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Recent Trends in Bridge Health Monitoring

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Abstract: **Advanced structural health monitoring (SHM) has become an important emerging field in which non-intrusive damage detection techniques are integrated into a structure to continuously monitor the complete bridge or individual bridge components. It is believed that a properly installed SHM system can extend the useful life of bridges by early identification and repair of structural damage or deterioration. This paper presents recent trends and popular technologies in SHM systems. The SHM systems presented are sponsored by several federal, state, or county agencies to address applications including evaluation of a relatively new material for use in bridges; protection of historically significant bridges from arson and vandalism; and detection of damage in fracture-critical bridges. As these leading edge systems prove their capabilities and as technology continues to further develop, it is expected that these state-of-the-art systems will quickly become tomorrow's state-of-the-practice systems. As these SHM systems continue to be improved and implemented, roadway networks across the world will continue to become safer and more manageable.**

Keywords: **bridges, sensor, data acquisition, data management.**

I. INTRODUCTION

In the recent past, there have been rapid advances in the development of technologies for the evaluation of bridges. Advanced structural health monitoring (SHM) has fast become an important emerging field in which non-intrusive damage detection techniques are integrated into a structure to monitor the complete bridge or individual bridge members. SHM is the process of evaluating the condition or change in condition by the collection and evaluation of data [1]. The process involves the observation of a system over time using either continuously monitored or periodically sampled response measurements coupled with analysis of the results. In general, SHM consists of various technological systems such as a sensory system, a data acquisition and processing system, a communication system, and a data management system. The practical applications for the SHM systems have been identified by bridge owners (e.g., state Department of Transportation, etc.) who have structures experiencing behavior that needs to be investigated. The main purpose of developing and implementing these SHM systems is for bridge-owning agencies to improve management of their bridge infrastructure and increase the safety of the nation's roadway systems. This paper presents popular technologies used in SHM and illustrates the state-of-the-art SHM systems deployed for a variety of applications.

II. MODERN BRIDGE HEALTH MONTIROING COMPONENTS

A. Sensors

The most common type of sensors used in SHM application includes displacement sensors, strain sensors, vibrating wire sensors (both temperature and strain), force sensors, and temperature sensors.Kinematic quantities (e.g., strain, displacement and acceleration) and environmental quantities (e.g., temperature, humidity, wind, etc.) are the two main quantities that are typically desired by a sensor based SHM system. For example, displacement transducers and settlement devices can be used to measure and monitor deflection, settlement, joint openings, and other movements of bridge members. Strain sensors are normally used to measure the change in the length of an object per unit length. Numerous research projects and technical reviews have shown that conventional sensors are easily affected by changes in external factors such as temperature, humidity, cable length, magnetic or electric fields, etc. These factors make it difficult to obtain stable and reliable readings over the long term. These common problems that are often encountered with conventional sensors can be overcome as advanced sensing technologies become more available for bridge applications.

Fiber optic sensor (FOS) technology is based on the principle in which a micromechanical resonator acts as the sensitive element of the sensor and has the promise of providing an alternative measurement method not previously available. They are used for detecting structural performance by sending light beams down a fiber optic cable at regular intervals and by measuring features of the reflected light content. Various types of FOS are used in bridge applications. Each type is based on a different property of the light waves traveling down the fiber. For example, Fabry-Perot sensor measures interference fringes while the measuring parameter of Fiber Bragg Grating (FBG) sensors is wavelength shift. Multiple Bragg Grating type sensors can be photo-imprinted along the same fiber, making it feasible to install large scale networks of thousands of sensors or more with a minimum of cables. Another type of fiber optic based sensor technology that has been recently getting attention is the use of Brillouin optical time-domain reflectometry (BOTDR). BOTDR is a distributed optical fiber strain sensor with operation based on the Brillouin scattering phenomena. FOS allows a structure to be continuously monitored with confidence in the usability of the long-term data record. FOS is known to exhibit low mechanical hysteresis and has high shock survivability. They are capable of measuring strains at multiple orders (two or three) of magnitude better than conventional electrical resistance gages. The use of the FOS can also reduce the number of sensors needed for the structure since they are capable of detecting damage along the entire length of the sensor (in the specific case of long-gauge FOS). Other advantages of FOS over conventional sensors include compactness and freedom from drift and electromagnetic interference [2]. Moreover, FOS can easily be incorporated into various types of measuring devices (e.g., accelerometers, displacement transducers, etc.), and many physical quantities can be measured simultaneously with the proper system design and calibration [3].

