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Highway IDEA Program

Long-Term Remote Sensing System for Bridge Piers and Abutments

Final Report for Highway IDEA Project 123

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TRANSPORTATION RESEARCH BOARD
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Long-Term Remote Sensing System for Bridge Piers and Abutments

IDEA Project NCHRP-123

For the period October, 2006 through October, 2009

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Transportation Research Board
The National Academies

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EXECUTIVE SUMMARY

This report summarizes research conducted under the NCHRP IDEA Project 123, Long-Term Remote Sensing System for Bridge Piers. Through the course of the research, a new bridge monitoring technology was developed. This new technology is based on the application of low-cost sensor arrays, located on the superstructure and bridge pier, to monitor bridge behavior and overcome certain limitations in existing technologies. The system developed through the research enables the long-term monitoring of bridge piers and abutments to detect and monitor the effects of long term settlements, scour and other structural displacements that could lead to instability or collapse of bridges.

Scour, subsurface erosion and locked bearings can affect the structural stability of bridge piers. Scour and subsurface erosion can undermine the foundation and lead to unexpected settlements and tilting of the bridge pier. Locked bearing can result in unanticipated lateral forces at the bearing, causing tilt and misalignment. These structural movements may be complex, including tilting of the pier or vertical settlement. Current sensor systems intended to monitor bridge pier movements are focused on short term events such as scour that can lead to large tilts in the pier. However, these systems are typically not capable of measuring vertical pier displacement or longer-term motions, due to limitations in the sensor technologies used. To address these issues, an innovative new sensor system has been developed that utilizes an array of low-cost tilt sensors strategically placed on the pier and superstructure of a bridge to monitor structural motions. Development of this unique new technology was achieved through a combination of the experimental testing in the laboratory and field implementation of the technology.

A specialized data logging system was developed to support experimental development of the sensor array technology in the laboratory. A test bridge was designed and constructed that allowed for calibrated motions of a model bridge pier and superstructure in three dimensions. Dual-axis electrolytic tilt sensors were utilized in array configurations to measure tilt and displacements on the model bridge. A series of algorithms were developed to enable the measurement of structural displacements in three dimensions. The algorithms developed detect and compensate for potential faulty sensor outputs, convert tilt data to a universal coordinate system, and report overall pier motions to the user. Laboratory testing of the system was conducted under a variety of scenarios to develop, test and evaluate the application of the sensor array technology to monitor the structural motions of the pier. This has included developing and testing a methodology for implanting sensor elements within concrete to reduce the effects of temperature variations in future field applications.

The technology developed through the research was implemented through a field test on a bridge in Rome, N.Y.. The bridge selected for field implementation had a history of bearing-related issues that needed to be monitored to evaluate effects on the structural motions of the supporting pier. Instrumentation and sensors suitable for application in the rugged environment of a bridge were developed and installed on the bridge. The instrument includes an integrated web server that provides real time data on the behavior of the pier via the web. The web site for the field test bridge allows users to view data outputs from 5 sensor arrays including 16 low-cost dual-axis tilt sensors located along the pier and superstructure of the bridge. Outputs of the sensor arrays are presented through a series of data summaries that capitalize on the array configuration to overcome certain limitations of existing technologies. The system was installed on the bridge and has provided uninterrupted monitoring from the time of installation through the time of this report. The effectiveness of the sensor array technology and supporting instrumentation developed through the research has been demonstrated through the successful field test. Evaluation of the system performance in the field test is ongoing.

The system developed through the research is available commercially to bridge owners, and implementation activities to make the transportation community aware of the new technology are ongoing. This has included presentations and papers published in relevant conferences and meetings attended by bridge owners.

IDEA PRODUCT

To address the need for reliable, long-term remote sensing and monitoring technology, an innovative sensor system has been developed. The product of the research is a field-ready, multi-channel bridge monitoring technology that allows for bridges to be monitored remotely over the World Wide Web. The product is a targeted health monitoring system that can be utilized by state Departments of Transportation (DOTs) for the purposes of:

- Monitoring new construction for unexpected settlements
- Monitoring the effects of locked bearing
- Monitoring long-term thermal effects over multiple seasons or years
- Monitoring subsurface erosions
- Monitoring long-term settlements of bridge supports
- Monitoring the effect of scour

The system developed through the research includes several innovations in sensor technology for highway bridges. This includes the use of multi-sensor arrays to provide reliable, redundant long-term measurements. Innovative new sensor configurations have been developed to address the need to provide thermal matching between the sensor array and the structure being monitored and to overcome limitations of existing sensor technologies. Low-cost sensors, with sufficiently high resolution, have been used to ensure the final costs of systems for field use are within the reach of DOTs.

The new capabilities introduced through the developments include the ability to reliably monitor the long term behavior of a highway bridge. The capability can be used for the practical management of highway infrastructure by providing a low-cost technology to monitor bridge behavior. This technology is a practically implementable tool that can be used to address known or suspected problems in a bridge, monitor that problem between required biennial routine inspections, and monitor the health of bridges over the long term.

The impact on transportation practice is to provide a realized application of health monitoring technology. Although many health monitoring technologies have been introduced in recent years, these systems have struggled to find effective and useful applications. In part this is because although many different parameters, such as strain, acceleration and displacements can be measured, the utilization of this data for managing the health of the structure is complex and often not well defined. These limitations stem from the difficulty in determining what these different parameters mean in terms of the health of the bridge. The system developed in the research is targeted at a specific measurement that can be effectively evaluated to determine the long term performance of the structure in a meaningful way. As such, the developed technology addresses real problems in the transportation community and provides a practically implementable tool for improving the safety of the highway infrastructure. The New York State Department of Transportation (NYSDOT) has an interest in the application of this technology for monitoring bridge problems, and provided a bridge for field testing of the technology and assisted in field installation. The system develop through the research was installed in the field and remains in-place monitoring the test bridge provided by NYSDOT.

CONCEPT AND INNOVATION

PROBLEM

Scour and other natural hazards have the potential to undermine the stability of highway bridges and the piers that support them. Scour occurs when flowing water removes material from around bridge piers, thus creating scour holes beneath footings that can jeopardize the stability of the bridge (Richardson, 2001). Other hazards, such as underground erosion and unexpected settlement, can also result in a loss of subsurface support. Such settlements of piers and abutments can cause the superstructure of the bridge to fall off of its support bearing and even lead to structural collapse. In addition, unexpected superstructure behavior can also cause superstructure elements to push off of their bearing supports. For example, situations such as locked bearings in bridges are common due to corrosion of the bearing caused by exposure to the environment and accelerated by the application of deicing salts to the bridge surface. The locked bearing restricts the thermal movements of the bridge, sometimes causing other bearings that are not locked to become overextended and even push off of the bearing seats. These effects have caused bridge collapse or near collapse in the past.

For example, the bridge in Missouri at Mark Twain Lake was pushed off its bearings, as shown in Figure 1, by unexpected displacement of the piers. In this case, the bridge had to be demolished and replaced, causing significant transportation disruptions in the area. Figure 1 (left) shows the displacement at the deck of the bridge resulting from the superstructure falling off of its bearing. The Figure also shows the bearing area, with the rocker bearing turned on its side and the bridge girder resting on the pier cap (right).

A bridge on I-787 in New York State also suffered a near collapse when the steel superstructure pushed off its bearing, and total collapse of the bridge was only avoided because the superstructure was caught by the edge of the pier cap. Extension of the bearing in the bridge had been apparent for several years prior to the event. However, superstructure forces combined with the extended bearing combined to push the pier, causing the superstructure of the bridge to fall off the bearings. An elevation photograph of the bridge is shown in Figure 2, showing the superstructure of the bridge resting on the pier cap after falling off of its rocker bearings. A large crack was found near the ground level of the pier, indicating that the pier had undergone significant bending stresses and displacement prior to the accident (NYSDOT, 2005).

Although the extension of the bearing had been apparent for some time, there was no way to track the behavior of the bridge in between biannual inspections, and as such the increasing movement of the pier went undetected. Were a simple monitoring system available that could detect the pier displacements developing over time, the excessive displacements that caused the accident could have been detected and appropriate mitigation actions taken to address the issue. Unfortunately, there were no monitoring systems available to detect these long terms effects, which had developed over many years. The system developed through the research reported here provides a new tool for monitoring this type of long-term structural displacements, to provide a new tool for use by state DOTs for managing bridges and ensuring bridge safety.

Figure 1. Photographs of a bridge that fell off its rocker bearings due to pier displacements

Figure 2. Bridge in New York that has fallen off its bearing and come to rest on the pier cap.

Systems for monitoring the tilt of bridges that have been available historically were intended primarily to monitor the effects of scour. A number of scour monitoring devices have been developed, several of which focus on monitoring unexpected movements of bridge piers (Schall, 2004). These systems typically consist of tilt sensors mounted to the piers that are used to monitor the bridge superstructure to detect the possible onset of bridge collapse or scour-related displacements (Richardson, 2003). However, these systems can have several important limitations. First, diurnal temperature variations cause the sensors to heat and cool at a different rate than the concrete pier itself. This is because the sensors are typically mounted on light metal brackets, while the bridge pier is constructed of a large mass of concrete. Because of the thermal behavior of concrete, the temperature variations of the concrete are out of phase with the diurnal temperature variations throughout the day. The resulting thermal differential between the sensor and the pier it is intended to monitor results in uncertainty in the source of measured angular tilt values. Additionally, the electronic sensors can drift over time, such that the sensors must be reset periodically. Because the system is intended to monitor scour events, which typically occur over time periods of a few hours to a few days, resetting sensors periodically does not present a problem; the systems will still detect short-term tilt events such as might be caused by scour. However, for longer term effects such as erosion, long-term settlement or the effects of locked bearings, tilting of the pier may occur over many years and could not be detected by such a system. Additionally, sensors traditionally used in scour monitoring systems are typically high-cost, such that a limited number of sensors can be used economically. As a result, only a few sensors may be placed on the bridge assuming the tilt will occur in a predictable manner based on rigid body rotations of the structure. In reality, the motions of the pier, both due to extreme events such as scour events and normal displacements of the bridge, are complex and multi-dimensional. To fully understand the displacements of the pier over the longer term, additional sensors are needed to describe the motions and detect unexpected motions such as vertical displacement of the pier in the absence of tilt, such as might occur in the case of pier settlement or underground erosions.

In addition, sensor failures that may occur over the life of the bridge can undermine the effectiveness of the system. Because these systems typically have a very limited number of sensors, a failing sensor may appear to indicate pier tilt is occurring when it is not. Even worse, a failing sensor may make it appear that the pier is stationary when it is actually tilting. Mounting additional sensors to provide systematic redundancy and/or confirmation of sensor outputs can alleviate this issue, but increase the system cost significantly when high-cost sensors are used.

There has historically been a lack of reliable, cost-effective, long-term monitoring devices capable of monitoring these conditions at bridge piers. Although many systems have been proposed for monitoring bridge health, few have had well-defined goals and targeted applications that would enable successful implementation of the technology. As a result, bridge owners have become disillusioned with health monitoring technology and unable to identify practical advantages to the system that help them meet their goals of ensuring bridge safety and effective bridge management. The technology developed within this research project is intended to provide a targeted, implementable and valuable new tool for bridge owners that can be applied to solve real-world problems.

INNOVATIVE SOLUTION

The concept of the proposed system was to utilize an array of low-cost tilt sensors, deployed on both the pier and the superstructure of the bridge to overcome the limitations of the existing systems. The initial concept for the sensor array approach was developed from examination of fuel sensor systems in the space shuttle external fuel tank, the large fuel tank that attaches to the bottom of the shuttle vehicle for launch. An array of fuel sensors in the tank, located at different elevations, is utilized to monitor fuel level to ensure sufficient fuel is in the tank to support launch. These sensors monitor different areas of that tank and its attachments, and specially developed algorithms are used to determine if low fuel readings are the result of faulty behavior of a sensor, or actually correspond to low fuel levels. A system of logic rules based on the output of the sensor arrays are used to discriminate fuel levels problems from false indications. Because sensor arrays are used in the process, rather than individual sensor outputs, redundancy in the system allows for more reliable operation of the critical sensor system.

The initial concept of the research proposed for this project was to apply this design concept from the space shuttle program to the difficult challenge of monitoring long-term bridge behavior. Using an array of tilt sensors located on the pier and superstructure of the bridge, rather than only a few sensors, could overcome many of the limitations of currently available technologies. The sensor arrays, shown conceptually in Figure 3 from the original proposal, could provide a similar system of redundant sensors as used in the shuttle external tank to improve the reliability of long term measurements. An array of low-cost tilt sensors distributed circumferentially around the bridge pier as shown in Figure 3 could provide measurement of tilt at several levels of the pier. The array would provide redundant measurement of pier tilt along two axes. This would allow for the characterization of the bending (curvature) that may occur in the pier as a result of locked bearings or other superstructure loading, such as occurred on I-787 in New York. The sensor density would allow for the addition of tilt measurement that are consistent across that plane of the pier, and elimination of systematic noise and drift via cancellation techniques and sensor correlations. The high number of redundant sensor measurements will allow algorithms to provide fault tolerance for the system (i.e. account for single or multiple sensor failures). By using this multiple sensor approach, lower resolution, lower cost sensors could be utilized, reducing the cost of the sensor system while improving its robustness. An additional array of sensors could be mounted on the superstructure of the bridge, along the lower flange adjacent to the pier bearing. This array could monitor the vertical displacement of the pier. The output of both sensor arrays would provide complete data on the three-dimensional motions of the pier. The correlation and interrelationship of sensor arrays could be used to improve signal to noise ratios and overcome thermal effects and long term drift. Sensor failure, which is inevitable in long-term applications spanning many years, could be overcome through the use of the sensor array concept. This could ensure more reliable operation of the system, enable the system to reliably detect smaller motions that occur, and differentiate displacements associated with thermal effects from actual pier displacements that could be indicative of a progressive failure mechanism in the pier. Additionally, multiple sensor measurements could be used to understand the complex behavior of bridges, and quantitatively measure displacements in three dimensions. Once developed, such a system would provide bridge owners with a new tool for managing bridges and ensuring bridge safety. This new tool would provide an important solution to the difficult problem of monitoring the long-term behavior of bridges.

