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Bridge Health Monitoring and Inspections Systems - A Survey of Methods

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16. Abstract (Limit: 250 words)

Since the collapse of the I-35W bridge in August 2007, bridge health monitoring has become an area of intense interest. This report defines terminology related to bridge health monitoring and provides a general glossary of available monitoring systems. The glossary is meant to help readers make an informed decision by understanding how different systems function and their strengths and weakness. The authors developed a questionnaire to send to commercial companies offering monitoring systems. Of the 72 questionnaires that were sent to commercial companies, 38 companies responded and are included in this report. From information provided with these questionnaires, available commercial systems are briefly summarized. Criteria for system evaluation were developed to help the bridge owner narrow down company choices for bridge application. After the owner answers a set of questions pertaining to a particular bridge, a program developed in Microsoft EXCEL helps the bridge owner decide the best system for a particular situation. An example is provided for program clarity. Once company choice is narrowed down, additional criteria were developed to aid in final product choice.

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Bridge Health Monitoring and Inspection – A Survey of Methods

Final Report

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Executive Summary

This report aims to simplify the process of selecting bridge health monitoring systems for the bridge engineer. Hundreds of bridges in the state on Minnesota are obsolete or structurally deficient. To safely extend the life of these bridges, rigorous inspection would be necessary. These inspections are both costly and time consuming. However, the field of bridge health monitoring may be able to relieve some of the cost and burden on the bridge engineer. Bridge engineers have many responsibilities and it is impossible to expect one to know: (a) the capabilities of a particular system and (b) which companies offer particular systems and services.

To help the engineer, the report gives a brief overview of the general systems that are commercially available. The report does not go into detail on each company's particular system, but offers the general characteristics, advantages, and disadvantages of a system. An overview of 25 systems based on different techniques is presented. These include: 3-D laser scanning, accelerometers, acoustic emissions, automated laser scanning, chain dragging, concrete resistivity, digital image correlation (DIC), electrochemical fatigue, electrical impedance (for corrosion), electrical resistance strain gauges, fatigue life indicators, fiber optic sensors, global positioning (GPS), ground penetrating radar (GPR), impact echo, infrared thermography, linear polarization resistance (for corrosion), string pots (linear potentiometer), linear differential variable transducer (LVDT), macrocell corrosion rate sensors, chloride content, scour devices, tilt and slope, ultrasonic C-scan, and vibrating wire strain gauge systems. The report also discusses other terminology that the authors consider necessary for understanding the report. Some of these terms have many different interpretations and need to be clearly defined. These definitions pertain to the time frame for monitoring, the scale of the monitoring, and the type of monitoring metrics used to identify bridge health.

To help understand commercial systems, the authors developed a company questionnaire. The goal of the questionnaire was to characterize the different types of systems and services that are available commercially. Due to the variety of objectives for the systems that are available, the nature and time frame of the monitoring must be known. Similarly, it is helpful to know the parameters that a particular company will measure and what these measurements can tell the owner. Software capabilities and services provided are a necessary component of system choice as the owner may want to have the system installed or to use automatic alarm capabilities. In general, the questionnaire seeks information on the major uses, components, and goals of the equipment and software that are available and necessary to define a company's system.

The report contains a very brief summary of each company that responded to the survey. The questionnaire was sent to 72 companies as a way to gather information on the capabilities and characteristics of their particular system and services. Thirty-eight (53%) of these companies responded to the questionnaire and are included in the report. The goal was to focus on companies that offer complete monitoring systems. A *complete system* was defined as one that comprises a control unit, communication, software, and sensors. Some companies only offer inspection systems, while others offer long-term solutions meant to work for many years. Many companies specialize in a particular type of system, while others claim to offer custom systems that can be tailored to a specific bridge. The majority of long-term and short-term monitoring companies offer an alarming feature. Normally, the alarm is triggered by breaching a pre-determined value and a message is sent to the bridge owner.

The authors developed evaluation criteria to help discern system needs. The criteria are subdivided into four main categories. These categories are: the nature of the monitoring, the type of bridge and bridge components to be monitored, the monitoring system features, and the evaluation of the supplier. The first three categories can help to narrow down which commercial systems are helpful and the bridge owner should use the fourth category as a guide for finalizing a particular system.

A selection program was developed using Microsoft EXCEL to help the owner choose a monitoring system. The owner must answer a list of questions pertaining to the bridge that needs monitoring. As the owner answers these questions, the program awards points to the companies whose systems or services match the owner's needs. Once all of the questions are answered, the program lists the companies that are the 'best fit' for the owner. After using the program, the owner should contact the companies that best match the owner's needs and use the criteria mentioned above to evaluate company performance. The report also explains how to add companies that are not in the database for future use.

An illustrative example of program use is presented. The example uses computer screen images of the Microsoft EXCEL spreadsheet to show how to answer particular questions by filling in the cells and explains the results that are given by the program. The example also shows how to use the weighting column and when the owner may want to change the weights of particular categories.

In summary, the report summarizes the types of systems that are commercially available for bridge health monitoring. The report explains criteria that are necessary for determining which commercial system will work for an owner's particular needs. As a final thought, the authors would like to note that many companies claim to offer 'turn-key' systems that are immediately useful to the bridge owner. However, it is difficult for the owner to know exactly what thresholds should be used for alarming purposes. Generally, only differences in data are truly known. It is difficult to automatically know the extent of the damage and if the bridge should stay in service. In general, the most useful condition report that most current systems can provide is a warning that changes have taken place in the system, which suggests that damage probably exists.

Chapter 1: Introduction

1.1 Brief discussion of aging infrastructure

The transportation infrastructure is quickly aging. Increases in traffic, in both urban and rural areas, puts more strain on the bridge networks than was originally intended. Bridge engineers need a reliable way to assess structural integrity of bridges to maintain the continuous operation of the road network while ensuring the safety of the public. Traditional visual inspection techniques are both time consuming and expensive. They are also qualitative and can only assess outward appearance. Any internal damage may go unnoticed for a long period of time. According to Minnesota Department of Transportation (Mn/DOT) records, as of March 17, 2009, 296 highway bridges are rated as structurally deficient or obsolete. Of these 296 highway bridges, 115 are structurally deficient along with 1,068 local bridges. How does a bridge engineer keep track of these problems? Are inspections conducted every other year enough? A possible solution to these issues is the use of a structural health monitoring system. These systems can detect changes in the bridge superstructure and, in some cases, predict impending failures. These systems can monitor bridges in real time and warn state engineers of possible problems to avoid tragedies like the I-35W collapse in August 2007.

1.2 Motivation for Report

State bridge engineers are responsible for many aspects of bridge networks. Due to the large number of systems that are available, it is impossible for an engineer to sort through all these systems without knowledge of: (a) the capabilities of a particular system and (b) which companies offer particular systems and services. This report briefly explains the concepts, advantages, and disadvantages behind commercially available health monitoring systems. It simplifies the task for system selection, from the large number of commercially available systems that exist, using a computer program to find the system that best fits the needs of a specific bridge.

1.3 Overview of Chapters

Chapter 2 offers a brief overview of the general systems that are commercially available. It does provide detailed information of the systems offered by each company that was surveyed, but offers the general characteristics, advantages, and disadvantages of a system. The chapter also discusses other terminology that the authors consider necessary for understanding the report. Some of these terms have many different interpretations and need to be clearly defined.

Chapter 3 describes the development of the company questionnaire. The goal of the questionnaire was to try to separate different types of systems and services that are available commercially. This questionnaire was sent to all of the companies of which the authors were aware offered commercial bridge monitoring systems as a way to obtain information on the capabilities and specifics of the particular systems.

Chapter 4 contains a very brief summary of each company that chose to participate in the report by responding to the questionnaire. The intent was to focus on companies that offer complete monitoring systems. A complete system was defined as control unit, communication, software, and sensors.

Chapter 5 describes the evaluation criteria developed to discern system needs. The criteria are subdivided into four main categories. The program uses the first three to narrow down systems and the bridge owner should use the fourth category as a guide for finalizing a particular system.

Chapter 6 discusses the selection program developed to help in the process of choosing a monitoring system. The chapter explains how to use the program and the process of awarding points to the companies. It also explains to the user how to add companies that are not in the database.

Chapter 7 contains an illustrative example of program uses. It describes how particular questions are answered by filling in the cells, and it explains the results that are given by the program. The example also explains the weighting column and when it should be changed.

Chapter 8 offers a summary of the paper and conclusions for the project. The project defines health monitoring vocabulary and defines criteria necessary for proper selection of commercially available health monitoring systems. The project also offers a Microsoft EXCEL program as a selection tool for the bridge owner.

Chapter 2: Overview of Health Monitoring Definitions and Systems

This chapter defines and describes the components and systems commercially available to monitor bridge health. In addition to different types of sensing systems, there are other terms applicable to bridge health monitoring that are also defined. It is important for the user to understand the terms related to health monitoring, as well as the methods and capabilities of the various sensing systems, when choosing a system to meet the bridge needs. A glossary is included in this chapter, the goal of which is to define terms used in the development of the health monitoring system criteria. The glossary consists of four sections. The first two sections define structural health monitoring, as well as different terms used to describe the implementation of the system and how it will be used. The next section, titled "Monitoring Metrics", defines the quantities that can be measured using commercially available health monitoring systems. For the final section of the glossary, a literature review was conducted. The information gathered was used to describe the theory behind each sensing system, what it measures, how it is applied in health monitoring applications, and possible advantages and disadvantages.

2.1 Definition of Bridge Health Monitoring

Bridge monitoring is the application of structural health monitoring (SHM) and inspection techniques to bridge structures. SHM for buildings and bridges has been evolving over the past decade from methods used in the health monitoring of other structures (e.g., aircraft, rotating machinery, etc.). A definition of the terminology associated with SHM is necessary before further discussion of the technologies used for the bridge monitoring.

According to Chang (1999), the goal of structural monitoring is to gain knowledge of the integrity of in-service structures on a continuous real-time basis. Scheduled maintenance and periodic inspections offer only limited knowledge of structural condition, and these methods are costly in terms of extensive labor and downtime. However, advances in sensing technologies, material and structural damage characterization, and monitoring diagnostic technologies enable the integration of distributed sensors for real-time inspection and damage detection. Thus, the essence of structural health monitoring is the development of autonomous systems for the continuous monitoring, inspection and damage detection of structures with minimum labor involvement. Unlike traditional non-destructive evaluation methods, structural health monitoring techniques use the change in measurements at the same location at two different times to identify the condition of the structure.

Chang et al. (2003) focus the goal of structural health monitoring as the determination of the location and severity of damage in buildings and bridges as they happen (i.e., in real time). Given the limitations of health monitoring technologies in 2003, Chang et al. adopt the expression "global health monitoring" as those methods that can determine if damage is present in a structure without locating the damage. Chang et al. also refer to non-destructive methods as "local health monitoring" methods because they can be used to locate damage once it has been established by the "global" methods that damage is present.

Worden and Dulieu-Barton (2004) make a more marked distinction between structural health monitoring (SHM) and non-destructive evaluation (NDE), even though they classify both, along with condition monitoring (CM) and statistical process control (SPC) under the umbrella of "methods for monitoring and assessing damage". According to Worden and Dulieu-Barton, SHM refers to sensor networks that monitor the behavior of structures while they are in service. However, they define NDE as the characterization of damage, the location of which is already known from the SHM network, after the structure is taken out of service temporarily. Worden and Dulieu-Barton further expand the definition of SHM by identifying five principal issues in damage identification: (1) detection of damage, (2) localization of its probable location, (3) classification of the type of damage, (4) assessment of the extent of damage and (5) prediction of the residual life of the structure.

Farrar and Worden (2007) further narrow the concept of structural health monitoring by tying it closely to a general definition of damage, in which the latter is any change to the materials or geometry of a structure such that it no longer operates in an optimal manner. In this scenario, structural health monitoring (SHM) is defined as the process of implementing a damage identification strategy. Farrar and Worden also distinguish between (1) SHM as a means for determining the ability of a structure to perform under the aging and damage accumulation that occurs from long-term use in its operational environment and (2) SHM as a tool for rapid screening to provide near real-time information about the performance of a structure during extreme events.

The definition and goals of structural health monitoring have been changing as technologies evolve. While there are several definitions that have been proposed for structural health monitoring, they coincide in several features that are essential for structural health monitoring. These include (1) real-time monitoring of (2) in-service structures using (3) an array or network of sensors to collect data the can be used to (4) represent changes in the condition of a structure over time. The data is (5) communicated over a network, and (6) data processing algorithms may be used, if possible, for damage localization, classification and assessment, as well as residual life prediction. The general definition for bridge monitoring, that is, the application of SHM to bridge structures, does not rule out inspection, non-destructive evaluation and short-term monitoring. In fact, in this document a broad spectrum of bridge monitoring interventions are envisioned, from inspection to short-term monitoring, and from long-term monitoring to collapse warning.

2.2 Types of Monitoring

Health Monitoring can be subdivided into multiple types of categories. Both the time frame of monitoring and the scale of monitoring are necessary considerations that need to be addressed before choosing a type of monitoring system. A bridge owner may want to monitor the bridge health for a period of a year or a few months, while in other cases only a one-time short-term solution may be necessary. Conversely, a new structure may have an expected lifetime of 50 years and the owner would like a monitoring system that would last an extended period of time as well. Regarding the scale of monitoring, a specific joint or member in a bridge that has been problematic in the past may be the focus of the monitoring. On the other hand, an overall assessment of bridge response to loading may be the goal. The following definitions have been established to address the issues above.

2.2.1 Time Frame

<u>Short-term</u> – monitoring to obtain bridge response information for a short-term objective. Examples include, but are not limited to load rating, tracking short-term fatigue growth, extending the life of a bridge for a year or less, or monitoring the response of a bridge for a permit vehicle.

Long-term – monitoring of a new, retrofitted, or structurally deficient bridge to track response over an extended period of time, usually more than one year.

Inspection – monitoring to assess the condition of the bridge or its components (e.g., the deck) as part of a regularly scheduled program (e.g., once every year or two).

Early Warning – monitoring that offers alarm features which will provide notification automatically when certain pre-determined parameters are exceeded.

Collapse Warning – monitoring that will close the bridge and warn motorists in the event of a bridge collapse.

2.2.2 Scale

Local – monitoring that focuses on a specific location in the bridge; examples include monitoring to assess growth of a known crack, local buckling, corrosion at specific locations, and strain measurements.

Member – monitoring that focuses on a specific member or member-sized region of a bridge; e.g., strain distributions in or deflections of a particular member.

Global – monitoring that focuses on the overall health of the entire bridge; examples include natural frequencies and mode shapes, bridge deflection distributions, acoustic emissions, temperature distributions, and wind profiles.

2.3 Monitoring Metrics

Monitoring metrics are a system of parameters intended to measure bridge condition and performance. Depending on the type of bridge and the needs of the bridge owner, different measurements should be taken in order to properly monitor bridge health. Some metrics can be measured for any type of bridge; however, there are some measurements specific to concrete and steel bridges. It is important to know how each metric applies to the bridge of interest and what will be useful in monitoring the health of the bridge.

2.3.1 General Metrics

Acceleration - the instantaneous rate at which the velocity of a point in a vibrating bridge is changing with time. Acceleration is the most common measure taken to characterize vibrations. It is possible to define the frequencies and shapes of the different modes of vibration from a single acceleration trace. The frequencies and modes can be compared to values obtained from previous acceleration measurements to determine if the bridge has deteriorated or has been damaged.

Climatic Conditions - pertains to the environmental conditions in the area of the bridge that may relate to bridge performance. Parameters that can be measured include: air temperature, wind speed, wind direction, relative humidity, and solar radiation.

Curvature - the rate of change of slope along the length of a flexural member and produced by transverse loading (i.e., normal to the longitudinal axis). From principles of structural mechanics, curvature is known to be directly proportional to bending moment in the member.

Displacements - the overall linear movement (i.e., translation) of a bridge either in relation to its original position or on a global scale. It is possible to measure the displacement in one, two or three independent directions.

Load - the total load of objects passing over a particular area of a bridge. This measure can be useful to enforce weight restrictions, as well as to define the range (i.e., spectrum) of typical traffic loads.

Tilt/Slope - the angular change of components in a bridge. This is useful in determining distortion in bridge geometry. Slope is the rate of change of deflection of a flexural member with respect to length. Angle changes with respect to a vertical plane are also useful to assess 'out-of-plumb' elements. It is useful to know if there has been a large change in angle on an element.

Scour - the removal of soil around the piers of bridges due to fast moving water currents during flooding. Removal of soil can lead to instability of piers.

2.3.2 Concrete Metrics

Corrosion - It is possible to determine whether or not the steel reinforcement embedded in concrete is at risk of depletion from attack of chloride or carbon dioxide. Some corrosion monitoring techniques determine the probability of corrosion occurring, while others determine the approximate corrosion rate. Different sensors and/or procedures may be required to monitor the corrosion of epoxy coated and non-epoxy coated rebar.

Cracking – the separation of concrete surfaces at the location of fractures is typically characterized by the width, length and number of cracks. Small-scale cracking (i.e., few, short, narrow cracks) is expected to take place in all concrete; however wider, longer and/or more numerous cracks are not expected. It is possible to detect the formation of these cracks through acoustic emission sensors. It is also possible to monitor known cracks using strain gauges placed over the area of interest.

Location of rebar/delaminations – The location of reinforcement in concrete can be determined using several non-destructive methods. These or similar techniques can be used to determine if the concrete above and below the reinforcement has begun to delaminate.

Strain – the relative elongation or shortening present in the concrete in specific locations of a bridge. In the service load range, the concrete behaves in a linear manner allowing the estimation of the stresses present at the particular location in the bridge.

Strength – the strength of concrete is typically characterized from tests of cylinder or cubes that are cast at the same time and from the same mix as the bridge member or component. For determining the initial in-situ strength of the concrete, measurements of concrete temperature can be taken while the member or component is curing and compared to previously obtained temperature-strength correlations for the particular concrete mix. This can be useful for quality control of the concrete during construction.

Tension (in rebar/tendons) – In post-tensioned systems, the tension in the cables is important to the overall strength of the concrete member. Also, if delamination occurs in reinforced concrete, the concrete cannot transfer forces to the rebar causing a reduction in stress. Thus, tension measurements can be used to assess the overall health of the structure.

2.3.3 Steel Metrics

Corrosion – the chemical reaction whereby steel loses electrons to water and oxygen and other corrosive materials (e.g., road salts). Monitoring is useful in order to determine extent and rates of corrosion within the structure.

Crack Growth – the elongation and/or widening of a known crack. Fatigue cracks may grow or remain static, with the former posing larger concerns than the latter regarding potential failure. Therefore, it is useful to a bridge owner to know if a fatigue crack is growing under the current loading conditions.

Cracking – the number, width and length of cracks in a steel member or component at locations of stress concentrations or fatigue loading. Such information is useful for predicting the remaining life in a steel bridge or for averting a sudden failure. Quantification of cracking is important because extensive cracking at a critical location or member in a steel bridge can cause large changes in stresses at other bridge locations.

Strain – the relative elongation or shortening present in the steel in specific locations of a bridge. In the service load range, the steel behaves in a linear manner allowing the estimation of the stresses present at the particular location in the bridge.

Tension (in cables)– Cables in suspension bridges are designed to handle tensile forces. Monitoring the magnitude of these forces is of interest, especially in cases where bridge loads have increased beyond design levels, or if deterioration of the cables is suspected or known.

2.4 Types of Systems

Many types of systems are available for bridge health monitoring. These systems involve a variety of different physical and chemical processes that have been harnessed to monitor certain bridge characteristics. In the following section, the different types of systems are defined, and the advantages and disadvantages of each are enumerated.

2.4.1 3-D Laser Scanning

A 3-D Laser Scanning system generally consists of one or more scanners that are installed on tripods. The scanner has a laser source and, depending on the type of scanner, uses either the time for the emitted laser beam pulse takes to reflect back to the scanner or the phase difference of the peak amplitude in the reflected light to measure the distance to the point. The laser can rotate to accommodate large structures. However, if multiple profiles of a bridge need to be monitored, more scanners would be necessary.

Accuracies of the scanning system can be from 10 mm to 1 mm (Park 2007). This makes 3-D laser scanning a fairly precise system. One advantage to this system is that an entire bridge can be surveyed without ever setting foot on the bridge. Another advantage is that entire views of a structure may be obtained instead of many measurements at discrete points that may be far apart from one another. However, there are also some disadvantages. Differences of surface types on the same bridge can have an impact on accuracy (Mina 2007). This may cause measurements on composite bridges to have more errors than on bridge surfaces that are just concrete or just steel. Also, weather conditions (fog, rain, etc.) can create noise in the signal response, possibly reducing accuracy (Mina 2007). This noise is due to premature reflections due to the weather conditions. However, others claim weather conditions are not an issue (Park 2007).

2.4.2 Accelerometers

Accelerometers have been widely used as a measuring device for dynamic phenomena for many years. These devices determine acceleration at a given instant and they can sample at high frequencies to produce high-resolution time histories of acceleration. The acceleration causes a known mass to generate a force in the sensor creating a small current or a change in the current. Since the force and mass are known, then the acceleration can be obtained by proper calibration. Using the acceleration versus time data, a displacement (or velocity) history can be obtained by numerical integration. Even though this type of system has been used for many years, there are still issues with the error that can be propagated during the numerical integration (Park 2007). Recent algorithms have made the calculations more accurate, but further improvements are still needed (Vaccaro 2006). Also, these devices generate large amounts of data, so intensive processing is necessary to get an accurate picture of deflection. One perspective on the use of accelerometers is that they can provide useful measurements, but due to possible error in their use, the data should be should be corroborated with another type of system. For example, some suggest that accelerometers coupled with GPS can negate the errors that both systems may exhibit (Roberts 2004).

2.4.3 Acoustic Emission (AE)

Acoustic emission (AE) systems generally use piezoelectric sensors to detect small amounts of energy that are released from a source, possibly damage. The energy is released as stress waves that travel away from the point of interest in a radial fashion. The piezoelectric sensor uses a ceramic medium that produces a current when force is exerted on the sensor by the elastic wave. A network of many sensors is necessary to determine the location of interest. The release of energy may be due to crack initiation, crack propagation, corrosion, etc. One useful feature about AE is that it detects events as they happen (Ji 2008). These events do not have to occur at the site of the sensor (like a strain gauge for instance), but can happen anywhere in the structure and still (most likely) be detected. Events are defined by intensity above a certain threshold and, possibly, length of duration. However, there are also some disadvantages to AE. The emissions themselves can be very weak, and sometimes hard to detect due to background noise from many other sources (cars, construction, rain, etc) (Ji 2008). The background noise may also be due to reflections of the stress waves within the medium. Typical systems detect frequencies from 1 kHz to 2 MHz (Carlos 2003). This is due to the low frequencies associated with background noise (e.g., less than 1 kHz) and the attenuation present in the material of the medium at high frequencies (e.g., more than 2 MHz). The processing of these signals is very important and can be difficult. Strategies involving triangulation and also neural networks coupled with arrival times are used to determine locations of damage. Also, discerning different types of damage is another challenging facet of AE. ASTM recognizes AE as a testing procedure and offers some guidelines, but these are more directly related to pressure vessels and not specific to bridges (Carlos 2003). For application in construction, it has been noted that AE develops lower energy levels in masonry structures than in concrete structures and may, therefore, be more difficult to implement for some materials (Shigeishi 2001). Steel is the easiest structure to monitor acoustically because it transmits the stress waves with much less attenuation.