Another advanced sensing technology that is being popularly explored by numerous manufactures and institutions is micro-electromechanical systems (MEMS). MEMS are miniature electromechanical sensor and actuator systems that are capable of being optimized in their design for a specific application. The advantage of MEMS is that they can be used in an environment to both sense and actuate. The key difference between conventional sensing technologies and MEMS sensing technologies lies in their processing capabilities. The majority of MEMS devices contain an on-board microprocessor within the system. The microprocessor can typically be used for digital processing, conversion from analog to digital, performing basic calculations, and providing interfacing functions. One advantage of using this technology and its design paradigm in bridge applications is the miniaturization associated with MEMS; MEMS features are typically on the scale of microns (10-6m). This small size allows them to be implemented in applications where conventional devices would be intrusive. The manufacturing process, known as vary large scale integration technology (VLSI), which is similar to those used for manufacturing computer chips, gives a great potential for the mass production of a particular sensor in a cost-effective manner.

B. Data Acquisition and Processing

Two different methods have widely been used for collecting and recording data from sensors. For a local SHM system with a small number of sensors or for a system that only requires a measurement at infrequent intervals, a portable or hand held indicator can be used to collect and store the data. Traditionally, SHM systems had analog sensors and Analog/Digital (A/D) converters at the data acquisition location to convert the analog signal into a digital format. Newer systems incorporate digital sensors to avoid A/D conversion and to ensure more reliable communication while also relieving the central data acquisition from the conversion load. Some devices allow measured parameter values to be read directly in the proper engineering units and store the data that are later downloaded for further analysis. For a global SHM system with a large number of sensors, or for a system that requires data to be collected and processed frequently or continuously, more complex systems are employed that can collect and process data from an array of sensors at predetermined time intervals.

Some deficiencies in system integrity may occur when sensors are located far from the data acquisition system. In practice, the distance from the sensors to a data acquisition system can normally range from couple of feet to several hundreds of feet. As the distance becomes longer, the analog signal may degrade due to unexpected noise sources present along the cable length. Also, it is possible that the change in monitored response from structural damage may be smeared and blended in with those from other factors such as temperature and excitation. Since data are normally measured under varying conditions, data normalization is very important in data processing. Data normalization is a procedure to separate signal changes caused by operational/environmental variations of the system from structural changes. If various unknown sources are involved, where not all sources directly related to structural changes can be eliminated, statistical quantification though appropriate measurements can be employed.

C. Communication

Traditional data collection systems are mostly based on wire-connected instrumentation where sensors are placed at critical points along a structure and connected to a central data acquisition system with cables of various types (coaxial, etc.). These wire-based systems typically have high installation and maintenance costs. The use of an Ethernet local area network (LAN) can mitigate the problems associated with thick bundles of transmission wires and makes a SHM system more robust against electromagnetic interference. By using Ethernet LAN in SHM applications, multiple sensor types can also be interconnected, thereby reducing the number and length of wires, and changes to the SHM system can be easily implemented by simply adding more connections.

Another way to overcome problems associated with wired communication is to use wireless technology. As a viable alternative to the wired systems, emerging wireless technologies such as radio frequency communication links, cellular phone networks, and others provide an opportunity to remedy the recurring cabling problem of conventional monitoring systems. Due to the potential advantages of wireless technologies over a conventional wired sensing system, a change in the communication industry has shifted the existing technologies into a new system. One example is a system for mobile communications that provide users with packet data service over GSM radio channels and external packet data networks. This type of technology has been explored for SHM systems. The most common protocols for transmitting data include Bluetooth and Zigbee.

D. Data Management

As current trends in SHM move toward the development of a real-time, continuous monitoring paradigm, the ability to efficiently transfer and manage a large amount of data is required. Even with digital signal processing (DSP) boards and algorithms, massive data transfer is still required if the monitoring is performed remotely. Also, if not properly processed, data may be subjected to loss of some useful information hidden in the recorded data through data compression and condensation. Experience has shown that the data transfer and management tasks involved in traditional SHM systems are non-cost effective [4]. In recent years, the economic considerations and other challenges have led the traditional SHM system to evolve toward serial systems, in which the number of transmission mediums is reduced by utilizing a robust communication protocol such as the Universal Serial Bus (USB). Concurrently, modern Internet-based database technologies allow utilizing various conceptual retrieval interfaces and corresponding visualization and analysis tools for a better management of the large amount of data and information.