During the course of the research, this initial concept was developed to provide a unique new bridge monitoring tool specifically designed to measure long-term bridge behavior. The system is capable of measuring both changes in rotations (tilt) and vertical displacement of a bridge pier. The sensors are deployed in several arrays, such that multiple sensor outputs can be integrated to increase signal to noise ratios, eliminate erroneous readings, and provide systematic sensor redundancy. Signal processing correlation algorithms were developed that use sensor density and location to better measure and understand long-term bridge rotations and displacements. A modular, specialized data acquisition system was developed that collects data from all sensors.

The data is collected and processed on-site and made available to state personnel over a website accessible via the Internet. A prototype system was developed based on the initial concept, and then implemented through a field test in cooperation with the New York State Department of Transportation (NYSDOT). For this field test, described in detail in later sections, the developed system has been applied to monitor the long-term behavior of a bridge with demonstrated over-extension of the bridge bearings to monitor the tilt of a critical pier where the extension is occurring. This real-world application is intended to demonstrate the new capabilities of the system, test the new concepts and methodologies employed, and evaluate the effectiveness of the system in real-world applications.

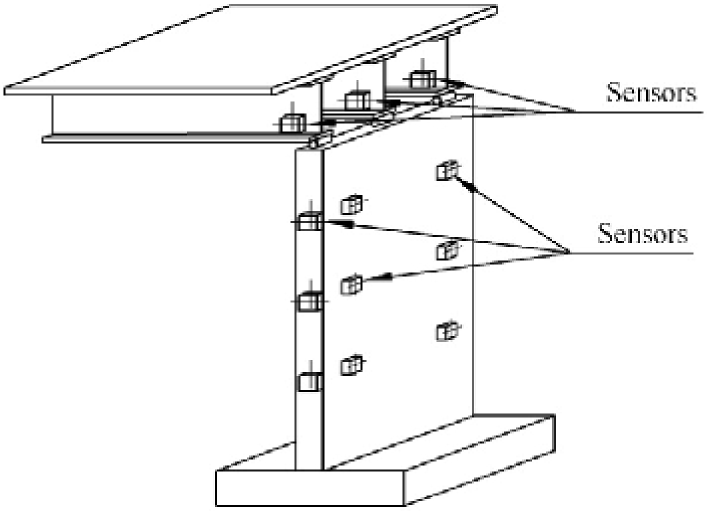


Figure 3. Sche **e pier and superstructure of a bridge.**

Unique and innovative aspects of the system include:

1. *A sensor array scheme for sensor placement that provides redundant, array-based measurements that are highly reliable and reduces long-term effects.*
2. *The ability to measure vertical displacement of a pier that may occur without tilt*
3. *New sensor designs that allow sensors to be embedded in the concrete and reduces harmful thermal effects*
4. *Data processing algorithms that reduce temperature and drift problems common to long-term monitoring systems*
5. *Reliable live-web data acquisition and analysis program that provides real-time tilt data and analysis for bridge owners*

The developed system provides a unique measurement technology that has not been previously available. The benefits of the system include

1. *The ability to remotely monitor structural stability of bridge piers over extended time periods*
2. *Development of a unique, high-density sensor array and supporting signal processing technique that provides long-term reliability*
3. *Improved methodology for evaluating and monitoring the effects of settlement, locked bearings, scour and other natural hazards on the structural stability of bridges*
4. *Improved bridge safety through health monitoring*

The system allows for monitoring of the structural stability of bridge piers not only for the effects of scour, but for other natural hazards including earthquakes, subsurface soil slides, and unexpected horizontal forces that may result from locked expansion joints in bridges. The technology developed provides for long-term, maintenance-free health monitoring, and applications are expected to extend beyond piers to retaining walls, abutments, wing walls and other civil structures. Application of such a system will help ensure safety of highway structures, allow states to monitor unusual situations and events, and provide a long-term measurement tool that could reduce the cost and frequency of inspections.

INVESTIGATION

SYSTEM DESIGN

The first task in the project was to develop the necessary technologies to support the overall development of the array system. This included two primary objectives: First, a suitable sensor needed to be selected for development of the system. Second, a test bridge that would allow for calibrated measurements of tilt and displacement in the laboratory needed to be designed for use in the laboratory. These objectives were met in the early phases of the project and a brief overview is provided here.

Electrolytic tilt sensors were selected as the primary sensor for the project. Figure 4 is a photograph of the sensor utilized in the research. The sensors chosen were dual-axis tilt sensors that operate based on a five pin configuration housed in an electrolytic fluid-filled capsule. Inside the capsule, an air bubble is enclosed which orients itself perpendicular to gravity. As the sensor tilts, the air bubble moves within the capsule causing a change in the sensor impedance and the resulting voltage output is directly related to the tilt angle of the sensor. A unique aspect of the sensor selected was that the tilt sensor module can be removed from the supporting electronics and mounted remotely. This provides the potential to mount the sensor in unique ways in the field, such as embedding it directly in the concrete to ensure detected sensor motions match actual movements of the pier and provide thermal matching between the sensor and the structure being monitored. Electrolytic sensors were selected over a MEMS-based technology due to their greater stability and precision. Semiconductor-based tilt sensors typically have an accuracy in the order of 0.1 degrees and as such do not have sufficient resolution for this application. The electrolytic tilt sensors also have a large linear range (+/- 8 degrees) that will allow for ease of installation, and ensure normal movements of the pier will not result in sensor readings outside the linear range of the sensors.

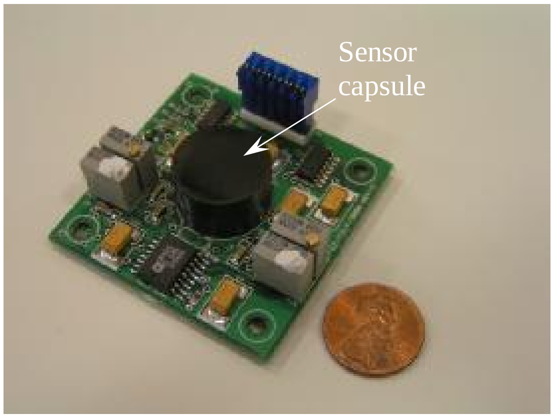


Figure 4. Photograph of electrolytic tilt sensors mounted used in the research.

The sensors were characterized to determine calibration factors and confirm temperature compensation factors. Calibration of the sensors was completed by rotating each sensor incrementally through its linear range. The voltage output was recorded using the data acquisition system, and calibration plots were created for each sensor axis as shown in Figure 5. Each axis on each sensor was calibrated to provide the necessary relationship between the voltage output of the sensor and the tilt angle unique to that sensor, though these calibration factors are typically very consistent with only slight variations between sensors.

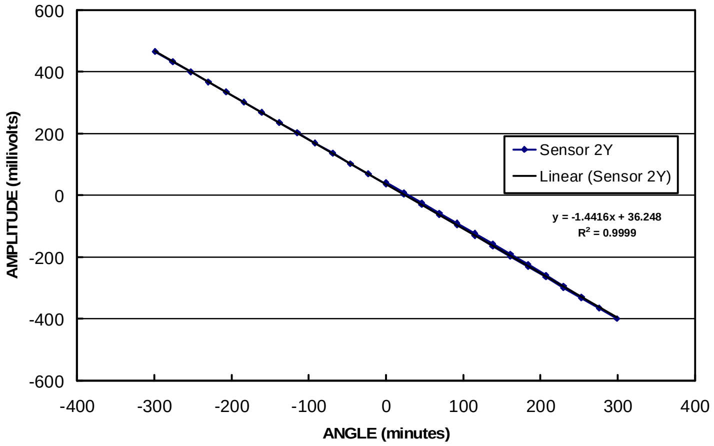


Figure 5. Graph showing an example calibration plot for electrolytic tilt sensor.

Correlation values (R^2) for these calibration tests were typically greater than 0.99, thus showing the highly linear behavior of the electrolytic tilt sensors. The temperature compensation factors for the sensors were also validated through laboratory testing of the sensors placed in an environmental chamber. This testing confirmed the operation of the sensors over a suitable range for practical application in the field, and verified temperature compensation values. Tests were also conducted to evaluate drift, identify noise levels, and determine experimental resolution of the overall system. The resolution of the system is dependent on several components, including the A/D converter, the test setup, and the sensors themselves. Based on the laboratory setup, the minimum resolution of the system was found to be no more than 28 arc-seconds (0.0078 degrees) for the configuration utilized in the laboratory.

Preliminary design information for the data acquisition system developed in the research was obtained based on the performance of the sensors. A design for a test bridge that was suitable for testing the sensors and data processing algorithms was developed. This test bridge was designed such that calibrated, 3-dimension motions could be induced in the test bridge and measured and experimentally evaluated by sensor arrays mounted on the laboratory test bridge.

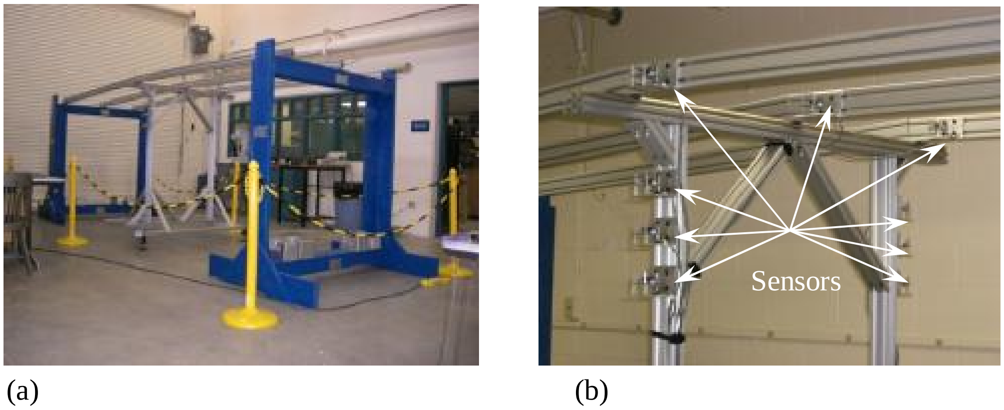
PRELIMINARY SYSTEM DEVELOPMENT

The second task in the project was to develop a suitable data acquisition system for the sensors selected in Task 1, and to construct the test bridge. This section describes briefly the efforts completed in this area.

Tilt sensor modules were identified and specified as described above. Based on the sensor parameters, a suitable laboratory data logger was developed by Fuchs Consulting, Inc. The laboratory data logger is a 32 channel system capable of measuring 10 dual-axis tilt sensors and the sensors' temperature output, as well as the ambient temperature and internal instrument temperature. A photograph of the laboratory data logger is shown in Figure 6. This data logger was used to provide the necessary power source for the sensors, control sensor operation and record sensor outputs at predefined time intervals. Program routines were also developed to automatically load and prepare instrument data for customized post-processing.

Figure 6. Photograph of data acquisition system used in laboratory testing.

A test bridge was designed and constructed on which the sensors could be mounted. Photographs of the bridge can be seen in Figure 7a below. Both the pier and three girder lines are composed of extruded aluminum parts from 80/20™ Inc. The pier has a triangular base with three spring-loaded feet on threaded struts ("screw jacks") that can be adjusted to tilt the pier in any direction or to induce a vertical displacement in the test bridge. Testing was conducted to calibrate the movement on the screw jacks with respect to the actual tilt of the pier in two dimensions. The aluminum test bridge allowed for simple mounting of the sensors anywhere on the structure, using angle brackets to mount the sensor boards and sensing elements as shown in Figure 7b. For testing in the laboratory, the sensing element was mounted on pin mounts, on the sensor electronics board itself. During later developments in the project, this sensing element was removed from the board to be mounted in a special enclosure intended to match the thermal behavior of the sensors to the thermal behavior of the bridge.



(a) (b)

Figure 7. Photograph of test bridge (a) and sensors on pier and superstructure (b).

SYSTEM DEVELOPMENT

Task 3 consisted of several parallel activities to develop and test the system. This included laboratory testing of the sensors and calibrated test bridge to ensure proper performance under laboratory conditions. The development of algorithms to correlate multiple sensor output and measure complex motions was also completed. This included developing algorithms to detect faulty sensors, identify and eliminate sources of noise, combine multi-sensor outputs to improve system reliability, and calculate tilt and displacement of the pier. Task 3 also included developing the final system design for the field-ready system, and identifying suitable test sites in cooperation with NYSDOT.

Algorithm Development

One aspect of this system that sets it apart from currently available monitoring systems is the use of multiple sensors in an array configuration. The use of multiple sensors allows one to achieve measurement redundancy, increase signal to noise ratios, identify inconsistent sensors, and utilize signal correlation to better define overall movements. These areas were the focus of algorithm development and testing. During this phase of the project, numerous algorithms were developed, programmed and tested. Algorithms were developed to filter noisy data, calibrate sensor outputs, provide temperature compensation, compute bridge movement, determine sensor inconsistencies, perform sensor correlation, and identify critical movements.

Combinations of constant and fuzzy thresholds were utilized as tools to process sensor data. Constant thresholds were used to determine sensor consistency, while fuzzy thresholds were applied as an initial filter as well as used to identify critical movements. In addition, a method of computing the actual movement of the pier was developed using vector comparison. A method of averaging of array outputs was used compute the overall movement of the bridge. Overall, algorithms developed during the laboratory portion of the research were capable of processing raw data output from the sensors, filtering noise, evaluating the consistency of sensor outputs, and using the data from the sensor arrays to calculate the actual movements of the pier in 3 dimensions. The algorithms developed also demonstrated how critical movements of both the pier and superstructure could be evaluated based on a fuzzy thresholds.

Movement Computation

One of the goals of this project is to develop a system that can detect both short term and long term movements that may occur in a bridge pier using tilt sensor measurements. Traditionally this has been accomplished by assuming the tilt will occur in a particular direction, and orienting tilt sensors with one axis of the sensor aligned with that direction. However, when monitoring a bridge pier for the effects of settlement or underground erosion, the direction that tilt may occur may be unpredictable, and the individual tilt measurements can be difficult to interpret. As a result, a means of converting the measured tilt angles to overall pier motion is needed to assess both the magnitude and direction of pier displacements in a meaningful way. In order to determine the magnitude and direction of pier movements, a method to compute the change in tilt of a pier over a certain time interval was developed using vector comparison. This vector comparison technique combines the two axes of the measured tilt into a single vector describing the tilt angle of the sensor that can be used to determine the total change in tilt over a specified time interval.