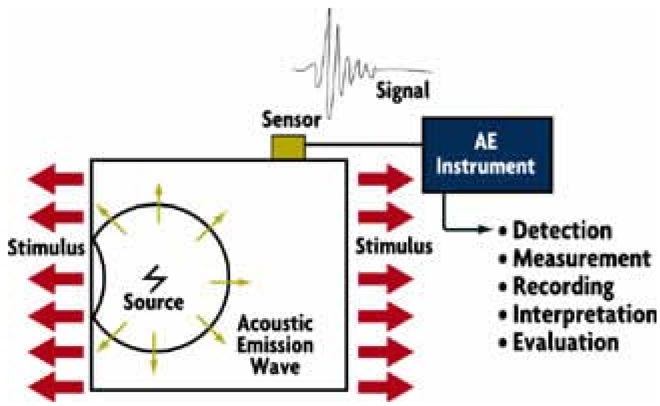


Figure 1: Acoustic Emission Schematic (ASTM.org)

2.4.4 Automated Laser Total Station

A laser Total station is a stationary laser system that is able to monitor the displacement of nodes on the bridge. By placing prism targets at areas of interest on the bridge and placing the total station at a location that has an unobstructed view of all targets, displacements can be measured. To calibrate the station, all prisms must be manually located. Then the total station is able to automatically measure the distance and relative angles for all prism points. This data can be converted into 3-dimensional coordinates (Merkle 2004). Laser total stations have been used to measure displacements of shorter bridge spans during load testing, as well as tests in a laboratory, and the data compared well to the values achieved using LVDTs and string transducers (Merkle 2004). One issue that has been noted is the inability to conduct dynamic measurements, as it takes time to scan and locate all targets on the bridge (Merkle 2004).

2.4.5 Chain Dragging

Chain dragging is used to determine bridge deck health. By dragging a chain across the deck of a bridge and listening to the acoustic response, subsurface abnormalities can be detected. Changes in the response mean indicate where these abnormalities are located. This method is widely used and accepted as a monitoring technique. However, results are highly dependent on the inspector that is listening to the sounds of the chain. Therefore, the method is subjective and different inspectors may obtain conflicting results (Scott 2003, Yehia 2008). Even though the results are subjective, it is a fairly accurate technique (Scott 2003). A disadvantage is that bridge lane closure is necessary for measurements. Currently, an automated chain dragging system is being developed by Mississippi State University (Hearn 2005). This system may be able to remove some of the subjective nature out of this method but sufficient literature is not yet available.

2.4.6 Concrete Resistivity

By comparing the resistivity between two or more electrodes, the user is able to get a general idea of the resistivity of the concrete in the region of interest. Resistivity can be a useful measuring metric for concrete, because it is indicative of whether or not corrosion can take place. If resistivity is high, ions cannot be transferred through the concrete, and the corrosive reaction cannot take place (Yang 2008, Reis 2006). At low resistance values for the concrete, corrosion becomes much more likely. Therefore, it is possible to assess the risk of corrosion based on the resistivity of the concrete in the area of the rebar. The resistivity can also be used to estimate the moisture content of the concrete, which can be indicative of the depth of corrosion (Yang 2008, Reis 2006). The carbon content of the concrete will have some effect on resistivity as well. However, there are no effective non-destructive methods to measure level of carbonation in the concrete (Yang 2008). It has been observed that if the area of measurement is too localized, chloride ions displacing hydroxyl ions can lead to an apparent increase in resistivity (Reis 2006).

2.4.7 Digital Image Correlation (DIC)

Digital Image Correlation (DIC) can be used to determine strain in a structure. The process involves a digital camera with a specific resolution being used to monitor a structure. A baseline image is taken, and a specific distance is correlated with a certain number of pixels. From this, the response of the structure can be determined with pictures from a later date. For the process to be most effective, a pattern must be painted on the surface or some other set of distinguishing marks must be present in the area under consideration (De Roover 2002). An advantage to DIC is that no gauges need to be placed on the surface of the bridge. Also, in complicated areas such as connections, the whole displacement field can be measured with one picture as opposed to many strain gauges (De Roover 2002). It has been shown that DIC is as accurate as an LVDT (De Roover 2002). A disadvantage is that the camera must stay in one specific place without being moved to make sure images can be compared. Another disadvantage may be that multiple cameras would be necessary for complete bridge monitoring otherwise a loss of accuracy would have to be acceptable. It should be noted that accuracy depends on the number of pixels per distance. It seems that DIC is best suited for specific members or connections that are worrisome and their behavior is poorly understood.

2.4.8 Electrochemical Fatigue Sensing System

Electrochemical Fatigue Sensor (EFS) systems are designed to detect the growth of fatigue cracks in metal at a specific location on the bridge of interest. By applying a polarizing voltage between the structure and the sensor, the sensors analyze the fluctuations of electrical current in an electrolytic solution in direct contact to the area of interest (Phares 2007, Li 1999, and Phares 2009). The fluctuations are a result of cyclic stress and can be indicative of fatigue damage, and fatigue crack growth. This allows the bridge owner to assess the presence of fatigue cracking and growth in critical metal components of a bridge. In tests it has been found that the results can be verified by visual inspection at the bridge location (Phares 2007 and Phares 2009). The sensing system is able to detect microplasticity in the metal, which indicates the likely formation of a crack (Phares 2009). The process of testing the metal does not affect the fatigue life of the area of interest (Phares 2007, Li 1999, and Phares 2009). This system is only able to monitor specific locations of a bridge for crack growth; therefore, care must be used to select inspection sites. The system has not been used as a continuous monitoring system, but the application may be possible.

2.4.9 Electrical Impedance (Post-Tensioning Tendons)

Electrical Impedance measurement of post-tensioning tendons in concrete are used to gather information concerning corrosion conditions in post-tensioning tendon ducts. The post-tensioning tendons are electrically isolated (as much as possible) from the concrete and reinforcement present in other parts of the bridge. A model can be constructed analogous to a resistor (any defects present in the ducts) and a capacitor (the duct) in parallel (Elsener 2005). An estimate of expected resistivity values between the tendons in the duct and the reinforcing steel can be made. Using alternating current, the impedance between the rebar and the tendon can be measured. The "real" part of the impedance is the resistance between the tendons and the reinforcement. Any drop in resistance when measuring a tendon indicates ingress of water, which may carry corrosion enabling chlorides. This allows the bridge engineer to note any tendons that will have potential corrosion issues in following years. It is not possible to detect where the defects are located, only that they are present. This system is relatively simple and does not require much extra equipment (Elsener 2005).

2.4.10 Electrical Resistance Strain Gauges

Electrical resistance strain gauges measure the relative stretching of a small segment of material. These strain gauges are typically made from a metallic alloy specially designed to ensure optimum measurements. As the location is stressed, expansion or contraction occurs, changing the length and cross-sectional area of material. This changes the electrical resistance properties of the wire, which allows the user to determine the strain at the location (Dally 2005). In short term monitoring situations, electrical resistance strain gauges have been found to agree well with other types of strain gauges (Ravisankar 2001, Watkins 2007). However, in long term applications, accuracy may become an issue. One issue with electrical resistance strain gauges is their inability to withstand exposure to the elements (Ravisankar 2001, Watkins 2007). Another issue with electrical resistance strain gauges is the noise present in the signal due to electrical wiring. However, it is possible to remove the electrical noise through signal processing (Watkins 2007). Electrical resistance strain gauge data can be used to calculate principal strains (and principal stresses if the material is assumed to be linear, elastic) when using strain gauge rosettes, which are multiple strain gauges at different angles, all in the same plane (Dally 2005).

2.4.11 Fatigue Life Indicator

The fatigue life indicator is designed to give an indication of the remaining design life for a critical metal joint on a bridge, specifically a welded joint. The sensor, consisting of a metal shim with an initial crack, is placed on the metal surface. As cyclic loading occurs the crack grows. Electrically conducting tracks are placed along the crack path and the sensor is able to measure the length of the crack. Crack propagation is proportional to fatigue life loss, and gauge readings indicate the number of tracks remaining, the latter which indicate the fatigue life that has been consumed. This can vary for different weld types (Tubby 2005). In order for the sensors to be installed on a pre-existing bridge, previous information about the joint is required. In cyclic loading tests, it has been shown that the sensors conservatively estimate the failure of the particular weld. In most cases, the sensor calculates failure after the calculated design strength, but still before the actual failure of the weld. The sensors do not conservatively estimate failure at very large cyclic stresses, unless special care is taken to ensure proper load transfer (Tubby 2005). Little testing has been done with large variations in loading for each cycle, but it is predicted that the sensors may be used as an indicator of fatigue life in these situations (Tubby 2005).

2.4.12 Fiber Optics

Fiber optic sensors are capable of monitoring several different metrics using a variety of physical principals to interpret changes in a signal of light traveling along a fiber-optic strand. The fiber optic strand contains the light, allowing it to travel the length of the strand. Fiber optic systems are based on 4 different principles: interferometry, polarization, spectroscopy, and light intensity (Casas 2003). Spectrally based fiber optic systems measure the change in wavelength of the original light source. A common example of this application is the Fiber-Bragg grating, which is designed to remove a specific wavelength, transmitting the remainder of the original signal. Light intensity based sensing systems measure the change in light intensity over the course of the optical fiber. In the case of interferometry, the change in shape of the light wave is investigated and used to infer changes in environmental conditions. Polarization based sensing analyzes the changes in optical polarization of a light signal (Yin 2008). Due to the wide variety of physical principals used in fiber optic technology, many types of measurements are possible. Sensors have been used to investigate strain, displacement, temperature, pressure, slope, acceleration, corrosion, loading, and cracking of concrete (Casas 2003, Inaudi 1999). These sensors can be embedded in concrete components of any bridge as well as be placed on exposed components. One issue with fiber optic sensors is that some systems may be sensitive to changes in temperature; however, it is possible to compensate by using a reference temperature gauge to correct any errors (Casas 2003). Another possible limitation to fiber optic sensors is that in some cases great care must be taken when installing the sensors (Fuhr 2000). Fiber optic sensors have a distinct advantage in being immune to electromagnetic interference since the signal is light based. It is also possible to connect multiple gauges to just one optical strand.

2.4.13 Global Positioning System (GPS)

Global positioning systems (GPS) are a relatively new approach to monitoring. The United States GPS system consists of three components: satellites orbiting the Earth, control stations, and GPS receivers (www.gps.gov). The satellites, of which the control stations know the position, constantly emit a signal. The signal is picked up by the receiver, which picks up multiple satellite signals to triangulate a position. GPS has been used to monitor bridges since the mid nineties with varying levels of success. Using this system alone, precision may be in the centimeter range (Duff 1998). However, receivers must always be in contact with at least four satellites, which may be challenging in certain locations. Depending on the goal of the monitoring, precision may or may not be what the owner needs, but precision down to a few millimeters is possible although expensive. To achieve such precision, a form of GPS called kinematic or relative GPS may be used (Brown 2006). This system involves a base unit with known coordinates and rover units. The difference in position can be used to obtain greater precision. For dynamic monitoring, the base sends out a carrier signal and the rovers transmit back to the base their position and time. In general, a GPS monitoring system is probably best used either in conjunction with other monitoring systems, or to give a qualitative description of the behavior of the bridge.

2.4.14 Ground Penetrating Radar (GPR)

Ground Penetrating Radar is used often to investigate general deterioration of concrete, typically in a bridge deck. GPR operates by sending out a radio signal. By measuring the time and intensity of the reflected radio waves and comparing these with previous results, the user is able to infer the condition of the material being studied (Parillo 2009, Yehia 2008). Typically, the radio waves reflect in a similar fashion off the rebar, unless the concrete is non-uniform, implying deterioration. By analyzing the data, the user is able to determine possible locations of cracks, voids, delamination, and corrosion in the concrete. Experiments have found that GPR has agreed strongly with visual inspection and chain dragging, and comparisons to core samples have also been accurate (Parillo 2009, Yehia 2008). There have also been tests to determine the ability of GPR to find voids in grouting in post-tensioning systems. It has been found that in a controlled lab setting it is possible, although there has been little research in this area (Giannopoulos 2002). One advantage of GPR is the speed at which data can be collected. One disadvantage of GPR is that traffic lanes must be closed to carry out the data collection. Also the data analysis can be a subjective process. However, computer programs are available to aid in the analysis of the GPR data from the site making the data less subjective (Parillo 2009). GPR can be operated manually or can be placed on a vehicle to increase the speed of data collection.

2.4.15 Impact Echo

Impact echo is a process that involves striking the surface of the deck with a round sphere and listening to the response. Depending on the frequencies present in the response, depth of the slab can be determined (see Figure 2.2). If the depth calculated is not equal to the actual depth, then a defect exists at that depth (Yehia 2007). Impact echo is generally used on bridge decks to search for delaminations, voids, grout voids, cracks, or other subsurface anomalies during routine inspections. Three-dimensional maps of a deck can be visualized using results from testing (Gucunski 2006). An advantage to impact echo is that defect depths can be calculated (Gucunski 2006, Yehia 2007). Another advantage is that the method is highly accurate (Yehia 2007). One disadvantage to impact echo is that many points have to be tested to get a comprehensive map of defects. Another disadvantage is that lanes must be closed to traffic while testing is being done. Also, interpretation of the results without specialized programs and training can be difficult (Gucunski 2006).

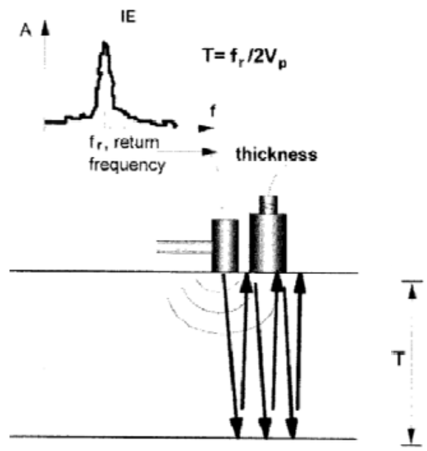


Figure 2: Impact Echo Schematic (Gucunski 2006)

2.4.16 Infrared Thermography

Infrared thermography is a way to scan concrete for sub-surface abnormalities. It is generally used for concrete deck assessment. The camera detects infrared radiation from the surface and maps the intensity. The intensity will depend on the emissivity of the surface. A difference in intensity usually means that there is an abnormality under the surface of the concrete. This abnormality may be due to delamination and spalling due to corrosion, among other things (Maser 1990). In the case of delamination, an air layer forms between the intact concrete and the spalled portion. This layer of air acts as an insulating layer. Many issues can arise when using infrared thermography. First, differences in surface texture or debris may cause changes in the intensity (Maser 1990, Yehia 2007). Also, if asphalt is overlaid on concrete, results can be misleading. Another consideration may be air temperature and weather, as these will impact the radiation emitted from the bridge deck as well (Maser 1990, Yehia 2007). However, it is noted that the metric of interest is radiation difference, not the absolute intensity. Additionally, if water is in the voids as opposed to air, the void will not be detected (Yehia 2007). Despite the disadvantages, there are many appealing aspects of thermography. One advantage to thermography is that it can be deployed with minimal traffic delays as opposed to other techniques such as chain dragging, chloride content tests, and corrosion potential (Maser 1990, Yehia 2007). Other advantages are that the results are easy to interpret and the equipment is portable (Yehia 2007).

2.4.17 Linear Polarization Resistance (LPR)

Linear Polarization Resistance is used to estimate the rate at which corrosion of steel rebar in concrete is taking place. A range of small polarizing electric potentials (positive and negative) is applied (in addition to the potential due to corrosion) between two electrodes, while the current is measured. Comparing current vs. potential yields a relatively linear relationship, the slope of which is the polarization resistance (Reis 2006). This value of polarization resistance, in theory, can give the rate at which corrosion is occurring based on a relatively simple set of equations (Yang 2008). Any system utilizing LPR must have a polarized electrode. Therefore, there must be a way of polarizing either the rebar or an electrode in order to monitor the LPR. LPR can both over- and under-estimate the rate of corrosion (Reis 2006, Vedalakshmi 2008, McKenzie 2005). However, LPR is quite capable of indicating a change in corrosion behavior. Ultimately, LPR is useful because it warns the bridge owner of sudden increases in corrosion activity on the reinforcement.

2.4.18 Linear Potentiometer (String Pots)

The linear potentiometer (see Figure 2.3) measures displacement. The end of a steel wire is attached to a point and the other end is wrapped around a spool. Since the radius is known, a displacement can be calculated by measuring the rotation of the spool. This device can also measure velocity by taking dynamic measurements. Potentiometers are slightly more accurate than LVDTs (Corda 2003). Also, the device has a larger measurement range than an LVDT (Corda 2003). The potentiometer can be used for any application where displacements should be measured. An example may be across an expansion joint or along the length of a suspension cable.

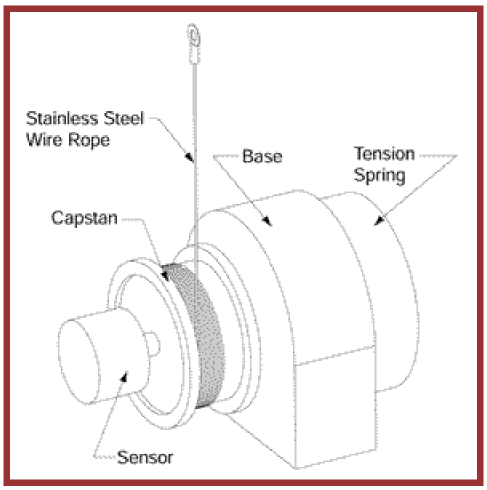


Figure 3: Linear Potentiometer Schematic (http://www.unimeasure.com/how-work.htm. Reprinted with permission)

2.4.19 Linear Variable Differential Transformer

A Linear Variable Differential Transformer (LVDT) sensor is capable of measuring the displacement in one direction of one point relative to another point on a bridge. This is accomplished by placing a cylindrical magnetic core attached to two points, with the core being placed inside three electric coils. An alternating current is applied to the middle coil. As the core moves in relation to this middle coil, a voltage is induced in the secondary (outer two) coils, with the amplitude and sign of voltage linearly related to the position of the core (McDonald 1998). Both AC and DC versions of LVDTs exist. The DC versions still require an oscillating current so more internal circuitry is necessary. Due to this increase in internal circuitry, the DC versions do not have as large of a temperature operating range as AC versions (Pierson 2009). The use of LVDTs to measure displacement is quite common. Often LVDTs are used to verify the accuracy of new displacement monitoring systems and prove to be very accurate compared to these other methods (Park 2007, Merkle 2004). It has also been shown that LVDTs are capable of performing in low temperatures, with minimal loss in accuracy (McDonald 1998).

2.4.20 Macrocell Corrosion Rate Monitoring

Macrocell Corrosion Rate Monitoring is useful in estimating the rate at which corrosion of the reinforcement is occurring in the concrete. It is possible to determine the onset of corrosion at a specific depth by using a piece of metal similar or identical to the reinforcement as an anode and using a metal resistant to corrosion as a cathode. In a typical chloride induced corrosion reaction, one section of the steel bar begins to rust, which frees up electrons. These electrons flow to the non-corroding portion of the reinforcement, where a chemical reaction converts the electrons, oxygen, and water into hydroxide ions. These flow to the anode portion of the steel (Yang 2008). It is possible to measure the electrical current and potential difference between the anode and the cathode (Raupach 2001). A large change in current implies a larger flow of electrons, which implies that the reaction is taking place at a faster rate. It is also possible to use a series of anodes in order to monitor depths at which corrosion can take place. Because measurements are not frequently obtained, getting exact corrosion rates is unlikely. However, it is possible to get an indication of the general corrosion behavior in the concrete. It is possible to get further information about the corrosion behavior through measurements of concrete resistivity (Raupach 2001).

2.4.21 Potential Measurements / Chloride Content

Measurements of electric potential of electrodes in concrete give the owner an indication of the possible risk of corrosion. This method requires two electrodes; one is the reinforcement of the bridge, while the other is a reference electrode (designed not to corrode), either embedded or on the surface (Yang 2008). The electric potential difference between the two electrodes is measured. A variation on this method uses an electrode coated in silver chloride instead of the rebar as one of the electrodes; the potential difference is particularly sensitive to the chloride content around the silver chloride (Yang 2008). In both cases, a higher potential implies concrete conditions at the reinforcement are typical of those found during corrosion, thus it is likely that corrosion is occurring. The potential is also dependent on the resistivity of the concrete at the reinforcement; thus humidity of the concrete should be taken into account when analyzing the potential data (Yang 2008, Elsener 2003). Tests on corrosion rates showed that the potential was correlated to the corrosion rate present in the concrete (Reis 2006, Raupach 2001). During an investigation into the correlation between chloride content and corrosion initiation, an increase in potential did not directly correspond to corrosion initiation (Reis 2006).

2.4.22 Scour Devices

Scour occurs when water flows at fast rates around bridge piers or past bridge abutments and can produce instability in the bridge. Generally, scour takes place during times of flooding when fast moving water accelerates near bridge piers due to contraction of the channel, and the current carries away sediment near the pier foundation (Lu 2008). Permanent scour detection devices must be able to withstand the large current and debris associated with flooding. Many methods for measuring scour are mentioned by Lu. One system is bridge mounted sonar, which provides a continuous and accurate record of scour depth. Another is Acoustic Doppler current profiling, which is portable and measures scour depth. This system is not well suited for flows with high turbidity or rapid flow rates. A third method is the application of GPR (ground penetrating radar), which is also not well suited for flows with high turbidity or rapid flow rates. A fourth method involves the use of Fiber-Bragg grating. Sensors are placed along a vertical fiber optic strand. Sensors detect changes in strain, especially large changes, which will correspond to initial sub-surface sensors becoming exposed (Lin 2005). Another method utilizes numbered bricks. The numbered bricks are placed into an excavated river bed. Then, as sediment is washed away, the numbered bricks float to the surface or are washed away. The scour depth can be found by checking which bricks remain. The sixth method is the sliding magnetic collar (SMC), which uses a collar that slides down to the river bed and measures depth. Yet another method is the steel rod method, which measures how far a steel rod must drop to come in contact with the riverbed. A recently reported method measures scour depth using a steel tube with filters throughout the height (Mercado 2008). The tube protects the system from debris and the filters are used to force air through the system. Depending on the resistance measured at different levels, soil depth (scour depth) can be detected. The advantage of this type of system is that it can withstand major flood events and be a permanent solution for bridges that undergo consistent flooding (Mercado 2008). It may also allow the bridge owner to close the bridge prior to pier movement and failure due to scour (Mercado 2008). This last type of scour monitoring system is the only type considered in the remainder of the present study.

2.4.23 Tiltmeters/Inclinometers

Tiltmeters and inclinometers measure the angle of inclination of an object. Generally, these devices would be used to monitor pier behavior in response to temperature changes and loading conditions. The fiber optic tiltmeter operates using a beam of light, a shield, and a sensor. Depending on the angle of inclination, the amount of light passing through the shield changes, causing a change in intensity. Measuring this change in intensity allows for a calculation of angle of inclination. The accuracy of these devices is around 0.005 degrees (Kulchin 2004). Other types of tilt and incline measuring devices are available as well. These include vibrating wire based sensors, Micro-Electro Mechanical Sensors (MEMS), electrolytic cell based sensors, and pendulum based sensors. Tiltmeters and inclinometers can offer the behavior of a specific point on a bridge. Displacement can be found by integrating the slopes along the span of the bridge. However, knowing the slope at one point will probably not offer a general view of what is happening to the bridge. To understand the full nature of the behavior of a pier, slopemeters would be necessary in numerous places. Therefore, slopemeters alone will probably not be an adequate way of monitoring a bridge.

2.4.24 Ultrasonic C-Scan

Ultrasonic C-scan imaging is done by sending out ultrasonic waves into a material. The reflections of these waves are read by a transducer and sent to a computer program. This program processes the data and creates a two-dimensional map of the bridge components. The image that is generated can be analyzed and the internal characteristics of the component can be deduced (Iyer 2003). Generally, this system is used to locate voids in grout and corrosion in post-tensioned bridge tendons. An advantage about C-scan imaging is that it can detect both corrosion and voids in a single test (Iyer 2003). A disadvantage is that analyzing the data can be a challenging task.

