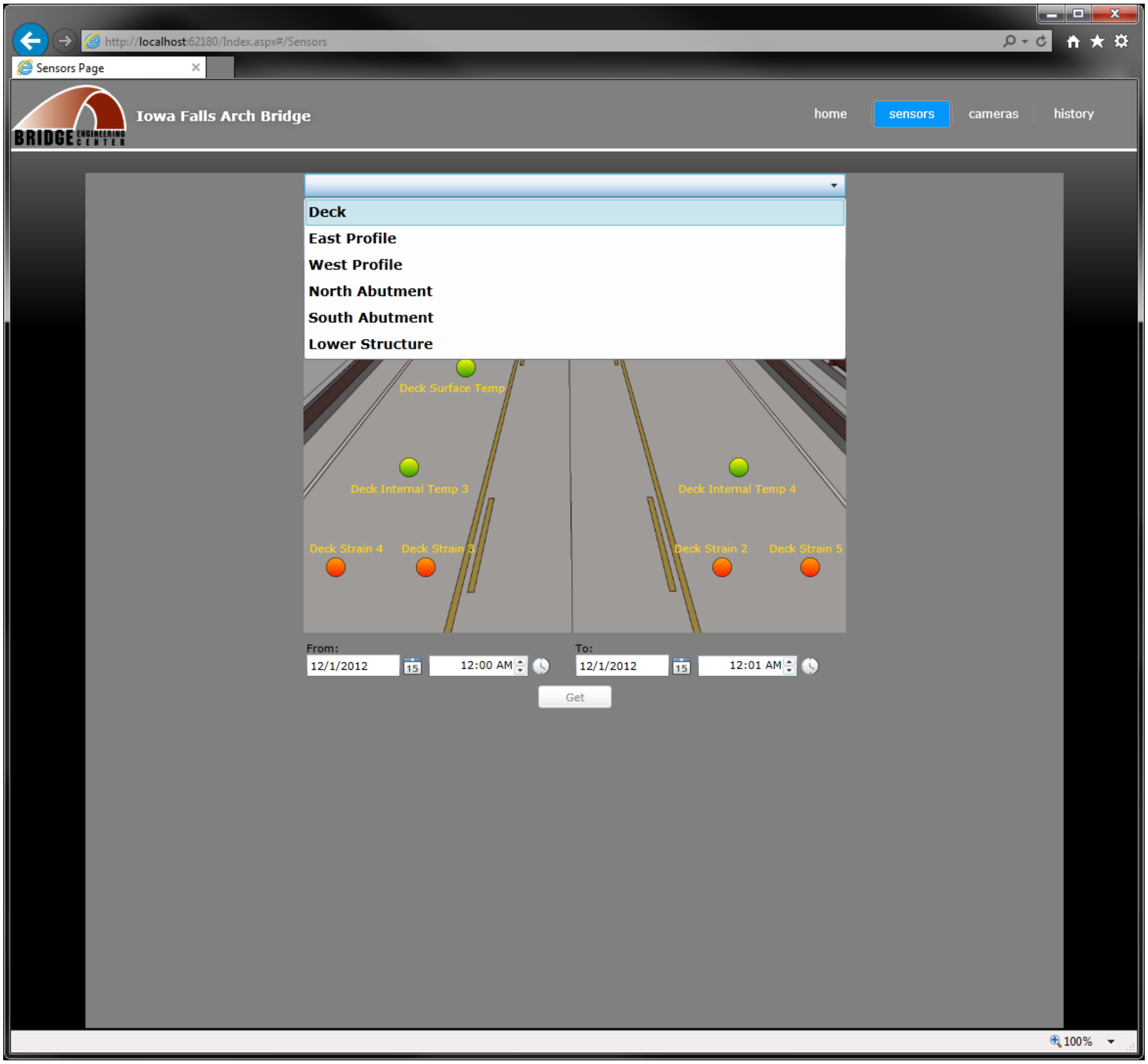


Figure 35. Iowa Falls Bridge data website profile selection

The number of views needed for specific bridges will depend both on the bridge complexity and the number/extent of installed instrumentation. The individual associated views of each profile for the Iowa Falls Bridge are included in Appendix A.

Sensor Selection

Once a profile of interest is selected, users can choose an individual sensor (Figure 36) or sensor group (Figure 37) from within the view by using their mouse and clicking on the sensor.

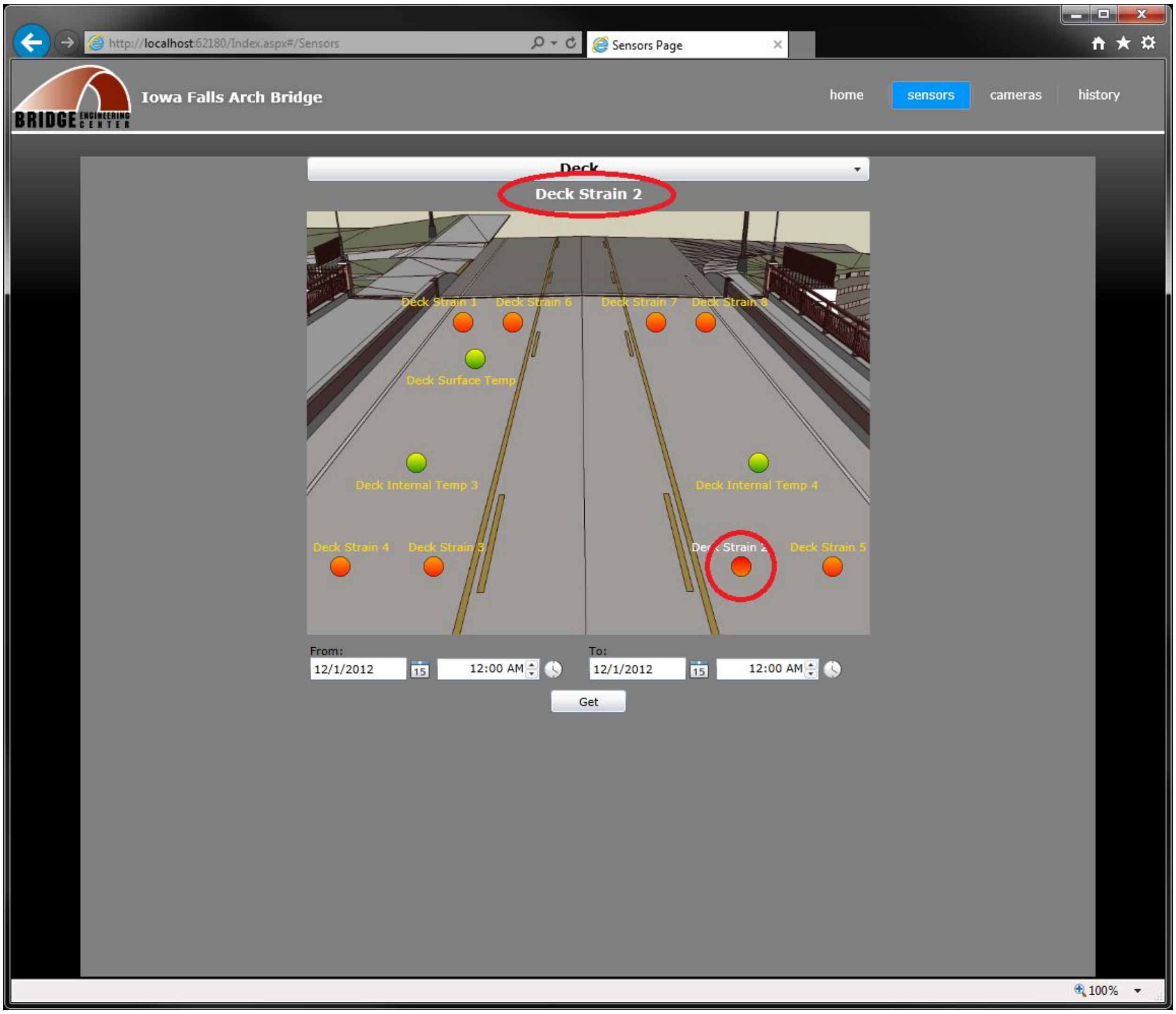


Figure 36. Iowa Falls Bridge data website single sensor selection

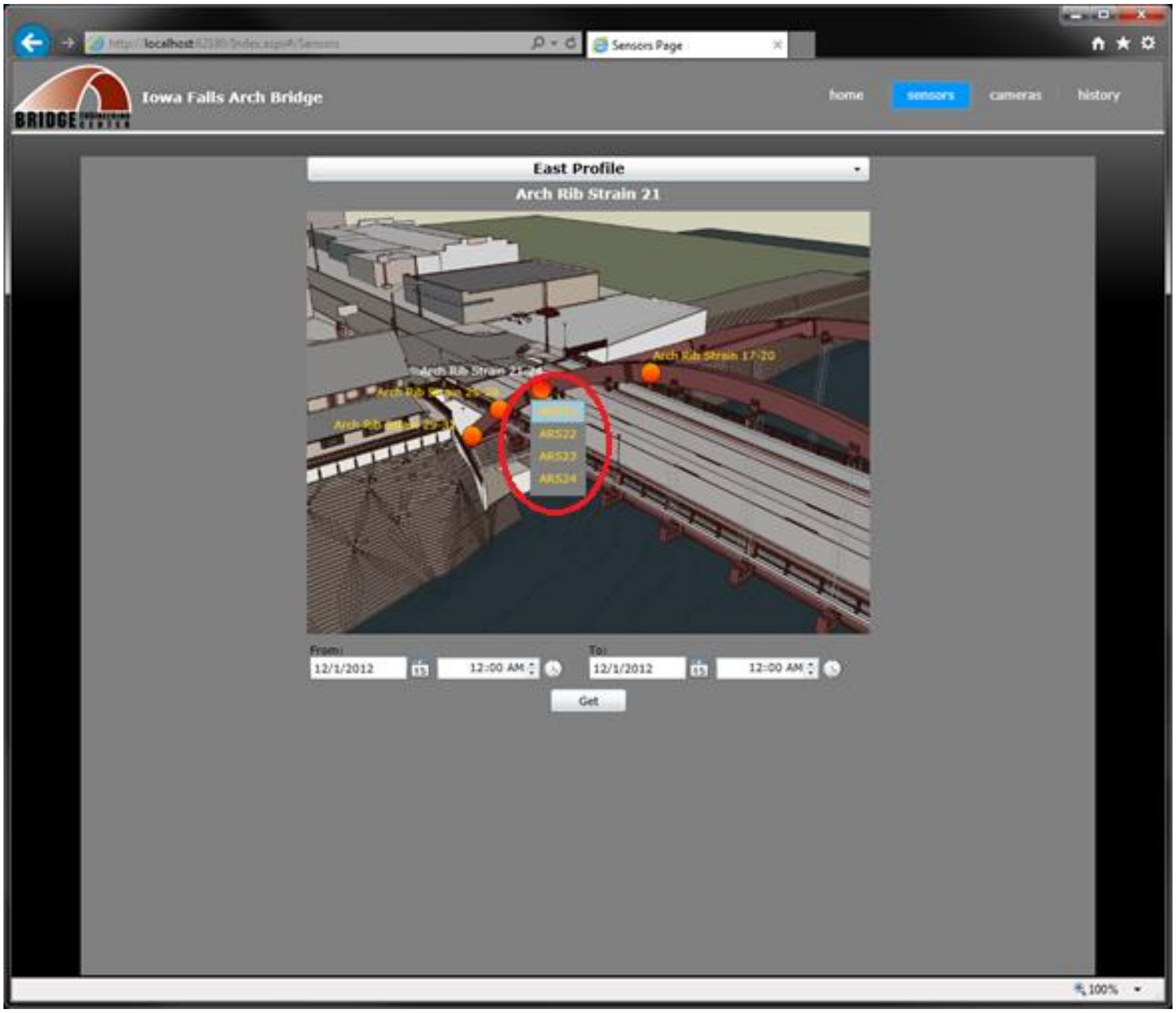


Figure 37. Iowa Falls Bridge data website group sensor selection

After an individual sensor is selected, the timespan selection options are made available to select a period of interest (Figure 38), and the user is allowed to click on the Get button.