The use of multiple sensors allows for invalid sensor measurements to be identified and excluded from post-processing. In this way, a sensor can go bad without jeopardizing the entire system, and users can be notified of the sensor failure without having to monitor system performance on a daily basis. For the laboratory test bridge, nine sensors were arranged in three separate arrays as shown in Figure 8. In this array configuration, array (A) was on one side of the pier, array (B) on the opposite side, and array (C) was mounted on the on the superstructure, as shown schematically in Figure 9.

The sensors are configured in this way so that each side of the pier has three sensors mounted directly on the test bridge to achieve sensor redundancy. The algorithms developed during laboratory testing checked for errant readings in each individual sensor in the array by comparing individual sensor outputs with the average output of the other sensors in the array. If a sensor is found to be inconsistent, its output could be excluded in future processing. In the case that a sensor is determined to be inconsistent and its output is disregarded, the remaining sensors in the array are evaluated in order to ensure consistency between the remaining measurements. Once each sensor is checked individually, the output of the entire array is analyzed to determine its variation with the other arrays to evaluate if separate array outputs are compatible. This utilization of multi-sensor output will improve the long-term reliability of the system and mitigate the effects of sensor failure and drift over the lifetime of the monitoring system.

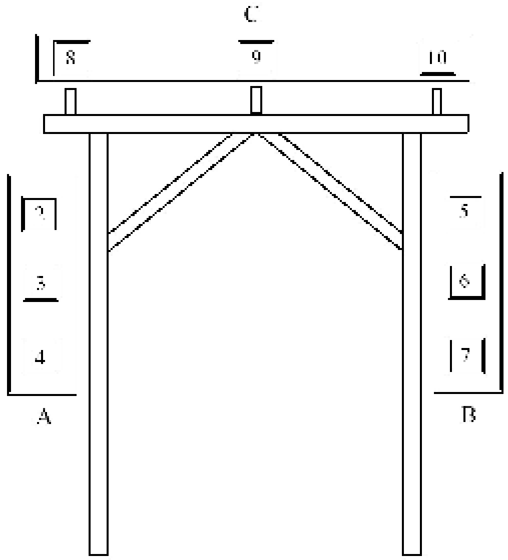


Figure 8. Diagram of sensor array configuration for laboratory test bridge.

Sensor Correlation

While sensor consistency algorithms were developed to identify inconsistent sensors, sensor correlation algorithms were developed to more accurately interpret the movement of the pier. Here, the concept of signal correlation was used both as a check of sensor outputs as well as a tool to more thoroughly model the behavior of the pier. For pier displacements, the system was designed with two sensor arrays, one on each side of the pier. Once the movement for each array of sensors is determined through sensor consistency checks, sensor correlation is used to compare these values and combine them into an overall movement of the bridge pier with respect to a universal coordinate system. As a result, the output of the sensor system can be derived from the composite output of many sensors in predefined arrays, to increase the accuracy and reliability of the measurement over the long term.

Critical Movement Identification

Due to diurnal and seasonal temperature variations, a bridge normally undergoes some tilt over time. To successfully monitor the pier behavior, critical movements need to be separated from these normal pier movements. A method of applying fuzzy thresholds to evaluate the criticality of individual measurements was developed in the laboratory. The algorithms include the application of a fuzzy threshold to the overall pier movements determined through the sensor correlation. Such fuzzy thresholds are easily computed based on neighboring (in time) points of pier movement data. The threshold for each record is set as the median plus three times the modified standard deviation. The modified standard deviation is computed based on the equation:

$$s_m = \sqrt{\tfrac{1}{N}\sum_{i=1}^{N} a\,(x_i - m)^2} \qquad (1)$$

where $a = e^{-a(b(x_i-m))^2}$, a = 0.5, b = 50, N = 48, $m = \frac{1}{n}\sum_{i=1}^{n} x_i$.

This algorithm can be used to indentify outliers that represent significant variations in movement, rather than inherent sensor noise, and to automate such processes if appropriate. Parameters for equation 1 were developed based on laboratory tested, and can be suitably adjusted for field application once initial data trends are identified.

Results of Laboratory Testing

Testing was conducted in order to evaluate the performance of the sensor arrays and test the processing methodologies developed. Several tests were completed in order to determine if the array system can accurately identify pier rotations and superstructure displacements. Testing was also completed in order to demonstrate the effectiveness of the multi-sensor system over single sensor systems. In addition, a method of embedding the sensors inside a concrete bridge element was developed and experimentally evaluated. Testing of the embedded sensors to determine their viability for field application was completed. The following sections describe the results of some of the laboratory tests.

Multi-Sensor Test

The use of multiple sensors allows for sensor redundancy, increases signal to noise ratios, and helps to create a clearer depiction of the motion of the bridge. In order to verify that the multi-sensor system was more effective than individual sensors, a test was conducted in which the pier was tilted in 0.0167° ± 0.0132° increments (1 arc-minute). Tilt of the pier was introduced by rotating the screw jacks at the base of the pier. Figure 9a shows the calculated movements computed over a 4 minute time period from individual sensor outputs under noisy sensor output conditions. Observing the output signals from the individual sensors shown in Figure 9a, it is difficult to separate the actual movements from the sensor noise, as the signal to noise ratio for these results is ~1.0. That is, the sensors noise is approximately at the same level as the signals from the small pier motions. The actual pier motions, which were applied by adjusting the screw jacks at the base of the pier an appropriate amount to cause the pier to tilt ~0.0167°, are shown as solid dashed lines in the Figure.

When the sensors are combined into a multiple sensor system in which the sensors work together (array), this signal to noise ratio is improved significantly, as shown in Figure 9b. When the individual sensors are considered in an array configuration, inconsistent outputs can be excluded from processing and signal correlation completed in order to measure pier movements. Figure 9b shows the results of combining sensor outputs from the array, and clearly shows the seven distinct movements that the bridge experienced. Again, the actual pier motions are shown in Figure 9b as dashed lines. The signal-to-noise ratio was increased from ~1.0 when considering sensors individually to ~3.0 when utilizing the multi-sensor logic of an array configuration. This laboratory test clearly demonstrates the beneficial effect of using multiple sensors to separate and measure actual pier motions.

Table 1 shows the magnitude of movement applied to the laboratory test bridge and the corresponding measured tilt values derived from the output of the sensor arrays. There were seven movements applied to the laboratory test bridge during this particular test and each of these movements was detected and measured by the sensor system. Measurement errors were relatively minor considering the magnitude of the applied movements (~0.0167°, ~1 min.) and the tolerances of the laboratory test bridge. Given the small magnitude of the movements, and the potential error in positioning the threaded support of the bridge to induce the small pier tilt, the error for each individual movement was conservatively estimated as ± 0.0132°.

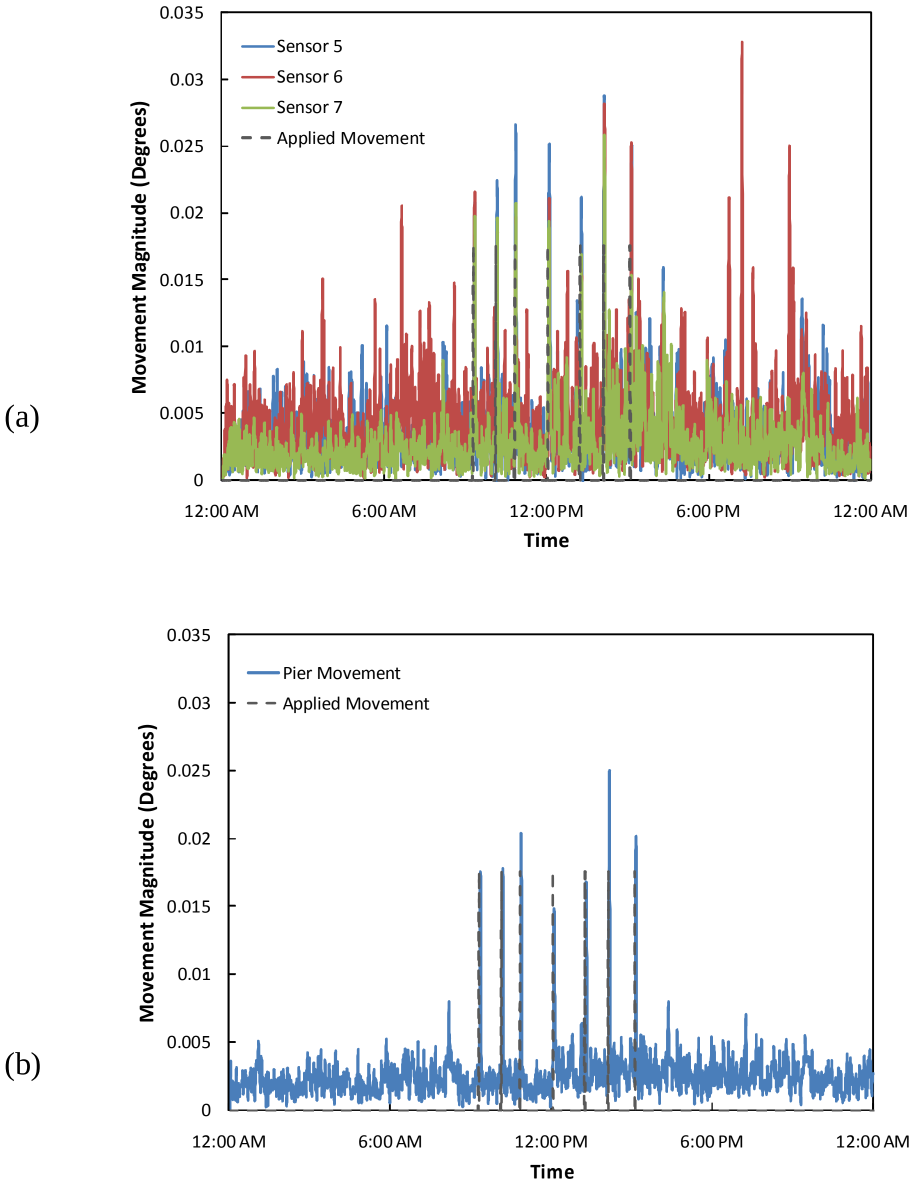


Figure 9. Pier movements detected and measured in the laboratory testing. Noisy data from individual sensors (top) and integrated data from the Array.

Another way of comparing the results from individual sensors to the results of the sensor system is to examine the mean and standard deviation of the signal outputs that were recorded when the bridge experienced no actual movement. These signal outputs are inherent noise in the system, resulting from either sensor noise or minor motions that are occurring to the test setup over the course of the day (for example, movement of the building in which the test bridge is located). Ideally, both the mean and standard deviation should be zero when no movements are occurring. By computing these statistics over a one day period for each sensor individually as well as the two sensor sets and the combination of all six sensors, it is clear that the combination of all six sensors provides the best results. The mean of the individual sensors ranges from 0.0020° to 0.0044°, while the standard deviation ranges from 0.0013° to 0.0033°. The average mean of the six sensors is 0.0034°, with the average standard deviation being 0.0023° for the six individual sensors. When all six sensors are combined into one system, the resulting mean and standard deviation lowers to 0.0024° and 0.0010°, respectively. Thus, the system of six sensors provides much better results than isolated individual sensors in terms of the inherent noisiness of the measurement system. This occurs because of the random nature of the noise sources and the effectiveness of average multiple output in mitigating the effects of the random noise.

Table 1. Applied and measured tilt values for laboratory test bridge.

Movement	Magnitude		Error (%)
	Applied	Measured	
1	0.0167° ± 0.0132°	0.0167	0
2	0.0167° ± 0.0132°	0.0167	0
3	0.0167° ± 0.0132°	0.0204	14
4	0.0167° ± 0.0132°	0.0149	19
5	0.0167° ± 0.0132°	0.0168	5
6	0.0167° ± 0.0132°	0.0250	30
7	0.0167° ± 0.0132°	0.0202	13

Pier Threshold Test

In order to verify and evaluate the algorithms developed in the laboratory, and quantitatively evaluate magnitude of detectable pier rotations, a test was conducted over the course of two weeks in which the pier was tilted at increasing increments from 0.8 arcminutes to 3.2 arcminutes. Raw sensor outputs for each individual sensor (6 sensors in 2 arrays) are shown in Figure 10.

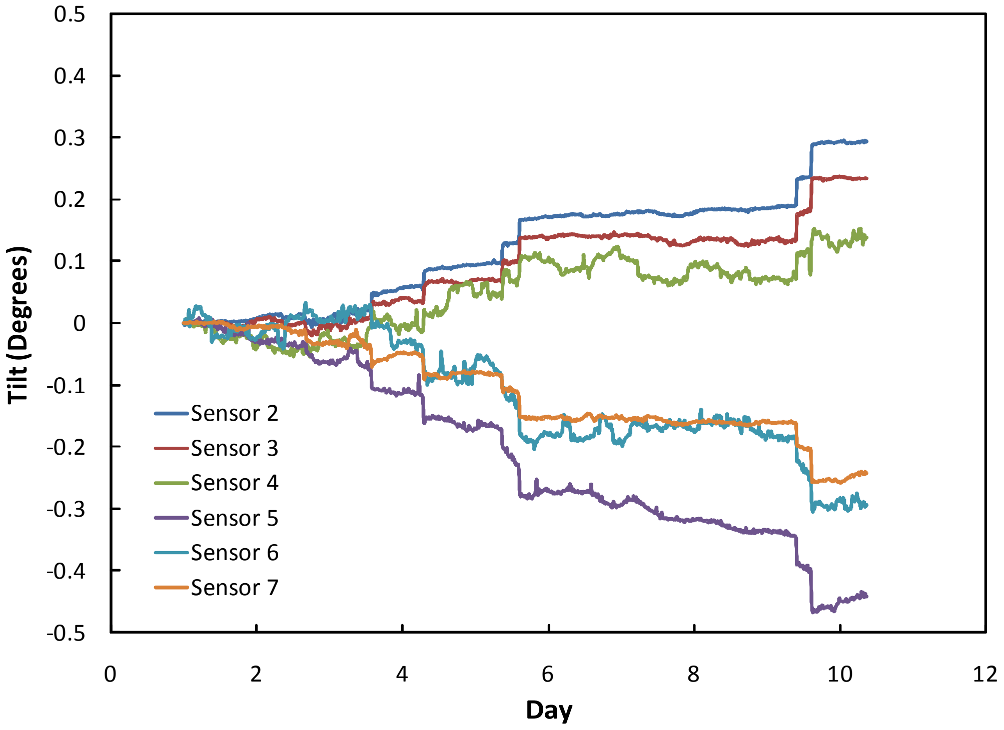


Figure 10. Sensor outputs during test in which 10 movements of incremental magnitudes occurred in the y-axis.