Although currently available hardware technologies appear to allow large amount of data to be collected, the ability to analyze and understand the massive datasets in a concise manner appears to be still lacking. In most SHM applications, the raw data alone is rarely of direct benefit to a bridge owner. The true value is predicated when useful information and knowledge are extracted for decision support or exploration of structural health status (e.g., as to whether the structure is healthy enough to continue fulfilling its functions). Clearly, the main issue of the current SHM community is not the lack of measurements, but rather is how to analyze and extract useful information.

The emerging knowledge discovery in databases (KDD) technology may provide a tool for creating an object-oriented information scheme for diagnostic interpretation of data [5]. KDD systems have created opportunities for computational tools that have a degree of cognitive intelligence; commonly referred to as artificial intelligence (AI). As a growing engineering area, the AI concept is frequently being evaluated as a tool for solutions that understand the fundamental problems being examined. This intelligent tool evolved from the intersection of research in various fields such as databases, statistics, machine learning, pattern recognition, reasoning with uncertainty, knowledge acquisition for expert systems, data visualization, information retrieval, and high-performance computing [6].

One common AI technology popularly being explored is Artificial Neural Networks (ANN). The objective of using the ANN approach is to transform the collected data and information into meaningful outputs from collected inputs. As a supervised learning technique, ANN came from the idea of developing an artificial system capable of simulating the function of a human brain or neural system [7]. Due to its powerful capabilities at universal approximation of nonlinear mapping functions with an arbitrary complexity, the ANN approach has been successfully used in multiple fields of science and engineering. Since its introduction, the use of ANN has been gaining interest in bridge monitoring applications as a statistical pattern classifier to identify and predict damage, which can be defined by the occurrence, location, and extent, in structural systems. The use of AI technology may allow the automation of the entire process of data analysis, implementation of specific algorithms for pattern extraction from data, and integration of the inferred knowledge from data with damage inferring indices for structural health assessment and decision making. Many researchers are currently focusing their effort on integrating the technology with a data management system.

III. STATE-OF-THE-ART BRIDGE HEALTH MONITORING SYSTEM – CASE STUDIES

A. Structural Health Monitoring System for Monitoring a High Performance Steel Bridge

The E. 12th St. Bridge over I-235 in Des Moines, IA, shown in Fig. 1, is a 298 ft -7 in. long two-span high performance steel (HPS) girder bridge, with an 8-in. thick cast-in-place concrete deck. The deck and sidewalks were constructed using high performance structural concrete with a minimum specified strength of 5,000 psi. The north span is 153 ft-3 in. long and the south span is 145 ft - 4 in. long. The girders are supported at the ends with integral abutments. The driving portion of the bridge consists of two lanes with a total width of 29 ft - 6 in. The pedestrian walkways, flanking both sides of the roadway, are each 7 ft - 10 in. wide. The six girders spaced at 8 ft - 8 in. are constructed with HPS with each girder having three longitudinal segments. The 113 ft - 6 in. long north region and the 103 ft - 1 in. long south region were constructed with HPS 50W steel, while the 82 ft - 0 in. long center region was constructed with HPS 70W steel.

The E. 12th Street Bridge was constructed with funding from the Federal Highway Administration's (FHWA) Innovative Bridge Research and Construction (IBRC) program. As a part of the IBRC program, it was required that the performance of the HPS bridge be monitored for a two-year period. The objectives of the monitoring were defined as the following:

- Evaluate the use of HPS in bridge applications
- Use innovative structural health monitoring techniques to continuously monitor the bridge performance for two years
- Develop initial concepts for monitoring bridge deterioration over time and develop a baseline record for identifying structural performance changes
- Conduct a fatigue evaluation with specific interest in the impact of design features associated with HPS
- Continue developing expertise in the broad field of SHM

With these objectives, this project was launched to help introduce a relatively new material to the industry and to help demonstrate the potent abilities of continuous SHM with cutting edge, state-of-the-art sensing and processing technology.