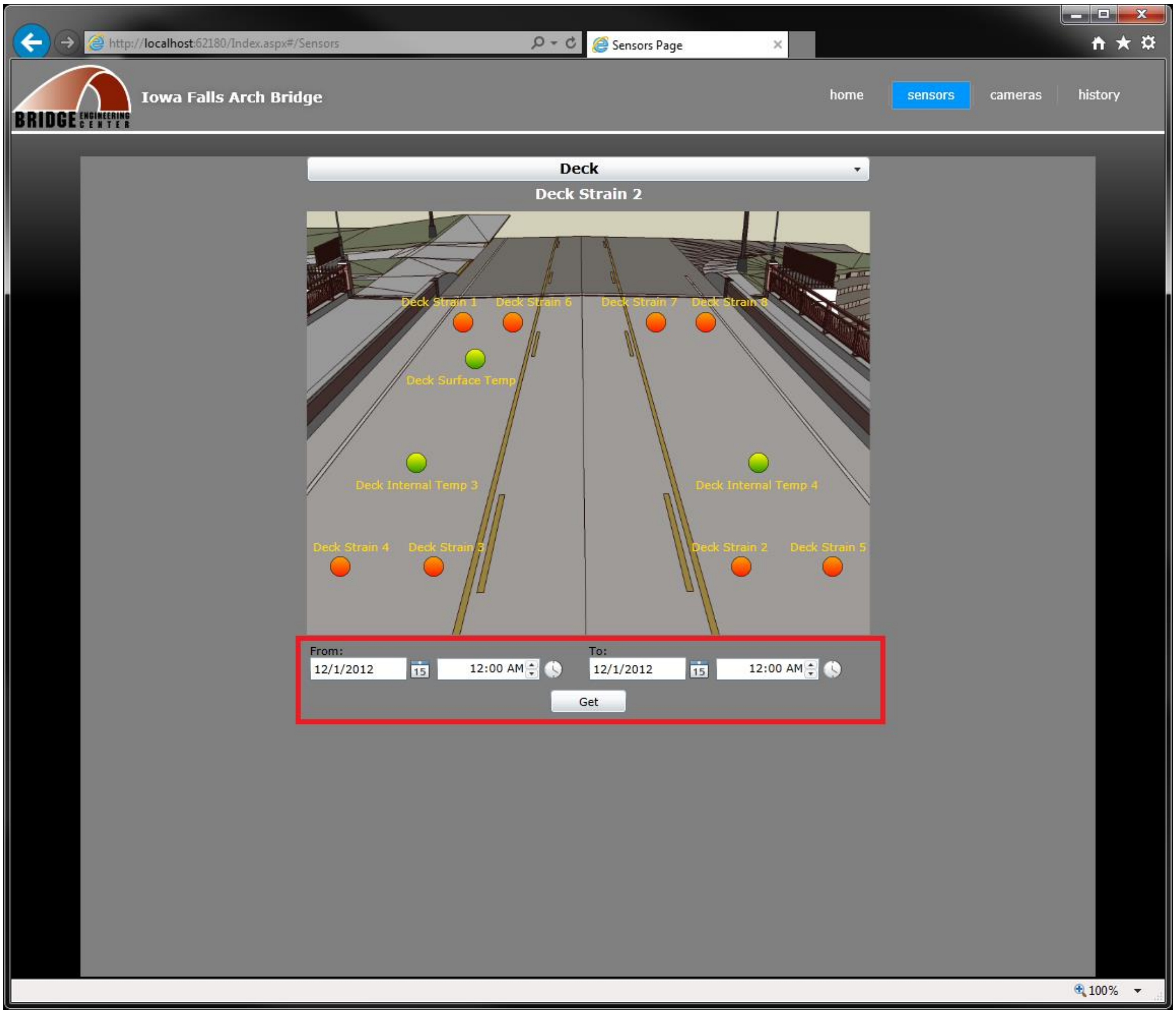


Figure 38. Iowa Falls Bridge data website timespan selection

As soon as the data are retrieved from the database, the information is displayed in a chart below the selection area, as seen in Figure 39.

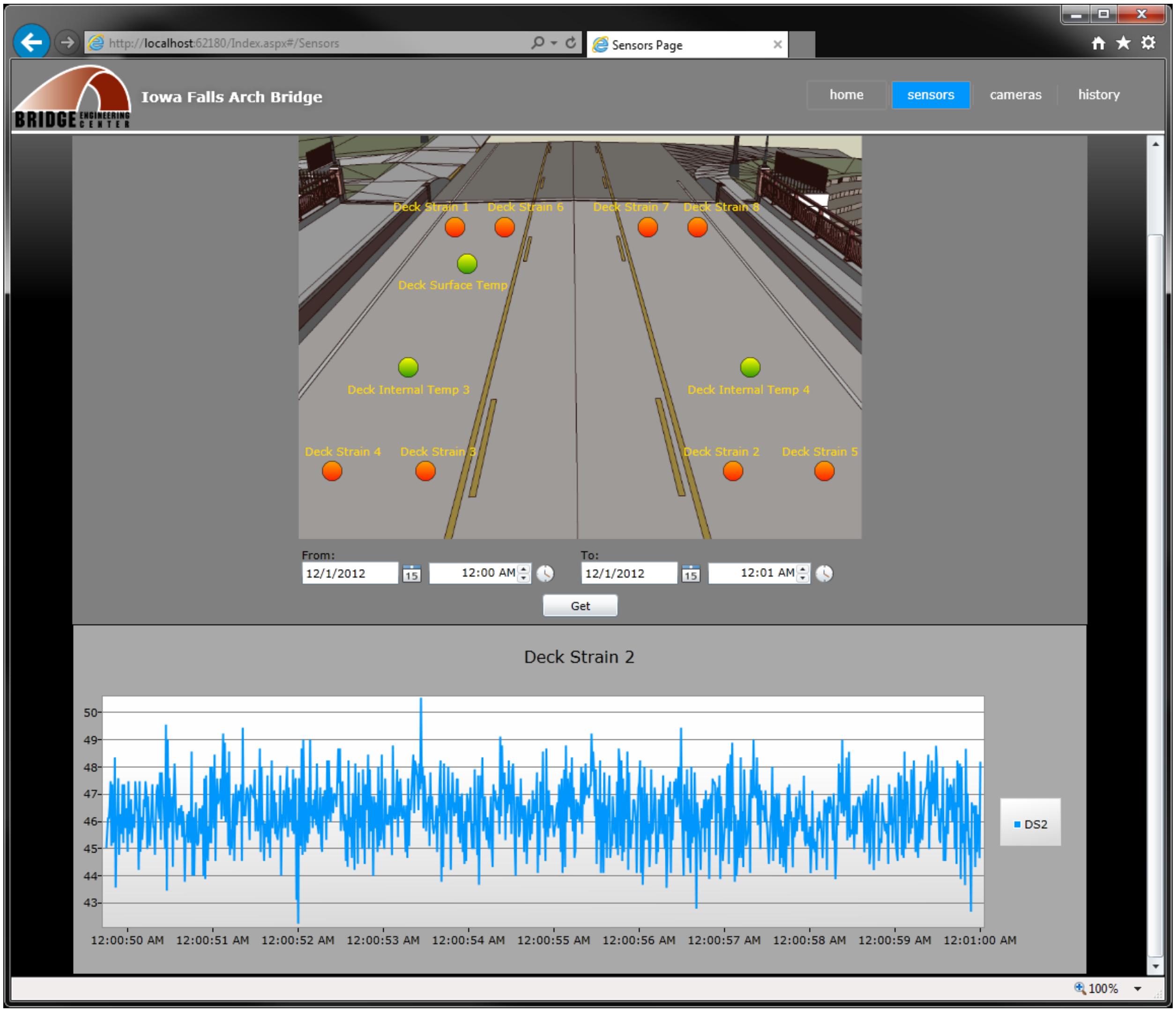


Figure 39. Iowa Falls Bridge data website sensor timespan results

Cameras Page

The Cameras segment of the website presents links to cameras positioned around and within the bridge (Figure 40).