2.4.25 Vibrating Wire Strain Gauge

Vibrating wire strain gauges are able to measure the strain at a point by monitoring the changes in vibration properties of a tensioned wire attached to the area. A wire under tension is anchored at both ends to the area under investigation. The wire can be excited by an electromagnetic force from a coil surrounding the wire housing. This same coil is able to measure the frequency of vibration of the coil. By comparing the new frequency measurement to the wire's vibrating frequency at installation, the strain can be calculated (Ravisankar 2001, Neild 2005). It is possible to install vibrating wire strain gauges either on the surface of a structure or embedded in concrete. Test results in laboratory experiments designed to simulate civil engineering applications found that the gauges predicted strain close to the theoretically expected values (Ravisankar 2001, Neild 2005, Zalt 2007). It was also found that comparisons to different types of strain gauges yielded similar measurement values (Ravisankar 200l, Zalt 2007). Due to differences in thermal expansion of the strain gauge and the material, it is possible for unequal strains in the medium and the sensor to develop, affecting the results (Ravisankar 2001, Neild 2005). However, this can be solved by using a reference temperature gauge at or near the area of installation of the strain gauge. It is necessary to calculate the "gage factor" for the sensor. This value is related to the physical properties of the wire. It has been observed that vibrating wire strain gauges are capable of reliable measurements over an extended period of time while monitoring an actual bridge (Domalik 2005).

Chapter 3: Development of Commercial Company Questionnaire

3.1 Standard Questionnaire

The standard questionnaire (Table 3.1) was developed from information taken from the research reports, journal and magazine articles, websites, and product prospectuses obtained by the research team. The preliminary questionnaire was modified based on feedback received by the research team from the Mn/DOT Technical Advisory Panel (TAP).

The questionnaire seeks information on the major uses, components, and goals of these systems that are available. First, it was considered necessary to make a distinction between systems that are meant for *short-term* monitoring, *long-term* monitoring, inspection, or early warning. Next, the second question requests information on the sensors a system uses so that the type of data that will be collected is known. This question leads to a third question that deals with how the measurements obtained by the system may be helpful. The fourth question asks about mobility of the system. The owner may want a system that can be moved from bridge to bridge, or one that is permanent and robust. The next two questions deal with *when* and *on what* the system may be used, a necessary piece of information for a bridge owner.

The seventh question seeks information on power source possibilities for the system. Since a bridge location may be far removed from direct power, or it may be strategically situated in direct sunlight, it is necessary to know what power options are available for a particular system. The next question addresses whether or not the company offers a full 'turn key' system or just some components of that system. A 'turn key' system is a complete system (control unit, sensors, communication, and software) that could be installed off the shelf and be immediately useful to the bridge owner. The ninth question addresses the operating temperature range of the equipment, which could be of concern in Minnesota due to the extreme cold in the winter or extreme heat in the summer (when exposed to direct sunlight on or near a roadway).

The next two questions focus on remote communication and alarming, two functions that could become mandatory on future bridges and offer convenience for the bridge owner. These two functions are the main reason that bridge health monitoring will become a helpful tool for the bridge engineer. A system that can let the bridge engineer know when a problem occurs without the need for constant visual inspection is vital to aging infrastructure. The twelfth question concerns the functions that the software will perform so that an estimate can be made of the effort that must be expended by a bridge owner to interpret the data. The next two questions focus on the services that the vendor provides so that the bridge owner can estimate the extra training and installation the bridge engineers may need to perform. The fifteenth question requests current applications of the bridge health monitoring and/or inspection equipment so that the owner may see examples of the work. Lastly, information is sought regarding the specific performance measures of the equipment, as these measures will be of interest in the criteria selection process.

Table 1: Standard Questionnaire

(1) What is the purpose of the system? • Long-term monitoring • Short-term monitoring • Inspection • Early warning • Other (please specify)

(2) What types of sensors or equipment are used?
• Accelerometers
• Acoustic Emission
• Strain Gauges
    • Fiber-optic
    • Electric Resistance
    • Vibrating Wire
• Load Cells
• Wind Gauges
• Tilt
• Temperature
• Displacement
    • GPS
    • 3-D Laser Scanning
    • LVDT
    • String Potentiometers
• Other (please specify)

(3) What performance measures are monitored and how are these helpful? (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)
(4) Is the system: • Permanent (any piece permanently fixed)? • Reusable (everything can be unattached and moved)? • Portable (nothing attached/installed and are easily moved)?
(5) When can/should the equipment be installed? • During Construction • Post Construction
(6) On what types of bridge can it be used? • Steel Girder • Steel Truss • Cable Stayed • Prestress Concrete Girder • Reinforced Concrete • Other
(7) What type of power source is used? • Solar • Battery • AC • Other
(8) Is it a complete system and what does it include (sensor, control unit, software, communication)? (9) What is the operating temperature range? (10) How does the system communicate remotely with the user (if at all)? (11) Does the system have an alarm feature and how is it communicated? (12) What does the software do (data processing, interface, communications, etc.)? (13) What services and or support are offered with purchase? (14) What training/installation is required of the user or are these included (ease of use)? (15) What examples/applications of the system are available? (16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

3.2 Completed Questionnaire Analysis

The completed questionnaires are included in Appendix A. Initial analysis of the data included in the completed questionnaires enables the following observations.

3.2.1 Components vs. Complete Systems

Some of the companies that were identified offer primarily components of systems, with specific applications. Others offer completely customized systems, with no "off-the-shelf" products readily available. However, many offer the 'turn key' systems described above. The majority of these companies offer complete systems that are already designed and typically measure specific properties and responses of the bridge with applicable and known data interpretation.

3.2.2 Monitoring Modes

Many of these companies can offer a variety of time frames for monitoring. However, most seem to be geared toward short-term or long-term monitoring. Bridge inspection companies were also identified that can perform very short term monitoring using portable equipment to test the health of a bridge. It is important to distinguish between these different types of companies as they all offer different approaches to health monitoring. By distinguishing the monitoring mode, a more structured selection process will help to identify the most appropriate type of system depending on the given task.

3.2.3 Permanent, Stationary and Movable Equipment

Other categories that might distinguish between systems may depend on whether the bridge is already in service or being built. Some systems are permanent because they can only be installed on bridges during construction or they require permanent attachment; for example, sensors may need to be embedded in the concrete or placed on the rebar. However, other stationary equipment may be easily movable as measurements are taken at different locations on the bridge. Still, other systems may record information as the equipment moves down the bridge, such as automatic chain dragging or GPR. It is important to realize that some systems will only work for specific kinds of bridges. A typical split from one system to another is between steel bridges and concrete bridges, with many systems working better on one, but possibly working on both.

3.2.4 Data Communications

Another criteria category will refer to the nature of data communications. This may refer to communications between the datalogger and the office that is analyzing the data. Or, it may refer to communications between different components of the monitoring equipment, such as the wireless systems. These tend to work for all bridge types and are typically implemented after construction, yet some may embed RFID (remote frequency identification) sensors in the concrete to look at strength or salt levels. The wireless systems can save the difficulties and cost of connecting many wires over large distances on long span bridges. However, fully wireless systems may be more difficult to power and the information can be difficult to synchronize with time.

Chapter 4: Health Monitoring Company Descriptions

4.1 Company Survey

Seventy-two companies were contacted regarding their health monitoring offerings, with approximately one-half opting to take part in this data collection phase. A summary containing pertinent information for each company's response has been prepared below. Each summary includes the type(s) of health monitoring system(s) available from the particular company, as well as other interesting characteristics. These companies were found through internet searches for systems, through information sent to Mn/DOT, through literature searches, and through a recent survey done by Iowa State for the Wisconsin Department of Transportation. Two of the 38 responding companies did not provide sufficient detail for the authors to include these companies in the program database. They offer completely customized systems that are difficult to quantify in the database. However, these companies are included in this summary section.

4.2 Company Descriptions

4.2.1 Acellent

Acellent offers both complete active and passive acoustic emission systems in coordination with temperature sensing. These systems can detect damage within a structure in the form of cracks, delaminations, and corrosion. The system works on multiple bridge types. They also offer alarm features for both the active and passive systems to alert the bridge owner.

4.2.2 Advitam

Advitam offers custom monitoring systems involving accelerometers, strain gauges, acoustic emission sensors, and many other sensors. They will monitor known specific defects or bridge health as a whole, both short-term and long-term. Advitam offers complete systems and will maintain the system if necessary. They offer remote capabilities and alarm features.

4.2.3 Advanced Telemetrics International (ATI)

ATI offers wireless monitoring capabilities. They can attach many types of sensors to their wireless units depending on the needs of the owner. Specifically, they offer a strain concentration sensor that measures strain within a 6 foot span. ATI offers complete systems (sensors, software, control unit, communications) with remote alarm communications.

4.2.4 Bridge Diagnostics Incorporated (BDI)

BDI offers both long-term and short-term monitoring solutions. These may be wireless or hard wired and have a wide variety of sensors depending on the owner's needs. BDI offers complete systems with remote communications and alarm capabilities. They specialize in load testing and monitoring, but offer a wide range of services and capabilities.

4.2.5 Crossbow Technology

Crossbow offers stations to wirelessly connect various sensor networks. These stations are meant for low power, low data-rate applications. Full systems can be purchased with processing software. The system has both alarm and remote communication capabilities. The products have a one year warranty. The networks are to be user installed.

4.2.6 Digitexx Data Systems

Digitexx offers long and short-term monitoring solutions for bridge owners. They offer a variety of sensing systems to be customized to particular applications. They offer full systems with alarm and remote communication capabilities. Digitexx will install and maintain the system if necessary.

4.2.7 Dunegan Engineering

Dunegan offers both short and long-term monitoring solutions. Their systems focus on acoustic emissions to detect fatigue cracking in steel members. Their AESmart2000 software package processes data to detect crack growth and depths.

4.2.8 Engius

Engius focuses on short-term monitoring of concrete. Their system uses embedded thermistors to keep track of concrete strength during and after construction of the bridge. The system has remote communication and alarm capabilities.

4.2.9 Excelerate

Excelerate offers an automated chain dragging system for inspection purposes. Their system uses chains and the acoustic response to determine delaminations in the concrete surface. The system is set up on a portable pushcart and runs on battery power.

4.2.10 Fiberpro

Fiberpro specializes in Fiber Bragg sensors. They offer long-term solutions using strain, temperature, acceleration, and displacement sensors. They offer complete systems for all types of bridges. Their systems require AC power and do not communicate remotely.

4.2.11 Futurtec

Futurtec offers a system called the “First Alert Monitoring System”. As the name suggests, the Futurtec solution is a health monitoring system. Various factors, such as displacement, tilt, vibration, wind speed, and temperature are used to provide an indication of structural behavior. The information collected can be observed over the internet and used to determine the overall health of the bridge. The system can also be linked to any gates or lights, preventing access to the bridge in case of large overall changes in the bridge. The acquired data is processed by a “neural engine” which makes decisions on condition. This system may be applicable to an early warning system for bridges at risk.

4.2.12 Geomation

Geomation offers long term bridge monitoring solutions. These custom systems can measure strain, temperature, loads, and displacements. They offer complete systems with remote communication and alarm capabilities. The systems work for any type of bridge and generally focus on quasi-static measurements for long-term health.

4.2.13 Geomedia Research and Development

Geomedia offers a system to detect delaminations, asphalt deterioration, concrete deterioration, and rebar corrosion using the Impact-Echo method. This complete system can be used on any concrete or asphalt element on the bridge. The software provided is able to store field data and conduct some data processing. Geomedia can provide training if requested.

4.2.14 GSSI

GSSI focuses on bridge deck assessment. Their system is a portable GPR unit that locates voids, rebar, and concrete cover. They offer a two year warranty with the system and also provide user training for up to two people. The system is complete with unit and software.

4.2.15 Harmonic Footprinting

Harmonic Footprinting uses sensors to determine the vibrations occurring at a specific metal joint. When the vibrations at the joint do not match previous vibrational signatures, an alert is sent to the owner. The company also offers customized health monitoring systems based on the bridge of interest. Harmonic Footprinting also offers completely customized systems to meet the bridge owner's needs. This company is not included in the database.

4.2.16 HBM

HBM offers both short and long-term monitoring solutions. They monitor strains, displacements, and vibrations to assess bridge health. These custom systems are available as a fully integrated complete system. The system has remote communication and alarm capabilities.

4.2.17 Impact Echo Instruments

Impact Echo focuses on inspection of bridge decks and concrete. Their system uses impact echo to assess the health of the bridge deck. Using the information that is recorded from the acoustic waves, the depth of the surface can be calculated. Calculated depths that are smaller than the overall depth can be used to find where damage exists in the concrete.

4.2.18 Infrasense

Infrasense offers long-term, short-term, and inspection health monitoring systems. These systems use GPR or IR (Infrared Thermography) to find corrosion, delamination, and debonding in concrete structures. The units come with software for data processing. Infrasense's main area of expertise is in bridge deck condition assessment.

4.2.19 Instantel

Instantel provides systems designed to monitor bridge vibrations as well as conditions around the bridge such as ground motions. The system is complete and the user is able to access the data off site; an alarm featuring is also possible. Training is available and Instantel may provide upgrades for software and hardware when equipment is returned for service.

4.2.20 Invocon, Inc.

Invocon specializes in wireless health monitoring systems for aerospace applications. The systems are capable of measuring accelerations, strain, humidity, temperature, pressure, or any measurement from an electrical resistance based sensor. The DIDS system monitors for collisions using acoustic emission, and can notify the user in case of an impact. Invocon provides the user with software and a variety of levels of training.

4.2.21 Leica Geosytems

Leica specializes in providing health monitoring systems that monitor 3-D displacements and tilt of the bridge. The systems can monitor 3-D displacement using GPS, 3-D laser scanning, or laser totaling stations. Computer software is used for analysis of the data and also for equipment support. The user can be notified of displacements exceeding a predefined threshold via email.

4.2.22 LifeSpan Technologies

LifeSpan offers both long and short-term monitoring solutions. The systems are custom designed and use a multitude of sensors to monitor metrics such as strain, acceleration, temperature, and displacement. They offer complete systems that have both remote and alarm capabilities. These solutions can be used on a variety of steel and concrete bridges.

4.2.23 MALA

MALA offers bridge deck inspection systems. The system uses GPR to find delaminations and voids due to corrosion. The portable system displays deck images in real time to survey the condition of the concrete on the bridge.

4.2.24 Matech

Matech offers an Electrochemical Fatigue Sensor (EFS) that can be employed on any metal element in order to detect crack initiation/propagation. An electric potential is constantly applied to the section of interest and the current is measured by the sensor. Changes in current may mean that steel cracking has occurred. A specially designed computer program analyzes the current data to look for crack indicators.

4.2.25 North American Geotechnical Co.

North American Geotechnical's system tests the resistance to airflow through different layers of sediment and water to measure scour. By analyzing the data, one can deduce where the soft unstable soil stops and the stable soil begins. This monitoring allows the engineer to know at what depth the piles are in stable ground. The device is made of a steel tube with numerous filters to test at different heights. The tube can corrode, but the company indicates that it will last 10-15 years in a coastal environment and longer in a freshwater environment. It is mainly meant for bridges that flood often and undergo large changes in volumes of water.

4.2.26 Omnisens SA

The Omnisens system takes distributed stain and temperature measurements over the bridge span using fiber-optic strain and temperature sensors. Remote monitoring is possible and software is able to process and store data from the bridge. Sensor layout is designed by Omnisens and training may be provided.

4.2.27 Osmos USA

Osmos offers a bridge health monitoring system that continuously monitors the condition of vital bridge components. Fiber optic sensors monitor both the static and dynamic displacement of the bridge. Analog sensors may also be implemented to measure other properties of the bridge at various locations, such as tilt and vibrations. The measurement of dynamic displacement allows an observer to determine whether the structure is behaving elastically, and whether the normal frequency signature is present. A "Weigh-in-Motion" device may also be implemented to help observe any affects from larger truck loads. All of the data is transmitted to the internet and may be viewed by any authorized persons.

4.2.28 Physical Acoustics Corporation (PAC)

Physical Acoustics Corporation offers both long and short-term monitoring solutions as well as inspection tools. The primary focus of a PAC system is on acoustic emission. AE is able to detect signs of failure (be it cracking, rupture, or rebar breaking) by detecting sound waves created by a release of energy. PAC offers other a variety of other sensors to augment the acoustic detection system. The system is complete and has alarm and remote communication capabilities.

4.2.29 Pinnacle Technologies

Pinnacle Technologies or Applied Geomechanics offers long and short-term monitoring systems. These systems use GPS to monitor bridge response in real time. They also augment the system with other sensors to verify the bridge response. They will provide installation and maintenance if the owner desires. The systems have remote communication and alarm capabilities.

4.2.30 Practical Technologies LLC

Practical Technologies manufactures a collapse monitoring system designed to monitor for the actual collapse of a bridge. This is accomplished by monitoring for breakage in fiber optic cables spanning the bridge. The system then allows the user to be notified as well as notifying those coming toward the bridge of the failure.

4.2.31 Roadmap GPR Services

Roadmap GPR services specializes in the use of Ground Penetrating Radar on bridges. The GPR system can be used to scan both reinforced concrete bridge decks and reinforced concrete bridge decks with an asphalt overlay. This information can tell the owner where damage in the concrete has occurred.

4.2.32 Roctest Group / Smartec

The Roctest group provides health monitoring systems using many types of sensors for any bridge type. The company is capable of monitoring crack formation and growth, strain, global displacement, rotation, accelerations, temperatures, loads, water level, tilt, corrosion, and vibration. Remote monitoring with a Roctest system is possible, with software provided to fit the specific needs of the bridge owner. Some additional services available are on-site service and support, data-analysis, and training sessions.

4.2.33 S + R Sensortec GmbH

S + R Sensortec GmbH specializes in the monitoring of corrosion conditions in concrete bridge structures. Their systems measure the corrosion rate using the Macrocell Corrosion Rate Monitoring technique. They also use a sensor that takes measurements at multiple depths to give the user the location at which conditions are indicative of corrosion. The company suggests annual measurements and use of the software to indicate if corrosion will be a problem. S + R Sensortec GmbH is also able to aid in the design of the system and in assessment of collected data.

4.2.34 Sensors & Software, Inc.

Sensors & Software Inc. specializes in the manufacture of GPR devices for use on bridges. Their system locates voids and damage within the concrete. Systems provided are complete and include software able to store GPR data collected on site and provide post-processing. Training for use of the system may also be provided by Sensors & Software Inc.

4.2.35 Strainstall

Strainstall offers a health monitoring system that is used for long-term monitoring and early warning of fatigue in welds. It may be installed during or after construction. The sensors are not reusable, but the other system components are reusable. Currently, the data must be retrieved by either manually reading an indicator or downloading the data to a laptop. There is no alarm feature. It is recommended that the data be analyzed at least every two years.

4.2.36 Structural Monitoring Systems Ltd.

The Structural Monitoring Systems Ltd. system monitors the initiation and growth of cracks on any solid surface. This is accomplished using a comparative vacuum monitoring system. Processing of the data is completed by the sensor, which also contains a data processor. Warning of cracking is sent to the user immediately. Training is provided by the company.

4.2.37 Vienna Consulting Engineers

Vienna Consulting Engineers (VCE) provides completely customizable systems for the bridge owner. VCE offers a wide variety of sensors for use in systems including vibration monitoring, strain, displacement, load and environmental conditions. The system can be programmed with alarm feature that can transmit alarm via internet text message or email. Software, training, system design and installation may all be provided by the vendor.

4.2.38 Virginia Technologies Inc.

Virginia Technologies offers an embeddable sensor specially designed to monitor corrosion in reinforced concrete structures. The system is designed to measure the rate of corrosion in concrete using Linear Polarization Resistance. The embeddable sensor also has capabilities for measuring resistivity, chloride content, and potential in concrete. It is possible to access the information off-site; however, there is no software for the user.

Chapter 5: Criteria for System Evaluation

A series of selection criteria have been developed based on several items. These items include the variety of systems identified in Task 1, as well as the data collected for the various systems from the vendors in Task 2. In addition, personal communications with various experts helped to shape the nature of the Selection Criteria.

The Selection Criteria have been subdivided and organized into a set of questions. Some of these questions (groups A, B and C) are meant to identify the needs of the bridge owner, and they will be used specifically to identify particular systems that have characteristics which satisfy the owner's needs. The questions are followed by possible answers. The owner is free to identify the options that best fit the needs of the particular bridge that is to be monitored. Some questions are followed by sub-questions to further narrow down what the owner would like to accomplish. The questions in group D are suggested by the research team for the user (i.e., bridge owner) to seek additional information to evaluate vendor performance once the search has been narrowed down.

The answers to the Selection Criteria (groups A, B and C) will be used to identify the best fitting system from the database of systems for which data have been collected. To achieve this goal, an EXCEL spreadsheet was developed that has the characteristics of the available commercially offered systems. The best matches between the answers to the selection criteria and the specific systems in the EXCEL database are reported by the program. The intent of this spreadsheet application is to identify the systems that will most closely accomplish the monitoring goals of the owner.

As indicated above, the questions in group D are suggested by the research team for the user (i.e., bridge owner) to seek additional information to evaluate vendor performance. This information can be used to further refine the system selections that are made using the EXCEL spreadsheet application. The questions in group D, as well as the associated database material, cannot be included in the EXCEL spreadsheet application. First, the effort needed to contact all of the previous clients for each of the vendors in the database is beyond the scope of the current project. Second, the information that is needed is time sensitive, and vendor performance should be evaluated using the most up-to-date information from previous clients. Thus, in the present project, vendor performance is addressed by proposing the group D questions which are to be evaluated at a future time by the user (i.e., bridge owner).