Fig. 1: Layout of the E. 12th Street Bridge over I-235 in Des Moines, IA.

The SHM System installed on the HPS bridge can generally be divided into three sub-systems: the Data Acquisition Sub-System (DASS), the Gateway Sub-System (GSS), and the Data Storage/Processing Sub-System (DS/PSS). The flowchart shown in Fig. 2 summarizes the data "flow" from its origin at the sensors to its final format.

The DASS, located at the bridge, consists of strain sensing equipment and communication equipment. The Si425-500 Interrogator collects raw data from 40 FBG sensors that are strategically located to assess both the local and global performance of the bridge. The DASS transfers the information to the GSS, which is located at a nearby secure facility, via wireless communication. Components of the DASS include the following:

- Strain Sensing Equipment
- 40 FBG Sensors
- Si425-500 Swept Laser Interrogator
- Communication Equipment
- 2.4 GHz Wireless-802. 11g Access Point

The GSS, located in a secure building approximately 450 ft from the bridge pier, consists of data management equipment, communication equipment, and video equipment. Components of the GSS include the following:

- Data Management Equipment (DME)
- Data Relay Server (DRS)
- Desktop Computer – 700 MHz Processor, 20.0 GB Hard Drive, 256 MB RAM
- Data Collection Server (DCS)
- Desktop Computer – 733 MHz Processor, 14.2 GB Hard Drive, 256 MB RAM
- Communication Equipment
- 2.4 GHz Wireless-802. 11g Access Point
- 2.4 GHz Wireless-802. 11g Router
- 678 DSL Modem
- Video Equipment
- VB-C10/VB-C10R Network Camera

The GSS WAP, DRS, DCS, DSL modem, and the video camera communicate with each other via the Linksys router. The DRS receives raw data from the DASS and relays the information to the DCS and the E. 12th Street website application. The DCS collects the raw information and converts it to ASCII text files that are 50 MB in size. The files are then compressed, sent to an FTP server, and are automatically downloaded and removed by the DS/PSS via internet connection. When the E. 12th Street website application receives the raw information, it is converted to strain and displayed in real-time along with streaming video of corresponding traffic crossing the bridge.

The DS/PSS is located at a remote site about 50 miles from the East 12th St Bridge. Composed primarily of data management equipment, the DS/PSS functions to transfer, permanently store, and process the performance data. DS/PSS components include the following:

- Data Management Equipment
- PowerEdge 4600 Server - 3.0 GHz Processor, 1.2 TB Hard drive, 4.0 GB RAM

The 50 MB compressed wavelength files are downloaded by the DS/PSS via the FTP process. After the data transfer is complete, general checks are performed on the data to ensure that it is continuous and free of errors. After these basic data integrity processes are complete, the wavelength data are converted to strain data, and additional data reduction procedures are performed. Examples of such data reduction procedures include the following:

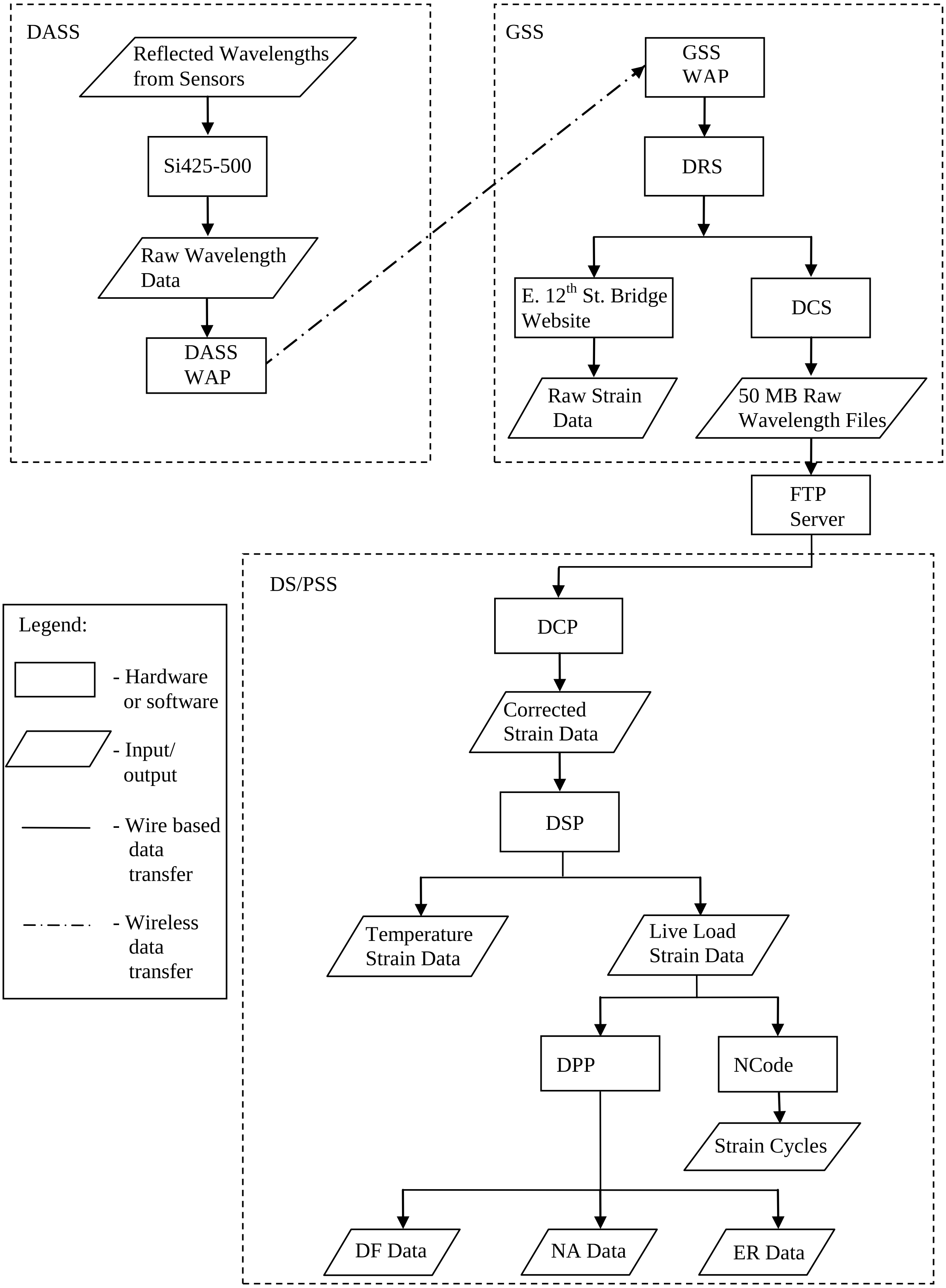

Fig. 2: E. 12th Street Bridge SHM System Data acquisition and processing flowchart.

- Elimination of temperature effects from the strain data to allow for assessment of long-term live load bridge performance
- Computation of global behavior indices [distribution factors (DF), neutral axix (NA) locations, and end restraint (ER) ratios] to evaluate time-dependent bridge performance

- Rainflow counting to record the number and magnitude of strain cycles at various sensor locations

With the SHM system deployed on the East 12th St. HPS Bridge, a significant step has been made in the ability to effectively (both in terms of information collected and cost) monitor and evaluate structures continuously from a remote location. A key element of the system is the ability of the Si425-500 Interrogator and FBG sensors to quickly, reliably, and repeatedly produce accurate, high quality strain profiles for each sensor. This is an obvious example of cutting edge technology that has prompted the development of a state-of-the-art SHM system. For a complete discussion of the SHM system capabilities, refer to The Remote Continuous Structural Health Monitoring of the East 12th Street Bridge [8].

B. Structural Health Monitoring System for Protecting Covered Bridges from Arson and Vandalism

The current Cedar River Bridge shown in Fig. 3 serves as a replacement to the original Cedar River Bridge that was in service for 120 years until it was burned by arsonists in 2002. The replacement bridge is a 66-ft single span bridge with a 42'-6" south approach span and a 21'-6" north approach span. The bridge is unique among others that exist because its truss design combines two truss styles, the queenpost truss and lattice truss. While the siding and roof are made from Cedar lumber, the structural members of the bridge are constructed from custom-milled Douglas Fir lumber [9]. More than 1,500 covered bridges exist in the United States. This population represents the portion of covered bridges that endured the Civil War, and thus, are historical landmarks.