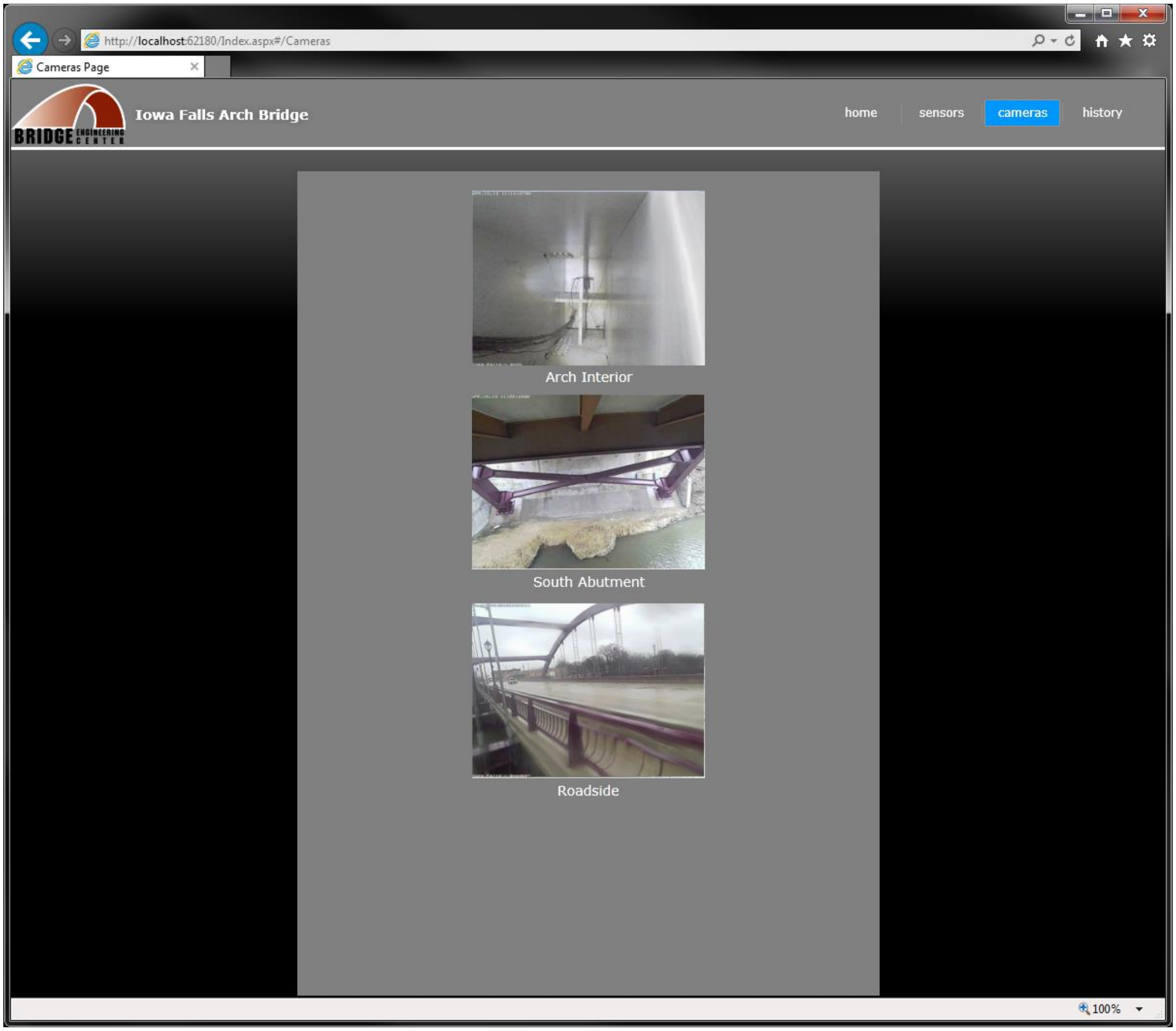


Figure 40. Iowa Falls Bridge data website camera selection

For the Iowa Falls Bridge, the South Abutment camera gives a live view of the southern abutment underneath the bridge, which also houses the equipment cabinets that store the data collection system onsite and the live traffic flow is viewed using the Roadside camera display located near the southbound lane. A third camera display, Arch Interior, is contained within the southwest base of the arch and is focused on the area of potential moisture build-up near the bottom of the arch.

History Page

Although the Sensor page provides a visual of data, it may not provide the best representation of large timespans and multiple sensors. The History page provides the ability to download larger datasets of multiple sensors from the website that the user is able to view in tabular software. Note that these tabular data are easily loaded into software such as Microsoft Excel for more advanced analysis and viewing For this particular bridge, data downloads are broken down into live load and time-dependent datasets, depending on which datalogger the data came from (CR9000X or CR1000, respectively).

As shown in Figure 41, the dataset type is selected from a drop-down list.

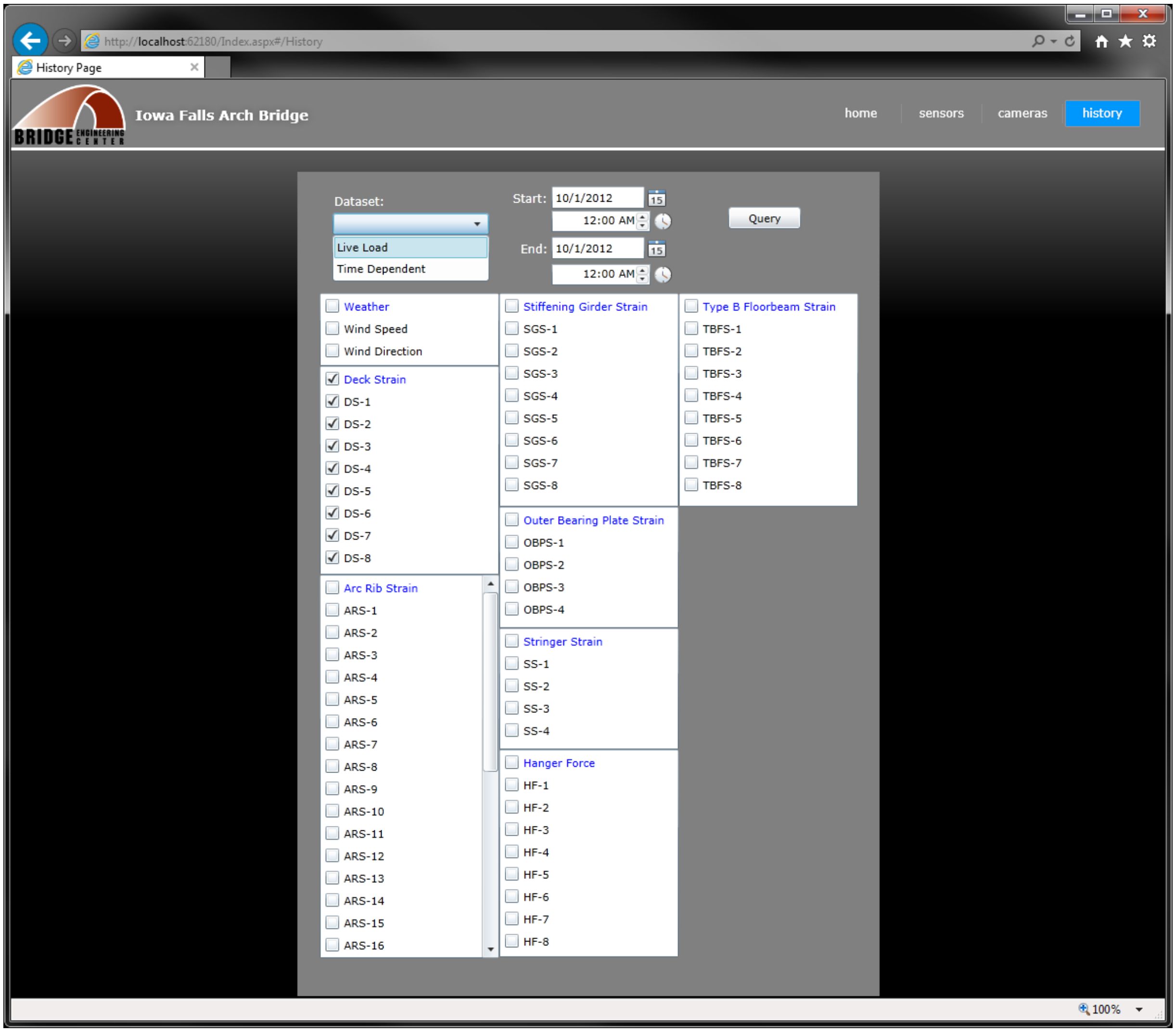


Figure 41. Iowa Falls Bridge data website historical live load selection

In this case, the Live Load dataset is shown along with the particular sensors available to download from the dataset. Given the sensor choices, a user can check the sensors of interest, select a starting and ending date/time, and click the Query button to retrieve the selected data in a comma-delimited text file.

The Time Dependent dataset selection shows the sensors available to download from time-driven data, as shown in Figure 42. The sensors are selected and queried in the same manner as the Live Load dataset described above.

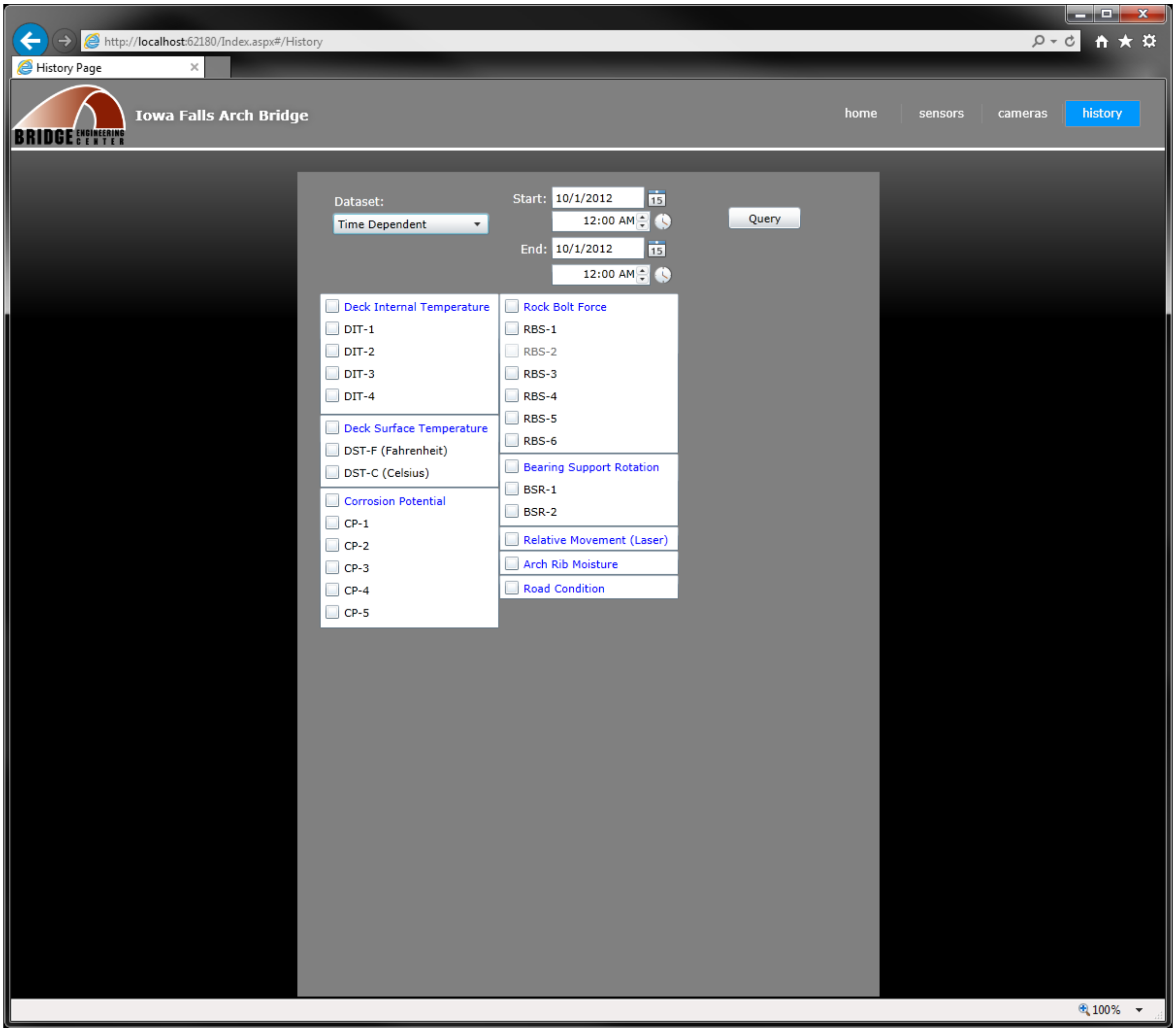


Figure 42. Iowa Falls Bridge data website historical time dependent selection

BRIDGE ENGINEERING CENTER ASSESSMENT SYSTEM (BECAS)

The refinement of damage detection processes has resulted in the continued development of the Bridge Engineering Center Assessment Software (BECAS) to assist in automated data acquisition, strain range data reduction, and statistical evaluation (Phares et al. 2013).