Table 2: Evaluation Criteria

A. Questions pertaining to the nature of the monitoring you seek to accomplish with this system?

1. What is the time frame for the monitoring?
   - (a) Short-term monitoring (e.g., load rating, fatigue crack growth monitoring, extension of bridge life, permit vehicles).
   - (b) Long-term monitoring (e.g., bridge health/condition for new or retrofitted bridges).
   - (c) Inspection (e.g., deck condition, corrosion monitoring, to be used during inspections).
   - (d) No preference
2. What warning systems are you looking for?
   - (a) Early warning (e.g., changes in structural condition that set off an alarm for immediate action).
   - (b) Bridge collapse or component failure (e.g., bridge continuity sensor indicating bridge collapse and linked to flashing lights/moving signs).
   - (c) No Preference
3. What is the size or scale of the monitoring?
   - (a) Local (e.g., known crack growth, local (plate) buckling, corrosion sensing, strain measurements).
   - (b) Member (e.g., strain distributions in member, member deflections).
   - (c) Global (e.g., natural frequencies of vibration, bridge deflections, temperature distributions, wind profiles).
   - (d) No Preference
4. When would you like to install the system?
   - (a) During Construction
   - (b) Post Construction
   - (c) No Preference

B. Questions pertaining to the type of bridge and bridge components that this system will monitor

1. What is the type of bridge to be monitored?
   - (a) Steel Girder
   - (b) Steel Truss
   - (c) Cable Stayed
   - (d) Prestressed Concrete Girder
   - (e) Reinforced Concrete
   - (f) Suspension
   - (g) Tied-arch
   - (h) Bridge Deck Only
2. What general properties of the bridge would you like to monitor? (To be answered for all bridge systems.) (pick any)
   - (a) Climatic Conditions (e.g., wind speed/direction/humidity, temperature/solar radiation, air pressure)
   - (b) Load
   - (c) Displacements

     Using what type of sensor/system?
     - i. GPS
     - ii. 3-D Laser Scanning
     - iii. LVDT
     - iv. Digital Image Correlation (DIC) of high-resolution images
     - v. Linear potentiometers (string pots)
     - vi. Fiber Optics
     - vii. Laser sensors
     - viii. No Preference

(d) Tilt/slope (using tiltmeters or slope indicators)
(e) Acceleration/Vibration (using accelerometers)
(f) Scour (using pneumatic tubes and filters)
(g) Curvature Sensors
(h) Over-Pressure
(i) Ground Velocity

3. <u>What properties of the concrete bridge components would you like to monitor?</u>
   (a) Strain (e.g., in concrete, steel reinforcing bar, steel wire, or prestressing tendon).
   <u>Using what type of strain sensor</u>?
      i. Electrical Resistance Gauges
      ii. Vibrating Wire Gauges
      iii. Fiber Optic Gauges
      iv. No Preference
   (b) Concrete Cracking (e.g., flexural, shear, shrinkage, D-cracking or spalling/crushing)
   <u>Using what type of sensing system</u>?
      i. Acoustic Emission
      ii. Strain Gauges (see choices in 3a).
      iii. No Preference
   (c) Locating Rebar/Voids or Delaminations
   <u>Using what type of sensing system</u>?
      i. Ground penetrating radar (GPR)
      ii. Automated chain dragging
      iii. Infrared thermography
      iv. Impact echo
      v. No Preference
   (d) Concrete Strength
      i. Thermistor
   (e) Corrosion
      1. <u>Measurements in concrete</u>
         i. Chloride content
         ii. Moisture Content
         iii. No Preference
      2. <u>Measurements on rebar</u>
         i. Chloride content
         ii. Linear Polarization Resistance (LPR)
         iii. Anode Current
         iv. No Preference
      3. <u>Measurements for post-tensioning tendons</u>
         i. TDR (Time-Domain Reflectometry) (U of Delaware holds a patent)
         ii. Impact-Echo
         iii. Electric impedance
         iv. Ultrasonic C-Scan (researched by Penn State)
         v. No Preference
      4. <u>Measurements for pre-tensioned concrete girders (see techniques for reinforcing bars)</u>
   (f) Tension
      i. Ultrasonic Sensors

4. <u>What properties of the steel bridge would you like to monitor?</u>
  (a) Strain (e.g., in plates, rolled sections, connections, etc.)
    Using what type of strain sensor?
      i. Electrical Resistance Gauges
      ii. Vibrating Wire Gauges
      iii. Fiber Optic Gauges
      iv. No Preference
  (b) Fracture (e.g., brittle, ductile, or fatigue)
    Using what type of sensing system?
      i. Acoustic Emission
      ii. Metal Fatigue (Metal fatigue life indicator)
      iii. Strain (ATIs strain concentration sensor)
      iv. Comparative Vacuum Monitoring
      v. No Preference
  (c) Crack Growth
      i. PeakStrain gauge
      ii. Electrochemical Sensors
      iii. Acoustic Emission
      iv. Comparative Vacuum Monitoring
      v. No Preference
  (d) Corrosion (portable ultrasonic gusset plate thickness measurements)
  (e) Tension Force in Cables
      i. Electrochemical Sensors

C. Questions pertaining to the type of monitoring system.

1. <u>Do you require this system to be reusable, movable or portable?</u>
  (a) Yes
    i. *Reusable* (All components can be unattached, moved, and reused.)
    ii. *Movable* (Nothing is attached and the equipment is easily moved, but it cannot be operated while it is being moved.)
    iii. *Portable* (Nothing is attached, the equipment is easily moved, and it is fully operational as it is being moved.)
  (b) No
    i. *Permanent* (Some or all components are permanently fixed).
2. <u>Do you want a complete system provided by a single vendor?</u>
  (a) Yes (All components provided by a single vendor in a fully integrated system.)
  (b) Yes (All components provided by a single vendor, but some may not be integrated.)
  (c) No (Components can be purchased from different vendors.)
3. <u>Would you like to be able to access the data offsite?</u>
  (a) Yes
    1. Is communication available at the site?
      a. Yes
        i. Telephone (landline)
        ii. Cable (landline)
        iii. T10
        iv. No Preference
      b. No
        i. Cell phone
        ii. Satellite phone
        iii. Radio Communication
        iv. No Preference

(b) No
   a. Direct Computer hookup
   b. Manual Collection
4. Is a direct power source available at the bridge?
   (a) Yes (Alternating Current)
   (b) No
   What source would you like?
   i. Solar
   ii. Battery
5. What will be the range of operating temperatures and other environmental conditions for the bridge?
   (a) High (Highest possible temperature)
   (b) Low (Lowest possible temperatures)
6. What would you like the software to accomplish?
   (a) Graphical user interface
   (b) Sensor calibration and checking
   (c) Data Analysis
   (d) Data Collection
   (e) Alarm thresholds and notification
   (f) Offsite monitoring capabilities
7. What services would you like included/available with purchase?
   (a) System Design
   (b) System Installation
   (c) Data Collection
   (d) Data Analysis
   (e) Software Training Courses
8. Is it acceptable for the system to require training of the operators?
   (a) Yes
   (b) No

D. Questions pertaining to the evaluation of the suppliers

Questions to ask the supplier

1. Has the supplier provided monitoring equipment in previous applications?
   (a) Yes
   i. 1 to 5 applications
   ii. 6 or more applications
   (b) No
   (c) Not known
2. If so, who were the clients who purchased the equipment?

Questions to ask previous clients

3. How long has the system been in continuous use?
   (a) < 1 year
   (b) 1-5 years
   (c) 5+ years
4. Was the equipment delivered/installed on time?
   (a) Yes
   (b) No
   (c) Not known
5. Was the equipment reliable?
   (a) Yes

(b) No
(c) Not known

6. How robust was the equipment? (i.e. how long did the equipment last)
   (a) < 1 year
   (b) 1-5 years
   (c) 5+ years
7. Did the clients find the monitoring data useful (measurements, alarms, etc.)?
   (a) Yes
   (b) No
   (c) Not known
8. Were the services provided by the vendor (if any) satisfactory?
   (a) Yes
   (b) No
   (c) Not applicable or not known
9. Was the vendor's warranty support acceptable?
   (a) Yes
   (b) No
   (c) Not known or not applicable
10. How easy was it to make contact with the company?
    (a) Responded quickly
    (b) Multiple Contacts necessary
    (c) No response
11. On a scale of 1-10 (ten being best), how would you rate the company's product and services?
    1 2 3 4 5 6 7 8 9 10

12. What feedback, if any, could you offer to future clients? (i.e. what problems, if any, did you encounter with the products or services)

Questions for the bridge owner

13. Is the feedback from previous clients mostly positive or mostly negative?
    (a) Mostly positive feedback
    (b) Mostly negative feedback
    (c) Feedback is unclear or not known
14. Does research support this type of general system?
    (a) Most papers find it applicable
    (b) Few papers find it applicable
    (c) No research available

Chapter 6: Monitoring Needs and Assessment Program

The assessment program for bridge health monitoring systems is based on the criteria articulated in Chapter 5. The program seeks to match the bridge owner's needs with the capabilities of a company's given system. After the owner answers questions based on the bridge in need of monitoring, the program will list the "best-fit" companies. Thirty-six of the 38 companies were included in the program database. Thus, the program effectively allows the user to choose one or more companies that will offer an effective health monitoring system, based on the user's needs.

The implementation of this assessment was made using the Microsoft EXCEL spreadsheet program. The first sheet in the EXCEL workbook is a survey for the user to complete based on the owner's needs, with the second sheet offering instructions for completing the survey. The survey is a sequential list of questions with "yes" or "no" answers. Any question that is not answered is assumed have a "no" answer, and thus it is not counted in the matching process. The program allows the user to define the weight they wish to place on each question. The program has a default value of 1, but allows the user to change the value to 2, 3, 5, 10, and 100 for each question. This is intended to let the user define the importance of various aspects of the health monitoring system. Built-in safeguards are included in the program. For example, if the user answers more than one "yes" answer in a section asking for only one choice, the program will show an "error" flag in the output column. The "error" flag is not removed until the answers are modified such that a single "yes" is provided in a section for which a single "yes" answer is necessary. Also, there are many questions that have sub-questions, which will only appear when a "yes" or "no" answer has been provided to a more general question. If a question has multiple sub-choices, at least one choice must be chosen for the program to count that question (with the option to answer "no preference").

As the user answers the questions pertaining to the bridge that needs to be monitored, the program assigns points to the different companies in the database. The number of points that a particular question is worth is determined by the weighting column. The third sheet of the EXCEL workbook has the companies listed with "yes" and "no" answers to the questions from the user survey on sheet one. The answers to the questions for a given company were deduced from the questionnaires that were sent out during the data collection phase of the project (see Chapter 3). The fourth sheet of the EXCEL workbook assigns the point value from the weighting column for "yes" answers and a zero otherwise.

The points assigned by the questions are added up in the final column. The program lists the best matching companies and calculates the percentage of the total possible score for each company. The user can choose to display 1, 3, 5, or 10 "best fit" companies. The column adjacent to the score shows the percent match compared to the "perfect" score. The "perfect" score is based on a hypothetical company that would have a "yes" for every possible question. The user should never have to look at sheets 3 (Company Database) or 4 (Scoring Sheet) unless: (1) they would like to see which questions matched correctly, or (2) they would like to add new companies to the existing database or modify the entries for an existing company. If either option is necessary, it is useful to know that the column headers correspond to the questions identified in Chapter 2. The headers are marked by the section letter, question number, and question answer.

6.1 Adding a Company

To add a company, first the sheet must be unlocked. This can be done under the Protection item, and the sheet is unlocked using the password "unlock". Then, the company should be typed in the row directly below the last company in sheets three and four. In the "Company Database" sheet, each question should be answered with a "Y" for yes or an "N" for no in the row following the company name. After this has been completed, on the "scoring sheet", click on the box corresponding to column C and the last row that was previously completed. Drag to the right to column DO so that the whole row is highlighted from column C to DO. Next, in the lower right hand corner, click and drag it down one row. This will expand the scoring formulas one more row down. Next, in column DQ, click on the lower right hand corner of the box above the new row being added and drag down one box. Then, double click on the new box, changing the last number in the entry by positive one.

After that is complete, column A needs to be changed. Double click in box A3. Change the second entry in the *RANK* function from $DQ$3:$DQ$37 to $DQ$3:$DQ$38. This will add the new row to the ranking function. If previous companies have already been added, the second number will be different and should correspond to the row number of the company being added. This completes the procedure on sheets three and four. Now go to sheet one (User Questionnaire) and go to the final list of suggested companies. In B170, in the function VLOOKUP, change the second entry 'Scoring Sheet'!$A$3:$DQ$37 by adding plus one to the last number. For example, 'Scoring Sheet'!$A$3:$DQ$37 would change to 'Scoring Sheet'!$A$3:$DQ$38. This also needs to be done to every other box in columns B and C rows 170 to 179.

6.2 Adding a Question

The process for adding a question to the program is more complicated. Please contact the authors of this report for more information.

Chapter 7: Program Use Example

7.1 Scope

The use of the program requires very basic knowledge of Microsoft EXCEL. Here, an example is shown to enumerate the use of the program described in Chaper 6. The program is a list of questions for the user to answer. These questions range from the time frame of the monitoring, to the metrics monitored, to bridge specifics, to services that are offered by a particular vendor.

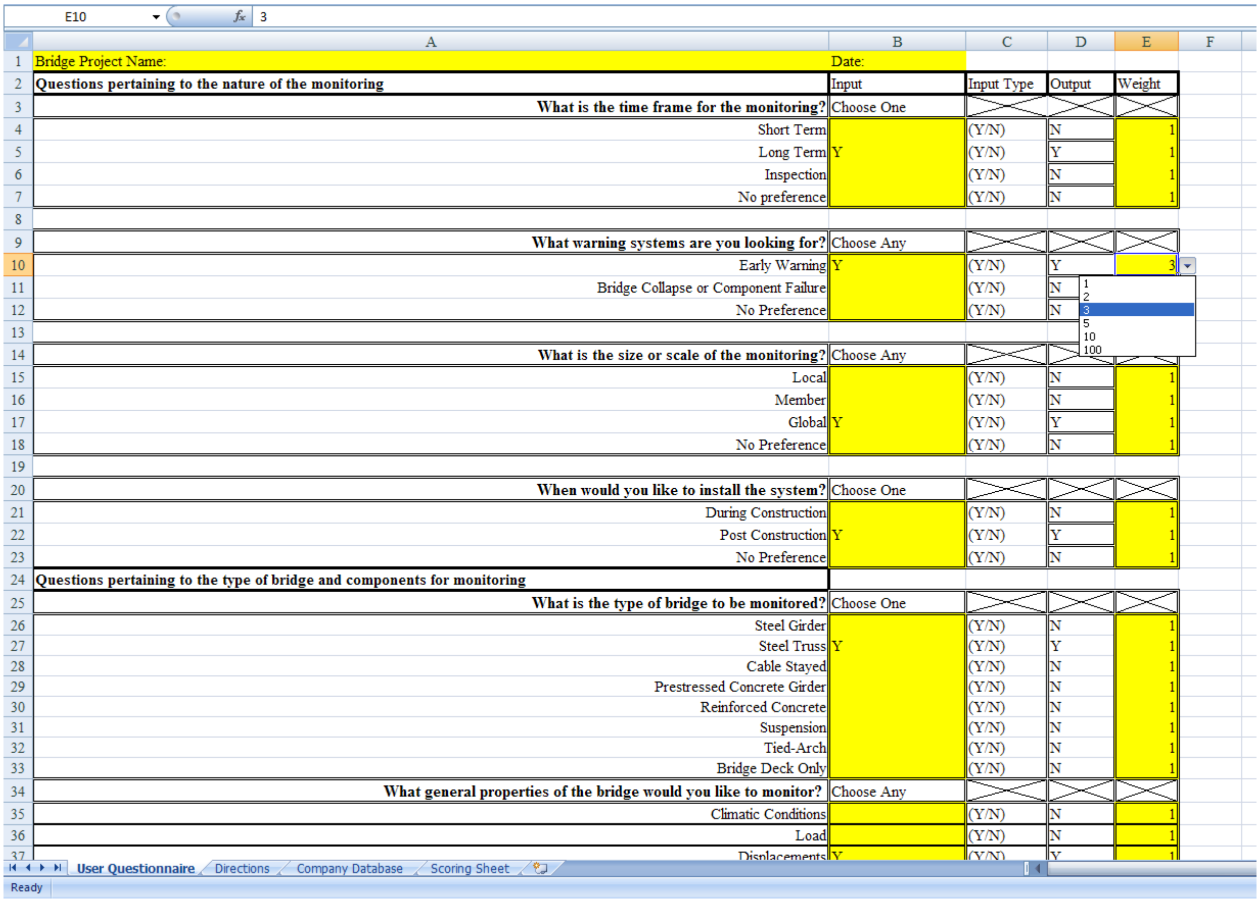
The sections highlighted in yellow are boxes that can be filled in or changed by the user. The sections highlighted in orange are sub-questions that the user may be prompted to answer depending on answers to previous questions in the program. Only yellow or orange boxes may be changed by the user. The rest of the worksheet is locked. The program also has a weighting column that can be changed by the user. These weights should be changed if a particular aspect of the monitoring system is very important to the engineer.

7.2 Example

Suppose the owner would like to monitor a bridge with the following monitoring abilities and site characteristics:

- Global long-term monitoring with early warning capability
- Existing Steel Truss Bridge
- Fatigue crack growth
- Occurrence of fracture
- Bridge/member displacement
- Communication available on site
- All Services and Software Capabilities required

First, the user would place a “Y” in the yellow box corresponding to the “Long Term” answer for the first question. The user is able to change the weight of this question, but decides a value of unity is appropriate. Second, the user places a “Y” in the yellow box corresponding to the “Early Warning” answer for the second question. Since this aspect of the monitoring is of great importantance, the user changes the weight from 1 to 3 (as seen in Figure 7.1). The user continues answering the question with a “Y” placed next to the “Global”, “Post Construction”, and “Steel Truss” options. The “Post-Construction” option is necessary because the bridge is an existing structure.



E10 | 3

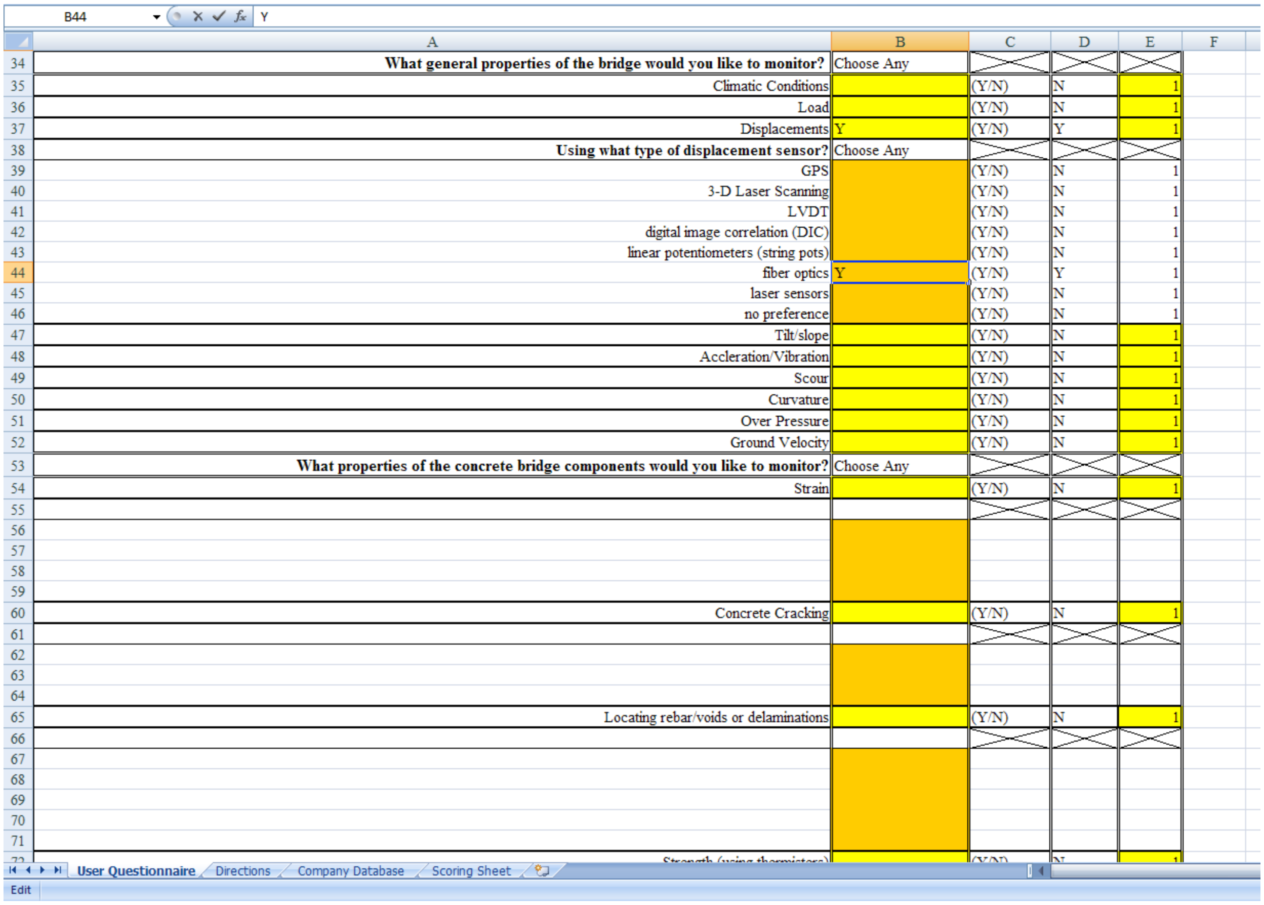
	A	B	C	D	E	F
1	Bridge Project Name:	Date:				
2	**Questions pertaining to the nature of the monitoring**	Input	Input Type	Output	Weight	
3	**What is the time frame for the monitoring?**	Choose One				
4	Short Term		(Y/N)	N	1	
5	Long Term	Y	(Y/N)	Y	1	
6	Inspection		(Y/N)	N	1	
7	No preference		(Y/N)	N	1	
8						
9	**What warning systems are you looking for?**	Choose Any				
10	Early Warning	Y	(Y/N)	Y	3	
11	Bridge Collapse or Component Failure		(Y/N)	N	1 2 3 5 10 100	
12	No Preference		(Y/N)	N		
13						
14	**What is the size or scale of the monitoring?**	Choose Any				
15	Local		(Y/N)	N	1	
16	Member		(Y/N)	N	1	
17	Global	Y	(Y/N)	Y	1	
18	No Preference		(Y/N)	N	1	
19						
20	**When would you like to install the system?**	Choose One				
21	During Construction		(Y/N)	N	1	
22	Post Construction	Y	(Y/N)	Y	1	
23	No Preference		(Y/N)	N	1	
24	**Questions pertaining to the type of bridge and components for monitoring**					
25	**What is the type of bridge to be monitored?**	Choose One				
26	Steel Girder		(Y/N)	N	1	
27	Steel Truss	Y	(Y/N)	Y	1	
28	Cable Stayed		(Y/N)	N	1	
29	Prestressed Concrete Girder		(Y/N)	N	1	
30	Reinforced Concrete		(Y/N)	N	1	
31	Suspension		(Y/N)	N	1	
32	Tied-Arch		(Y/N)	N	1	
33	Bridge Deck Only		(Y/N)	N	1	
34	**What general properties of the bridge would you like to monitor?**	Choose Any				
35	Climatic Conditions		(Y/N)	N	1	
36	Load		(Y/N)	N	1	
37	Displacements	Y	(Y/N)	Y	1	

User Questionnaire / Directions / Company Database / Scoring Sheet

Ready

Figure 4: Weighing Column

Next, the user scrolls down to answer the general properties that should be monitored (see Figure 7.2). The user places a "Y" next to "Displacements" and sub-choices appear below (i.e., the sections highlighted in orange). It is decided that fiber optic sensors should be used for these measurements. However, the "no preference option" would be available as well. If "no preference" was chosen, any of the available sensors that are shown would be included in the results. If no answer is given in the orange section, no answers would be counted toward the final tally. Notice that the answers for the concrete bridge components are left blank and that the orange sections are not asking for answers.