After the individual movements of each sensor were determined, these movements were compared to others in their appropriate array. Inconsistent outputs were disregarded and an overall movement of the pier was determined for each record in time. The resulting overall pier movement from this test is shown in Figure 11. The Figure shows the fuzzy threshold value over time and considered the directions of the identified movements in order to pinpoint critical pier movements. The results from applying this threshold can be seen in Figure 11, where the green line indicates that varying amplitude of the fuzzy threshold; the red circles indicate the measured motions of the pier, and the significant motions identified through processing the acquired tilt sensors.

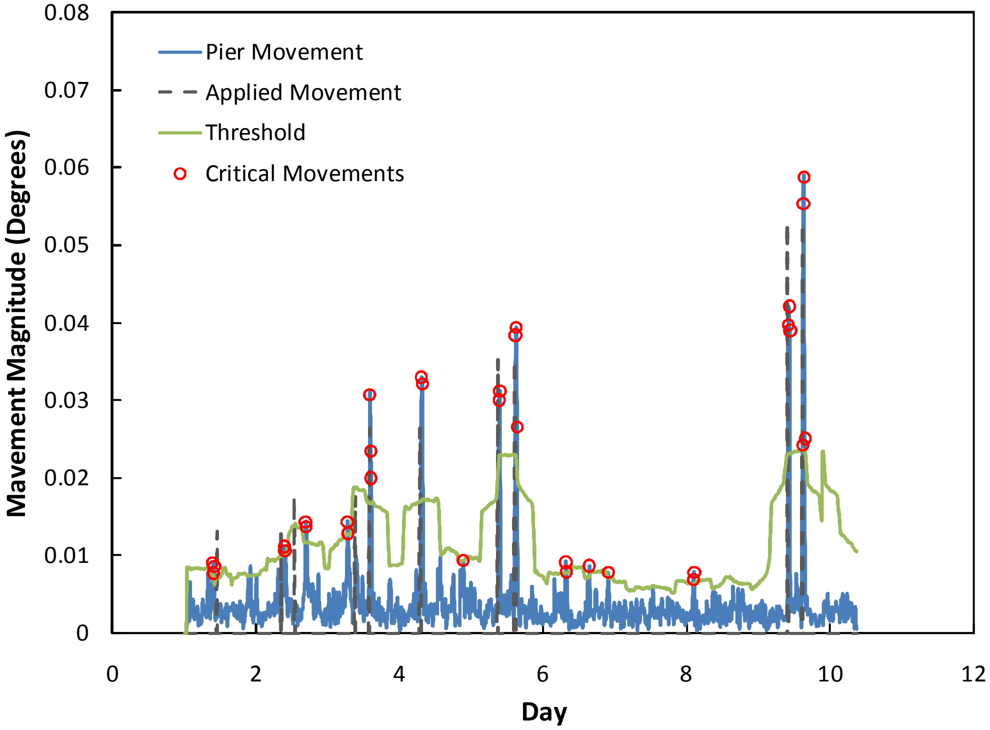


Figure 11. Graph of overall pier movement with fuzzy threshold applied.

The movements identified by the program correspond to actual movements that the bridge pier experienced. Table 2 shows which movements occurred and which were detected. In this case, data was analyzed over time windows of 45 minutes to simulate the data processing that would occur over longer term applications in the field. As a result, the detection of the pier motions is slightly delayed from the actual application of the tilt to the bridge pier.

Table 2. Results of tilt detection measurement.

Movement	Time		Magnitude		Error (%)
	Applied	Measured	Applied	Measured	
1	5/19/08, 10:46 AM	--	0.0132 ± 0.0132	--	--
2	5/20/08, 8:22 AM	--	0.0132 ± 0.0132	--	--
3	5/20/08, 12:39 AM	--	0.0167 ± 0.0132	--	--
4	5/21/08, 8:53 AM	--	0.0167 ± 0.0132	--	--
5	5/21/08, 1:40 PM	5/21/08, 2:00 PM	0.0265 ± 0.0132	0.0307	14
6	5/22/08, 6:50 AM	5/22/08, 7:15 AM	0.0265 ± 0.0132	0.0330	20
7	5/23/08, 8:49 AM	5/23/08, 9:30 AM	0.0353 ± 0.0132	0.0312	13
8	5/23/08, 2:25 PM	5/23/08, 3:00 PM	0.0353 ± 0.0132	0.0394	10
9	5/27/08, 9:43 AM	5/27/08, 10:15 AM	0.0529 ± 0.0132	0.0421	26
10	5/27/08, 2:45 PM	5/27/08, 3:15 PM	0.0529 ± 0.0132	0.0587	10

As indicated in the tables, every movement above 0.0265° was accurately detected over this longer time period. Thus, it is clear that the lower limit of detectable pier movements is no more than 0.0265° ± 0.0132° or 1.6 arc-minutes when the fuzzy threshold was applied to this laboratory data, on a 45 minute time scale. The parameters of the fuzzy threshold are adjustable as shown in equation 1, such that this system measurement capability can be adjusted to match the needs in the field.

Multi-dimensional Pier Rotation Tests

Further testing was conducted in the laboratory to demonstrate system capability to detect rotation about both axes simultaneously. To be effective in the field, it is necessary for the sensor arrays to be capable of measuring tilt of the pier in any direction, not just along a particular axis chosen to match the anticipated behavior of the pier. To evaluate the sensor arrays in the laboratory, multi-dimensional pier rotation tests were conducted that include rotation about both axes of the sensors, and vertical displacement of the pier in the absence of tilt.

The first of these tests was conducted in order to evaluate the output of the sensors arrays when pier rotation was about both sensor axes. Figure 12 shows the output from x- axis of the sensors in the 2 arrays located along the pier during the multi-dimensional test. This figure shows individual outputs of each of the six sensors.

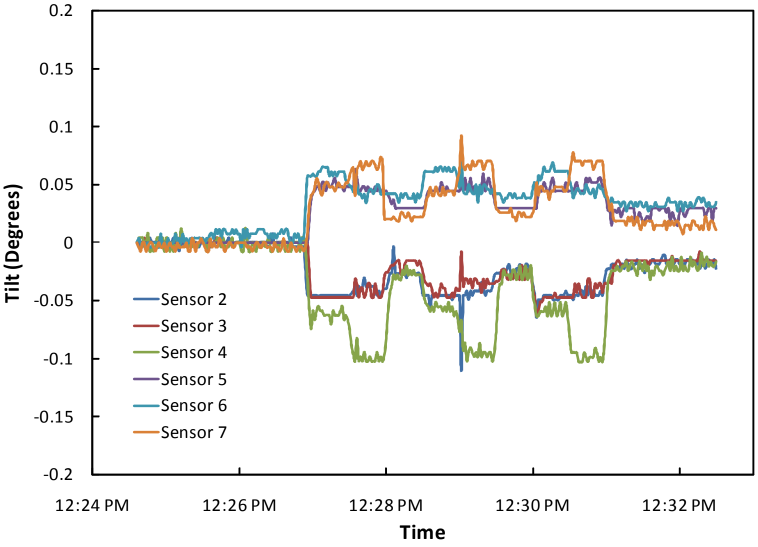


Figure 12. Sensor output from x-axis for multi-directional pier rotation test.

Combining the outputs from the two sensor arrays, the overall motion (displacement) of the pier was determined and is shown in Figure 13. In Figure 13, the three clusters of points represent the *location* of the top center portion of the pier, calculated based on the combined output of the individual rotations (tilt) from the sensor arrays mounted on the pier. The single point in the center is the initial position (encircled). As each screw jack was tightened at the base of the pier, the top of the pier tilted in the direction of the screw jack. Figure 13 shows that the multi-dimensional motion of the pier was effectively detected by the sensor arrays and converted to physical motions (displacements) of the pier based on the measured tilt.

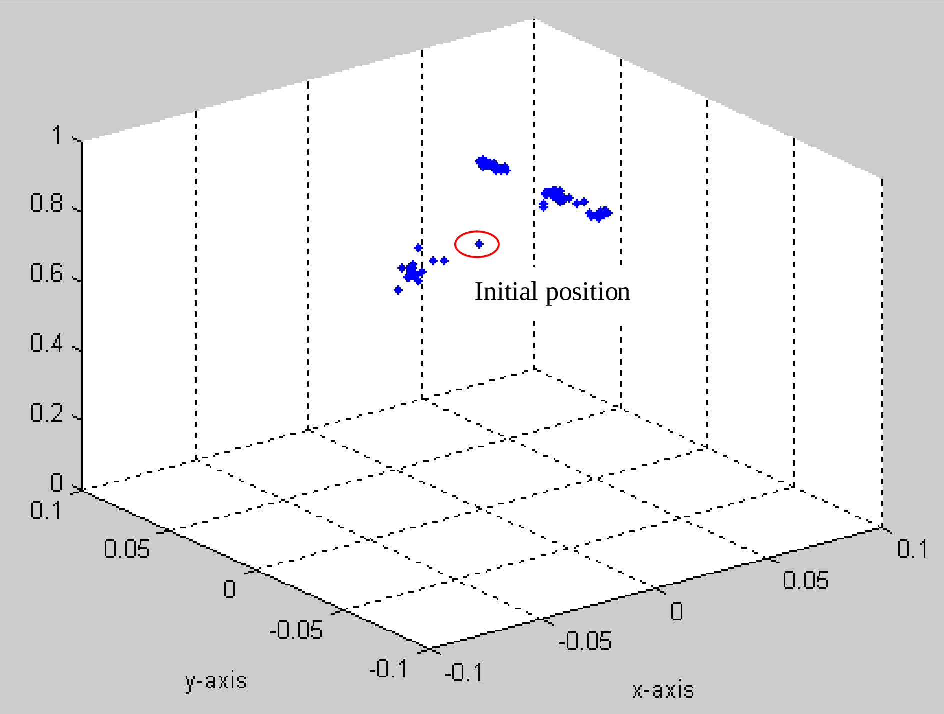


Figure 13. Displacements of the pier determined from tilt measurements by sensor arrays.

Superstructure Displacement Test

The superstructure displacement test consisted of raising the bridge pier incrementally by turning each screw jack equally, resulting in a vertical displacement of the pier without tilt. The output from the three sensors located on the superstructure is shown in Figure 14. This Figure shows the tilt output measured in the superstructure of the test bridge as a result of the center pier of the bridge displaced vertically. This test was conducted to demonstrate the ability of a sensor array located on the bridge superstructure to respond to vertical pier displacements, as might occur if unexpected settlement were occurring in the bridge and causing settlement of the bridge without any tilt actually occurring in the pier itself. The sensor outputs were used to determine the movement of the bridge pier, specifically the vertical displacement of the superstructure at the pier that would result from vertical displacement of the pier. Table 3 shows the result of the superstructure displacement test. The Table indicates both the movement applied to the bridge, and the vertical displacement calculated based on the tilt of the superstructure array sensors (Array C) and using the fuzzy threshold approach.

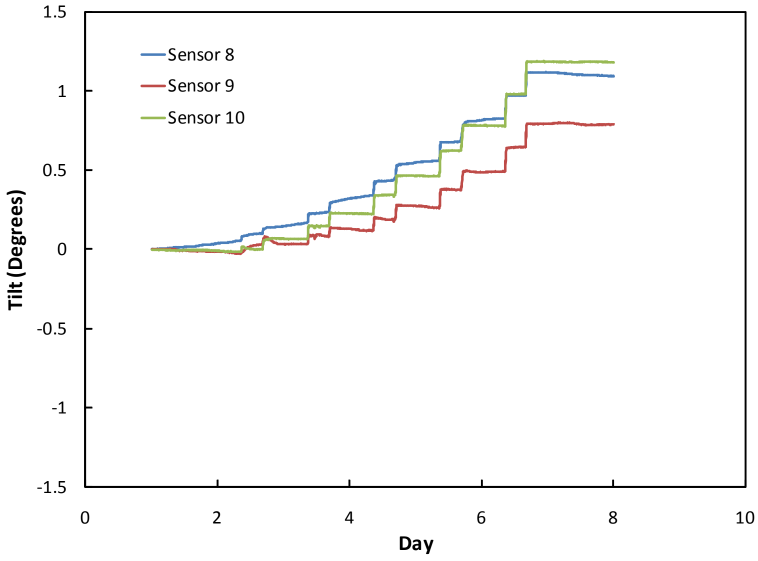


Figure 14. Output from sensors mounted on the test bridge superstructure.

As shown in Table 3, every movement was detected by the system and measured within a 25% error. It is worth noting that, in general, as the applied movements increase in magnitude, the error in the measurements decreases, as would be expected. In addition, the smallest displacement tested, 0.045 ± 0.011 inches corresponding to 0.029 ± 0.007 degree change in tilt of the superstructure sensors for the test bridge, was detected and measured by the superstructure array. Overall, the test was successful in verifying the effectiveness of the superstructure array and the corresponding algorithms to detect and measure an overall vertical displacement of the pier in the absence of tilt, based on tilt of the superstructure members.

Table 3. Applied and measured movements from vertical displacement test.