The basic concepts of the damage detection methodologies explained in the previous citation remain intact. Data are read, cleansed of abnormalities, zeroed, and filtered, and then truck event detection occurs. Additions to BECAS processing were created to enhance the capabilities of data consumption and output generation. A data merge process was designed to allow for multiple logger outputs to be combined into one homogeneous data file through timestamp synchronization. Further enhancements to the truck identification and strain range calculations allow for event lane designation and temperature classification.

As seen in Figure 43, after an event has been identified and verified, it is classified by lane of travel and further grouped into bins based on user-defined temperature ranges. These data bins are then individually fed through existing damage detection methodologies.

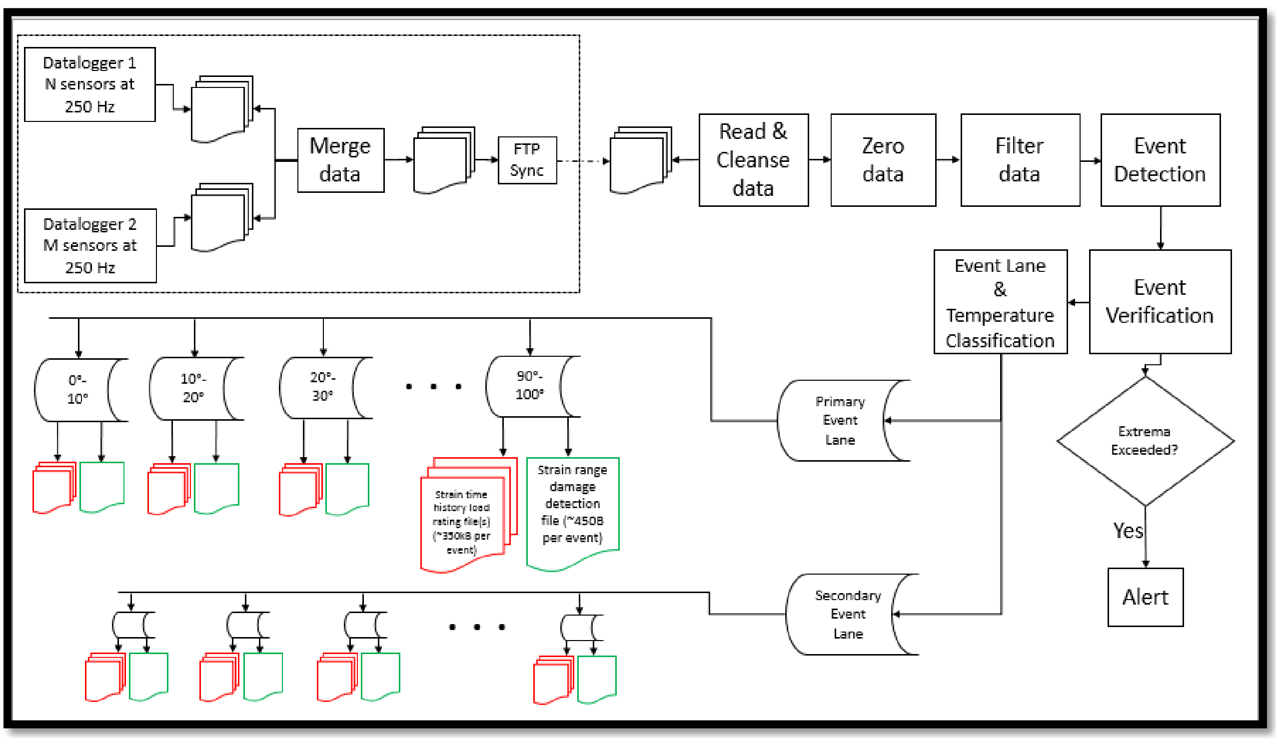
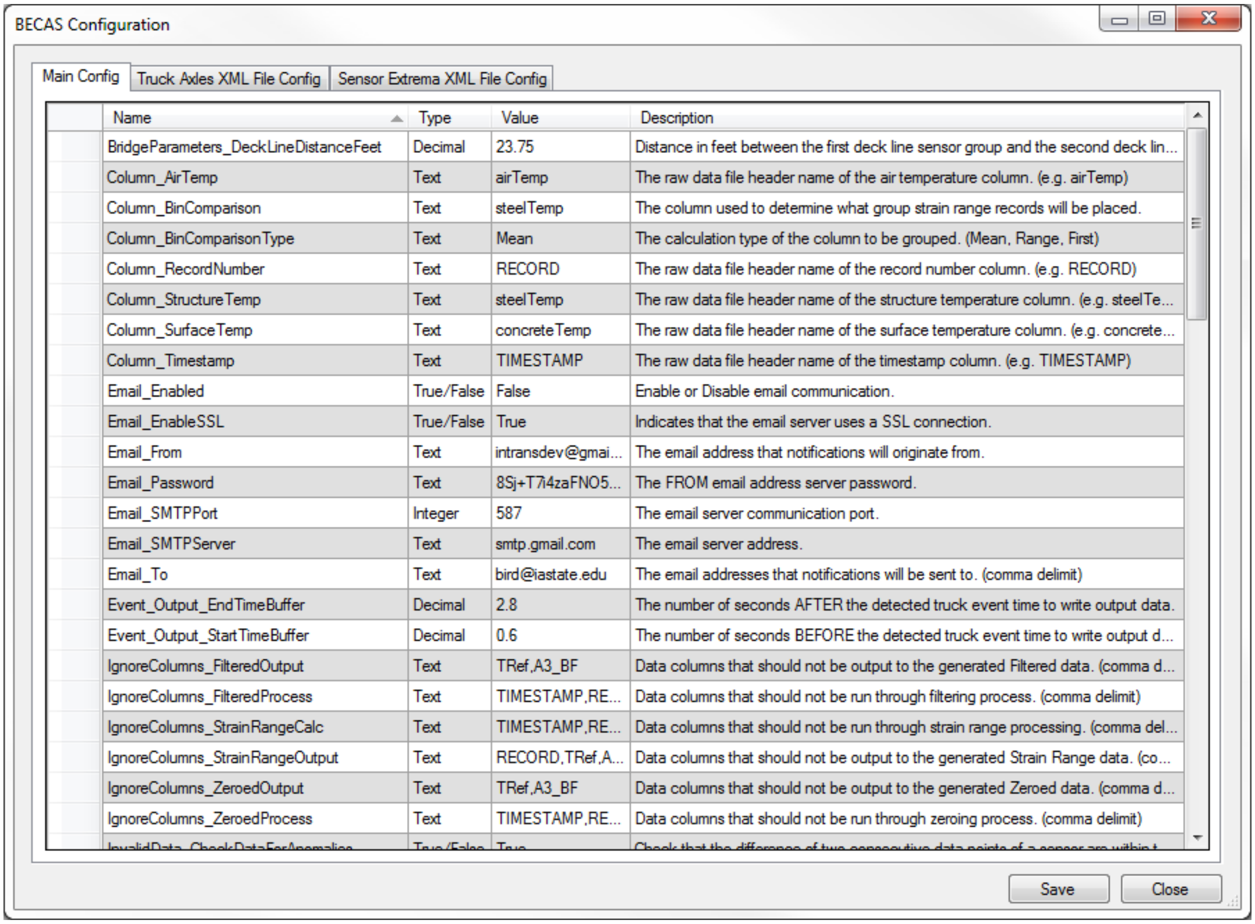


Figure 43. BECAS truck event detection process flow

BECAS has been extended to allow users to define parameters through various configuration interfaces. The main configuration interface, shown in Figure 44, allows various setting options for truck parameters, event thresholds, bridge sensor parameters, raw data file constraints, and output data choices.



Name	Type	Value	Description
BridgeParameters_DeckLineDistanceFeet	Decimal	23.75	Distance in feet between the first deck line sensor group and the second deck lin...
Column_AirTemp	Text	airTemp	The raw data file header name of the air temperature column. (e.g. airTemp)
Column_BinComparison	Text	steelTemp	The column used to determine what group strain range records will be placed.
Column_BinComparisonType	Text	Mean	The calculation type of the column to be grouped. (Mean, Range, First)
Column_RecordNumber	Text	RECORD	The raw data file header name of the record number column. (e.g. RECORD)
Column_StructureTemp	Text	steelTemp	The raw data file header name of the structure temperature column. (e.g. steelTe...
Column_SurfaceTemp	Text	concreteTemp	The raw data file header name of the surface temperature column. (e.g. concrete...
Column_Timestamp	Text	TIMESTAMP	The raw data file header name of the timestamp column. (e.g. TIMESTAMP)
Email_Enabled	True/False	False	Enable or Disable email communication.
Email_EnableSSL	True/False	True	Indicates that the email server uses a SSL connection.
Email_From	Text	intransdev@gmai...	The email address that notifications will originate from.
Email_Password	Text	8Sj+T7i4zaFNO5...	The FROM email address server password.
Email_SMTPPort	Integer	587	The email server communication port.
Email_SMTPServer	Text	smtp.gmail.com	The email server address.
Email_To	Text	bird@iastate.edu	The email addresses that notifications will be sent to. (comma delimit)
Event_Output_EndTimeBuffer	Decimal	2.8	The number of seconds AFTER the detected truck event time to write output data.
Event_Output_StartTimeBuffer	Decimal	0.6	The number of seconds BEFORE the detected truck event time to write output d...
IgnoreColumns_FilteredOutput	Text	TRef,A3_BF	Data columns that should not be output to the generated Filtered data. (comma d...
IgnoreColumns_FilteredProcess	Text	TIMESTAMP,RE...	Data columns that should not be run through filtering process. (comma delimit)
IgnoreColumns_StrainRangeCalc	Text	TIMESTAMP,RE...	Data columns that should not be run through strain range processing. (comma del...
IgnoreColumns_StrainRangeOutput	Text	RECORD,TRef,A...	Data columns that should not be output to the generated Strain Range data. (co...
IgnoreColumns_ZeroedOutput	Text	TRef,A3_BF	Data columns that should not be output to the generated Zeroed data. (comma d...
IgnoreColumns_ZeroedProcess	Text	TIMESTAMP,RE...	Data columns that should not be run through zeroing process. (comma delimit)

Figure 44. BECAS main truck detection configuration interface

A complete list of current configurable items and definitions is included in Appendix B.

The truck axle configuration, shown in Figure 45, allows for the identification, grouping, and strain thresholds of sensor placements of the bridge being used to find events via BECAS.