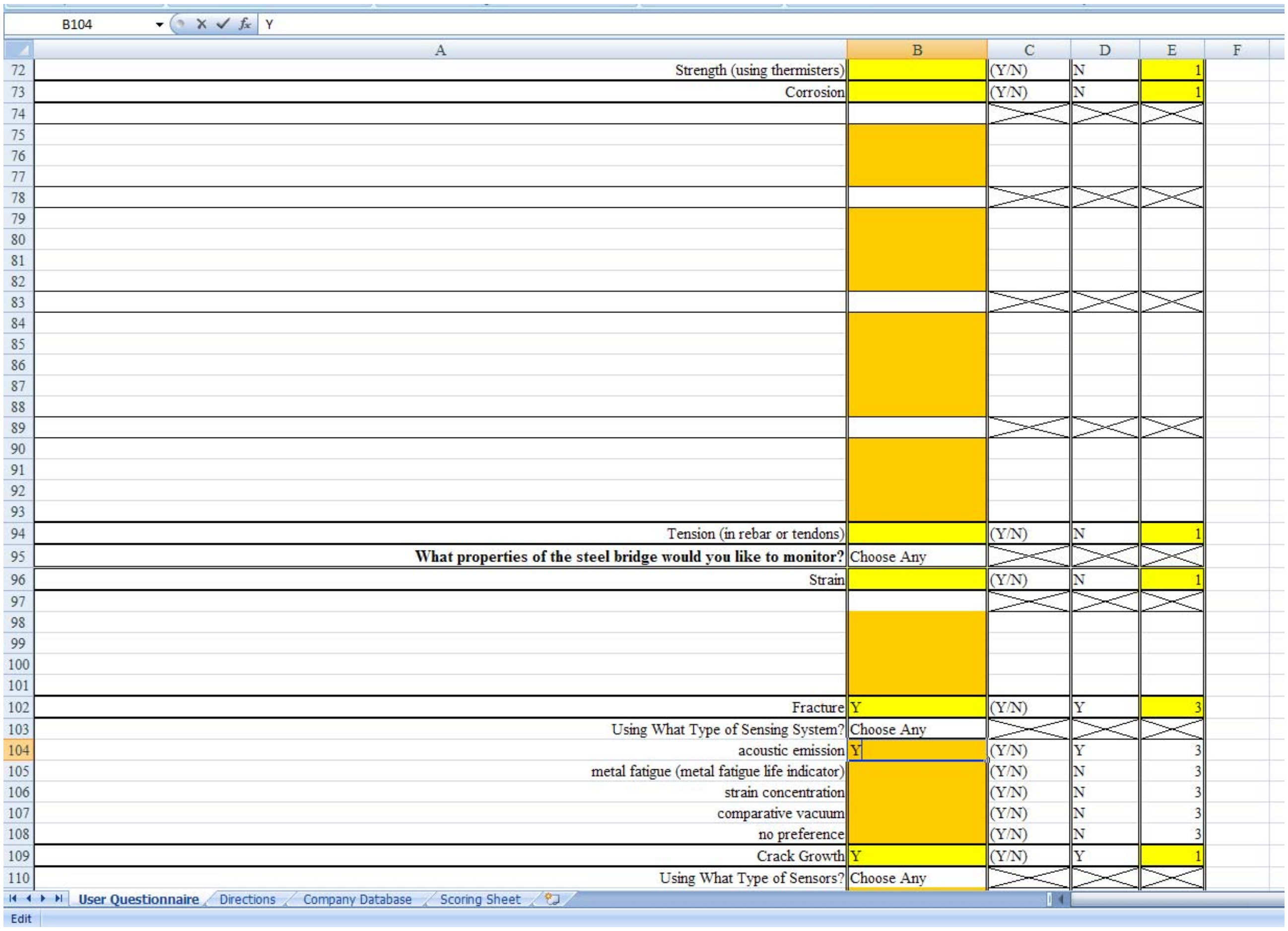


B44 | Y

	A	B	C	D	E	F
34	**What general properties of the bridge would you like to monitor?**	Choose Any				
35	Climatic Conditions		(Y/N)	N	1	
36	Load		(Y/N)	N	1	
37	Displacements	Y	(Y/N)	Y	1	
38	**Using what type of displacement sensor?**	Choose Any				
39	GPS		(Y/N)	N	1	
40	3-D Laser Scanning		(Y/N)	N	1	
41	LVDT		(Y/N)	N	1	
42	digital image correlation (DIC)		(Y/N)	N	1	
43	linear potentiometers (string pots)		(Y/N)	N	1	
44	fiber optics	Y	(Y/N)	Y	1	
45	laser sensors		(Y/N)	N	1	
46	no preference		(Y/N)	N	1	
47	Tilt/slope		(Y/N)	N	1	
48	Accleration/Vibration		(Y/N)	N	1	
49	Scour		(Y/N)	N	1	
50	Curvature		(Y/N)	N	1	
51	Over Pressure		(Y/N)	N	1	
52	Ground Velocity		(Y/N)	N	1	
53	**What properties of the concrete bridge components would you like to monitor?**	Choose Any				
54	Strain		(Y/N)	N	1	
55						
56						
57						
58						
59						
60	Concrete Cracking		(Y/N)	N	1	
61						
62						
63						
64						
65	Locating rebar/voids or delaminations		(Y/N)	N	1	
66						
67						
68						
69						
70						
71						

Figure 5: Displacement Sensing

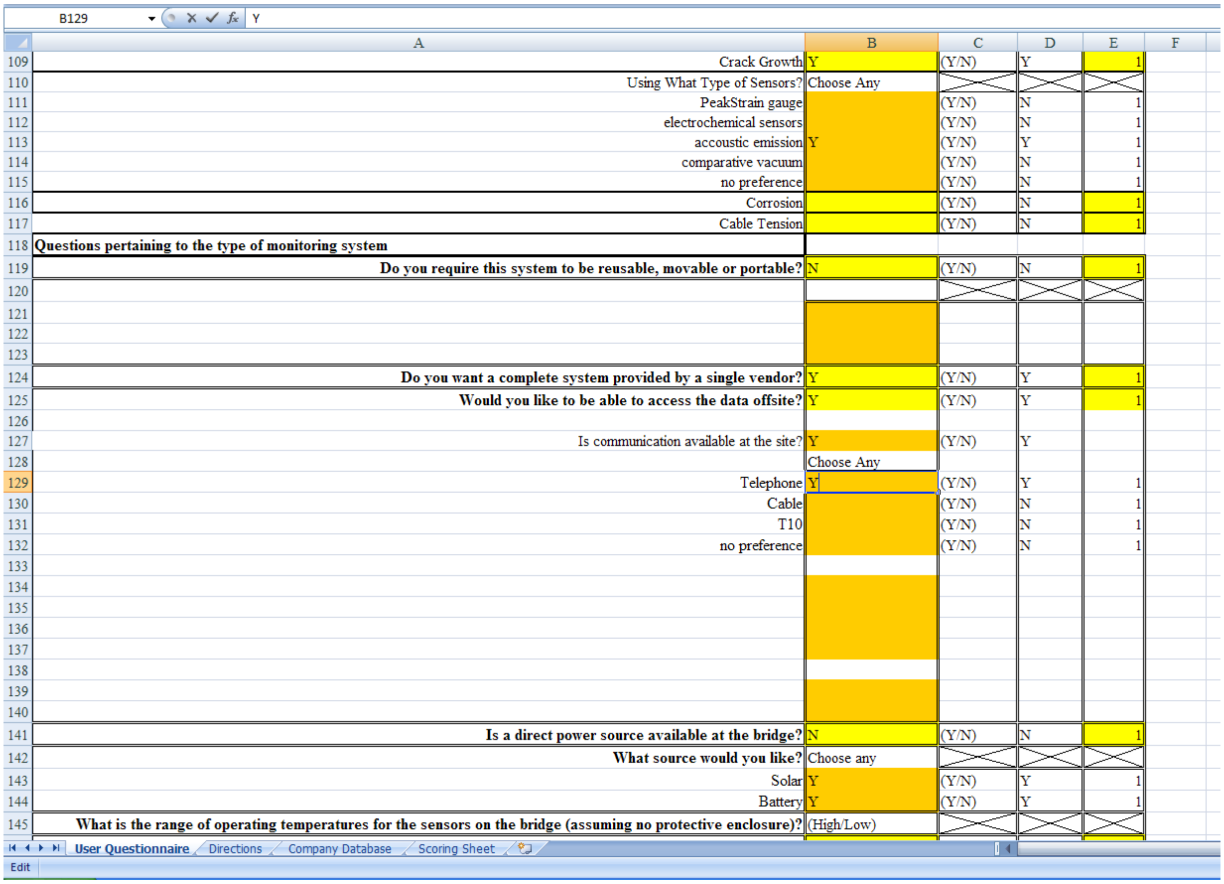
Next, the user answers questions pertaining to steel bridges. To monitor fracture, it is decided that acoustic emission should be used. The bridge is fracture critical so that this is given a weight factor equal to 3 (Figure 7.3). Crack growth is also chosen and can be monitored with acoustic emission (AE) as well (Figure 7.4). Notice that there is an "N" in the question about being portable. However, this is no different than leaving it blank since a question left blank is automatically assumed to be an "N". The user wants remote communication and is prompted to answer whether or not communication is available. It is, so a "Y" is entered. There is a telephone line nearby that can be accessed, so internet is available. However, direct power is unavailable at the bridge, so solar and battery power are chosen



B104 Y

	A	B	C	D	E	F
72	Strength (using thermisters)		(Y/N)	N	1	
73	Corrosion		(Y/N)	N	1	
74						
75						
76						
77						
78						
79						
80						
81						
82						
83						
84						
85						
86						
87						
88						
89						
90						
91						
92						
93						
94	Tension (in rebar or tendons)		(Y/N)	N	1	
95	**What properties of the steel bridge would you like to monitor?**	Choose Any				
96	Strain		(Y/N)	N	1	
97						
98						
99						
100						
101						
102	Fracture	Y	(Y/N)	Y	3	
103	Using What Type of Sensing System?	Choose Any				
104	acoustic emission	Y	(Y/N)	Y	3	
105	metal fatigue (metal fatigue life indicator)		(Y/N)	N	3	
106	strain concentration		(Y/N)	N	3	
107	comparative vacuum		(Y/N)	N	3	
108	no preference		(Y/N)	N	3	
109	Crack Growth	Y	(Y/N)	Y	1	
110	Using What Type of Sensors?	Choose Any				

Figure 6: Fracture Critical Sensing



B129 Y

	A	B	C	D	E	F
109	Crack Growth	Y	(Y/N)	Y	1	
110	Using What Type of Sensors?	Choose Any				
111	PeakStrain gauge		(Y/N)	N	1	
112	electrochemical sensors		(Y/N)	N	1	
113	accoustic emission	Y	(Y/N)	Y	1	
114	comparative vacuum		(Y/N)	N	1	
115	no preference		(Y/N)	N	1	
116	Corrosion		(Y/N)	N	1	
117	Cable Tension		(Y/N)	N	1	
118	**Questions pertaining to the type of monitoring system**					
119	**Do you require this system to be reusable, movable or portable?**	N	(Y/N)	N	1	
120						
121						
122						
123						
124	**Do you want a complete system provided by a single vendor?**	Y	(Y/N)	Y	1	
125	**Would you like to be able to access the data offsite?**	Y	(Y/N)	Y	1	
126						
127	Is communication available at the site?	Y	(Y/N)	Y		
128		Choose Any				
129	Telephone	Y	(Y/N)	Y	1	
130	Cable		(Y/N)	N	1	
131	T10		(Y/N)	N	1	
132	no preference		(Y/N)	N	1	
133						
134						
135						
136						
137						
138						
139						
140						
141	**Is a direct power source available at the bridge?**	N	(Y/N)	N	1	
142	**What source would you like?**	Choose any				
143	Solar	Y	(Y/N)	Y	1	
144	Battery	Y	(Y/N)	Y	1	
145	**What is the range of operating temperatures for the sensors on the bridge (assuming no protective enclosure)?**	(High/Low)				

User Questionnaire / Directions / Company Database / Scoring Sheet

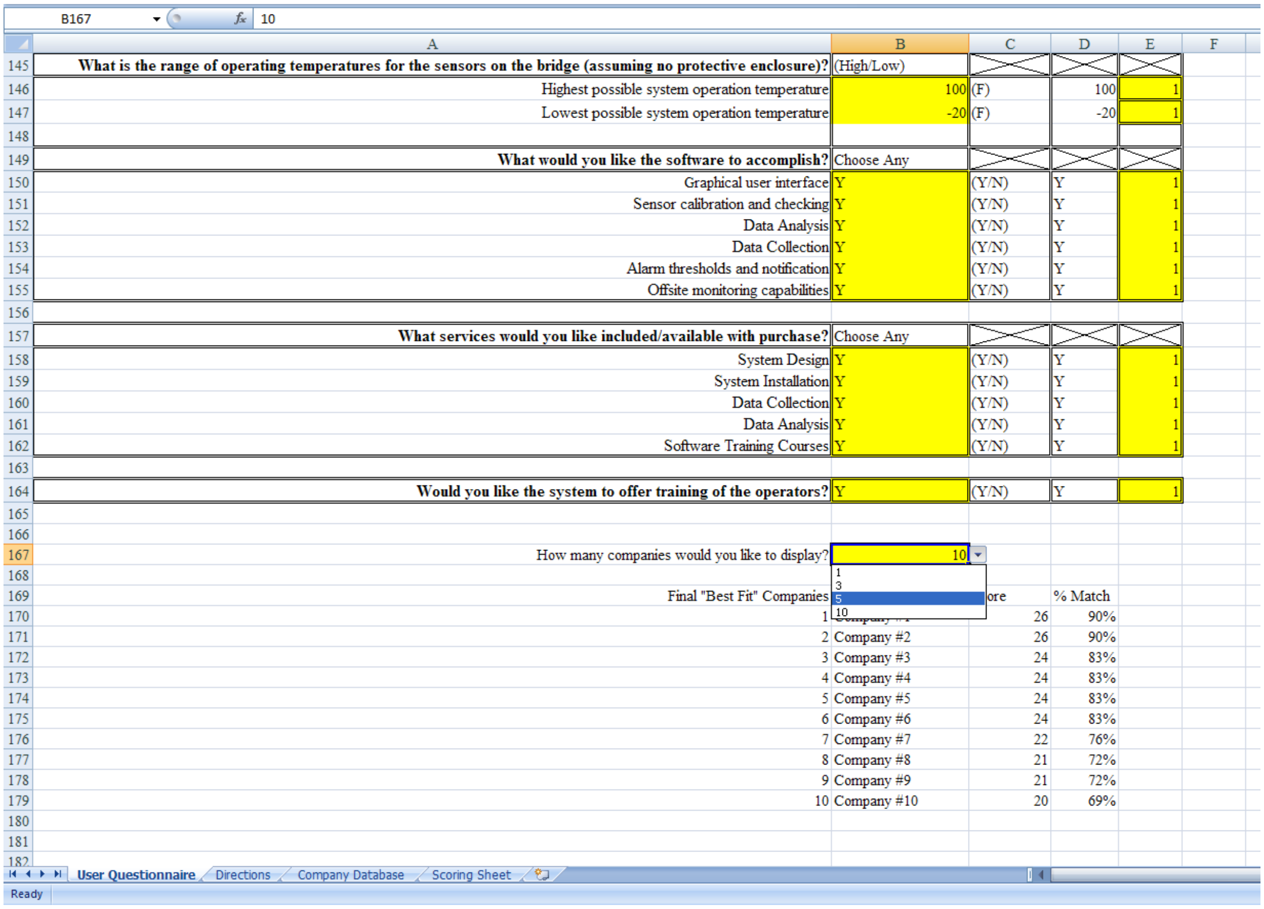
Edit

Figure 7: Crack Growth Sensing and Power Options

Next, the user needs to answer questions about operating temperature. The bridge sees a large range of temperatures, from 100 to -20 degrees Fahrenheit. Notice that the program reminds the user that the temperatures are in degrees Fahrenheit. The user would like all of the software and services to be available to them, even if they are not initially needed; therefore, all of the final options are answered with a "Y" (see Figure 7.5). The last choice the user need to make is how many companies to display. It is a good idea to choose 10 to start to make sure that there is enough differentiation between the companies. If not very many answers have been given, many companies may have the same score.

Figure 7.5 shows the drop down list that can be changed to show 1, 3, 5, or 10 companies. The column next to the company names shows the total number of questioned that were matched. The next column shows the percent match from the "perfect" company. The "perfect" company has a "yes" for every answer in the database. The user can see that two companies matched at 90% and should probably investigated into further. If these two do not seem worthwhile, the companies that matched at 83% could be contacted. Once a match is made, the user should go to the summaries in Chapter 3 and to Appendix A and read the descriptions and questionnaire for that particular company to get a description of what they offer.

Finally, contact with the company should be made and responses to Questions 1 and 2 in Part D of the Evaluation Criteria (Table 5.1) should be requested. Additionally, a list of previous clients should be obtained from the company, and responses to Questions 3 - 12 in Part D of the Evaluation Criteria (Table 5.1) should be requested from each of the compnay's previous clients. Finally, the owner should use the information collected from the company and its previous clients to answer Questions 13 and 14 in Part D of the Evaluation Criteria (Table 5.1). The answers to these questions should enable the owner to make a final decision regarding the suitability of the company as a vendor of monitoring systems and services.



B167 | 10

	A	B	C	D	E	F
145	What is the range of operating temperatures for the sensors on the bridge (assuming no protective enclosure)?	(High/Low)				
146	Highest possible system operation temperature	100	(F)	100	1	
147	Lowest possible system operation temperature	-20	(F)	-20	1	
148						
149	What would you like the software to accomplish?	Choose Any				
150	Graphical user interface	Y	(Y/N)	Y	1	
151	Sensor calibration and checking	Y	(Y/N)	Y	1	
152	Data Analysis	Y	(Y/N)	Y	1	
153	Data Collection	Y	(Y/N)	Y	1	
154	Alarm thresholds and notification	Y	(Y/N)	Y	1	
155	Offsite monitoring capabilities	Y	(Y/N)	Y	1	
156						
157	What services would you like included/available with purchase?	Choose Any				
158	System Design	Y	(Y/N)	Y	1	
159	System Installation	Y	(Y/N)	Y	1	
160	Data Collection	Y	(Y/N)	Y	1	
161	Data Analysis	Y	(Y/N)	Y	1	
162	Software Training Courses	Y	(Y/N)	Y	1	
163						
164	Would you like the system to offer training of the operators?	Y	(Y/N)	Y	1	
165						
166						
167	How many companies would you like to display?	10				
168		1				
169	Final "Best Fit" Companies	3 5	ore	% Match		
170	1	10	26	90%		
171	2	Company #2	26	90%		
172	3	Company #3	24	83%		
173	4	Company #4	24	83%		
174	5	Company #5	24	83%		
175	6	Company #6	24	83%		
176	7	Company #7	22	76%		
177	8	Company #8	21	72%		
178	9	Company #9	21	72%		
179	10	Company #10	20	69%		
180						
181						
182						

User Questionnaire / Directions / Company Database / Scoring Sheet

Ready

Figure 8: List Display

Chapter 8: Summary and Conclusions

With the relentless aging of the civil infrastructure, bridge health monitoring is becoming more important every day. There are many methods to assess structural integrity and each method has its advantages and disadvantages. Many companies sell products and services that bridge owners will need in the coming years to assess which bridges can be safely left in service and which need to be repaired, retrofitted or replaced. However, the sheer number of companies offering differing health monitoring systems can be daunting for bridge owners to sort through.

The authors contacted 72 companies offering health monitoring systems and had more than one-half of the companies (38) agreed to participate by answering a questionnaire on the products and services offered by each company. The authors focused on companies that offer complete monitoring systems (control unit, sensors, communication, and software). The companies contacted were found through internet searches, word of mouth, documents sent to Mn/DOT following the I-35W bridge collapse, and scholarly articles. In particular, the authors referenced a Wisconsin Department of Transportation (Wi/DOT) report (Phares et al. 2005) to find many of the companies that were contacted. This report offers a brief description of the products and services offered by the companies that agreed to participate.

In addition to the summaries for each particular company, this report offers a summary description of the different kinds of monitoring systems that are commercially available. Without knowing the uses, advantages and disadvantages of a particular system, it is difficult for the bridge owner to know what systems could be useful. The descriptions are based only on general classes of systems, and not on the particular systems that the surveyed companies may offer.

The report identifies criteria that are necessary to consider when selecting health monitoring systems. The criteria include questions that pertain to the nature of the monitoring, the type of the bridge and components to be monitored, and the features the owner desires. Additionally, the set of criteria has a fourth section that offers questions to help the owner evaluate particular companies once the choices have been narrowed down. Questions of cost, performance, and contracts are identified for the owner in the fourth section, but not addressed in the program.

The criteria led to the development of a Microsoft EXCEL program. This program helps the owner, by means of a list of questions, to sort through which companies offer the particular system that seems to fit the needs of the particular bridge that needs monitoring. The program does not rank companies, but helps to match which companies offer what the owner desires for a particular bridge. The program matches owner desires to company specifics that were returned in the questionnaire and lists the companies that best fit the owner's needs. The evaluation of the products and services that the companies offer is left to the owner. Since the authors of this report could only take information from the vendors and not actually test the products, the authors were not in a position to rank how well an individual company performs.

As a final thought, the authors would like to point out that many companies claim to offer 'turn key' systems that are immediately useful to the bridge owner. However, for the particular case of damage detection for failure prediction, it is difficult for the owner to know exactly what thresholds should be used for the purpose of triggering the alarm feature. Generally, only differences in data that show structural change can actually be obtained by many of the systems considered. For example, a strain gauge can only measure changes in strain since the system was installed because absolute strains are nearly impossible to measure. Similarly, an accelerometer-based system can only determine vibration frequencies and mode shapes since the system was installed and, therefore, does not know the original frequencies and mode shapes. These issues make it difficult to determine the extent of the damage. In general, the best performance that can be expected from most current systems is to warn the owner that changes in the system are present, and such changes can be taken to mean that damage probably exists.

Monitoring systems that can automatically and reliably warn the owner when failure is imminent do not seem to be available at this time. Such systems are yet to be developed and may become a very useful tool in the future. For example, acoustic emission systems can locate damage, but it is difficult to quantify the extent of damage and the remaining service life. Thus, such information cannot warrant closure of the bridge. Moreover, many assumptions are made in bridge design, and these assumptions are normally conservative oversimplifications. This fact makes determination of significant threshold values for monitoring metrics even more difficult.

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APPENDIX A: COMPLETED COMPANY QUESTIONNAIRES

The appendix contains the completed questionnaires received from the companies selling bridge health monitoring equipment. The questionnaires have been reformatted to fit a standard template. The content, however, has not been changed.

Company: Acellent (1 of 4)

(1) What is the purpose of the system?

- **Long-term monitoring**

  Acellent sensor networks are usually permanently affixed. This gives the most fidelity in comparing the condition of the structure in present-day state status with baseline information that was gathered much earlier, such as immediately after sensor network installation.
- **Short-term monitoring**
- **Inspection**

  Acellent sensors detect structural damage, corrosion, bolt loosening, or rivet relaxation occurring after sensor installation.
- **Early warning**

  Changes in behavior of transmitted acoustic waves within a structure may be indicative of an impending failure.
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**

  Acellent uses piezoelectric sensors to receive ultrasonic acoustic information on passive systems, and to both generate and receive information on active systems. We provide both passive monitoring systems and active (interrogation/analysis) ultrasonic acoustic analysis platforms.
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**

  While Acellent commonly uses thermoelectric temperature sensors in our networks for purposes such as system calibration for robust acoustic analysis, temperature sensing alone is not our primary mission.
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

Company: Acellent (2 of 4)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Acellent networks monitor changes in structures that occur after the sensor network installation. These changes include corrosion, fatigue, fracture formation or propagation (including within welds), bolt loosening, rivet relaxation, buckling, hole formation, and delamination. Load cycling and impacts are commonly associated with such damage.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**

  Piezoelectric sensor networks (that both transmit and receive acoustic signals) remain permanently affixed to maintain integrity of baseline information gathered at or shortly after installation. These typically consist of flexible circuit material with embedded sensors, though fine wires are used in some instances. In some cases, such as passive detection of impacts, a controller/analyzer remains with the sensor network. In the case of periodic active testing of integrity, the supporting electrical equipment (often a laptop computer and an interface box) can be moved from one network to another.
- **Reusable (everything can be unattached and moved)?**

  While Acellent sensor networks are fixed, analysis equipment can be moved from one sensor network to another for periodic inspections. Basically, the sensors cannot be removed without damaging their sensing functions.
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**

  Installation during construction commonly provides the least total expense and the earliest opportunity to gather baseline acoustic transmission information.
- **Post Construction**

  Post-construction installation allows damage that occurs or propagates after installation to be detected.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**

  Acellent systems may monitor steel girders, other beam types, and structures where such objects are components that may change in acoustic transmission properties that indicate damage, fatigue, or corrosion.
- **Steel Truss**

  Acellent networks are applicable to steel truss structures.
- **Cable Stayed**

  Components that receive high loading, such as cable stay attachment plates, would be candidates for structural health monitoring with Acellent products.
- **Prestress Concrete Girder**

  Acellent would welcome interaction to demonstrate applicability to detecting damage on pre-stressed concrete structural components.
- **Reinforced Concrete**

  This is an area of exploration for Acellent.
- **Other**

Company: Acellent (3 of 4)

(7) <u>What type of power source is used?</u>

- **Solar**

  Photovoltaic solar can be used to charge the battery that is used to power our hardware.
- **Battery**

  Acellent products can be incorporated using hardwired or battery-powered environments.
- **AC**

  Yes.
- **Other**

  Other sources that may charge a battery (such as wind) would be in a category similar to solar power of Acellent products.

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Acellent furnishes both complete systems and components for systems. It is common for Acellent to provide all equipment except for a laptop computer, which the customer often already owns. Sensor systems, control units, and software are typical. Communication is often already available via the network the laptop computer is associated with.