The primary objectives associated with this project include the following [10]:

- To develop a monitoring system that will ensure the long-term preservation of historic bridges
- To develop and demonstrate a system for long-term monitoring of timber bridges of various types
- To advance the state-of-the-art system and to develop expertise in design, installation, and implementation of long-term remote monitoring systems

Fig. 3: Photograph of the Cedar Bridge in Madison County, IA.

With these objectives identified, a system was developed to help ensure that the covered bridges of Madison County will remain safe from arson and vandalism. Successful implementation of such a security system will benefit anyone who chooses to visit the bridges, as well as the people and businesses of Madison County that depend, to a large extent, on the tourism generated by the presence of the bridges. In addition to monitoring timber covered bridges, recommendations were developed on how the employed technologies can be used to monitor other bridge types for various types of threats.

Differing from the previous SHM systems described previously, the monitoring of the Cedar Bridge SHM System involved technologies that monitor several parameters, not just strain information. The monitoring equipment selected for use in this system is as follows:

- Strain Sensing Equipment
  - 12 FBG Sensors
  - Si425 series Swept Laser Interrogator
- Flame Detection Equipment
  - SS4-A Multi-Spectrum™ Electro Optical Digital Fire Detector
- Infrared Equipment
  - Thermovision A20M Infrared Camera

The fiber optic sensing equipment was connected to computers to process the data generated and to connect to a notification system. FBG sensors was installed at various locations throughout the bridge and is primarily used to detect fires by detecting rapidly changing temperature levels. The flame detector selected for the project senses utilizes visible, ultraviolet (UV), and infrared (IR) spectrums to detect flicker rates along with UV and IR signatures that are unique to fire. IR cameras detect heat gradients, and since all objects emit heat, the IR cameras are used to detect when a fire is set, as well as the presence of individuals at the site during restricted times. The IR cameras allow for monitoring in all conditions, including darkness and variable weather conditions.

C. Structural Health Monitoring System for Detecting Damage in Fracture-Critical Bridges

The Highway 30 Bridge, presented in Fig. 4 is a three-span (97'-6" end spans and a 125'-0" main span), fracture-critical bridge that crosses the Skunk River near Ames, IA. Supporting two eastbound traffic lanes, the structural skeleton of the bridge consists of two exterior plate girders, two interior stringers, and transverse floor beams that span between the exterior girders and support the stringers. The two exterior plate girders are the only members capable of fully supporting traffic loads, and thus, the bridge is classified as fracture critical.

The Skunk River Bridge represents one out of approximately 50 bridges of this type that exist on the Iowa roadway system. When these fracture-critical bridges were constructed in the 1960s, it was common practice to weld stiffeners to the compression flange of the plate girder, but not the tension flange. It has since been proven that this connection detail causes fatigue cracks to develop in web gaps of stiffeners that connect the floor beams to the plate girders, and as a result, cutback retrofits were performed on these stiffeners in the negative moment region of the bridges. However, this retrofit is only partially effective. As a result, the Skunk River Bridge and the other fracture-critical bridges in Iowa have connection details known to cause fatigue cracks. Should a fatigue crack form and propagate through the plate girder, a catastrophic bridge collapse could occur.

The primary objectives associated with this project include the following [11]:

- Develop a continuous SHM system for fracture-critical, steel girder bridges with the following specifications:
  - Detect the formation structural damage such as the formation of fatigue cracks or a propagating crack
  - Be versatile and applicable to any steel girder bridge
  - Identify the difference between sensor damage and bridge damage
  - Collect average daily traffic (ADT) information such as speed, weight, distribution, etc.
  - Be user-friendly and easily deployable to bridge owners and work forces
- Address the future needs identified from the E. 12th Street SHM System project
  - Develop methods for mining large data files to find the packets useful for structural analysis
  - Develop methods for clearly presenting the analytical results from the continuous monitoring

By addressing the future needs identified in the E. 12th Street SHM System project, the SHM system for the Skunk River Bridge has not only further advanced a state-of-the-art system, but it also introduced a unique approach to monitoring structural behavior.