Movement	Time		Pier Displacement (in)		Change in Tilt (degrees)		Error (%)
	Applied	Measured	Applied	Measured	Applied	Measured	
1	6/9/08 8:30 AM	6/9/08 8:45 AM	0.045 ± 0.011	0.037	0.029 ± 0.007	0.024	20.8
2	6/9/08 4:20 PM	6/9/08 4:45 PM	0.045 ± 0.011	0.059	0.029 ± 0.007	0.038	23.7
3	6/10/08 8:45 AM	6/10/08 9:00 AM	0.091 ± 0.011	0.103	0.058 ± 0.007	0.066	12.1
4	6/10/08 4:30 PM	6/10/08 5:00 PM	0.091 ± 0.011	0.103	0.058 ± 0.007	0.066	12.1
5	6/11/08 8:35 AM	6/11/08 9:00 AM	0.136 ± 0.011	0.148	0.087 ± 0.007	0.095	8.4
6	6/11/08 4:40 PM	6/11/08 5:15 PM	0.136 ± 0.011	0.153	0.087 ± 0.007	0.098	11.2
7	6/12/08 8:40 AM	6/12/08 9:15 AM	0.182 ± 0.011	0.202	0.117 ± 0.007	0.129	9.3
8	6/12/08 4:45 PM	6/12/08 5:15 PM	0.182 ± 0.011	0.194	0.117 ± 0.007	0.124	5.6
9	6/13/08 8:40 AM	6/13/08 9:00 AM	0.227 ± 0.011	0.251	0.145 ± 0.007	0.161	9.9
10	6/13/08 4:00 PM	6/13/08 4:30 PM	0.227 ± 0.011	0.258	0.145 ± 0.007	0.165	12.1

Embedded Sensor Test

An important issue in the field application of the tilt sensor technology is the effects of normal ambient temperature variations on the tilt measurements of a bridge pier. Because the pier heats and cools at a much different rate than the surrounding environment, including sensors intended to measure the pier motion, the measured motions and actual piers motions can be inconsistent. One approach to addressing this issue would be to embed the sensor within the concrete, such that it heats and cools at the same rate as the concrete. Such a sensor configuration would help reduce the uncertainty of measured tilt values, which may be affected by variations in the tilt measurement stemming from changes in tilt of the sensor associated with the sensor mounting configuration. To evaluate this innovative concept, laboratory tests were conducted with the tilt sensor module embedded in concrete. Commercially available tilt sensors are not typically configured to enable this type of installation. Figure 15 shows a schematic diagram of the laboratory test configuration, with the sensor module disconnected from the supporting electronics and embedded in a 2 inch diameter block-out in a concrete slab set on-end. The sensor module was mounted in a 1 in. square plastic tube, potted in epoxy, and then grouted into the block-out. A series of shims were used to cause tilt to the concrete slab for measurement validation. Tilt sensors in a normal, board-mounted configuration were mounted on the surface of the concrete slab and utilized as a test control. These control sensors were used to compare the results for the embedded sensor.

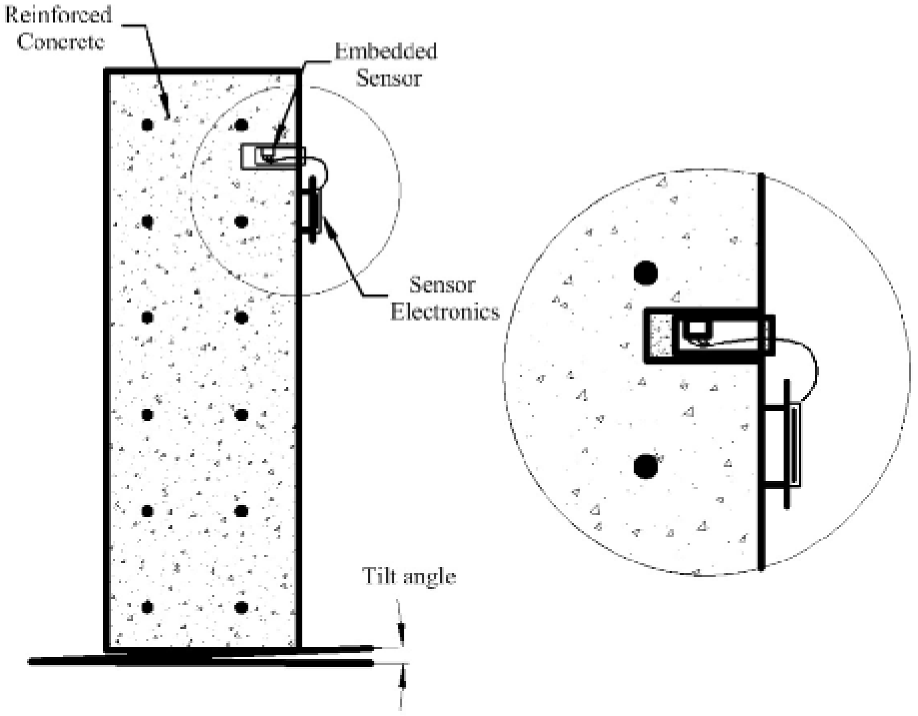


Figure 15. Diagram of embedded sensor design used for laboratory testing.

Laboratory testing included a long-term drift/noise test to evaluate the sensor performance while embedded in concrete, and a tilt test to compare sensor outputs from the embedded sensor with a normal configuration. The results of the drift/noise test showed that sensors embedded in concrete had much less drift and noise than the control sensors. This result indicated that the sensor mounting on the tilt sensor electronics board, where the sensor module rest directly on a 5 pin connection, resulted in an increase in drift and noise relative to the sensors placed within the concrete. This result indicated that the sensor technology was improved by moving the sensor module off the board, and that the 5 pin mounting on the sensor board was apparently a source of sensor drift.

The second portion of the test was a tilt test, in which the block was tilted incrementally using wooden wedges. Table 4 shows the resulting movement magnitudes for the embedded and control sensors as well as the percent difference between the two.

As Table 4 indicates, the difference between the embedded and non-embedded sensors for every movement was less than 3.69%. Thus, it was concluded that the embedded sensor configuration resulted in measured tilt values that were consistent with the control sensors. In addition to the movement magnitudes, the directional results were also determined for the control and embedded sensors. These results indicated that there was no apparent effect on the directional characteristics of the sensor outputs from placing the sensor separately from the support electronics.

Table 4. Movement magnitudes for embedded sensor test.

Movement	Movement Magnitude (degrees)		Percent Difference
	non-embedded	embedded	
1	1.830	1.797	1.83%
2	1.753	1.784	1.80%
3	1.560	1.602	2.68%
4	1.570	1.520	3.16%
5	2.601	2.505	3.69%
6	2.373	2.319	2.26%
7	1.844	1.880	1.98%
8	1.592	1.549	2.69%
9	1.779	1.778	0.01%
10	1.704	1.667	2.21%

FIELD SYSTEM DEVELOPMENT

To implement the results of the investigation, a field-ready system was developed. This included a field data acquisition system designed to provide long-term data acquisition from tilt sensor arrays, unique tilt sensor design developed to overcome limitations associated with traditional tilt sensing technologies, and specialized software to support data collection, analysis and monitoring via a dedicated web site. The developed instrumentation features an on-board web server that enables direct access to real-time measurements from the field, accessible via the web. This section provides descriptions of the system developed for field application.

INSTRUMENTATION

Based on the developments in the laboratory, specialized field instrumentation for data acquisition was developed to support field implementation of the sensor array technology. This instrument provides long-term remote data acquisition of 58 sensor channels and provides a web interface for remote monitoring of a bridge. The system was designed to support 16 dual-axis tilt sensors, each with a temperature sensor used to compensate for temperature variations at the sensor. The system includes additional system parameter sensors, including ambient temperature sensors, internal instrument temperature, internal data acquisition module temperature, and system battery voltage monitoring. The system also provides two video channels that can be used to monitor conditions at the bridge. The system architecture is designed in a modular fashion, such that the number and type of data acquisition channels can be modified to meet specific needs in the future.

The instrument is design to be powered by 120 VAC line power to ensure long-term reliability of system operation. A backup battery system provides approximately two days of operation without line power. This power configuration was selected to provide the most robust system operation and minimal long-term maintenance.

The instrument can be remotely accessed for data viewing and system maintenance. Remote access is provided through a DSL line that was installed on the bridge. The instrument contains an embedded web server so that the instrument is accessible via a dedicated web page. The specifications for the data acquisition system developed for the research are shown in Table 5.

The features of the system developed make it a unique tool for the field testing of bridges and include:

- Very low power operation (<70 W)
    - Extended operation battery backup
- Redundant data collection and backup
- Embedded web server

    - Remote setup and maintenance
    - Stand-alone operation
    - Local wireless access for setup / configuration
- Video camera support
- Small footprint (18x16x10 inch)
- Flexible modular subsystems
- Secure multi-role user access

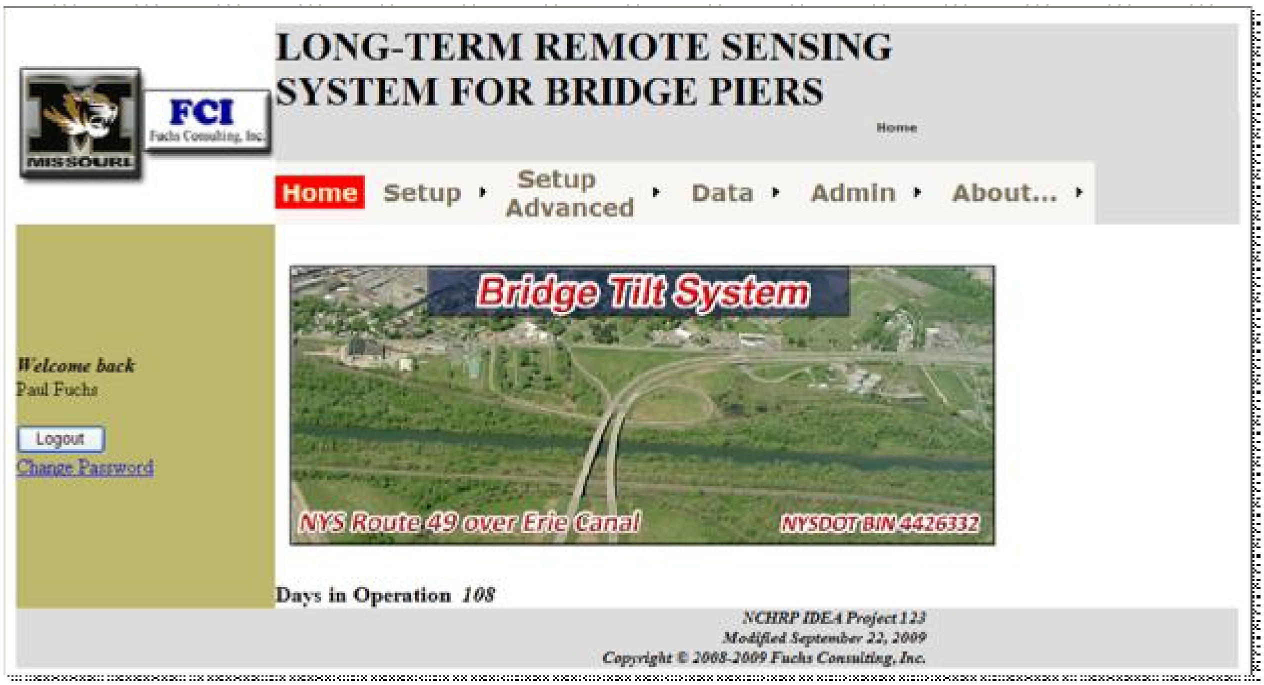
Table 5. Specifications for data acquisition system.

System	Parameter	Specification
Sensor	Channels	58
	Types	Dual axis tilt Temperature Battery voltage
Embedded Computer	Hard Drive	160 GB, IDE
	Processor	AMD Geode GX 400 MHz
	Memory	512 MB
	Operating System	XP Embedded
Communications	ISP Type	DSL
	Wireless	Wireless G access point 802.11g/802.11b
Power	Total system power	120 VAC @ 0.56 amps (67 W)
	Battery Type	12 V @ 100 Amp-Hour, SLA
	Battery backup	2 days of operation
Video	No. of Cameras	2
	Type	Day/night 1/3” color, Weatherproof
System Size	Main instrument	18 x 16 x 10 inches, 43.5 lbs
	Battery	17 x 16 x 10 inches, 74.5 lbs

The instrument can be accessed remotely via an embedded web server. There are three levels of accounts for the instrument website. Each level provides varying degrees of access to the instrument, from simple viewing of summary data and instrument videos to full system administration. Using these separate levels of access to the instrument allows for users of the system, such as bridge owners, to have the ability to access the data that they need on the system, without concern that they could modify the operating parameters of the system. System developers, using accounts with broader access to the instruments operational parameters, can remotely test the system, install upgrades or implement changes to the system as needed over time. Because the system uses a dedicated web server in the instrument, complete remote access to all of the operational aspects of the system is available, including restarting the system if necessary to address operational changes, adjusting the sensor parameters, etc..

ONLINE DATA

Data from the sensor array outputs can be accessed via the dedicated web site developed as part of the system. The web site home page is shown in Figure 16. From the home page for the bridge tilt system, a user has access to all of the data collected from all of the sensors, dating back to the original date of installation. Data is displayed in a variety of formats. Summary graphs are provided that contains a host of information and data from the sensors arrays. The data presented for remote monitoring of bridge behavior will be discussed in more detail in later sections.


LONG-TERM REMOTE SENSING SYSTEM FOR BRIDGE PIERS

Welcome back
Paul Fuchs

Days in Operation *108*

NCHRP IDEA Project 123
Modified September 22, 2009
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Figure 16. Homepage for the bridge tilt system installed in Rome, NY.

DATA PRESENTATION

Software was developed and implemented to provide simple presentation of the output of the sensor arrays for evaluating the long term behavior of the bridge. The primary data presentation that is shown when accessing the web site displays data processed to provide key information on the behavior of the bridge pier. First, the graph shows the average output for a given array, shown as a green line in Figure 17. The array averages are the weekly average of measurement from the given array. The graph shows 3 months of data (12 weeks) from the test bridge in New York; this time interval is adjustable and may be increased in the future as additional data is collected. A bar representation on the graph shows the average output of a specific sensor in the array (each bar is the average over a one week period), such that individual sensor outputs can be readily observed. Finally, the overall average for all of the sensors over the entire time interval (12-weeks) of the graph is shown. This data shows the change in tilt values over the range of the graph, relative to the initial sensor readings at the time the system came on line (September 18, 2009). A data table at the bottom of the plot shows the actual measurements from each of the sensors for each time interval of one week. To observe data from a different sensor in the array, a user simply presses the “page down” key to go to the next sensor. The output of each axis for each array is shown on the initial data screen when the web site is accessed, such that the overall behavior of the bridge pier can be quickly assessed by the user by looking at one page of data.