(9) <u>What is the operating temperature range?</u>

Approximately –50 to +230 degrees, Fahrenheit for the sensor network. Acellent often runs tests for customers that involve fairly extreme temperature cycling.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Acellent’s customers frequently define the remote communication methodology, such as with satellite applications of our sensors. With active sensing with the user on-site, the controlling computer’s communication network is typically used. However, Acellent is certainly willing to explore alternate remote communication requirements as the need arises.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Acellent’s passive detection systems are typically alarmed. Communications vary by application, and may be customer-determined. (These needs often vary with the installation location, whether the inspection is to be periodic or continuous, and accessibility of the application to those performing the testing.) Active systems may be alarmed if automatic (such as periodic) inspections are performed without a person present. Otherwise, any detected damage shows up brightly in a screen display in front of the user.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Acellent’s software drives the active sensors, and reads information from passive sensors. It processes this through damage detection algorithms to show if damage was detected, an indication related to damage size, and a location of the damage site. It stores this information in data sets, typically on a laptop Windows-based computer.

(13) <u>What services and or support are offered with purchase?</u>

Company: Acellent (4 of 4)

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Acellent offers customer training on site or at Acellent's headquarters in Sunnyvale, California. A typical training course takes 1-2 days to complete, but training lessons can be restructured in accordance with specialized customer needs.

(15) <u>What examples/applications of the system are available?</u>

Please visit www.acellent.com to see some of the numerous examples.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Acellent can provide all of the above.

Company: Advitam (1 of 5)

(1) What is the purpose of the system?

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**
    - Mitigation of maintenance costs:
    - Early detection of structural vulnerabilities, coming from local diseases or from modifications of the static scheme
    - Early detection of main failure risks (elements with few or without redundancy) due to visually undetectable phenomenon (fatigue, internal corrosion for example)
    - Validation of design hypothesis (concerning environmental and traffic hypothesis, and their action on the structure)
    - Quantification of special events (storms, seisms, collisions…)
    - Direct evaluation of their impact on the structure and decision trees
    - Mitigation of user risks:
    - Detection of risks for the users (black ice, wind…)
    - Ability to maintain traffic after a special event
    - Real time traffic regulation

(2) What types of sensors or equipment are used?

- **Accelerometers**
  Capacitive
- **Acoustic Emission**
  Piezoelectric
- **Strain Gauges**
  Short or long range
    - **Fiber-optic**
      Yes for long term installation
    - **Electric Resistance**
      Yes, but for short term installation
    - **Vibrating Wire**
      Almost never (too slow)
- **Load Cells**
  Yes
- **Wind Gauges**
  Yes
- **Tilt**
  Yes
- **Temperature**
  Yes
- **Displacement**
    - **GPS**
      Few because of the price
    - **3-D Laser Scanning**

Company: Advitam (2 of 5)

Very few

- **LVDT**

  Or other displacement sensors

- **String Potentiometers**

  No

- **Other (please specify)**
  - Electromagnetic sensors for tension force measurement in cables
  - Ultrasonic sensors for tension measurement in bars
  - Curvature sensors
  - Laser for displacement measurement

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

I would simplify and make two categories:

1. Monitoring of a bridge with known problem. In this case, monitoring is used as a diagnosis tool to understand the extend of the problem
   a. Example: monitoring of cracks: which will be used to define the most suitable repair method
   b. Example: acoustic monitoring of cables which will be used to locate area with corrosion and assess the extent of the problem
   c. Many other example are not so straight forward. In many cases, visual inspection have shown abnormal problems with unknown origin, and the monitoring is custom designed to help identifying the origin of the problem.
2. Preventive structural health monitoring. In this case, the monitoring is designed to detect changes in the bridge behaviour, focusing on the key risks of the bridge.
   a. Example: monitoring of fatigue from wind or traffic on a steel arch bridge that would involve wind measurement, strain gages and load cells and rainflow analysis
   b. Example: monitoring of the Rion Antirion viaduct which involve about 300 sensors of different type and provides very useful data to bridge designer to assess all un expected event:
      i. Earthquake
      ii. Un usual wind configuration
      iii. Effectiveness of heavy maintenance

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

Each system is different based on the client needs and the risk to monitor. We usually make two category: permanent and temporary.

Permanent monitoring is used when traditional methods can not detect or can not react quickly enough. It is usually the most efficient way.

Company: Advitam (3 of 5)

Temporary is used for assessment of a particular problem or for long term monitoring of slow ageing phenomenon. For example, control of balancing of a cable bridge doesn't need to be permanent. One reading every two years is usually sufficient.

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

  When possible the system should be installed during construction, it helps to detect early sign of deterioration but also to confirm some of the assumptions made during the design.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**

  Yes
- **Steel Truss**

  Yes
- **Cable Stayed**

  Yes
- **Prestress Concrete Girder**

  Yes
- **Reinforced Concrete**

  Yes
- **Other**

  We design and build systems on demand. The systems are adapted to the particular risk of the bridge. So it can be applied to any type of bridge, but this is not the good question. The good question is: "what do I fear on this bridge ?". "What are the evens that I can use as early warning ?". "How can I detect these early warning events?"

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**
- **Other**

  Most of equipment can be powered with AC and/or DC (battery or solar). Battery and solar panel are used for temporary system (limited to some months in practice). When system shall be used for years, we always recommend wired powering.

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes, Advitam usually furnish complete systems which include: sensors, one or multiple acquisition unit on-site, acquisition software customized for the structure, and remote communication with Advitam software for data collection.

We usually are responsible of maintenance of the system over years.

(9) <u>What is the operating temperature range?</u>

Company: Advitam (4 of 5)

It is a criteria that we include in the design. We have experience of system working in Asia in very humid and warm environment. We also have experience of systems working in Russia with very low temperature in winter.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

The system can be accessed remotely as long as a way of communication exists on-site. Depending on the elements available and the amount of date to transfer, the system can be remotely access via: landline, GSM, DSL/Cable, Wireless.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Yes the system includes alarm features. The "health rules" are setup on case by case basis. It can be as simple as threshold on each sensors or can be advanced rules characteristic of bridge response. For example, in many cases a vibration in itself is not abnormal, but becomes abnormal if we know that it is associated with a low wind. Advanced health rules usually involve several sensors and monitoring of the bridge response associated to the loads.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Typical functions are:

- Data acquisition & automatic alert management in order to detect abnormal phenomenon
- Real time data acquisition and synchronisation
- Password protected secured access, with different level of access (viewer only, setup of acquisition parameters, data analysis, …)
- Setup of
  - Acquisition frequency per sensor
  - Recording frequency per sensor
  - Alarm and alert level
- Auto diagnostic system. Detection of system anomalies (sensor failure or de connection, power failure, software crash, …)
- Detection of the aberrant or impossible values
- Real time review of data and time history
- Review of global bridge condition
- Setup of virtual channels
- Preliminary data processing
  - Fourier transform
  - Filtering
  - Min, Max, & average over periods
  - Integration and derivation
- Log files
- Automatic reports in case of abnormal events or on demand
- Export of data to Excel

Company: Advitam (5 of 5)

(13) What services and or support are offered with purchase?

- Design the system
- Customization of the monitoring software
- Installation &commissioning
- Training to use and routine maintenance
- Remote data management and checking of the installation
- Maintenance & multi years guarantee extension

(14) What training/installation is required of the user or are these included (ease of use)?

Training to the use of the system and to the routine maintenance. All GUI interface are customized to the project and are very easy to use.

(15) What examples/applications of the system are available?

- Rion-Antirion, Antirion, Greece
- Plock bridge, City of Plock, Poland
- Millau Viaduc, Millau city, France
- Severn Bridge
- Forth Road Bridge, England
- St Cloud Viaduct, France
- Keppel viaduct Singapore
- Penang Bridge, Malaysia
- Seyssel Bridge, France
- OA6, France
- Dieulouard bridge, France
- See also www.advitam-group.com

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

Sampling rates is usually 1Hz (quasi static) or 500Hz (dynamic). Dynamic is required as soon as dynamic phenomenon or fatigue are expected.
Data range and resolution is really case and sensor dependant;
Accuracy is not a suitable word unless you specify how you define accuracy.

Company: ATI (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

We offer wireless systems for both long term monitoring as well as short term monitoring. Our long-term systems can also be used for early warning. Remote Transmitters and sensors are mounted on the bridge, and communicate with a conveniently located receiver unit. Receivers can operate stand-alone, or in conjunction with a PC-based data acquisition system. Our systems are quick and easy to install. They eliminate long cable runs as transmitters are mounted very close to the sensors.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

We offer systems for use with most any type of sensors including, but not limited to:

-Strain gages- electric and vibrating wire.
-Load cells
-Accelerometers- strain gage and ICP style.
-LVDTs and string potentiometers
-Thermocouples, RTDs and thermistors.
-Wind gages.
-Tilt, yaw and roll sensors.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Most any type of physical measurement can be monitored with our system. We offer a strain sensor that will detect high strain concentrations anywhere within a 6 ft or longer span, while only using one channel. This is particularly useful for detecting problematic areas and areas of potential fracture.

Company: ATI (2 of 3)

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  Certain types of our sensors can be permanently fixed.
- **Reusable (everything can be unattached and moved)?**
  Yes, most all of our equipment can be removed and re-used.
- **Portable (nothing attached/installed and are easily moved)?**
  We offer portable as well as permanently-mounted systems.

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**
  Either. Primarily depends on the types of sensors used.

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**
  They can be used on any type of bridge.

(7) What type of power source is used?

- **Solar**
- **Battery**
- **AC**
- **Other**
  All of the above types of power can be used.

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

It is available as a complete system, including sensors and a computer-based data acquisition system.

(9) What is the operating temperature range?

Our transmitters and receivers can operate in -20 to 140 degree F environments.

(10) How does the system communicate remotely with the user (if at all)?

The system can be queried over the internet with a wireless internet interface. Remote transmitters communicate with a central Receiver, which reports over the internet.

(11) Does the system have an alarm feature and how is it communicated?

Alarm status can be automatically transmitted over the internet.

Company: ATI (3 of 3)

(12) What does the software do (data processing, interface, communications, etc.)?

Automatically counts peaks occurring within programmed zones (such as microstrain zones). Multiple zones provided. Histograms, timeplots and FFT displays. Data can be exported to most any third party software package. Custom algorithms available.

(13) What services and or support are offered with purchase?

We offer complete testing services, or just on-site assistance. Quick turn-around for repairs.

(14) What training/installation is required of the user or are these included (ease of use)?

Training is usually not required as the system is very easy to use. However, on-site or factory training can be provided.

(15) What examples/applications of the system are available?

References available at University of Michigan and University of Maryland. U of Michigan has an eight channel system with 8 discrete transmitters that report to one receiver. Each transmitter connects to an extensometer or any type of strain gage-based sensor or vibrating wire. U of Maryland has two 16 channel transmitters that report to two receivers. The receivers connect to a PC-based data acquisition system.

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

Measurement accuracy of the system is within +/-.25%. The overall accuracy is primarily determined by the sensors used. 16 bit resolution at 500 samples per second per channel is typical. Higher sampling rates are available.

Company: BDI (1 of 4)

(1) What is the purpose of the system?

- **Long-term monitoring**
  BDI-Structural Monitoring System, BDI-Fatigue Monitoring System BDI-SMS:
- **Short-term monitoring**
  BDI – Structural Testing System (STS-WiFi) STS-WiFi:
- **Inspection**
  N/A
- **Early warning**
  BDI-SMS, BDI-FMS
- **Other (please specify)**
  BDI has several different systems depending on the application. However, most of our experience is in live load testing using our Structural Testing Systems (STS WiFi) and then using the data to help develop accurate load ratings.

(2) What types of sensors or equipment are used?

- **Accelerometers**
  Yes – Generally peizoresistive accels
- **Acoustic Emission**
  No
- **Strain Gauges**
  - **Fiber-optic**
    No
  - **Electric Resistance**
    Yes – BDI Strain Transducers also standard foil gauges (http://bridgetest.com/products/strain_transducers.html)
  - **Vibrating Wire**
    Yes – We supply Geokon Sensors
- **Load Cells**
  Yes- Various Manufacturers, usually full bridge strain gage types
- **Wind Gauges**
  Yes- from Campbell Scientific
- **Tilt**
  Yes- usually VW type from Geokon
- **Temperature**
  Yes- usually thermistors from Geokon
- **Displacement**
  - **GPS**
    No
  - **3-D Laser Scanning**
    No
  - **LVDT**
    Yes- Various Manufacturers, usually RDP or Honeywell DCDT's.
  - **String Potentiometers**
    Yes- Various Manufacturers
- **Other (please specify)**

Company: BDI (2 of 4)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  BDI-SMS
- **Reusable (everything can be unattached and moved)?**
  STS-WiFi, BDI-SMS
- **Portable (nothing attached/installed and are easily moved)?**
  STS-WiFi

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
  Yes- Usually VW, longer term systems for monitoring construction loads.
- **Post Construction**
  Yes- System selected if monitoring for live load or dead load effects.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Probably yes, but never used for this application
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  Movable Bridges- Bascule, rotating, etc.; Walls, Abutments, Piers, Columns, Bents, etc.; Hydraulic structures- Spillway gates, lock gates, couter weights; Amusement park rides

(7) <u>What type of power source is used?</u>

- **Solar**
  Yes
- **Battery**
  Yes
- **AC**
  Yes
- **Other**

Company: BDI (3 of 4)

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

All systems are turn-key

(9) <u>What is the operating temperature range?</u>

-40 to +85 degrees C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Dial-up modem, cell modem

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Can be programmed to page a person on-call

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Interface, communication, data collection, data processing (averages, rainflows, min, max, etc.)

(13) <u>What services and or support are offered with purchase?</u>

Varies.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Varies.

(15) <u>What examples/applications of the system are available?</u>

BDI has used its STS systems successfully to perform over 300 load tests throughout the world-example reports are available on our website's support page: (http://www.bridgetest.com/support/support.html)

BDI_CFM has been used on several large movable structures to balance loads in cables

BDI_SMS and BDI_FMS have been used on approximately 25 structures for various types of monitoring from crack grown to rotation as a function of tidal flow to deterioration as a function of an increase in legal weight limit. Note that the SMS and FMS have nearly the same functionality, but SMS systems are for use with low sample rate sensors (i.e. vibrating wire) and FMS are for sensors with higher frequency capabilities (i.e. resistive type gages, strains, accels, etc.)

<u>(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

See specs provided within the links given in first question.

Andrew, thanks for letting us participate in the survey. As you can see, there is a large range of equipment/services that we offer which will vary substantially from project to project. Rather than attempt to provide too many details here (all of which are very accessible on our website), I wanted to mention that our overall approach to any project is to try and keep it as simple as possible, which usually means fewer sensors, etc. Since we are structural engineers, we have a good idea on what types of measured responses are going to actually help the bridge owner make decisions. Sometimes if a system is designed for pure research, then the goals are different and the system can be more involved. However, most state bridge engineers have thousands of bridges to take care of, so having complex field monitoring systems installed on many bridges is not attractive due to cost and maintenance issues. We have encountered many suppliers who's primary goal is to sell high-dollar systems, period.

Company: BDI (4 of 4)
In general, the fancier the system, the more trouble it will have, no matter who is telling you how well it will solve all of the problems. Also, it's not always clear if monitoring will actually solve any problems on a particular structure. Hope this helps a little, and that your project is successful! Thanks again, Jeff Schulz/BDI

Company: Crossbow Technology (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

  Our Mote products can be used for all these purposes. The devices are battery-operated and are easily deployed to offer users predictive and preventative maintenance capabilities. The time constraint is based on the batteries and the duty cycle that is used. The Mote devices are optimized for low power, low data rate type of applications and used correctly can offer multi-year monitoring capability.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  This is up to the customer. Crossbow offers various sensor platforms with an integrated sensor suite including accelerometers, temperature, GPS, etc. However, we also offer MDA boards that give users the ability to take their own sensor and make it wireless. The only constraint is that the sensor being integrated should output no more that 0-3.3V and be able to be powered by the AA batteries the Motes use if no other external power source is available.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Again, this is determined by the sensors customers integrate into their application and what the primary target of the deployment is.

Company: Crossbow Technology (2 of 3)

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

The system can easily be deployed and installed as well as moved and reused. Please note that the hardware we provide is at the board level and will need to be packaged for the environment into which it will be deployed.

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

The devices can be deployed at either time as they are wireless nodes. The nodes themselves form an ad-hoc, self-forming, self-healing network where a node can easily join and leave the network as necessary.

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

I am not entirely sure exactly what types of bridges the nodes have been deployed on, but they can be used on any of the bridges listed above.

(7) What type of power source is used?

- **Solar**
- **Battery**
- **AC**
- **Other**

The off-the-shelf device used 2 AA alkaline batteries. However, there are customers who integrate solar cells or other power sources that work with their application.

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

The system is sold in a modular form. The Mote platforms provide the wireless sensor network portion, the sensor boards or data acquisition boards provided the sensing element and the Gateway interface boards provide the base station capability to allow the data to be transferred to your PC or enterprise system. The software platform is included and provides you with access to the binaries for the mesh networking protocols and source code access to the sensor applications.

(9) What is the operating temperature range?

All components are rated to the industrial temp range of -40 to +70C. When used with alkaline batteries, the operating temp range is limited to -10 to +40C.

Company: Crossbow Technology (3 of 3)

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

The system communicate via RF. The devices are available in 2.4GHz (using 802.15.4 radios) or 868/916MHz (using 802.11b radios). The data is transmitted wirelessly over the network and sent to the base station which can send the data directly to your PC or LAN network or provide web access via a standard web browser to the internet.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

The system has the ability to set up alerts so that if a certain threshold or level is reached an email, SMS text message, etc. is sent to ensure that something is done.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Yes, the software has the ability to do all of the above. This is our MoteWorks software package and can be downloaded from the website here http://www.xbow.com/Support/wSoftwareDownloads.aspx.

(13) <u>What services and or support are offered with purchase?</u>

All of our products come with a limited 1 year warranty from the date of delivery. You have complete access to our user knowledge base as well as tech support via phone and email during standard business hours.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

The devices are designed to be easily deployed and installed by the user. The manuals document how each hardware component works and there are several white papers to enhance your user experience such as which antenna to use, etc. As these items are sold at the board level for standard applications, customers will need to package the Mote and sensor board in an enclosure that meets their environmental requirements and accommodated the sensors they are using. Once this is done, the units may be deployed.

(15) <u>What examples/applications of the system are available?</u>

There are several case studies on the Crossbow website as well as current updates of applications using these products for structural monitoring on our blog site at http://blog.xbow.com/.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Depending on the product you are looking at there are datasheets with information on each of these specifications as well as users manuals under the support section (http://www.xbow.com/Support/wTechnicalSupport.aspx)

Company: Digitexx Data Systems (1 of 3)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
- **Early warning**
  Yes (even driven notification)
- **Other (please specify)**
  Earthquake Damage Detection & Location on tall buildings; Real-time data broadcasting over the Internet to multiple locations for real-time data analysis.

(2) What types of sensors or equipment are used?

- **Accelerometers** – Yes
- **Acoustic Emission**
- **Strain Gauges –** Yes
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells -** Yes
- **Wind Gauges –** Yes
- **Tilt –** Yes
- **Temperature –** Yes
- **Displacement –** Yes
  - **GPS –** Yes
  - **3-D Laser Scanning**
  - **LVDT –** Yes
  - **String Potentiometers**
- **Other (please specify)**

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Acceleration, velocity, displacement, hysteresis loops, inter-story drift, natural frequency, response spectrum, normal modes

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?** Yes
- **Portable (nothing attached/installed and are easily moved)?** Yes

(5) When can/should the equipment be installed?

- **During Construction –** Yes
- **Post Construction –** Yes

Company: Digitexx Data Systems (2 of 3)

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder** – Yes
- **Steel Truss** – Yes
- **Cable Stayed** – Yes
- **Prestress Concrete Girder** – Yes
- **Reinforced Concrete** – Yes
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery** – Yes
- **AC** – Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes – The system can be complete with sensors, server, software, communication and clients. We also can provide a partial system if an existing sensor network is in place.

(9) <u>What is the operating temperature range?</u>

-25 to +85 °C (Digitexx Accelerometers); 0-50˚C Data Acquisition and Server/Controller

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Via Internet (DSL or LAN) – the server, located at the monitoring site, broadcasts over the Internet (IP) for the client software to pick up.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Yes. The user can configure triggers for event notification and there is also a built in alarm for system malfunction. These are sent to the user via SMS text. If an event trigger is activated the server will also write the event data to a secure FTP site for retrieval. Handheld PDA and Cell phones can receive user's specified data and/or information.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Everything. The server software interfaces with the sensors, analyzes the signals, broadcasts the data, sends alarms and records events. The client software is available to view the activity at the server real time as well as record and analyze any data the user desires.

(13) <u>What services and or support are offered with purchase?</u>

24/7 maintenance, regular software updates.

Company: Digitexx Data Systems (3 of 3)

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>
Digitexx installs the system and software. Training is not required though it can be provided is the user requests.

(15) <u>What examples/applications of the system are available?</u>

There are multiple systems in place on bridges, buildings and wind turbines, campus setting to monitor ground motion response. Custom made Clients (GUI) for various levels of alarms to 1st responders, consulting engineers, building owners and operators, relevant government authorities.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Up to 500 S/s/channel, 16 or 24 bit resolution, -25 to +85 °C, +/- 3g, 120 dB dynamic range, 24/7 monitoring, user configurable triggers and alarms, complex damage detection algorithms.

A. Mark Sereci

October 27, 2008

Company: Dunegan Engineering (1 of 2)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
- **Early warning**
  Yes
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
  Yes
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Acoustic Emissions provide warnings of steel fatigue cracking.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  Can be permanent
- **Reusable (everything can be unattached and moved)?**
  Sensors can be clamped on and removed
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**
  Yes

Company: Dunegan Engineering (2 of 2)

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**
  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

The systems include sensors, software and hardware.

(9) <u>What is the operating temperature range?</u>

Around -40 to 70 C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Does not seem to have remote capabilities (direct hookup at site)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Thresholds can be set, but alarming features are unclear

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The AESmart2000 software package can process data and detect crack growth and crack depth even in a noisy environment using modal ratio analysis. The software exports the data into excel for graphs and other output.

(13) <u>What services and or support are offered with purchase?</u>

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

(15) <u>What examples/applications of the system are available?</u>

It has been used on a few rail bridges. See http://www.deci.com/news.htm

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

See specs for specific products at http://www.deci.com/main.htm

Company: Engius (1 of 2)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**

  Short-term monitoring
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Thermistor

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

System gives real time concrete strength during early ages

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**

  The sensors are permanently embedded. The rest of the system can go job to job
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**

  During Construction
- **Post Construction**

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**

Company: Engius (2 of 2)

- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

    All parts that are concrete

(7) <u>What type of power source is used?</u>

- **Solar**

    Radio repeater is solar
- **Battery**

    Most of the system is battery
- **AC**

    Radio base station is AC
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Complete

(9) <u>What is the operating temperature range?</u>

I'd have to look up the exact numbers. Somewhere around -10C to 110 C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Wireless – radio link – mesh topology – range measured in miles

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Next software release has alarms to cell phone and/or email

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Downloads sensor data – displays data – prints reports

(13) <u>What services and or support are offered with purchase?</u>

On site training in most locations

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

On site, telephone, or internet training

(15) <u>What examples/applications of the system are available?</u>

See case studies on www.engius.com

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Thermistor is +/- 1 C, samples and calculates maturity (strength) every 1 minute. Logs data for days/years depending on configuration

Company: Excelerate, Inc. (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
  ACDS finds delaminations in concrete slabs
- **Early warning**
  Finding delaminations is an early warning sign in preventing pot holes and other issues resulting from delaminations
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
  Acoustic sensors excited by chains
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Quickly, affordably, and accurately identifying delaminated areas in concrete surfaces allows for quick repair of the affected area and provides historical information to monitor areas of concern and establish trend data to identify what methods, conditions, usage, and technologies reduce the formation of delaminated areas.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**

There are no consumable parts associated with chain drag so it is continuously reusable.

Company: Excelerate, Inc. (2 of 3)

- **Portable (nothing attached/installed and are easily moved)?**
  It is a mobile, on wheels, detection platform.