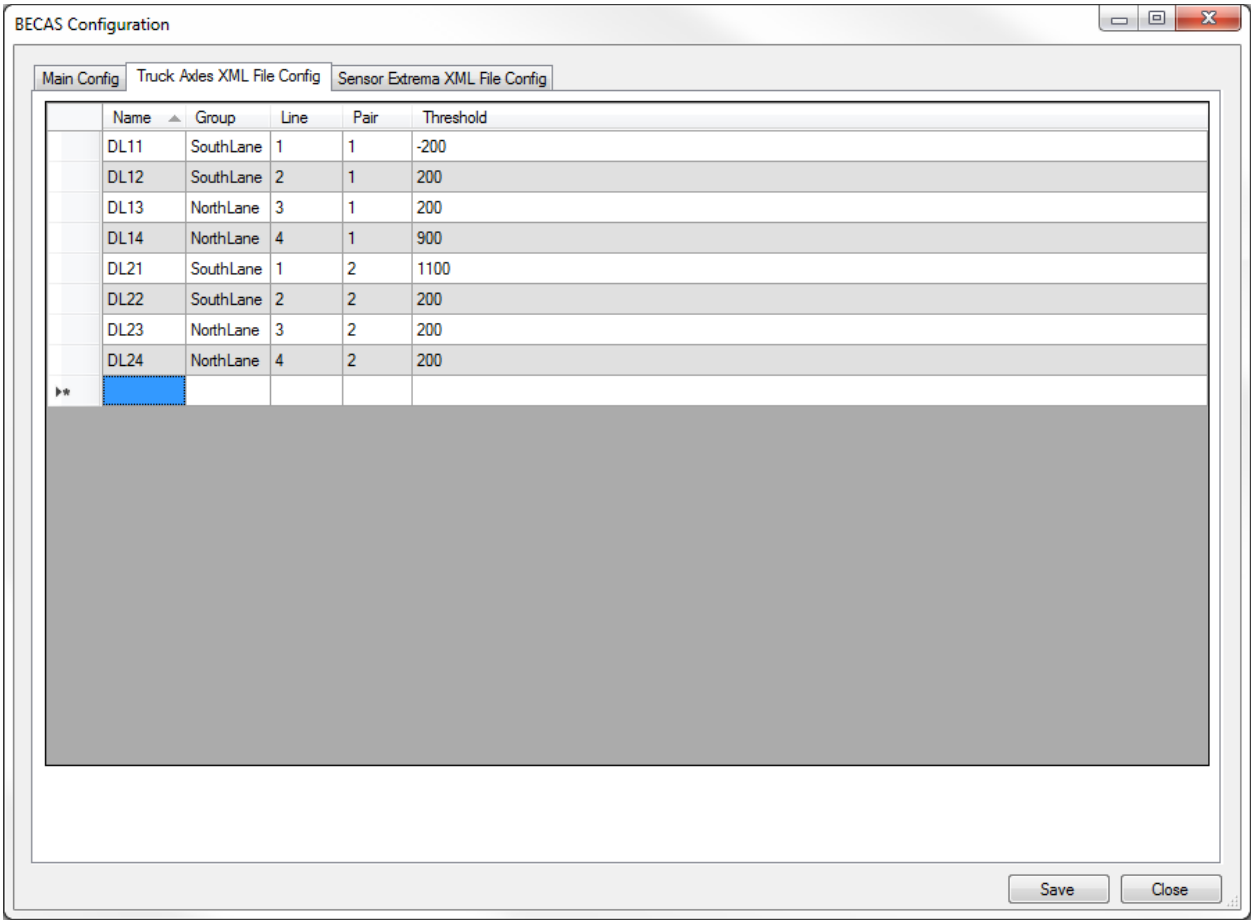
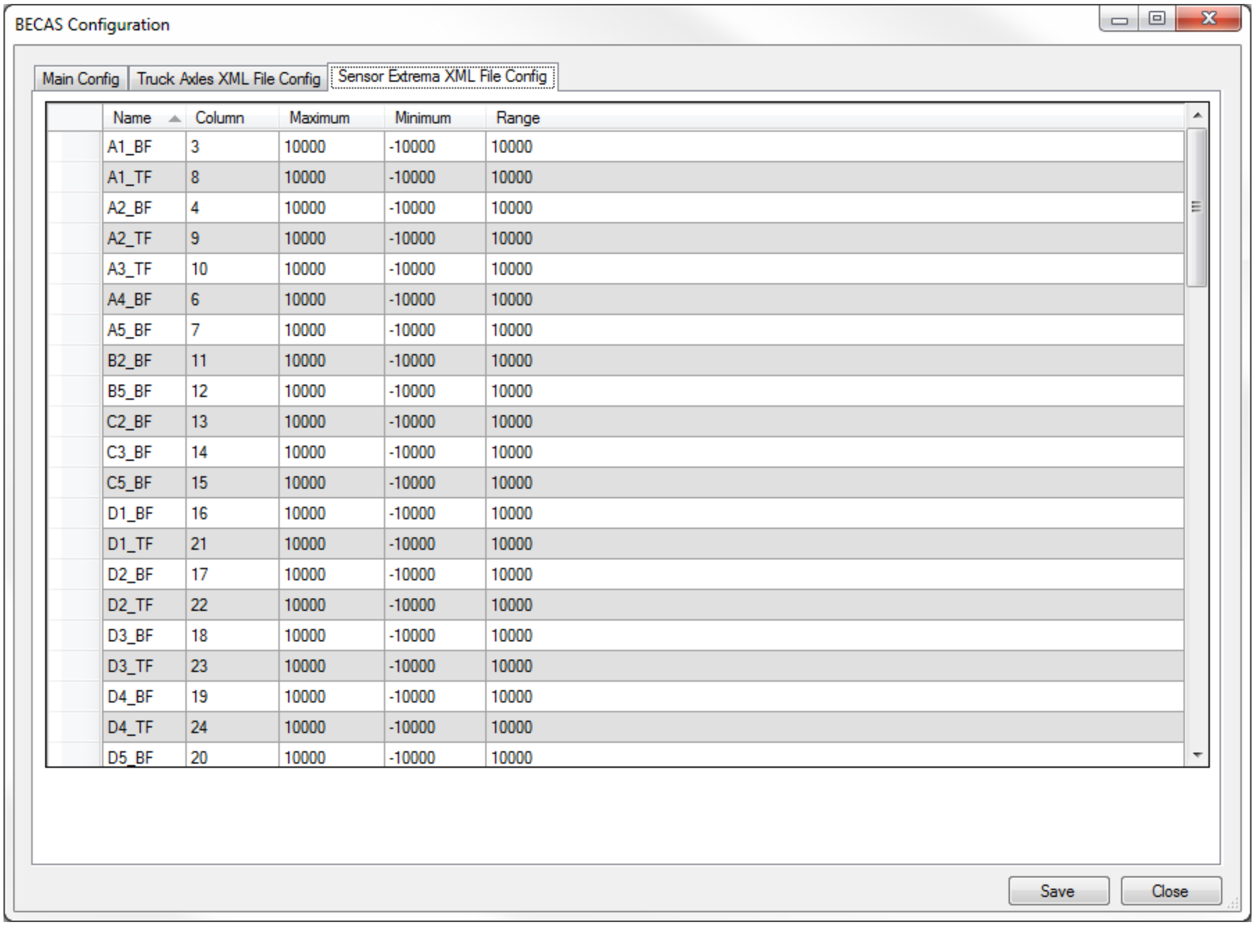


Figure 45. BECAS truck axle configuration interface

The sensor extrema configuration, shown in Figure 46, provides an interface to classify the minimum, maximum, and range extrema values of each individual sensor's strain values.



Name	Column	Maximum	Minimum	Range
A1_BF	3	10000	-10000	10000
A1_TF	8	10000	-10000	10000
A2_BF	4	10000	-10000	10000
A2_TF	9	10000	-10000	10000
A3_TF	10	10000	-10000	10000
A4_BF	6	10000	-10000	10000
A5_BF	7	10000	-10000	10000
B2_BF	11	10000	-10000	10000
B5_BF	12	10000	-10000	10000
C2_BF	13	10000	-10000	10000
C3_BF	14	10000	-10000	10000
C5_BF	15	10000	-10000	10000
D1_BF	16	10000	-10000	10000
D1_TF	21	10000	-10000	10000
D2_BF	17	10000	-10000	10000
D2_TF	22	10000	-10000	10000
D3_BF	18	10000	-10000	10000
D3_TF	23	10000	-10000	10000
D4_BF	19	10000	-10000	10000
D4_TF	24	10000	-10000	10000
D5_BF	20	10000	-10000	10000

Figure 46. BECAS sensor extrema configuration interface

CONCLUDING REMARKS

For this project, the development and finalization of general hardware and software components for a bridge SHM system were investigated and completed. This development and finalization was framed around a demonstration installation on the Iowa Falls Arch Bridge. The goal of this work was to move SHM one step closer to being ready for mainstream use by the Iowa DOT Office of Bridges and Structures. The hardware system focused on using off-the-shelf sensors that could be read in either "fast" or "slow" modes depending upon the desired monitoring metric. As hoped, the installed system operated with very few problems.

In terms of communications—in part due to the anticipated installation on the I-74 bridge—a hardline DSL internet connection and grid power were used. During operation, this system would transmit data to a central server location where the data would be processed and then archived for future retrieval and use via the described database, visualization, and retrieval tools.

Through this demonstration project, it has been observed that the biggest hurdle to widespread use of a system like this is storage of historical data. With data being collected at relatively high rates, a very large volume of data is collected on a daily basis. Although from an operational perspective this is not an insurmountable problem, there are difficulties associated with physically storing this much data. As a result, for future installations it is recommended that the DOT develop a policy regarding how long historical data should be retained.

The project team recommends that the Iowa Falls Bridge SHM system be integrated into normal operations on a graduated trial basis to prepare for the upcoming I-74 bridge construction and SHM system installation. The motivation for this would be to identify areas for practical improvement and to demonstrate the value added by such systems. To accomplish this integration, the following steps are recommended:

Step 1 – Purchase and configure a high-capacity webserver running Internet Information Server. Sufficient hard drive space should be integrated into the webserver to allow for retention of at least 12 months of data.

Step 2 – Develop final enterprise level database configuration using either SQL Server or Oracle in coordination with Iowa DOT Information Technology staff. Additionally, the processes for file transfer and data import should be refined and finalized based on the database configuration.

Step 3 – Finalize vehicle detection parameters including the establishment of strain rate thresholds. The truck detection process should be field verified.

Step 4 – Establish engineering-based alarming thresholds in coordination with the Iowa DOT Rating Engineer. For the six months following establishment of these limits, alarm notifications should only be sent to the research team to assess appropriateness and false alarm rates.

Step 5 – Establish statistics-based alarm thresholds in coordination with the Iowa DOT Rating Engineer. For the six months following establishment of these limits, alarm notifications should only be sent to the research team to assess appropriateness and false alarm rates.

Step 6 – Add Iowa DOT Rating Engineer to alarm notification recipients and revise alarm thresholds as needed.

Step 7 – Finalize integration of weather information into Iowa DOT Operations.

Step 8 – Establish thresholds for infrared security camera detections. For the six months following establishment of these limits, alarm notifications should only be sent to the research team to assess appropriateness and false alarm rates.

Step 9 – Add City of Iowa Falls Police Chief to alarm notification recipients.

Step 10 – Assist the Iowa DOT Assistant Maintenance Engineer on review of collected data for the purpose of enhancing biennial inspection process and results.

Step 11 – Conduct mock bridge “attacks” including evaluation of the system to detect overload and security violations.

While the recommended steps are listed as individual events, they are not necessarily sequential in nature as many of the activities do not depend upon other steps. It is anticipated that the process—including system testing and verification—could be completed in 18 months or less.

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Chakraborty, S. and DeWolf, J. T. (2006). Development and implementation of a continuous strain monitoring system on a multi-girder composite steel bridge. *ASCE Journal of Bridge Engineering*, 11(6):753-762.

Farhey, D. N., (2006). Instrumentation System Performance for Long-term Bridge Health Monitoring. *Structural Health Monitoring.* 5:143-153.