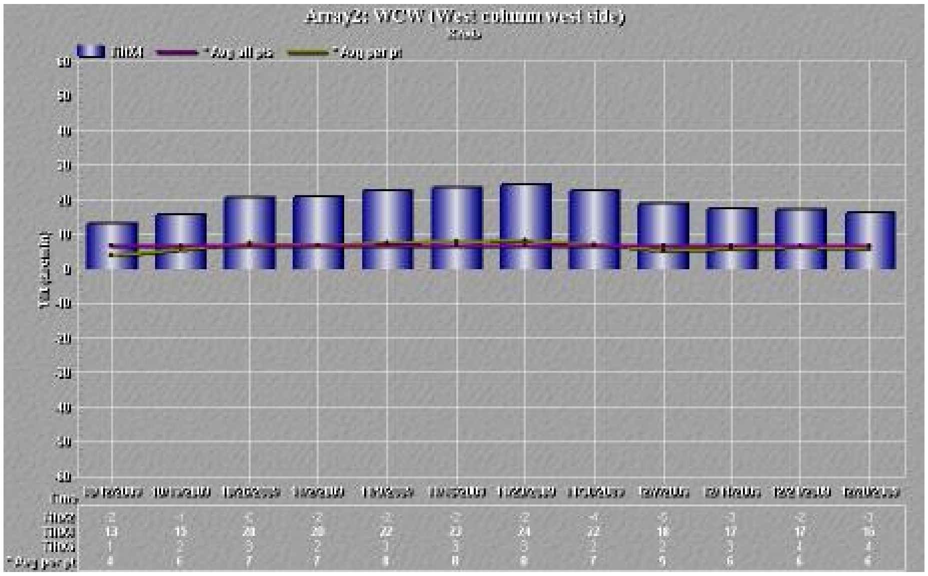
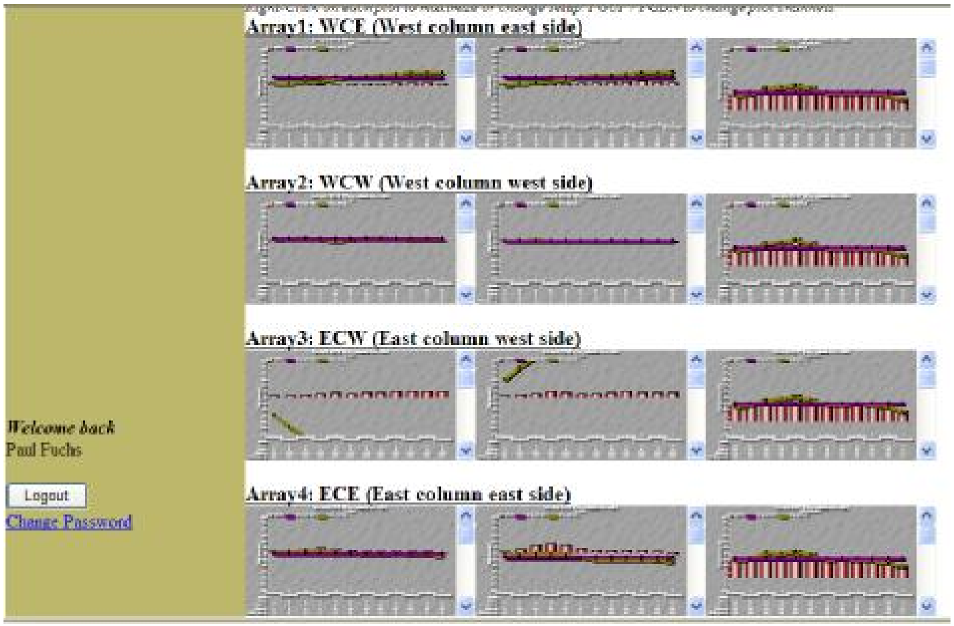


Figure 17. Data presentation for output of bridge pier tilt monitoring system.

The data plots for each of the 5 sensor arrays are shown on the DataView page of the website, and these graphs load automatically when the page is accessed. The Data View page is shown in Figure 18 (four of five array are visible in this figure). As shown in the Figure, graphs include the X and Y axis data for each sensor array, and the temperature measurements from the arrays. This graph provides easily accessible, quick summary of all of the data from all of the arrays. This data plot shows the long-term trends in an easy-to-interpret manner with all arrays displayed together. Each graph can be maximized by simply clicking on the graphic, and a user can zoom-in on specific data of interest by simply encircling the data of interest with a mouse selection box. Figure 17 is a maximized version of the plot for array 2 that is shown in Figure 18 in reduced form.

Further analysis of the data can be accomplished by predefined plots for displaying sensor data. This includes plot for individual sensors, or arrays of sensors. Various parameters such as the time period included in the plot, sensor parameters and scaling are all available on-line to the user. Data can also be downloaded for off-line analysis. The plotting functions and dedicated website were all developed as part of the research effort.



Array1: WCE (West column east side)

Array2: WCW (West column west side)

Array3: ECW (East column west side)

Array4: ECE (East column east side)

Welcome back
Paul Fuchs

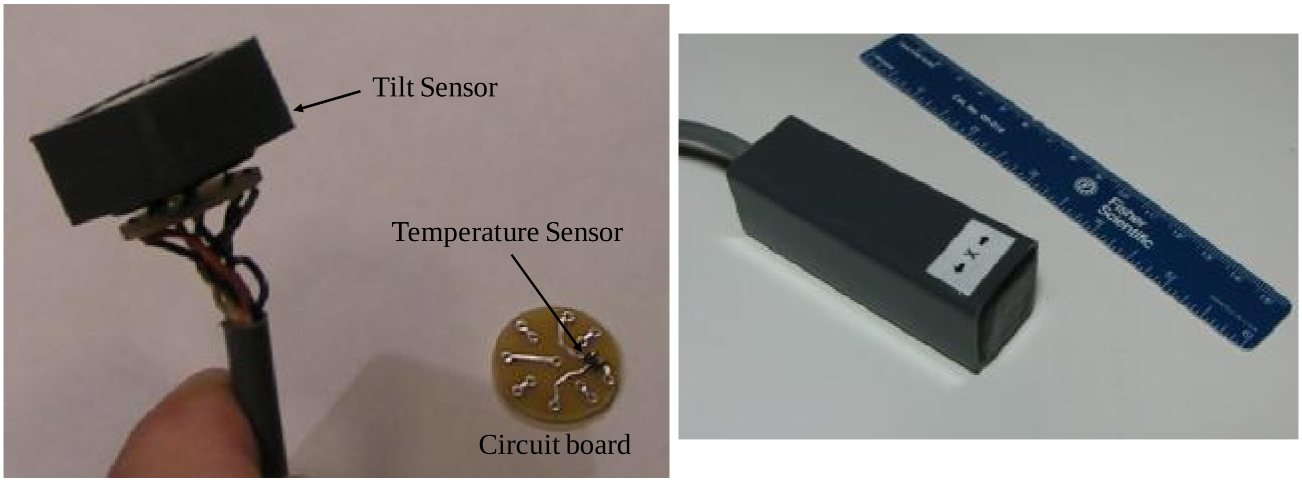
Figure 18. Image showing data view for summerized tilt data from field test bridge.

SENSOR DESIGN

To implement the sensor arrays in the field, a specialized sensor design was developed to place the tilt sensor in contact with the surface of the concrete pier and allow the sensor temperature to match the concrete temperature. The primary purpose of the unique sensor design was to enable the sensors to be mounted on the structure in such a manner that the sensors and the concrete of the bridge would be maintained at the same temperature, such that thermal effects of sensor mounting hardware would be minimized. The dual-axis electrolytic sensors were mounted on a specially fabricated circuit board that enables the tilt sensor and a temperature sensor to be mounted remotely from the supporting electronics, such that sensors themselves could be mounted directly on the surface of the concrete. The same sensor design would also enable the sensors to be placed inside the concrete by coring a small, 1 inch diameter hole in the concrete and grouting the sensors within the concrete, as previously discussed. This configuration was not used in this initial testing, but was developed and tested as part of the research and can be utilized in the future.

Each electrolytic sensor module was mounted on a specially fabricated circuit board shown in Figure 19a. A semiconductor temperature sensor was integrated on the board to provide accurate temperature measurements at the sensor. These temperature measurements at the sensor are necessary to provide temperature compensation for the small thermal variations in the sensor electrolyte. The specialized circuit board with integrated temperature sensor was designed and developed as part of the laboratory research effort.

For installation on the bridge, this sensor was mounted within a polymer enclosure and potted using a special epoxy with thermal conductivity close to that of steel, as shown in Figure 19b. The epoxy was chosen to provide a thermal path from the concrete (or steel) on the bridge and the sensor itself, to provide thermal equilibrium between the materials. When installed on the bridge, each sensor is covered with a thermal shield to protect the sensor from diurnal temperature changes in the environment, which are always out of phase with the thermal changes in the concrete due to the concrete's large thermal mass and relatively low thermal conductivity. This unique sensor design was used to ensure that tilt measurements made by the sensor matched the actual tilt of objects being measured, rather than the result of thermal changes to the mounting hardware holding the tilt sensor.



(a) (b)

Figure 19. Photograph of the tilt sensor and the circuit board with temperature sensor (a) potted in sensor housing (b).

An electronics module was designed and manufactured to support the sensor modules. Each electronics module contained the drive electronics for the sensors, signal conditioning and output signal from the sensors. Power was supplied to the electronics modules from the main system instrument mounted on the bridge. Each electronics module supported two sensors, as shown in Figure 20. The drive electronics in the module are independent for each sensor, such that the sensors that share an electronics module could be part of different sensor arrays when configured on the bridge.

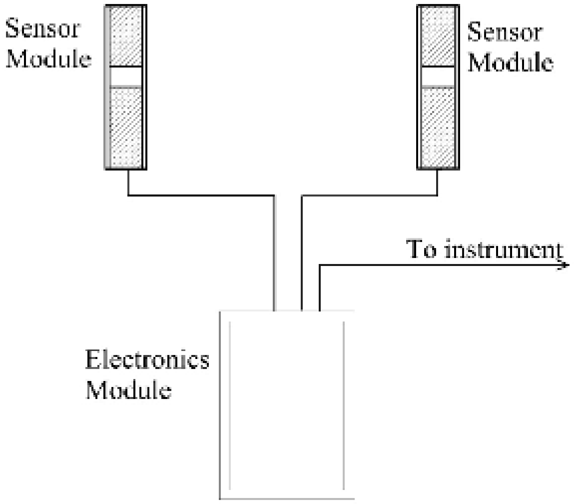


Figure 20. Schematic diagram of sensors and electronics modules.

FIELD INSTALLATION

Test Bridge Description

The field test bridge selected for system installation was located in Rome, N.Y. on NYS route 49/365 over the Erie Canal. Figure 21 shows an aerial photograph of the portion of the bridge where the key pier, pier 3, is located. The bridge is a steel girder bridge with continuous spans constructed in 1980. The deck of the bridge is concrete with steel stay-in-place forms. The seven-span structure has six piers, with a four-span and three-span continuous bridge sections meeting at Pier 3.

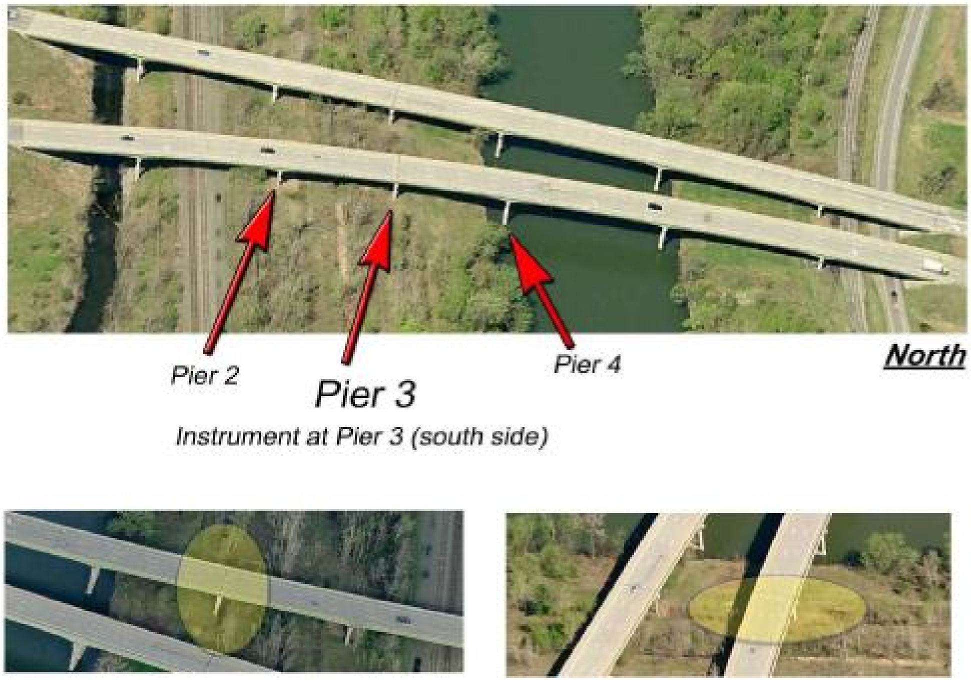


Figure 21. Aerial photographs of the field test bridge location.

An elevation view of pier three is shown in Figure 22. The pier extended ~24 ft. from the ground level. The piers were constructed of three circular concrete columns extending to a pier cap that supported five girders comprising the superstructure of the bridge. The bridge was selected as the field test site for the tilt monitoring system because the bearing at pier 3 had unusual extension under normal operating conditions. The bearing at pier 3 consists of a slider plate, as shown in Figure 23. At the time of the photograph, the temperature was ~40 °F and the bearing was fully extended, as shown in Figure 23. If operating normally, the bearing should be fully extended only under high temperature conditions in the summer; during cooler temperatures, the bearing would be expected to not be fully extended. The expansion bearing had been previously relocated to accommodate bridge movements and the extension of these bearing devices. This was accomplished by jacking the bridge and moving the bearing plates to accommodate the motions of the bridge, as shown in Figure 23. Previous bridge inspection reports had also indicated that the bearing device was fully extended at 70 °F. The source of the displacements occurring at this bearing is not known. Such unusual behavior of the bearing devices could result in lateral forces pushing on the top of the pier, as the bridge attempts to expand and contract under changing thermal conditions. Lateral forces applied at the top of the pier were not anticipated in the design of the bridge, since a sliding expansion device was provided to accommodate superstructure movements. This could have eventually displaced the bearing and led to unexpected behavior of the bridge. Due to the condition of this bearing device and the potential for unexpected lateral forces at the top of the pier, this pier was selected for monitoring. The objective of the monitoring is to evaluate the tilt behavior of the pier, and to monitor the movement of the pier over longer periods of time to determine if the pier has irregular motions that could help explain the performance of the expansion device.