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**
  ACDS is used following installation for maintenance and health monitoring.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
  ACDS is used to detect delaminations between the rebar and concrete.
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
  Rechargeable batteries
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

It is a complete user friendly system. We will be including a data management feature in the future.

(9) <u>What is the operating temperature range?</u>

0 – 40 deg C; can be made to go lower and higher with additional cooling or heating.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Simple set of indicator lights. This was by design to make the unit simple to operate.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Audio and visual indication of detected delaminations. Delaminated surface is also marked for visual indication.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Currently, we are not including or require software with the system. A future design will allow data to be stored then transferred by Ethernet or USB to a post processing workstation.

(13) <u>What services and or support are offered with purchase?</u>

Warranty and training.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

The system can be operated without extensive training. Simply turn it on and push along the surface. Future models will include a wide platform and a cab mounted controller.

Company: Excelerate, Inc. (3 of 3)
(15) <u>What examples/applications of the system are available?</u> The ACDS is scheduled to be available for market the first quarter of 2009. We are currently pre orders and the units are built to spec. The technology was extensively tested by the Mississippi State University. Excelerate purchased the right to the Automated Chain Drag patent for productization. **(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>** We can provide data collected by Mississippi State University at this time.

Company: Fiberpro (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  It's for long-term monitoring with high specification
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  We have used strain sensor, temperature sensor, accelerometer, displacement sensor. These sensors are based on Fiber Bragg Grating.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

We applied for our solution in various application. Through these tests we measured strain contraction, expansion, vibration, displacement, temperature elevation, etc.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  FBG sensors are permanent type or reusable type. It depends on how to attach FBG sensors. Bare fiber type FBG sensors are permanent and package type is reusable.
- **Reusable (everything can be unattached and moved)?**
  Package types can be attached and removed easily with reusable plate and screw type.
- **Portable (nothing attached/installed and are easily moved)?**
  Our IS7000 is a portable type.

Company: Fiberpro (2 of 3)

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

  It depends on the business application. Most of them the equipment is installed after construction. But FBG sensors can be embedded during construction or attached post construction in accordance with the application surrounding condition.

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

  We applied for our solution in a suspension bridge, concrete bridge, etc.

(7) What type of power source is used?

- **Solar**
- **Battery**
- **AC**
- **Other**

  Our solution need for power line. It doesn't have battery.

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

Yes, we can provide the total solution including data logger, all sensors, software, etc.

(9) What is the operating temperature range?

Sensor can be different from the package type and data logger is around 10~40'C. But it was used in out of building in cold days. But we can guarantee the above exactly.

(10) How does the system communicate remotely with the user (if at all)?

Our unit is controlled by PC with USB or RS232 cable. For the remote control you will need internet or modem. But we can't support this remote control yet.

(11) Does the system have an alarm feature and how is it communicated?

Yes the system has a function to set –up the alarm (safety) in program.

(12) What does the software do (data processing, interface, communications, etc.)?

Our unit is operated by PC including software. It measures physical elements like as strain and temperature. It can be saved and it also has OSA function to see the profile of FBG quickly.

(13) What services and or support are offered with purchase?

We have done many business in fiber bragg grating sensor business. Therefore we can support you in technical point.

Company: Fiberpro (3 of 3)

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

It is very easy to operate the unit. Regarding as sensor installation the engineers should be familiar with FBG sensor (fiber sensor). But if they try to do it several times and are careful to handle it the process will not be difficult.

(15) <u>What examples/applications of the system are available?</u>

We already sold out many units in various applications.

- Civil engineering: Dam or bridge or tunnel monitoring
- Aerospace application
- Windmill blade monitoring
- Railroad acceleration monitoring
- Complicated material application
- Air plane Wing monitoring
- Naval architecture (LNG carrier monitoring)
- etc

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Please see the attached file. (leaflet) As you know well FBG sensor can be designed for your application. It can be made in strain sensor, temperature sensor, displacement sensor, pressure sensor, accelerometer, etc. If these sensors based on FBG method can be used with our data logger. The application is very huge. Therefore if you purchase 1 unit you can develop many applications and use with various FBG sensors. If you have any questions please feel free to contact me.

Best regards,

MJ

Company: Futurtec Savcor (1 of 4)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  Yes
- **Early warning**
  Yes
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
  Yes
- **Acoustic Emission**
- **Strain Gauges**
  Yes
  - **Fiber-optic**
    Yes
  - **Electric Resistance**
    Yes
  - **Vibrating Wire**
    If needed
- **Load Cells**
  Yes
- **Wind Gauges**
  Yes
- **Tilt**
  Yes
- **Temperature**
  Yes
- **Displacement**
  - **GPS**
    Yes
  - **3-D Laser Scanning**
  - **LVDT**
    Yes
  - **String Potentiometers**
    Yes
- **Other (please specify)**
  Cameras to visually monitor the areas of the bridge-Yes
  Humidity-Yes
  Corrosion-Yes

Company: Futurtec Savcor (2 of 4)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

From the Futurtec website

Environmental factors:

Wind speed/direction/gust frequency and force, ambient and structural temperature, visibility, wave height / water level /Ice level, precipitation, seismic events, solar irradiation, icing, corrosion build-up/penetration,

Functional Factors:

Material breakage, strain/stress peak/accumulation, externally generated vibration (traffic, wind, ground), vehicle classification, speed and category, video streaming of traffic, corrosion.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  Yes
- **Reusable (everything can be unattached and moved)?**
  Yes- There is a portable
- **Portable (nothing attached/installed and are easily moved)?**
  Yes

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
  Yes
- **Post Construction**
  Yes

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**

Yes – Likely all kinds

Company: Futurtec Savcor (3 of 4)

(7) <u>What type of power source is used?</u>

- **Solar**
  Yes
- **Battery**
  Yes
- **AC**
  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes the system contains sensors, control unit, communication, data server, and software.

(9) <u>What is the operating temperature range?</u>

Temperature sensor used for portable unit has data range of -10 C to +60 C, which is also the operating range. For the other components the lowest maximum temperature is +70 C and the highest low temperature is -30 C. Was not able to find temperature data for non-portable system. Normal operating temperature for the system -30 - + 70.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Data is stored on an onsite server then sent through a tcp/ip connection to the user over the web, The user is able to access information online. Portable system stores data on USB flash drive, and not accessed remotely

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Yes, the alarm can either be handled directly by the processing unit, or it may be raised at the wish of the user. The alarm condition is capable of restricting access to the bridge, via lights or gates. No alarming feature is evident for the portable system.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The software allows the user to directly access the data, assuming the user has access to the internet. The software also allows the user to directly set off the alarm feature given the information provided. The software provides the user with a graphical/visual representation of the data for the sensors present on the bridge. For the portable system the software is capable of interpreting the stored data from the USB memory stick.

(13) <u>What services and or support are offered with purchase?</u>

Supply of all sensors and components
Technical support and training
System installation and commissioning
System monitoring and data storage and data analyzing/reporting.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Installation can be handled by the company, training is provided, however it is unclear if it is required. Training for the permanent system is always included in package. For the portable system is not necessary but ofcourse possible if client is asking.

Company: Futurtec Savcor (4 of 4)
(15) <u>What examples/applications of the system are available?</u> Nova Bridge and Nova Bridge 2 in St. Petersburg, Russia (both cable stayed bridges) Isohaara Bridge Alexander Bridge (cable stayed bridge) Kirjalansalmi Bridge (suspension bridge) **(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>** The information gathered for this survey was found using information provided by Futurtec and information available on the Futurtec website. We are using 24-bit A/D-conversion and normal sampling rate is 100 Hz.

Company: Geomation (1 of 3)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Historically, Geomation systems have been used exclusively for long term monitoring and surveillance.
- **Short-term monitoring**
  With the introduction of or our 3400 Series FDLs (Field Data Loggers) last year, we have added stand-alone field data logging to the product mix. However, the 3400 FDLs can also be used in on-line monitoring situations, providing back-up data logging locally in case of network connection outages.
- **Inspection**
  Not usually. Geomation systems are generally used for alarm notification as well as generating data histories for long-term analysis.
- **Early warning**
  Yes. Geomation systems are often used in an early warning strategy, with the objective of postponing a construction solution to a high-risk structure until further analysis and/or funding is available to correct a structural deficiency.
- **Other (please specify)**
  Basically, Geomation systems are comprised of standard products to measure and acquire physical data from structural, geotechnical, and environmental sensors in harsh environments, where battery/alternate power sources must often be used.

(2) What types of sensors or equipment are used?

- **Accelerometers**
  Accelerometers can be measured if followed by an average, RMS or peak responding detector, as is done with a "vibration meter." Geomation systems are for sampling levels at relative low rates. Therefore, you cannot record, say, a 100 kHz vibration signal through our data acquisition equipment; it is not designed for transient capture, and recording the AC signal.
- **Acoustic Emission**
  No. this is basically the same issue as above regarding bandwidth, except involving much higher frequencies that must be processed in a very specific way. Geomation equipment is general purpose data acquisition equipment for physical parameters that are quasi-steady state.
- **Strain Gauges**
  - **Fiber-optic**
    Yes, with appropriate interfacing.
  - **Electric Resistance**
    Yes.
  - **Vibrating Wire**
    Yes. Direct interfaces.
- **Load Cells**
  Yes.
- **Wind Gauges**
  Yes. We have an order presently for wind monitoring on 7 San Francisco Bay Bridges.

Company: Geomation (2 of 3)

- **Tilt**
  Yes.
- **Temperature**
  Yes.
- **Displacement**
  - **GPS**
    Not directly through our system.
  - **3-D Laser Scanning**
    Not directly through our system.
  - **LVDT**
    Yes.
  - **String Potentiometers**
    Yes.
- **Other (please specify)**

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Normally, strain, load and displacement in General.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  This is optional, depending on the application.
- **Reusable (everything can be unattached and moved)?**
  Yes.
- **Portable (nothing attached/installed and are easily moved)?**
  Can be portable.

(5) When can/should the equipment be installed?

- **During Construction**
  Sometimes.
- **Post Construction**
  Oftentimes.

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**
  Any or all of these may be appropriate; it depends on the problem. We're assuming here that you are not going to instrument bridges some uniform method unless there is a specific problem or question that needs to be answered, right?

Company: Geomation (3 of 3)

(7) <u>What type of power source is used?</u>

All of the below, depending on the application. Typically solar where AC power is not available, which is often the case.

- **Solar**
- **Battery**
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Geomation offers complete systems. We do not manufacture sensors, but rather support direct low-power interfaces to most available structural, geotechnical and environmental sensor technologies in use today.

(9) <u>What is the operating temperature range?</u>

-40 to + 85 deg C.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Radio, Internet, Microwave, satellite, cellular modem, fiber optic, wireline.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Complete alarm interface in the software package offered.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

All the above. Extensive alarm interface and acknowledgement capabilities, web based capabilities, across-Internet acknowledgements at multiple locations, etc.

(13) <u>What services and or support are offered with purchase?</u>

Typical of any manufacturer, Geomation is not a contractor. However, we offer installation supervision, project-specific system integration services, and training on use and maintenance.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Geomation provides regularly-scheduled training classes (3-day) at our Golden, Colorado office. Geomation does not provide site-preparation or civil work, but rather instruction manuals and training for user or contractor physical installation.

(15) <u>What examples/applications of the system are available?</u>

Numerous; more so related to dams, tunnels, landslides, and environmental monitoring. Many of the same instrumentation methods that would be used on bridges.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Given the Geomation OutDAQ System capabilities, this is such a broad question, and the answers are too application-specific. For example, resolution, accuracy and data range are dependent on type of measurement, sampling rate is dependent on type of measurement and link devices employed; operating temperature was already answered. Perhaps you should tell us what you want to measure, under what circumstances, with what kind of communication links, and then maybe we can arrive at an understanding.

Company: Geomedia Research and Development (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**

  We have two pieces of equipment, designed for testing the quality of new road/runway construction; others have been put this equipment into service for bridge-deck and prestressed concrete girder inspection. The designed purpose of the equipment is to measure the ultrasonic modulus of concrete and asphalt pavement materials, either in-situ or in core/cylinder specimens. Valid measurements are made in both wet and dry conditions, modulus measurements can be made as early as 8 hours on fresh concrete, and asphalt cooled to accessibility.
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  We use a solenoid impact source with one, or more, accelerometers recording the response of the material to the impact. We also measure temperature, given its control on asphalt modulus.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

We measure the surface wave dispersion curve and/or standing wave resonances, depending on source-receiver and specimen geometry. The elastic modulus of a layered geometry is derived from the surface wave dispersion information. This modulus provides a measure of deterioration of layers within the bridge deck and is sensitive to delamination, asphalt deterioration, concrete deterioration, and rebar corrosion. Orthogonal dispersion curve

Company: Geomedia Research and Development (2 of 3)

measurements provide information on the anisotropy of crack development. The fstanding-wave measurements provide an index of the depth to deterioration.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

The system is portable. The surface wave dispersion measurement system weighs about 15 lbs, sets on the bridge deck/girder, and makes the measurement in less than 15 seconds. The resonance measurement weighs 6 lbs, sets on the deck/girder and measures in less than 8 seconds.

(5) When can/should the equipment be installed?

- **During Construction**
  Yes
- **Post Construction**
  Yes
  Measurements can be made during construction and after construction at any time.

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**

Concrete structural elements and concrete, asphalt, and polyurethane decks may be inspected/monitored.

(7) What type of power source is used?

- **Solar**
- **Battery**
  Yes
- **AC**
- **Other**

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

We provide it as a complete unit: sensor/electronics package, USB cable, and laptop.

(9) What is the operating temperature range?

-10^{o}C to 50^{o}C, depending on material type and behavior at temperature.

(10) How does the system communicate remotely with the user (if at all)?

User interface on laptop screen.

Company: Geomedia Research and Development (3 of 3)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Software collects/archives stress-wave measurements, computes the dispersion curve for layered structures or average modulus or cylinders.

(13) <u>What services and or support are offered with purchase?</u>

We provide on-site training if desired.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Basic/routine measurements can be made with about 4 hrs training of a high-school graduate. Comprehensive forensic analyses can require up to several days for a doctoral graduate.

(15) <u>What examples/applications of the system are available?</u>

Within MnDOT, the following paper discusses one application. http://www.mrr.dot.state.mn.us/research/apt/data/cs12-03.pdf Numerous other papers can be accessed through http://ctis.utep.edu/staff/pre_publication.php?Lg=imad .

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Specifications used by Texas DOT purchasing, for the more comprehensive of the two systems, follow this answer. In-situ modulus measurements are typically repeatable at the level of 3-8% depending on surface condition and level of material inhomogeneity. Absolute accuracy of modulus is difficult to quantify, due to frequency, strain-level, and boundary condition differences between different measurement techniques.

Company: GSSI (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**
    - Bridge Deck Condition Assessment
    - Concrete cover assessment (primarily for new bridge decks)
    - Location of rebar, pipes, post tension cables, conduits, etc.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
    - **Fiber-optic**
    - **Electric Resistance**
    - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
    - **GPS**
    - **3-D Laser Scanning**
    - **LVDT**
    - **String Potentiometers**
- **Other (please specify)**

    Ground Penetrating Radar

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

- Bridge Deck Condition Assessment
- Concrete cover assessment (primarily for new bridge decks)
- Location of rebar, pipes, post tension cables, conduits, etc.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

    Portable

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

    Post Construction

Company: GSSI (2 of 3)

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

    Post Construction

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**

    Reinforced Concrete

- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

    Battery

- **AC**

    AC

- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Bridge deck evaluation system, includes:

- SIR-3000 Data Acquisition System
- SIR-3000 transit case
- Model 5100 1.5 GHz antenna
- Model 623 cart
- 2-meter antenna cable
- battery charger & two batteries
- sun shield
- RADAN software
- Bridge Assessment module
- 2 training credits for classes held at GSSI. 1 training credit per person per class. Travel & living expenses are not included.

(9) <u>What is the operating temperature range?</u>

-10C to 40C ambient

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Color screen

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Company: GSSI (3 of 3)

(12) What does the software do (data processing, interface, communications, etc.)?

- Bridge Deck Condition Assessment
- Concrete cover assessment (primarily for new bridge decks)
- Location of rebar, pipes, post tension cables, conduits, etc.

(13) What services and or support are offered with purchase?

2 year warranty
Free product and application support

(14) What training/installation is required of the user or are these included (ease of use)?

Attend a GSSI BridgeScan training class

(15) What examples/applications of the system are available?

See attached

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

See attached

Company: Harmonic Footprinting (1of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**

- **Other (please specify)**

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

Company: Harmonic Footprinting (2 of 3)

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**
-

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>
(9) <u>What is the operating temperature range?</u>
(10) <u>How does the system communicate remotely with the user (if at all)?</u>
(11) <u>Does the system have an alarm feature and how is it communicated?</u>
(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>
(13) <u>What services and or support are offered with purchase?</u>
(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>
(15) <u>What examples/applications of the system are available?</u>
(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

The Harmonic Footprinting system is uniquely designed to address a large variety of large structure analyses. The system can be used to detect bridge structure failures and predict failures of such a structure to monitoring an oil rig structure predicting structural defects as well as monitoring the rotating machinery potential defects or hydraulic system dynamics.

This diverse system allows for users to incorporate the exact measurements they need at the time while incorporating existing technologies with new technologies for greater analysis. The system is also expandable to incorporate future needs, expansions, or new detection methods.

The Harmonic Footprinting team does not offer an ‘out of box’ solution for every application. Instead Harmonic Footprinting’s teams is constantly investigating new technologies and state of the art algorithms to better define and predict failure of structures and the machinery involved.

Company: Harmonic Footprinting (3 of 3)

Harmonic Footprinting understands that every structure has its own set of characteristics. A steal bridge for example has dozens of different design differences. Two that may look the same while having different responses based on the environment they are in as well as the type of assembly used to the type of earth it is attached to. Let alone the volume and type of traffic. With this in the forefront of Harmonic Footprinting's approach to the market each and every system is taken to heart to come up with the best solutions for predicting the potential failures our customers foresee. Simultaneously reporting useful information as well about the environment, traffic conditions, and volume trends.

The Harmonic Footprinting system is a configured system to meet the needs of each unique customer. Many customers have different capabilities of data transmission and internal protocols for transmitting such data. Additionally, each existing structure typically has specific structural needs for reliability where as a new structure can be learned of how it can react to its environment and usage. The different sensing options offered by Harmonic Footprinting does not limit customers to a particular technology choice. Harmonic Footprint believe if a user is accumulating information in a way they are familiar with the Harmonic Footprinting team will incorporate that into the system while increasing the capabilities of any down falls the existing technology has.

Harmonic Footprinting is fore fronting the large structure analysis market to provide a universal system for unique applications.

Company: HBM (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
- **Early warning**
  Yes
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
  Piezoelectric, Yes
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
    Yes
  - **Electric Resistance**
    Yes (clamped)
  - **Vibrating Wire**
- **Load Cells**
  Yes
- **Wind Gauges**
- **Tilt**
- **Temperature**
  Yes
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
    Yes
  - **String Potentiometers**
    Yes
- **Other (please specify)**
  Others will work with the system, but are not shown available on the website

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Strain, Displacement, Vibration. These can all be used to model the behavior of the bridge compared to how it should be behaving.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  Can be permanent for long term monitoring

Company: HBM (2 of 3)

- **Reusable (everything can be unattached and moved)?**
  Yes, most components can be clamped on and moved to other locations
- **Portable (nothing attached/installed and are easily moved)?**

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**
  Either

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**
  Any of the above where strain, displacement, or acceleration should be measured

(7) What type of power source is used?

- **Solar**
- **Battery**
  Yes
- **AC**
  Yes
- **Other**

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

All components are available as an integrated full system.

(9) What is the operating temperature range?

In general, the components work from -10 to 60 C

(10) How does the system communicate remotely with the user (if at all)?

Via the internet and a server

(11) Does the system have an alarm feature and how is it communicated?

email

(12) What does the software do (data processing, interface, communications, etc.)?

The Catman software suite can do basically all things, post-processing, data acquisition, data analysis, measurements, etc.

(13) What services and or support are offered with purchase?

Calibration and technical support is available

(14) What training/installation is required of the user or are these included (ease of use)?

Installation is available as well as training courses and seminars

(15) What examples/applications of the system are available?

Many. See www.hbm.com for examples

Company: HBM (3 of 3)
(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u> Sampling rates can be either far apart (like once or twice a day) or up to 17 kHz for many devices (see spec sheets).

Company: Impact Echo Instruments (1 of 2)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**

  Yes
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Piezo-Electric, impact-echo

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

  Yes

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

  Both

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**

Company: Impact Echo Instruments (2 of 2)

- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**

  Yes
- **Reinforced Concrete**

  Yes
- **Other**

  Bridge Decks

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

  120/250V Battery
- **AC**

  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes, See impact-echo.com

(9) <u>What is the operating temperature range?</u>

0-75 C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Computer

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Signal processing and FFT

(13) <u>What services and or support are offered with purchase?</u>

Tech Support

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Training Manual provided

(15) <u>What examples/applications of the system are available?</u>

See impact-echo.com

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

See impact-echo.com

Company: Infrasense (1 of 4)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

  All of the above

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**

  Yes- Infrared Thermography (IR)
- **Displacement**
  - **GPS**

    Yes
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Ground Penetrating Radar (GPR)
  Impact Echo
  Distance Measuring Instrument (DMI)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Subsurface levels of corrosion, chloride content, delamination and debonding. Monitoring these performance measures facilitates maintenance and rehabilitation decisions improving not only the condition of the facilities but the economic efficiency of the agency.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

  All of our systems are both reusable and portable.

Company: Infrasense (2 of 4)

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

  Post Construction

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

To fully answer this question it is important to know the limitations of our two main systems; Infrared and Ground Penetrating Radar. The IR method detects the surface temperature change cause by subsurface debonding and delamination. Its reliable detection capability is limited to a depth of 4 inches

(see ASTM D-4788-97).

Also, the presence of an AC or epoxy overlay may limit the effectiveness of the IR method. The GPR method detects rebar-level delamination based on variations in the strength of rebar reflections, and deteriorated concrete under an asphalt overlay based on changes in the concrete dielectric properties (ASTM D-6087-03). The rebar level detection method works when there is a uniform mat of transverse rebar, as occurs in girder-type decks, but not on slab decks (no girders) where the density of steel varies with longitudinal position.

(7) What type of power source is used?

- **Solar**
- **Battery**

  Yes
- **AC**
- **Other**

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

Yes, both are complete systems.

GPR Sensor: 1 GHz air coupled horn antenna
IR Sensor: FLIR Systems A40 Infrared Camera
Control Unit/Communication: A laptop acts as both of these for both systems.
Software GPR: Radan. Infrasense also has its’ own software for the processing and analysis stages.
Software IR: FLIR Systems Researcher

Company: Infrasense (3 of 4)

(9) <u>What is the operating temperature range?</u>

Ground Penetrating Radar is not dependent on temperature whereas Infrared is. Infrasense uses infrared mainly for the condition assessment of bridge decks. Aside from the aforementioned limitations of infrared, a temperature increase of approximately 20 degrees must be achieved from the decks "cooled down state" (occurring at night). A typical temperature range for a concrete bridge deck during the time of the survey is anywhere from 75-110 degrees Fahrenheit.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

The user is able to communicate with the system remotely through the use of a laptop computer. During both surveys the laptop allows for the monitoring, organization and collection of the data.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The software used during both surveys allows the user to communicate with the system, as well as both monitor and regulate the data being collected.

(13) <u>What services and or support are offered with purchase?</u>

Infrasense specializes in ground penetrating radar and Infrared Thermography bridge deck and pavement surveys as well as the design, development, and implementation of numerous non-destructive evaluations, measurement programs, & inspections for civil engineering.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Our company offers a <u>service</u> which is highly specialized.