Lu, P. (2008). A statistical based damage detection approach for highway bridge structural health monitoring. Graduate Theses and Dissertations. Iowa State University. Ames, Iowa.

Phares, B., Greimann, L., and Choi, H. (2013). *Integration of Bridge Damage Detection Concepts and Components, Volume I: Strain-Based Damage Detection*. Bridge Engineering Center, Iowa State University. Ames, Iowa.

Phares, B. M., Wipf, T. J., Lu, P., Greimann, L., and Pohlkamp, M. (2011). *An Experimental Validation of a Statistical-Based Damage-Detection Approach.* Bridge Engineering Center, Iowa State University. Ames, Iowa.

Wipf, T. J., B. M. Phares, and J. D. Doornink. (2007). *Evaluation of Steel Bridges (Volume I): Monitoring the Structural Condition of Fracture-Critical Bridges Using Fiber Optic Technology.* Bridge Engineering Center, Iowa State University. Ames, Iowa.

APPENDIX A. WEBSITE BRIDGE PROFILE VIEWS OF SENSOR PLACEMENTS

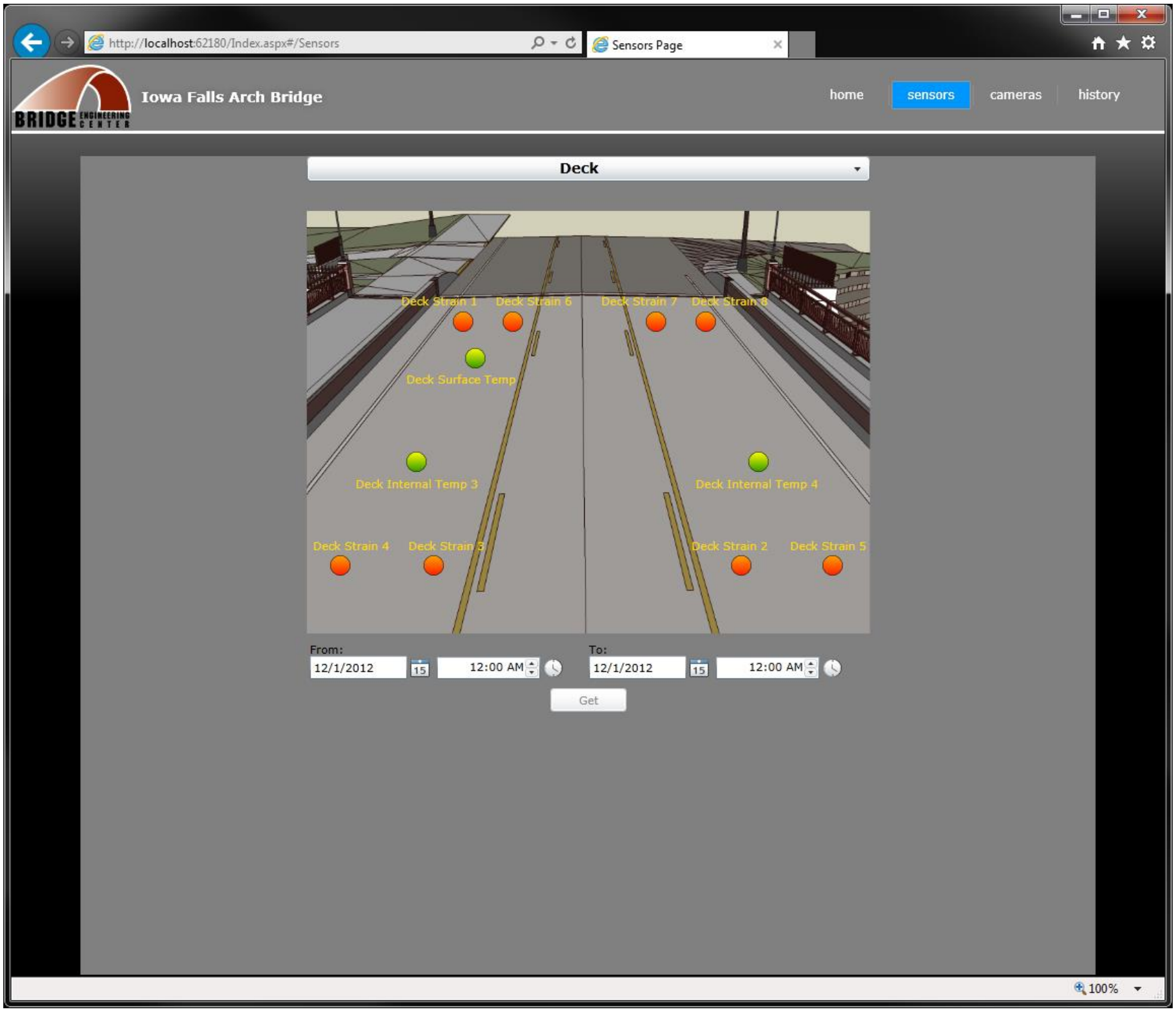

Figure 47. Iowa Falls Bridge data website view selection (Deck)

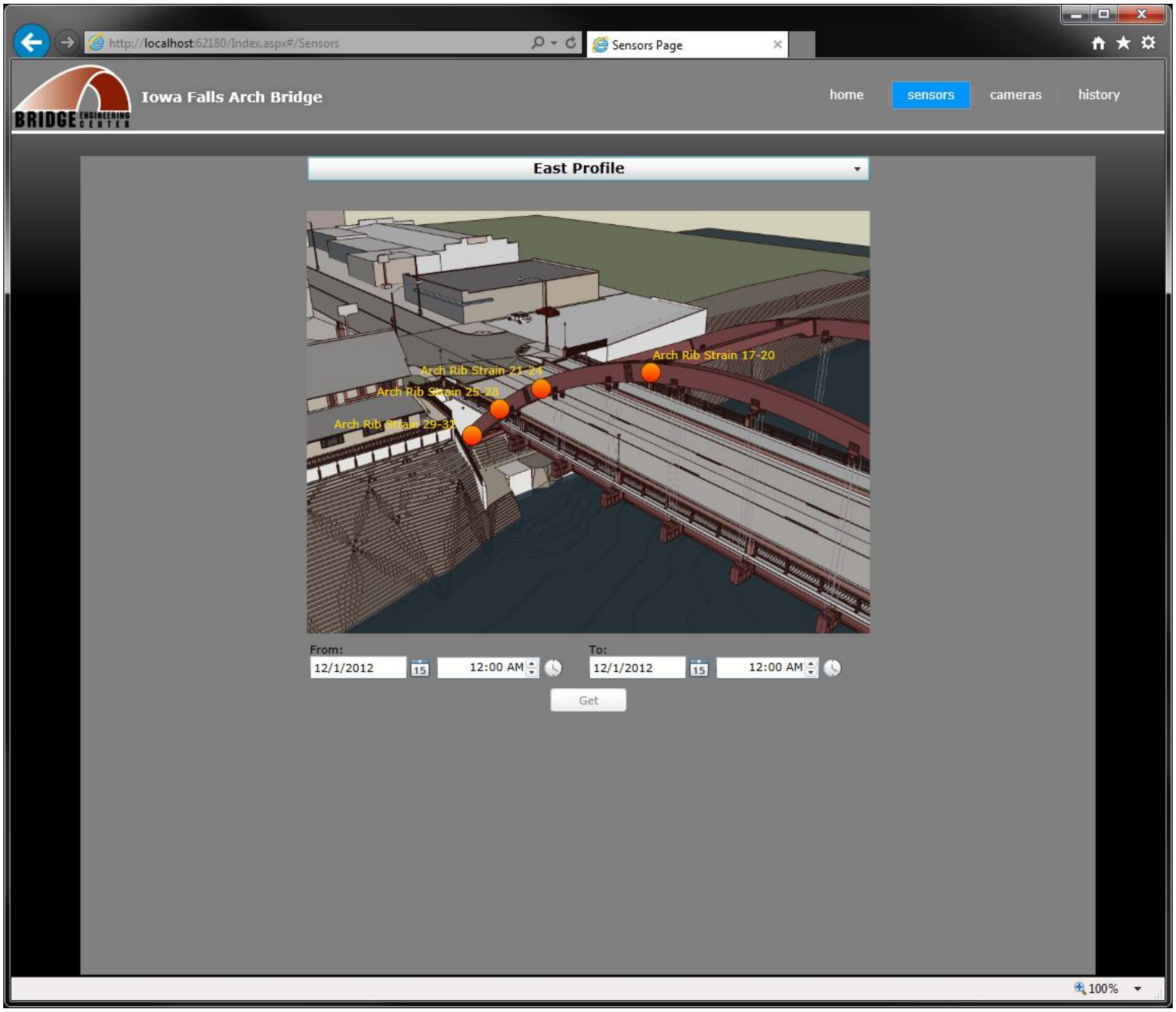

Figure 48. Iowa Falls Bridge data website view selection (East Profile)

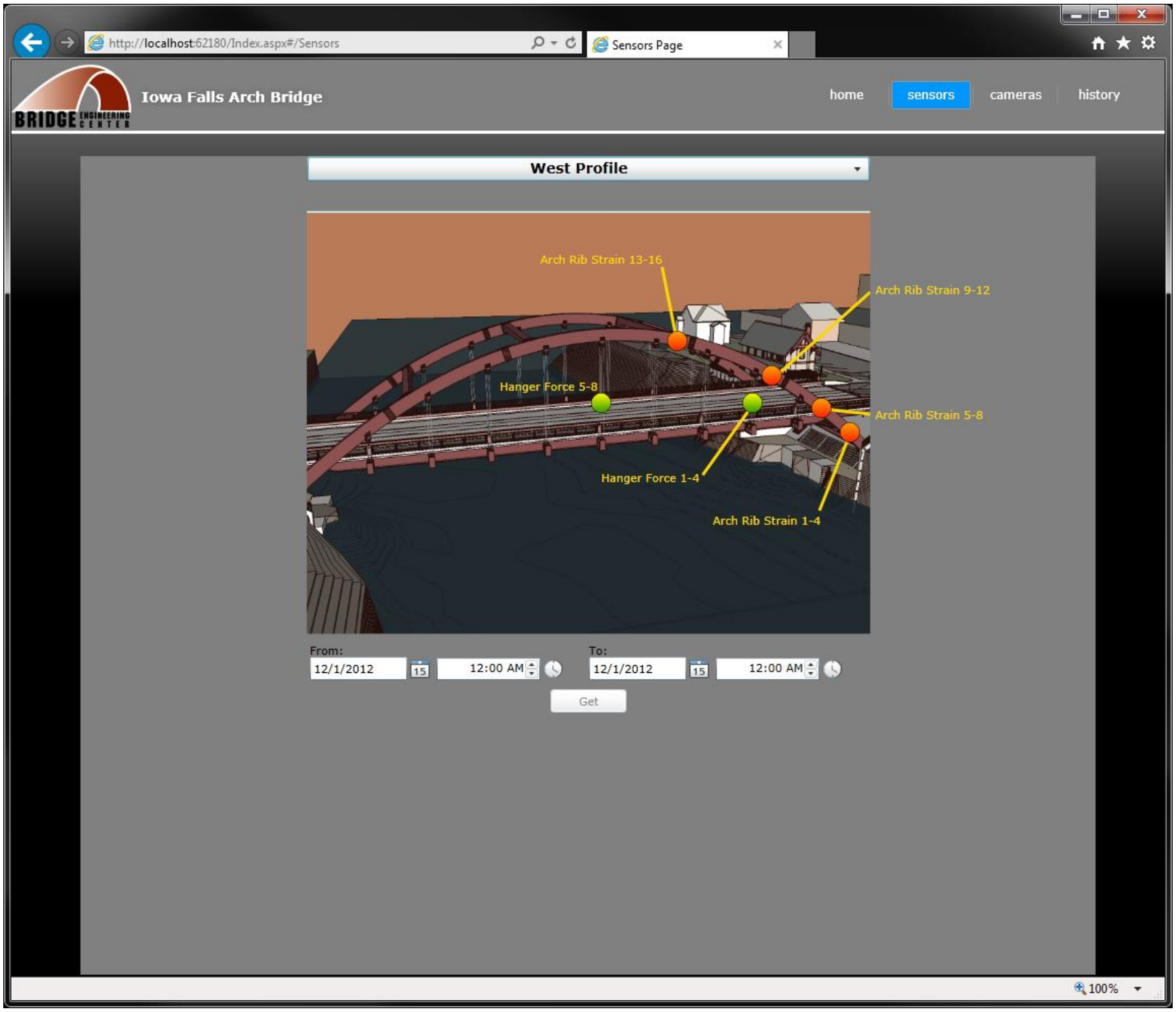

Figure 49. Iowa Falls Bridge data website view selection (West Profile)