Figure 22. Photograph of pier 3 of the bridge.

Figure 23. Photograph of expansion device at pier 3.

Infrastructure at the Bridge

The field data acquisition system operates from the battery system that is continuously charged with standard, 120 V AC power. Power was acquired at the bridge from an existing utility system utilized to power navigational lights along the fascia of the bridge. The power was hard-wired to the field system with the assistance of the NYSDOT. Data communication with the field system is achieved via a DSL line installed at the bridge. The necessary telephone line was installed in the field by Verizon, the local telephone provider. Due to the location of the bridges, this required installing a new telephone line and routing that line underground over about 2,500 feet. The routing of the DSL service resulted in unexpected delays in the installation of the system in the field. A hard-wired communications option was chosen for long-term reliability, maximum performance during extreme weather events, lower instrumentation cost, and for needed high-speed internet access for optimal performance for multiple users accessing the system via the web server.

Sensor Layout on the Bridge

A sensor layout design was developed for the bridge to monitor pier 3. To monitor the long-term displacements, five arrays were assembled. This included four arrays on the vertical portions of the pier and one array on the bridge superstructure. The arrays along the length of the pier columns are intended to monitor the tilt of the piers, while the sensor arrays on the superstructure of the bridge are intended to monitor vertical displacements. The schematic layout of the sensors and electronics modules is shown in Figure 24. Each array mounted on the bridge pier columns consisted of three sensors mounted vertically up the pier, separated by ~5 feet. In this configuration, Array 1 and Array 2 monitor the west pier column, and sensor Arrays 3 and 4 monitor the east pier column. Arrays 1 and 2 should provide redundant measurements of the west pier movements, while Arrays 3 and 4 should provide redundant measurements of the east pier.

The sensors placed on the superstructure of the bridge were fastened to the web of the girder using a special epoxy and a magnetic holder to ensure the sensor remained stable over time. These sensor will measure the rotations of the superstructure of the bridge. Over shorter time intervals, these sensors might show rotation of the bridge members as a result of live loading passing over the bridge. However, for our application, these sensors are sampled over longer time intervals to detect trends in motions of the overall superstructure rather than these short–term rotations. The sensors were placed in pairs on two of the superstructure members to provide two independent measurements of the superstructure rotation at each location. This provides redundant measurements at each member to ensure reliable data outputs and for comparison when analyzing data. The sensor module numbers in each of the arrays is tabulated in Table 6.

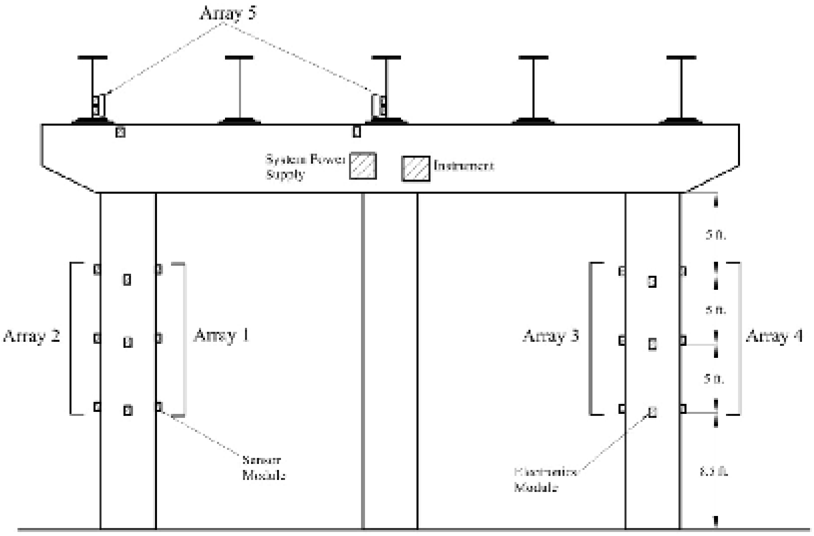


Figure 24. Schematic diagram of sensors placement on the bridge in Rome, NY.

Table 6. Sensor array configuration.

	Array 1	Array 2	Array 3	Array 4	Array 5
Sensor Module	1	2	7	8	13
	3	4	9	10	14
	5	6	11	12	15
	-	-	-	-	16

The sensor modules were mounted directly on the surface of the concrete columns to ensure close thermal matching between the sensors and the concrete. The sensors were secured in a mounting bracket that was mechanically fastened to the concrete using Tapcon screws. A typical sensor mounted on the surface of the concrete is shown in Figure 25 (left). Epoxy was used to secure the sensor to the concrete surface to provide second means of attachment for the sensor, which is primarily held in place by the mechanical connection provided by the bracket.

The sensors were mounted is arrays extending vertically up the piers as shown in Figure 25 (right). In this figure, three sensors are shown along the side of a column at pier 3 of the bridge, with thermal shields in place to reduce the effects of diurnal temperature variations. The thermal shields were used to cover the sensor and were also secured to the pier mechanically with a second metal bracket. These thermal shields are constructed of insulating Styrofoam, and protect the sensor from inadvertent impact as well as ensuring close thermal matching between the sensor and the concrete.

Figure 25. Sensors mounted on bridge: individual sensor (left) and a three sensor array (right).

The instrument to support the sensor, collect data and provide the web server for observing the data from the field test bridge was mounted on the side of the pier cap as shown in Figure 26. The instrument was hard-wire to the power source at the bridge and to each of the tilt sensors on the pier and superstructure of the bridge. The battery and instrument were attached mechanically to the pier cap. All sensors and associated system instrumentation were installed over a 2-day period on September 17 and 18, 2009. The instrument initiated data acquisition from the sensor arrays at 5:00 pm on September 18, 2009.

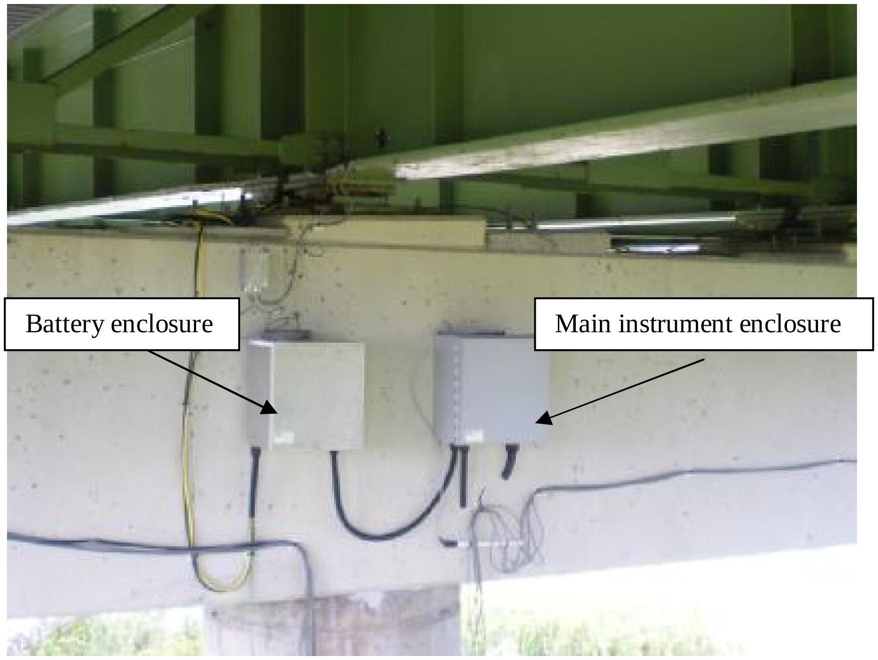


Figure 26. Photograph of main instrument enclosure and battery enclosure mounted on the bridge.

MONITORING RESULTS

Initial results from the field installation of the system have indicated that the monitoring system is performing well. All sensors and sensor array are functioning, and the system has collected more than 150 days of continuous data on the tilt and displacement behavior of the bridge. Sensor data is of very good quality and all sensors exhibit low-noise performance as designed. The system has undergone loss of AC power and has maintained its uninterrupted operational status throughout the power outage using the battery backup. The DSL service, provided locally by Verizon, suffers periodic interruptions due to the quality of the Verizon DSL service locally in Rome, NY. Limited access to the bridge site and difficulties working with the DSL vendor from a non-local area has precluded having the vendor fully address the quality of service. However, the system operation is not interrupted by these outages, and all data from the sensor arrays is maintained on the system. This section provides some initial results of the monitoring of the field test bridge. This includes an example of 10 days of data to illustrate the thermal effects on the array, and a longer 90 day interval showing the long-term monitoring characteristics of the bridge.

10 day example

Figure 27 below shows the output of arrays 3 and 4, located on the east pier. The sensor array outputs shown in the Figure represent the motions of the bridge pier in the longitudinal direction of the bridge over a 10 day period. The data shown in the graph is derived from the tilt measurements from 6 sensors in two arrays, arrays 3 and 4, located on the east pier of the field test bridge. Temperature measurements are also shown in the Figure 27. The ambient temperature measurement values (°C) are plotted on the right vertical axis, the sensor data (arc-minutes) values are plotted on the left vertical axis. The sensor array output for array 3 and array 4 are shown, as well as the average of the sensor array output. The sensor arrays are located on opposite sides of the pier column. The data shows a number of interesting characteristics from the bridge. First, the daily rotations associated with the diurnal temperature measurements can be observed, and track closely with the ambient temperatures. Typical daily rotations range over ~ 5 arc-minutes or 0.0833° can be observed. These rotations display the normal, small movements that could be expected for a bridge. The Figure also shows that the rotation measurements are out of phase (delayed) relative to the ambient temperature variations. This is the result of the thermal mass of the concrete pier, which heats and cools at a different rate than the ambient temperature variations.

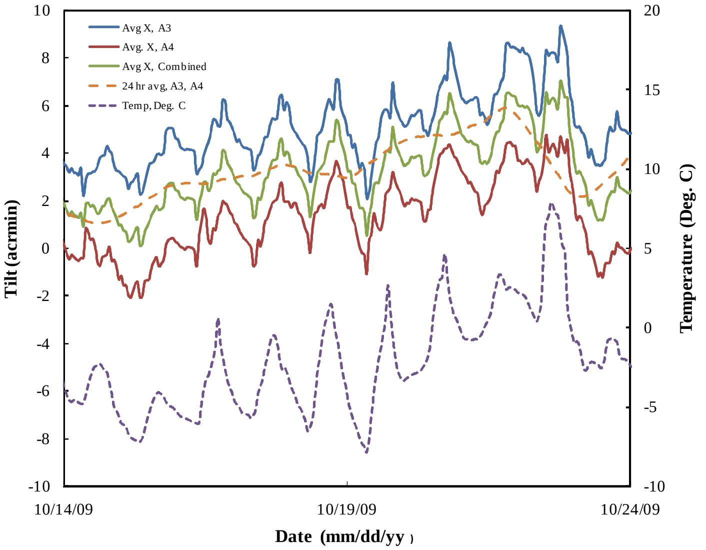


Figure 27. Sensor array ouputs from arrays 3 and 4, and diurnal temperature variations at the sensors.

Figure 27 also shows the 24 hour average tilt measurements, which is determined from the average of the two sensor arrays, averaged over 24 hours. This data shows the longer term trend of tilt of the bridge pier, and the trend of the rotations (tilt) follows the overall trend of the temperature data, as would be expected if the sensors were tracking closely the tilt of the pier, and the pier was not tilting in an unusual manner. This trend of the tilt measurements, when observed over a longer time period of a year or more, can be used to detect the long-term displacements of the pier and detect if movement is occurring. This data shows the value of the measurements and the ability of the system to monitor long-term displacements, as well as the successful implementation of the original design concepts proposed for the research.

Three Months of Data from the Test Bridge

This section includes data from the first quarter of monitoring the field test bridge. The data presented includes raw data from the sensors, sensor array modules, and data on the longer term trends. Data shown are taken directly from the system web site and represent that type of output plots created by the system and accessible to an operator.

Figure 28 (top left) shows the output from the monitoring system over a period of three months from October 1 through December 31, 2009. The figure shows the output from each sensor in Array 2, showing both the x-axis tilt (parallel to the bridge superstructure), the Y-axis (perpendicular to the bridge), and the temperature measured at each of the three sensors in Array 2. The data shows the effects of diurnal temperature variations, which appear as high frequency noise when the data is viewed at the three month scale. These minor variations in the tilt measurement are indicative of the normal daily motions of the pier, and give a measure of the magnitude of normal daily tilt. The Figure also shows the data from the month of December (top right) and a single day in December (lower left). The correlation between the sensor response and the daily temperature variations can be seen most easily in the plot of data from a single day. Three weeks of data (lower right) is also shown for only the x-axis of Array 2. This plot is derived from the zoom function available on the web site that allows the user to simply encircle data that they want to view, and a new plot is created that shows only the selected area of the original plot.

The data from the initial three months of monitoring illustrates some important advantages of the array system. Because there are multiple measurements occurring, the effects of daily temperature variations can be easily observed and confirmed. One channel of data, the x-direction tilt of sensor 16, drifts slightly from the other sensors for some portion of the three month period, but trends back to correspond to the other sensor output over the three month period. The data shown in Figure 28 illustrates the ability of the system to successfully monitor the bridge over long time periods without interruption, and detect the bridge rotations associated with diurnal temperature variations, which are relatively high frequency, and the longer term trends associated with seasonal temperature variations. The system is monitoring the bridge continuously, and longer term trends are expected to become apparent over time.

Figure 28 also illustrates the relative ease of use of the system, providing visual examples of the data output that is available to the bridge owner when accessing the system web site. Fully functional graphing tools enable a user to zoom in on any period of time in the data for further analysis, adjust the parameters for the data to be graphed, and observe the output of the monitoring system at different time scales.