The SHM system includes data collection equipment, communication equipment, and data management equipment. With some equipment technologies similar to those of the E. 12th Street SHM System, the equipment used in this project includes:

- Strain Sensing Equipment
  - 40 FBG Sensors
  - Si425 series Swept Laser Interrogator
- Communication Equipment
  - 2.4 GHz Wireless networking with long-range, directional antennas
- Data Management Equipment
  - Precision 670 Workstation – Dual 3.2 GHz Xeon Processors, 3.0 GB RAM, 146 GB Hard Drive

The Skunk River SHM System functions with two categories of sensors: target sensors and non-target sensors. Target sensors are the FBG sensors that are positioned in areas of the bridge that are prone to damage, and non-target sensors consist of any sensors that are not target sensors. To initialize the system, the strain files encompassing days, weeks, or even months of continuous strain data are loaded into the SHM system software to “train” the system how to identify normal structural performance. During this training, each target sensor establishes a series of relationships with each non-target sensor. After training is completed, the monitoring application is launched, and for each traffic event that crosses the bridge, the resulting structural performance at each target sensor is classified as normal or abnormal by using the relationships that were established with the non-target sensors during the training process.

Data mining processes have been developed that isolate only the useful packets of the data files for the system training, and thus, the time required for training has been optimized and minimized. In addition, the data mining processes tremendously reduce the strain data that is stored for long-term use. Finally, the versatility of the system has been accomplished by utilizing actual strain profiles for training, rather than theoretical profiles produced by computer models [11].

Fig. 4: Photograph of the fracture-critical Highway 30 bridge over the Skunk River near Ames, IA.

IV. CONCLUSION

The ability to monitor the condition of a bridge structure to detect damage or changes in condition at early stages is of significant interest to many bridge owners, and SHM provides such an option. This paper has presented some of the popularly used SHM technologies deployed on roadway networks. In addition, a few unique, state-of-the-art SHM systems were showcased. As these leading edge systems prove their capabilities and as technology continues to further develop, it is expected that these state-of-the-art systems will quickly become tomorrow's state-of-the-practice systems. As these SHM systems continue to be improved and implemented, roadway networks across the world will continue to become safer and more manageable. For more detailed information on each topic, readers are directed to the referenced articles, papers, and reports.

REFERENCES

[1] Lee, Y.S., B.M. Phares, and T.J. Wipf, "Structural Health Monitoring with an Active Data Management System for Secondary Road Bridges", Journal of American Concrete Institute-Special Edition, ACI – SP292 Structural Health Monitoring Technologies, October 2013.

[2] The 2nd International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA, September 1999.

[3] Udd, E. "Fiber Optic Sensors, An Introduction for Engineers and Scientists." John Wiley & Son's, Inc. New York, New York, 1991.

[4] Reda Taha, M., Kinawi, H., and El-Sheimy, N. The Realization of Commercial Structural Health Monitoring Using Information Technology Based Techniques. Proceedings of the ISIS 2002 Structural Health Monitoring Workshop, Winnipeg, Manitoba, Canada, 2002.

[5] Fayyad, U., Piatetsky-Shapiro, G., and Smyth, P. From Data Mining to Knowledge Discovery in Databases. AI Magazine, Fall 1996, pp. 37-54.

[6] Ko, J.M. Structural Health Monitoring Large-scale Bridges: Research & Experience, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, 2004.

[7] Albert, N. Neural Networks for Pattern Recognition. MIT Press, Cambridge, Massachussettes, 1993.

[8] Hemphill, D.J. The Remote Continuous Structural Health Monitoring of the East 12th Street Bridge. M.S. Thesis, Iowa State University, 2005.

[9] A Covered Bridge Rises Again. Workbench Magazine, April, 2005, pp. 94-96.

[10] Phares, B.M., Laviolette, M.D., Wifp, T.J., and Ritter, M.A., Remote Monitoring of Historic Covered Timber Bridges in Madison County for Prevention of Arson and Vandalism, U. S. Department of Agriculture Forest Service - Forest Products Laboratory, RIP-EML-001, 2010.

[11] Wipf, T.J., B.M. Phares, Doornink, J.D., and Lee, Y.S., "Evaluation of Steel Bridges – Volumes I&II: Structural Health Monitoring System for Secondary Road Bridges," Final Report, Center for Transportation Research and Education, Iowa State University, Ames, IA, 2007.