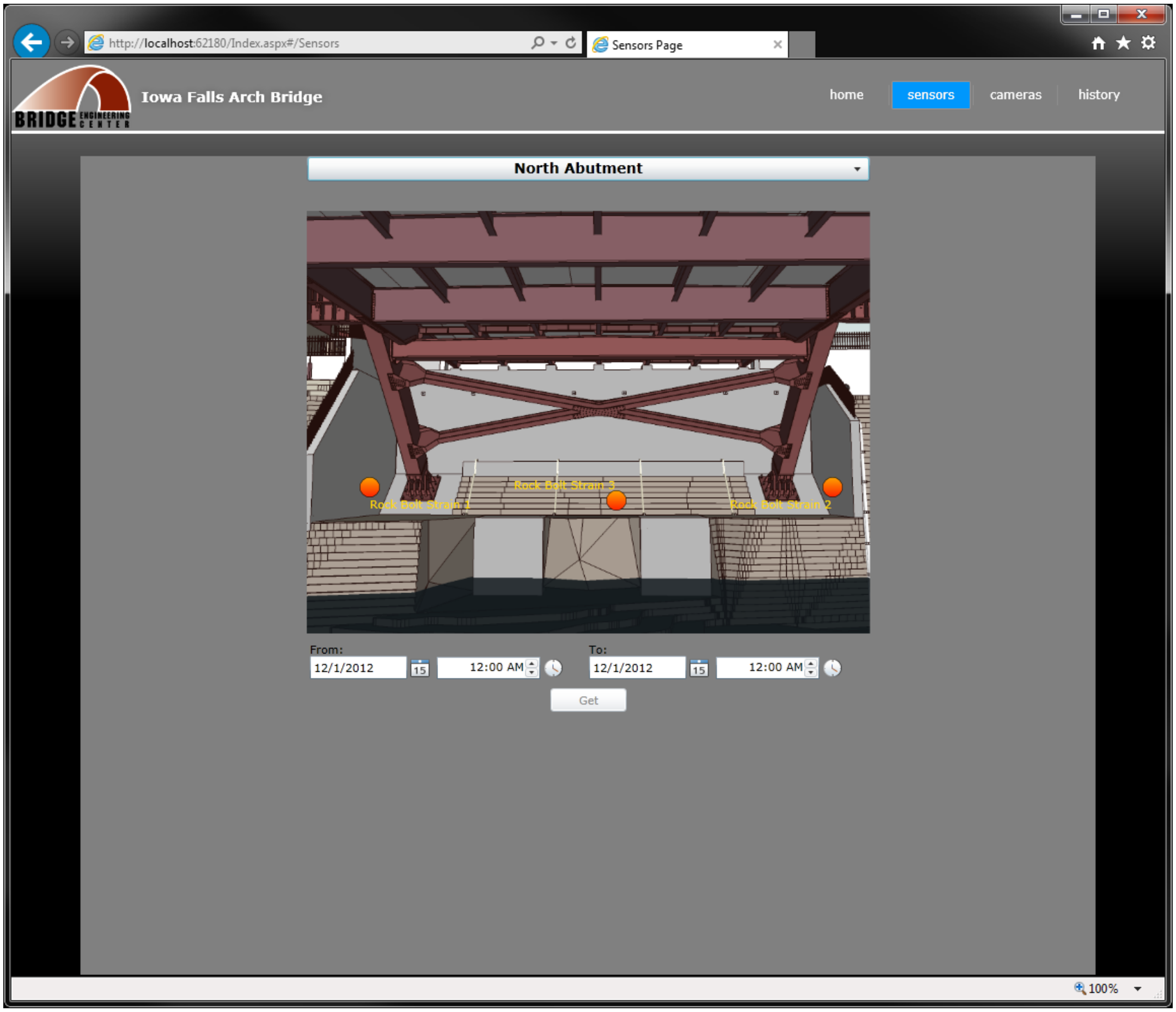

Figure 50. Iowa Falls Bridge data website view selection (North Abutment)

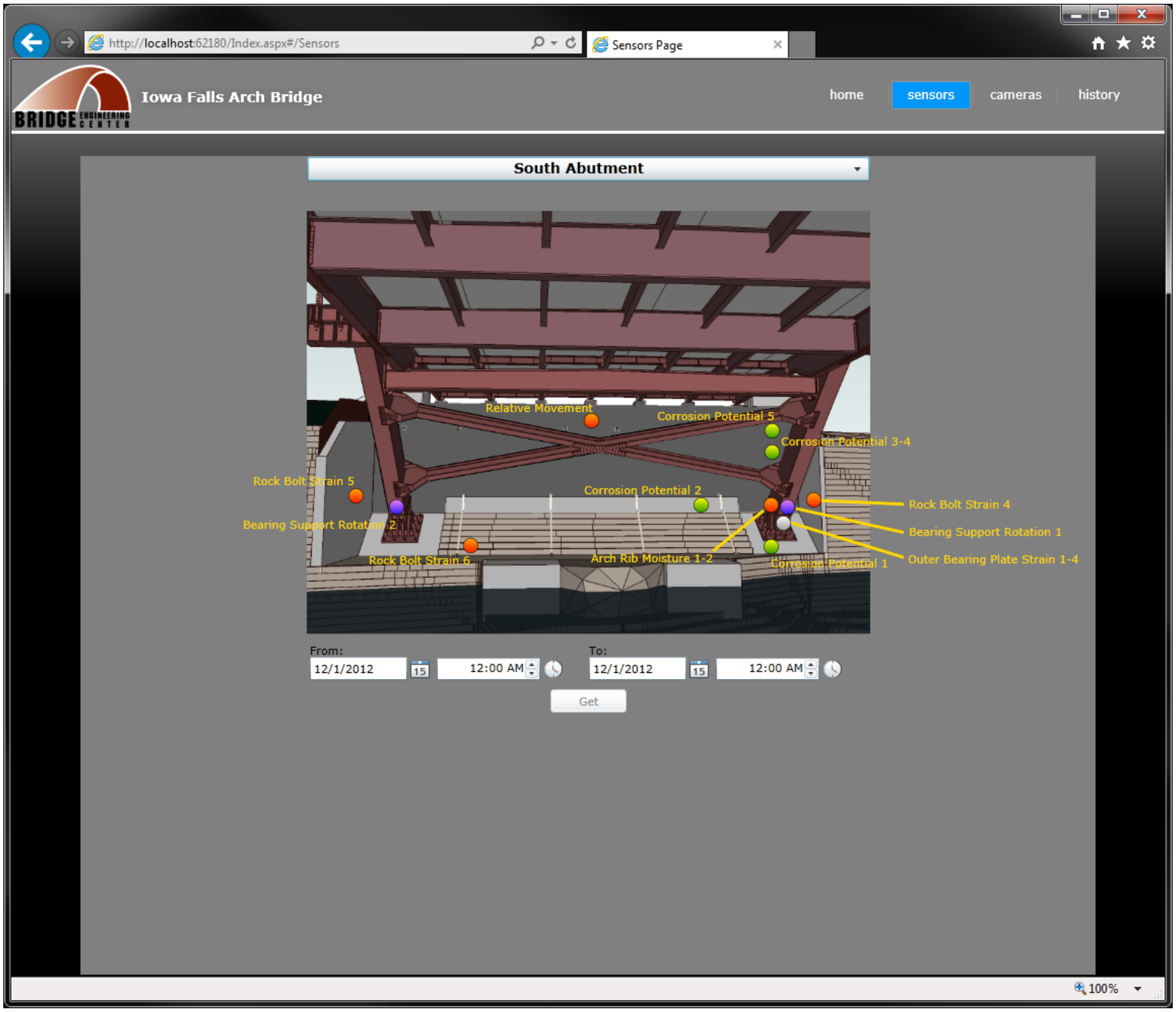

Figure 51. Iowa Falls Bridge data website view selection (South Abutment)