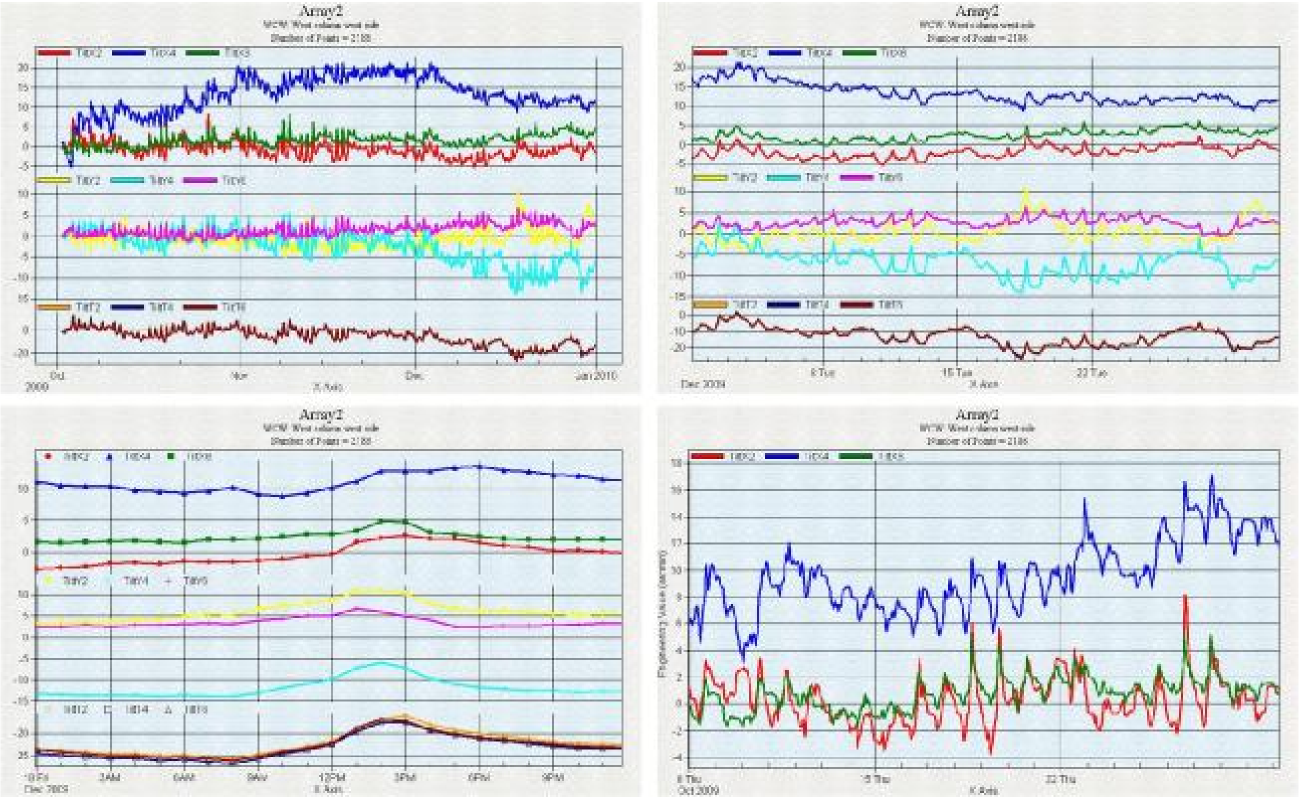


Figure 28. Graphs of data from the initial three months of field testing.

The combined data from arrays 1, 2, 3, and 4 are shown in Figure 29. This Figure shows the overall tilt of the pier structure over the entire three month period, using the array configuration to reduce the effects of diurnal temperature variations and reveal the long term tilt of the pier. The Figure shows the combined output for both the x and y axes of the sensor arrays, as well as the ambient temperature variations over that time period (October 1 thru December 31, 2009). As shown in the image, when the arrayed sensors outputs are combined, the effects of the drift of individual sensor is eliminated to show the actual tilt behavior of the structure in a simple and easy to review plot. The temperature variations over this time period are also shown (right axis). These tilt variations have been very small over the initial three month period, about 0.1°, or 6 arc-minutes, over three months. For the tilt along the x direction, a maximum positive tilt of less than 0.1° (6 arc-minutes) was experienced. However, as the Figure shows, over the long term this tilt measurement corresponds or tracks with the longer term temperature trends of the bridge during the seasonal change from fall to winter. Over the course of the year, this tilt is expected to track with the seasonal changes, and can be observed to determine if this tilt continues to perform in that anticipated manner. In any case, the displacements of the bridge pier are very minor and within expected limits over this time period.

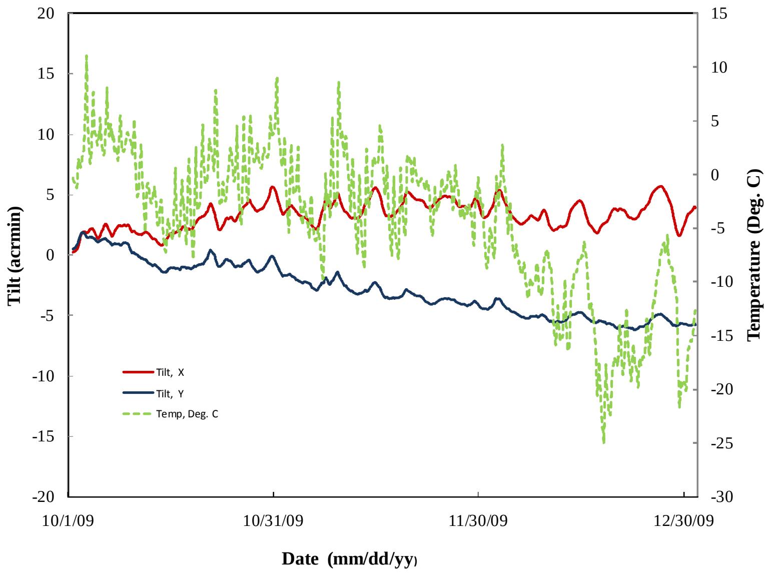


Figure 29. Pier rotations for the initial three months of monitoring.

System Performance After 1 Year

This section of the report describes the results from the monitoring system after 1 year of operation. During this time period, the system collected data without interruption. Data was collected from each of the sensors in each of the arrays, for both the four arrays on the piers and the array located on the superstructure. This section provides a summary of the data output for a time period of 1 year for the arrays located on pier 3 (October 1, 2009 thru September 30, 2010). At this time of this report, the system continues to operate and collect data at the site.

Tilt data from the individual sensors shows that a few sensors are providing erroneous data. Based on the sensor output, it would appear that these sensors may have been damaged during installation or there was a problem with the mechanical connection of the sensor to the pier that caused sensor output quality to deteriorate over time. Since the array system provides a series of redundant measurements, individual sensors that suffer malfunction, damage or installation issues can simply be removed from the data processing to provide a suitable data set for analysis. Figure 30 shows the combined data output from the sensor arrays over the course of 1 year, for the both the X and Y orientations of the sensor in Arrays 1, 2, 3 and 4 combined to provide a single tilt measurement for the pier. Overall, tilt measured for the pier remains relatively small, and generally track with the ambient temperature changes over the course of the year. For tilt in the X direction, aligned with the longitudinal axis of the bridge, there appears to be a slight tilt developing of only approximately 15 arc minutes (0.25 degrees) based on the averaged output of the sensor arrays. For tilt in the Y direction, perpendicular to the axis of the bridge, sensor outputs have indicated some very small motions of the pier that appear to be centered around zero tilt relative to the original position at the time of installation.

After more than one year in operation, the system continues to successfully monitor rotations of the bridge pier and superstructure. Over the course of that year, data was collected without interruption from each of the sensors. No on-site system maintenance or repair has been required following the initial installation of the system, and the system has operated independently over that time period.

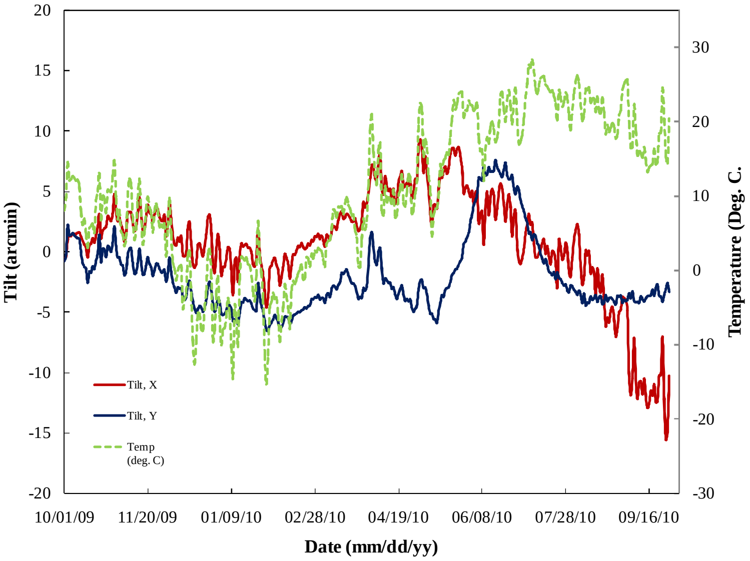


Figure 30. Pier rotations over a 1 year period.

SUPERSTRUCTURE MEASUREMENTS

Sensor Array 5 is located on the superstructure of the bridge, along the webs of two of the girders. The output of these sensors has shown very slight tilt corresponding to temperature variations at the bridge. Figure 30 shows the rotations of the superstructure sensors 15 and 16 (left axis) and the temperature variations (left axis) over a 10 day period. The superstructure of the bridge has had the unusual behavior in that the tilt occurs over short time periods, and then is maintained for a short time periods before returning to its original position, showing a square wave pattern rather than the sinusoidal variations that typically occur in response to diurnal temperature variations. These measurements may indicate a stick–slip behavior of the bearings, as the tilt does not follow the temperature behavior through the course of a day, but rather occur in sudden, short time periods and then holds in position. These tilt measurements are very small in magnitude, only about or 0.05° (3 arc-minutes). Analysis of the data for the superstructure sensors over 1 year have not indicated any unusual behavior or erroneous sensor outputs.

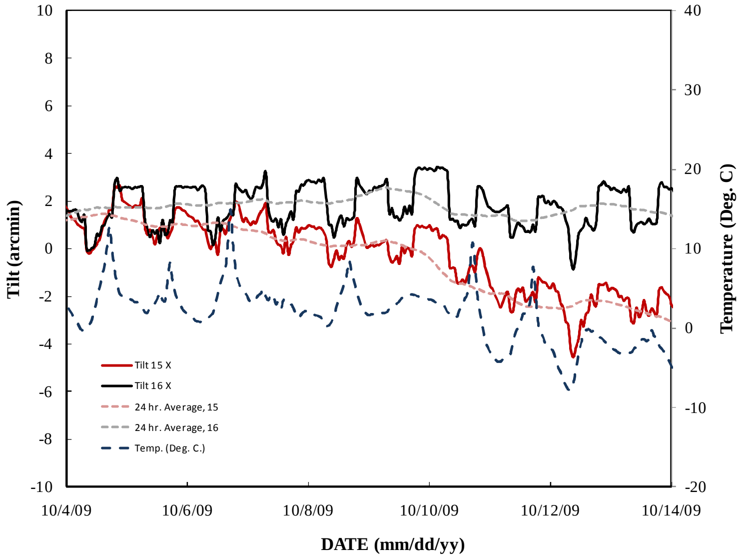


Figure 31. Superstructure rotations over a 10 day period.

CONCLUSION

Unexpected settlement, locked bearings, scour and other natural hazards have the potential to undermine the stability of bridge piers. The goal of this project was to develop and implement a system of tilt sensors capable of monitoring the long-term motion of bridge piers. The innovative concept of the research was to utilize multiple tilt sensors configured in a series of arrays, mounted on both the superstructure and pier of a bridge, to enable long-term monitoring of pier displacements. Initial tests were completed in order to determine sensor characteristics such as calibration factors, temperature compensation factors, resolution, and drift effects. Laboratory testing was completed to develop methods for utilizing the unique array design to reduce noise, counteract the effects of diurnal temperature variations and drift, and allow for reliable measurements to be made over long time intervals (years). Based on the laboratory testing, a field-ready instrument including 16 dual-axis tilt sensor configured in 5 arrays was designed, developed and field tested. A field test bridge that had unusual bearing behavior was selected for field testing, to evaluate if the bearing behavior was resulting in unusual displacements or tilt along the supporting pier. A complete system was deployed in the field, and has been monitoring the field test bridge for more than 13 months without interruption. All sensor data is available over the web, and a variety of data analysis functions are available on–line to allow for remote monitoring of the bridge behavior. Initial analysis of the output from the system has indicated that the sensor arrays are monitoring the pier behavior successfully. The use of the sensor array successfully reduced the diurnal temperature variations and drift associated with the use of individual sensors. The pier behavior has been observed to be tracking with the seasonal temperature variations, as would be expected. Sensors on the superstructure of the bridge are monitoring small, intermittent tilt behavior that may be associated with the bearing behavior. Overall, this initial testing has demonstrated the utility of the innovative, array-based design to overcome limitations of existing approaches for remote bridge monitoring. The initial concepts and design proposed for the research have been successfully developed, implemented and demonstrated in the field.

FUTURE IMPLEMENTATION

The research project has resulted in a field-ready instrumentation and sensor system for long-term monitoring of bridge piers. The developed system is appropriate for monitoring applications including:

- *Monitor new construction for unexpected settlements*
- *Monitor the effects of locked bearing*
- *Monitor long-term thermal effects over multiple seasons or years*
- *Monitor subsurface erosions*
- *Monitor long-term settlements of bridge supports*

The innovative new system has been developed with implementation in mind, such that systems can be reproduced for commercial purposes. The instrumentation was designed in a modular fashion to allow for simple modifications such as adding additional sensor channels, or modifying the types of sensor used to monitor the bridge. For example, for field implementation, a bridge owner may wish to include strain or displacement sensor at the bearing assembly to provide additional data on pier behavior to supplement the data on the tilt of the bridge pier. The instrumentation system was designed with these applications in mind, such that the system can be modified to include such sensors easily. The developed system is available commercially for use by bridge owners.

Additional implementation plans include introducing bridge engineers to the technology by allowing access to the system web site. At the web site, the tilt behavior of the pier can be viewed readily through automatically generated plots that show the long-term behavior of the bridge. The web site include a plethora of information regarding the design of the system and the research overall, and is suitable as a communication vehicle for this new technology.

The results of the research have also been reported to the transportation community at a series of important meetings and events, including publishing papers and making presentation to TRB committees, as part of the TRB Bridge management conference, the FHWA-sponsored Structural Materials Technology conference, and others. Additional implementation and applications for the technology to monitor bridges and help ensure bridge safety are anticipated.

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