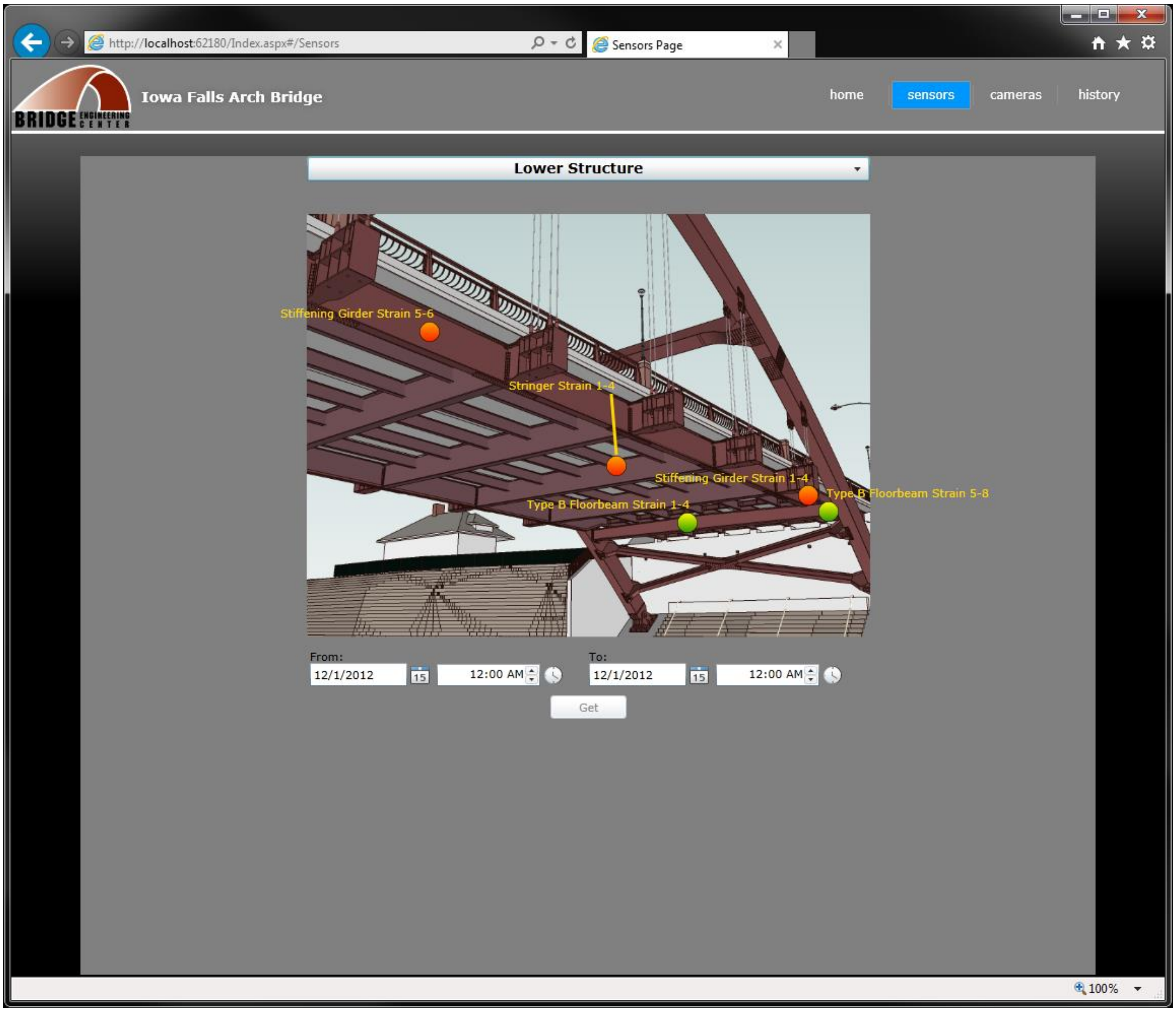

Figure 52. Iowa Falls Bridge data website view selection (Lower Structure)

APPENDIX B. BECAS MAIN CONFIGURATION PARAMETERS AND DEFINITIONS

- BridgeParameters_DeckLineDistanceFeet
  - Distance in feet between the first deck line sensor group and the second deck line sensor group.
- Column_AirTemp
  - The raw data file header name of the air temperature column. (e.g., airTemp)
- Column_BinComparison
  - The column used to determine what group strain range records will be placed.
- Column_BinComparisonType
  - The calculation type of the column to be grouped. (Mean, Range, First)
- Column_RecordNumber
  - The raw data file header name of the record number column. (e.g., RECORD)
- Column_StructureTemp
  - The raw data file header name of the structure temperature column. (e.g., steelTemp)
- Column_SurfaceTemp
  - The raw data file header name of the surface temperature column. (e.g., concreteTemp)
- Column_Timestamp
  - The raw data file header name of the timestamp column. (e.g., TIMESTAMP)
- Email_Enabled
  - Enable or Disable email communication.
- Email_From
  - The email address that notifications will originate from.
- Email_To
  - The email addresses that notifications will be sent to. (comma delimit)
- Email_Password
  - The FROM email address server password.
- Email_SMTPServer
  - The email server address.
- Email_SMTPPort
  - The email server communication port.
- Email_EnableSSL
  - Indicates that the email server uses a SSL connection.
- Event_Output_EndTimeBuffer
  - The number of seconds AFTER the detected truck event time to write output data.
- Event_Output_StartTimeBuffer
  - The number of seconds BEFORE the detected truck event time to write output data.
- IgnoreColumns_FilteredOutput
  - Data columns that should not be output to the generated Filtered data. (comma delimit)
- IgnoreColumns_FilteredProcess
  - Data columns that should not be run through filtering process. (comma delimit)
- IgnoreColumns_StrainRangeCalc
  - Data columns that should not be run through strain range processing. (comma delimit)

- IgnoreColumns_StrainRangeOutput
  - Data columns that should not be output to the generated Strain Range data. (comma delimit)
- IgnoreColumns_ZeroedOutput
  - Data columns that should not be output to the generated Zeroed data. (comma delimit)
- IgnoreColumns_ZeroedProcess
  - Data columns that should not be run through zeroing process. (comma delimit)
- InvalidData_CheckDataForAnomalies
  - Check that the difference of two consecutive data points of a sensor are within the range specified in Extrema.xml, if not, change second value to match first.
- InvalidData_CheckRecordSequentiality
  - Check that record numbers are arranged in a sequence with a tolerance indicated by InvalidData_SequentialDifferenceTolerance.
- InvalidData_Convert
  - The value to convert invalid data to. See InvalidData_Values.
- InvalidData_Correction_Enabled
  - Search data for values equal to those specified by InvalidData_Values.
- InvalidData_SequentialDifferenceTolerance
  - The maximum difference between a sequence of two record numbers.
- InvalidData_Values
  - Raw data values that indicate invalid data. (comma delimit)
- Log_Enabled
  - Enable or Disable the process logging.
- Output_CombinedStrainRangeData_Enabled
  - Enable or Disable the output of strain range data into a single combined output file.
- Output_DataByBins_Enabled
  - Enable or Disable the output of processed data by groups.
- Output_FilteredData_Enabled
  - Enable or Disable the output of the filtered processed data.
- Output_LoadRating_Enabled
  - Enable or Disable the output of load rating information to the Filtered data output.
- Output_StrainRange_Filename
  - The name of the file to output strain range data.
- Output_StrainRange_NumRecordsPerFile
  - The number of lines to output to a strain range data file before moving it to the path indicated by ProcessData_TransferFilePath' and generating a new one. (Minimum 200)
- Output_StrainRangeData_Enabled
  - Enable or Disable the output of the strain range processed data.
- Output_ZeroedData_Enabled
  - Enable or Disable the output of the zeroed processed data.
- PrimaryLane_PrimaryDeckSensor
  - Deck sensor of the primary lane to detect truck axles.
- PrimaryLane_SecondaryDeckSensor
  - Partner deck sensor of the primary lane to detect truck axles.

- ProcessData_ArchiveFilePath
  - Location to move processed raw data file(s).
- ProcessData_InputFilePath
  - Location of the raw data file(s).
- ProcessData_OutputFilePath
  - The file location of the strain range output file.
- ProcessData_TransferFilePath
  - The file location to move the strain range output file to after it reaches the designated number of records as indicated by Output_StrainRange_NumRecordsPerFile'.
- RawData_FileDelimiter
  - The character data are separated by.
- RawData_FileExtension
  - File extension of raw data file(s) to process.
- RawData_FileHasHeader
  - Indicates that the raw data file contains header line(s).
- RawData_FileHeaderRow
  - Specifies which line is the main header.
- RawData_FileSampleRate
  - The frequency at which the raw data are collected. (e.g., 250 (250Hz))
- RawData_FileSkipColumns
  - Number of columns to skip starting from the left side and moving right.
- RawData_FileSkipLinesAfterHeader
  - Number of lines to skip after the specified header row location.
- RawData_FilesToParallelProcess
  - The number of files to process in parallel.
- RawData_ProcessImmediately
  - Process files immediately as they arrive in ProcessData_InputFilePath' or wait for the file count to be >= the value indicated by 'RawData_FilesToParallelProcess'.
- SecondaryLane_PrimaryDeckSensor
  - Deck sensor of the secondary lane to detect truck axles.
- SecondaryLane_SecondaryDeckSensor
  - Partner deck sensor of the secondary lane to detect truck axles.
- Temperature_Air_Enabled
  - Enable or Disable the processing and output of air temperature data. (e.g., airTemp)
- Temperature_Structure_Enabled
  - Enable or Disable the processing and output of stucture temperature data. (e.g., steelTemp)
- Temperature_Surface_Enabled
  - Enable or Disable the processing and output of surface temperature data. (e.g., concreteTemp)
- Trigger_PrimaryEventLane
  - The primary lane identifier matching the "group" element of the TruckAxles.xml
- Trigger_SecondaryEventLane
  - The secondary lane identifier matching the "group" element of the TruckAxles.xml

- TruckAxle_DeckLine1PreferredSensor
  - The first deck line sensor to focus truck axle detection.
- TruckAxle_DeckLine2PreferredSensor
  - The second deck line sensor to focus truck axle detection.
- TruckAxle_DetectNumOfAxles
  - The number of axles to trigger detection.
- TruckAxle_MaxAxlePeakTimeDifference
  - The maximum time between each peak to be considered an axle of a single truck.
- TruckAxle_MaxSpacingAxle1ToAxle2
  - The maximum distance between truck axle 1 and axle 2 in feet. (feet)
- TruckAxle_MaxSpacingAxle2ToAxle3
  - The maximum distance between truck axle 2 and axle 3 in feet. (feet)
- TruckAxle_MaxSpacingAxle3ToAxle4
  - The maximum distance between truck axle 3 and axle 4 in feet. (feet)
- TruckAxle_MaxSpacingAxle4ToAxle5
  - The maximum distance between truck axle 3 and axle 5 in feet. (feet)
- TruckAxle_MinSpacingAxle1ToAxle2
  - The minimum distance between truck axle 1 and axle 2 in feet. (feet)
- TruckAxle_MinSpacingAxle2ToAxle3
  - The minimum distance between truck axle 2 and axle 3 in feet. (feet)
- TruckAxle_MinSpacingAxle3ToAxle4
  - The minimum distance between truck axle 3 and axle 4 in feet. (feet)
- TruckAxle_MinSpacingAxle4ToAxle5
  - The minimum distance between truck axle 3 and axle 5 in feet. (feet)
- TruckAxle_PeakDetection_Delta
  - The distance a point needs to be from the preceding (to the left) point to become the max value during truck axle detection. (current_point < (current_Max - Delta))
- TruckAxle_PeakDetection_DistDelta
  - The distance a point needs to be from the preceding (to the left) peak to be considered a new peak during truck axle detection.
- TruckAxle_PeakDetection_Increment
  - The amount to shift the peak detection threshold during peak evaluation for truck axle detection.
- TruckAxle_PeakDetection_MaxThreshold
  - The maximum threshold that can be reached for peak evaluation to terminate truck axle detection.
- TruckAxle_PeakDetection_MinThreshold
  - The minimum threshold that can be reached for peak evaluation to terminate truck axle detection.
- TruckAxle_SpeedPercentMaxDivergence
  - The percentage modifier for testing truck axle distance difference based on vehicle speed.
- TruckEvent_CheckExtrema_Enabled
  - Enable or Disable data checks on maximum, minimum, and range thresholds.

- TruckEvent_Detection_AdvanceTime
    - The number of seconds of data to test for concurrent truck events after the discovered truck event. (seconds)
- TruckEvent_Detection_AssumedSpeedFPS
    - The assumed speed of all trucks crossing the bridge. (feet per second)
- TruckEvent_Detection_LagTime
    - The number of seconds of data to test for concurrent truck events before the discovered truck event. (seconds)
- TruckEvent_PrimaryGirderSensor
    - The primary girder sensor to evaluate truck detection.
- TruckEvent_SecondaryGirderSensor
    - The secondary girder sensor to evaluate truck detection.