(15) <u>What examples/applications of the system are available?</u>

<u>Applications Include:</u>

Bridge decks
Highways
Airfields
Pipelines
Storage Tanks
Railroad tracks
Structures/Facilities

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Company: Infrasense (4 of 4)

GPR Specifications

1 GHz air coupled horn antenna: Data is collected in a survey vehicle. System allows data to be collected at driving speed. In general with GPR, resolution increases and penetration decreases with the increase in frequency of the antenna. For this type of antenna penetration is generally no greater than 2 feet. Keep in mind the material being surveyed also depicts the depth at which the antenna can penetrate.

900 and 400 MHz ground coupled antennas: Data collected on foot. The ground coupled antennas have a lower resolution but are capable of penetrating 3-9 feet respectively.

IR Specifications

Infrared data is collected within a survey vehicle and at one frame per foot of travel. These frames are later stitched together to create strip images of each pass taken across a structure. With the system in place the data can be collected up to 5mph. As previously indicated the temperature range of the data is broad and is dependent on a number of variables including; intensity of solar radiation, ambient air temperature, material, surface anomalies, etc.

Company: Instantel (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  Yes
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
  Yes
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Geophones
  Overpressure Sensors

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Accelerations/Vibrations
Geophones measure the velocity of ground motions
Overpressure microphones measure pressure in air

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
  Yes
- **Portable (nothing attached/installed and are easily moved)?**

Company: Instantel (2 of 3)

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**

  Yes

- **Post Construction**

  Yes

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**

  Yes

- **Steel Truss**

  Yes

- **Cable Stayed**

  Yes

- **Prestress Concrete Girder**

  Yes

- **Reinforced Concrete**

  Yes

- **Other**

  Should work for all types

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

  Yes

- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes sensors, control units, software, and communication are available through intstantel.

(9) <u>What is the operating temperature range?</u>

Blastmate III, Minimate Plus, and 8-channel units -20 C to 60 C

Minimate IV -40 C to 50 C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Auto Call Home feature allows the user to access data over a secure website, also Blasware mail allows the user to set up a mailing list for the files to be emailed. Also communication is possible through text messaging.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

The system can be equipped with an alarm, which connects to the control unit, an audible alarm is sounded on site if the primary or secondary thresholds are reached.

Company: Instantel (3 of 3)

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Features of the Compliance module:

Download events, Manage event files, Produce Compliance reports, Produce FFT reports, Upload monitor settings, Configure remote monitoring systems.

Additional Features present in the advanced module:

Set up the monitor to use custom sensors, Set up the monitor to use multiple sensor types, set up the monitor for extended sample rates, perform post-event signal processing, analyze waveform data, analyze histogram data, conduct timeline analysis, conduct signaturehole analysis, create custom frequency standards, customize monitor commands and prompts for any language.

(13) <u>What services and or support are offered with purchase?</u>

Services include free software and hardware upgrades when equipment returned for service, Instalink web based monitoring, warranty available (need to register to view warranty), on-line technical support.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Training available

(15) <u>What examples/applications of the system are available?</u>

Sungai Prai Cable Stay Bridge Penang, monitoring of piles during blasting (during construction)

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Information was gathered by resources available on the Instantel website.

Company: Invocon, Inc. (1 of 7)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
  Yes (EWB MicroTAU)
- **Acoustic Emission**
  Yes - Distributed Impact Detection System (DIDS)
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
    Yes (MicrosWIS-XG, Mite WIS, Microsafe, and WSGIS systems)
  - **Vibrating Wire**
- **Load Cells**
  Yes (MicrosWIS-XG and Mite WIS)
- **Wind Gauges**
- **Tilt**
- **Temperature**
  Yes (MicrosWIS-XG and Mite WIS)
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  The MicroWIS-XG and Mite WIS acquisition systems both capable of receiving measurements from any electrical resistance based sensor (this includes strain, temperature, humidity, pressure, etc.)

  The MicroSAFE system collects strain data, and uses the ASTM Rainflow Cycle Counting Algorithm.

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Systems offered by Invocon allow the user to measure accelerations, strain, humidity, temperature, pressure, or any other data that can be measured using electrical resistance based sensors. Additionally, the Enhanced Wideband MicroTAU system operates with charge output (pC/g) type transducers.

The EWB MicroTAU system provides data suitable for modal analysis due to its resolution and synchronization capabilities. The software does not presently include any built in algorithms for modal analysis. Invocon can add this capability if a customer needs it.

The ASTM Rainflow Cycle Counting Algorithm counts the occurrences of certain cycles of stresses occur, which allows the graphical illustration of the movement of the material along the stress strain curve, which can aide in the determination of the life expectancy.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
  Yes
- **Portable (nothing attached/installed and are easily moved)?**

(5) When can/should the equipment be installed?

- **During Construction**
  Yes
- **Post Construction**
  Yes

(6) On what types of bridge can it be used?

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**

(7) What type of power source is used?

- **Solar**
- **Battery**
  Yes
- **AC**

Other

Company: Invocon, Inc. (3 of 7)

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

The systems consists of the wireless data acquisition systems, a receiver, and software

(9) <u>What is the operating temperature range?</u>

-40 C to +85 C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

The systems communicate via RF wireless link for command, control, data transmission, and data downloading. For high bandwidth systems that collect large amounts of data (Enhanced Wideband MicroTAU, etc.), the systems also contains USB downloading capability. However, this is not always necessary since the smart sensor units contain onboard DSPs to perform distributed processing prior to sending the results (low-bandwidth) to the receiver.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No. DIDS=Yes - communicates via RF back to the PC software.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The Graphical user interface allows the user to set up schedules for sampling for the wireless sensors including schedules contingent on certain measurements (for example it is possible to increase the sampling rate if an unexpected value occurs.

(13) <u>What services and or support are offered with purchase?</u>

Invocon provides training and product support as agreed upon with the customer. This ranges from simple support to extensive software training and installation consultation.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

For most systems, the user manual is enough to get started performing meaningful monitoring. A brief phone call can often clear up any confusion that a customer may have.

(15) <u>What examples/applications of the system are available?</u>

The WSGIS and the EWB MicroTAU systems are designed for use on the space shuttle.

The Mite WIS system is being used to monitor repaired concrete sections in the Westerschelde tunnel in the Netherlands; the strain in important sections was monitored.

The Micro WIS has been used in both bridge monitoring and tunnel monitoring. The tunnel application occurred during the construction of three tunnels in the Netherlands and monitored the grout pressure to ensure quality and safety requirements were met. The MicroWIS system was also used during the construction of a bridge in Houston to measure the stresses on the system during construction and ensure this would not decrease the lifetime of the bridge. In this instance both temperature and strain was measured.

Company: Invocon, Inc. (4 of 7)

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

EWB MicroTAU

Data Acquisition Rate Factory set up to 20KHz.

Synchronization ±4µs between remote units at all sample rates

Sensors 3 external accelerometers. Factory settable gain for wide range of charge output accelerometers. 86dB Dynamic Range

Internal Temperature10-bit A/D with one quarter degree C resolution—Sample Rate 1Hz.

Processing RMS Signal Analysis, Frequency Analysis, Decimation, Peak Detection

Power Battery powered, 3.0-4.0V input range.

Operating Temperature Range -40°C to +85°C (Reduce battery life by 50% when continuous operation at -35°C.)

Battery Life 50-200 cumulative hours of data acquisition or trigger mode (depending on the sample rate). Extended-life external batteries are available.

Memory 256M-byte non-volatile

Packaging Flange enclosure (pictured) with replaceable internal battery Approximately 7cm x 3.8cm x 8.3cm (not including flanges).

MicroWIS

Data Acquisition Rate Programmable via wireless link: 1 sample per second to 1 sample per hour.

External Sensor Optional full-bridge completion configuration; 1.2V excitation; 24-bit A/D; factory programmable gain and filter parameters.

Internal Temperature 10-bit A/D with quarter degree C resolution.

Power Battery powered, 2.8-4.0V input range.

Company: Invocon, Inc. (5 of 7)

Operating Temperature Range - 35C to 85C (Reduce battery life by 50% when continuous operation at -35oC.)

Transmit Distance Up to 100 feet in open air. (This may increase or decrease depending on the transmission path.*)*

Battery Life Standard internal battery: 6 month @ 1 sample/min.

Packaging Screw-on enclosure (pictured) with replaceable internal battery.

Sensor Types MicroWIS-*XG* can accommodate strain gages, RTDs, pressure sensors, humidity sensors, accelerometers, or any other sensor with an active resistive element.

MITE WIS

Sample Rate 1 sample every 15 seconds to 1 sample/hour, programmable via wireless link

(Optional: Up to one sample/second configured at factory with reduced number of units in operation)

Memory 2 Mbytes – Stores up to 145 days of data when sampling all four channels plus internal temperature at once per minute.

Transmission Rate 55.6 kilobits/second

Communication Mode Half duplex @ 916.5 MHz

Max Transmit Power 1 milliwatt

Coverage Range

Direct Line-Of-Site (LOS): Up to 200 feet

No LOS: Up to 100 feet

Battery

Type Lithium, 3.6 volts, Tadiran model TL-5135 (for applications with operation below 0°C use

TL-2135)

Life 2 yrs @ one sample/minute (Reduce battery life by 50% when continuous operation below 0°C.)

Unit Storage/Operating Temperature -35 to +85°C

Company: Invocon, Inc. (6 of 7)

Transducers

Quantity Up to four input channels

Type Resistive, optional full bridge completion or Voltage-output

Excitation 1.2 to 2.5V, factory set

Gain/Filter Factory set to customer requirements

A/D 16-bit Sigma Delta

Connector 4-pin, Fischer 102-Series

Internal Temperature Sensor

Type 10-bit Digital

Accuracy ±2°C

FS Range -35 to +85°C

Resolution 0.25°C

Antenna

Type 902 MHz Duck Antenna (9 cm length)

Connector SMA (optional 90° elbow as pictured on page 1)

Microsafe

Sample Rate 32 Hz

Excitation Voltage 1.2 V

Gain & Strain Gauge Nominal Resistance Factory set to user requirements

Operational Temperature-35°C to 85°C

WSGIS

Data Acquisition Rate .1Hz to 20kHz
Synchronization ±4μs between remote units on the four high-speed channels

Company: Invocon, Inc. (7 of 7)
Sensors 4 high-speed channels and 4 low-speed channels are factory settable for a wide range of resistive and voltage output transducers. **Internal Temperature** 10-bit A/D with one quarter degree C resolution—Sample Rate 0.1Hz. **Processing** RMS Signal Analysis, Frequency Analysis, Decimation, Peak Detection **Power** Battery powered, 3.0-4.0V input range. **Operating Temperature Range** -40°C to +85°C (Reduce battery life by 50% when continuous operation at -35°C.) **Battery Life** 50-120 cumulative hours of data acquisition or trigger mode (depending on sample rate). Extended-life external batteries are available. **Memory** 256M-byte non-volatile **Packaging** Flange enclosure (pictured) with replaceable internal battery. Approximately 7cm x 3.8cm x 8.3cm (not including flanges & antenna).

Company: Leica Geosystems (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  Yes
- **Early warning**
  Yes
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
  Yes
- **Temperature**
- **Displacement**
  - **GPS**
    Yes
  - **3-D Laser Scanning**
    Yes
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Leica's instruments (GPS, TPS) are used to measure true 3 dimensional displacements. We also provide the marketplace with tiltmeters for high-accuracy inclination measurements, and laser scanners for high-definition 3D scans.

Company: Leica Geosystems (2 of 3)

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- Our equipment is commonly installed prior to, during, and after construction.

  Yes
- **Reusable (everything can be unattached and moved)?**

  Yes
- **Portable (nothing attached/installed and are easily moved)?**

  Yes

  Leica's TPS, GPS, and tiltmeters can be used for the first three scenarios, whereas the 3D laser scanners are used in a campaign style deployment.

(5) When can/should the equipment be installed?

- **During Construction**

  Yes
- **Post Construction**

  Yes

  Our equipment is commonly installed prior to, during, and after construction.

(6) On what types of bridge can it be used?

- **Steel Girder**

  Yes
- **Steel Truss**

  Yes
- **Cable Stayed**

  Yes
- **Prestress Concrete Girder**

  Yes
- **Reinforced Concrete**

  Yes
- **Other**

  All of the above

(7) What type of power source is used?

- **Solar**

  Yes
- **Battery**

  Yes
- **AC**

  Yes
- **Other**

  All of the above

Company: Leica Geosystems (3 of 3)
(8) Is it a complete system and what does it include (sensor, control unit, software, communication)? We typically provide complete solutions with associated hardware and software support packages. We can also provide subsets of a monitoring system, depending on the customer's preference. **(9) What is the operating temperature range?** Depends of the project setup, but generally -20 to + 50 degrees Celsius. **(10) How does the system communicate remotely with the user (if at all)?** Leica has developed software packages such as GeoMoS and Spider that manage arrays of instruments and provide threshold notifications via e-mail or other distributive services. **(11) Does the system have an alarm feature and how is it communicated?** Via e-mail, SMS, SCADA, etc. **(12) What does the software do (data processing, interface, communications, etc.)?** Our software provides instrument management support, interface support, processing support, analysis support, and communication support. **(13) What services and or support are offered with purchase?** Our projects are typically sold with 1 year support packages know as Customer Care Packages (CCP) **(14) What training/installation is required of the user or are these included (ease of use)?** A Leica system commissioning service is typically built into the cost of each project. **(15) What examples/applications of the system are available?** We have published numerous research and white papers about our projects, and make extensive product brochure information available. **(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?** See attached data sheets.

Company: LifeSpan Technologies (1 of 4)

(1) What is the purpose of the system?

- **Long-term monitoring**

  LifeSpan specializes in long-term monitoring solutions for long-span bridges (>200 feet). Solutions are custom configured to meet the information needs of the owner and/or third party engineer. Peak strain values can be captured without power, and alarms set to alert the bridge owner if observed displacement/strain values exceed pre-established limits.
- **Short-term monitoring**
- **Inspection**

  LifeSpan offers a manual monitoring solution that can serve as an "inspection tool" for monitoring visible defects, such as fatigue or shear cracking. The manual solution offers a more objective, lower cost alternative to physical, visual inspection and can be accomplished without a dedicated power source.
- **Early warning**

  For long-term monitoring solutions, LifeSpan Technologies typically provides for early warning alerts to owners and/or third party engineers if certain displacement/strain values are exceeded.
- **Other (please specify)**

  LifeSpan Technologies can use commercial cell phone networks or satellite to send captured data to a secure, high-uptime server farm. Our clients can access this secure website using a unique password to view any/all captured data.

(2) What types of sensors or equipment are used?

- **Accelerometers**

  Yes
- **Acoustic Emission**

  Yes
- **Strain Gauges**
  - **Fiber-optic**

    Yes
  - **Electric Resistance**

    Yes
  - **Vibrating Wire**

    Yes
- **Load Cells**

  Yes
- **Wind Gauges**

  Yes
- **Tilt**

  Yes
- **Temperature**

  Yes
- **Displacement**

Company: LifeSpan Technologies (2 of 4)

- **GPS**
  No
- **3-D Laser Scanning**
  No
- **LVDT**
  No
- **String Potentiometers**
  No

- **Other (please specify)**

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

We contend there are several important project objectives for owners when using advanced condition assessment technology. These include, but are not limited to the following:

- Objectively determining the actual structural condition, or "health" to safely extend operating life of the bridge – visual inspection protocols are inherently subjective and quite variable, as reported by the FHWA. To optimize long-term bridge management with lowest life cycle costs, the owner must know with certainty the actual condition of a bridge. Strain, displacement, temperature, and tilt are the principle variables of interest necessary to make a determination of structural health.
- Diagnosing certain structural deficiencies – visual inspection cannot be used to determine which members are overstressed, validation of localized stress conditions suitable for onset of fatigue cracking, excess strain resulting from section loss, out-of-plane bending, crack propagation, etc.
- Confirmation of the safe operating envelope – determination that the structure is capable of safely handling all legal loads.
- Objective prioritization of construction program – with limited funding, it will become more and more important to properly prioritize projects to maximize safety, minimize risk, and optimize spending.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  No
- **Reusable (everything can be unattached and moved)?**
  Yes
- **Portable (nothing attached/installed and are easily moved)?**
  Yes; LifeSpan's manual monitoring solutions are considered portable

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

We contend that consideration for investing in a structural monitoring solution should be principally triggered by classification of the bridge as "structurally deficient", driven by its superstructure condition.

Company: LifeSpan Technologies (3 of 4)

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  LifeSpan's structural monitoring solutions are not applicable for masonry or wood bridges.

(7) <u>What type of power source is used?</u>

- **Solar**
  Only if line power is not available on the bridge, used for recharging battery packs
- **Battery**
  Only if line power is not available on the bridge.
- **AC**
  Preferred power source.
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

LifeSpan's solutions generally consist of a sensor suite, system control unit with on board data handling and alarming features, wireless communication capability, configurable software (e.g. data capture frequency), remote diagnostics, and secure Network Operations Center (NOC) data storage and customizable presentation.

(9) <u>What is the operating temperature range?</u>

Generally speaking, LifeSpan's solutions can operate effectively from minus 30 degrees F to 150 degrees F.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

LifeSpan's solutions provide highly reliable communication features via the web to the user.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

LifeSpan includes an alarm feature for any sensor the owner or his consulting engineer decides is important to carefully monitor.

Company: LifeSpan Technologies (4 of 4)

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The software controls all aspects of the solution.

(13) <u>What services and or support are offered with purchase?</u>

We offer training on how to use the website feature, on-going support for both hardware and software, and troubleshooting if there is a system malfunction.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

A LifeSpan solution is very easy to use. If you can find a website using a URL, use of the Internet feature is intuitive.

(15) <u>What examples/applications of the system are available?</u>

LifeSpan has very detailed independent reports available in PDF format that explain unique monitoring projects on two Interstate bridges and their outcomes.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

LifeSpan's solutions require **<u>NO MAINTENANCE</u>**. LifeSpan's PeakStrain™ sensor is designed such that is needs **<u>NO CALIBRATION</u>** while in use.

Company: MALA (1 of 3)

(1) What is the purpose of the system?

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**

  Yes
- **Early warning**
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  GPR

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

GPR can be used for identifying in-bedded structures in concrete, potential corrosion of reinforced steel, possible areas of delamination and voids in concrete decks.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

  Yes

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

Yes

(6) On what types of bridge can it be used?

- **Steel Girder**

  Yes

Company: MALA (2 of 3)

- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  Meant for Bridge Decks and concrete components

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
  Yes
- **AC**
  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

ProEx and CX-11 systems:
* Control unit
* Transreflective color Monitor
* Easy to use software interface
* High frequency antennas (1.2, 1.6 or 2.3 GHz)
* Lithium-Ion battery
* Battery charger
* Operator's manual
* More advanced ProEx offers more flexibility, faster data collection and multi-channel capabilities

(9) <u>What is the operating temperature range?</u>

See technical spec sheets

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Direct (Ethernet to computer or attached monitor)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Displays images in real time, can also be used by other software packages to process and display data on a PC

(13) <u>What services and or support are offered with purchase?</u>

Support is offered if necessary

Company: MALA (3 of 3)

(14) What training/installation is required of the user or are these included (ease of use)?

Intuitive design, but training is offered

(15) What examples/applications of the system are available?

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

Both systems (ProEx and CX) offer too wide of a variety of options (antenna frequencies and settings) to elaborate on in a brief paragraph. See technical spec sheets for more info.

Company: Matech (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**

  R&D work is continuing to achieve this, though not necessary for highway bridges.
- **Short-term monitoring**

  Short term inspection (2 to 3 days, up to one week)
- **Inspection**

  Inspection to find cracks that visual and other NDE methods miss
- **Early warning**

  Gives early warning of not only fatigue cracking but also the microplasticity (the slip bands that form prior to initiation and propagation). If Microplasticity is occurring then it is likely that initiation and propagation will occur (S-N curve behavior).
- **Other (please specify)**

  Retrofit and repair verification and decision making. Use of the EFS system has been for the purpose of immediately determining the efficacy of repairs through the microplasticity and early growing crack detection, as well as "trying out" various retrofits (varying designs and pricing) and testing to determining which is the most cost effective.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Electrochemical Sensors (developed by MATECH and similar to an EKG patch). Sensors with stainless steel mesh and water-based electrolyte are attached to a modified potentiostat through alligator clips. A small polarizing voltage is applied to anodically polarize the area under the sensor. As a crack grows, new steel is exposed upon which a passive layer forms. This changes the resulting current read back at the potentiostat data link. It is recorded and streamed wirelessly to a laptop. Truck traffic which causes the cracks to grow will induce plastic deformation readily visible in the data acquisition software live on the screen. All data is further analyzed to determine the amount of crack growth activity.

Company: Matech (2 of 3)

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Crack formation and propagation

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**

  Sensors and electrolyte are disposable. Potentiostat Data Link (PDL)'s are magnetically affixed to the bridge, 10 are in a set, 1 PDL per two sensors. They are moveable and portable, lightweight. Sensors are just peeled off when testing is complete.
- **Portable (nothing attached/installed and are easily moved)?**

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**

(6) On what types of bridge can it be used?

- **Steel Girder**

  Yes
- **Steel Truss**

  Yes
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

(7) What type of power source is used?

- **Solar**
- **Battery**

  Yes
- **AC**

  Yes, when available, Battery otherwise.
- **Other**

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

Sensors, electrolyte (injected), Potentiostat Data Link (PDL), Wireless network access point, Laptop, grounding magnet

(9) What is the operating temperature range?

Above 32 degrees F, Below 110 degrees F

Company: Matech (3 of 3)
(10) How does the system communicate remotely with the user (if at all)? Inspection crews stream data wirelessly from PDL's to laptop through access point. Since it is a short term monitoring system, this is all that is needed. Could easily be adapted for remote data access. **(11) Does the system have an alarm feature and how is it communicated?** No alarm trigger per se. It has a timed data collection trigger used for overnight monitoring to conserve battery life. **(12) What does the software do (data processing, interface, communications, etc.)?** Provides data acquisition from each PDL, provides online monitoring and viewing of current (uA) signal, provides preliminary data analysis through proprietary algorithm, allows for further engineer analysis in office. **(13) What services and or support are offered with purchase?** Training and Tech Support are offered. Also, inspection service is offered without system purchase. Also, rental is available. **(14) What training/installation is required of the user or are these included (ease of use)?** Very Easy to use, we suggest 4 full days of training for installation, trouble shooting, and data analysis in classroom/lab and 1 day field training. Training is included, (i.e. we will not sell system without the training, since it is a "new" technique). **(15) What examples/applications of the system are available?** System has been used in 8 states on highway bridges and on 1 commercial railroad bridge. Has also been used twice at the TTCI center in Pueblo, CO. Also, the FHWA has purchased a full system as part of the Steel Bridge Testing Program. **(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?** Hardware Temperature Range: 10 degrees F to 110 degrees F Applied Sensor Voltage: Zero to 1.0 V PDL Current Resolution: +/- 0.001 mamp Data Sampling Rates: 100 Hz and 200 Hz On board storage: 1 GB SD card Wi-Fi: 802.11 b/g Communication Range with Omni directional antennas: up to 2500 Ft On board battery life: Up to 4 weeks with power saving features engaged (depending on Wi-Fi and Analog usage). Up to 12 hours with Wi-Fi and Analog boards on continuously

Company: North American Geotechnical (1 of 4)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Monitor depth of scour around bridge piers or abutments on demand
- **Short-term monitoring**
  Operates during both floods and non-flood river stages on demand, so it can be used also to determine scour conditions on a short term basis and provide early warning of dangerous scour conditions.
- **Inspection**
- **Early warning**
  Operates during a flood so early warning of critical scour condition is available
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  The probe contains a vertical array of filters attached individually to pneumatic hosed brought to the bridge deck for access. Each filter is attached to a fixed volume of high pressure air which is released into the river bottom sediments. The electronics measures the pressure decay rate at each filter in the vertical array, providing pressure decay graphs at multiple depths.

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

The pressure decay rate is significantly higher in soft, unconsolidated soils vs. competent soils. The distinct break in pressure decay rate vs depth when the probe crosses the boundary between unconsolidated soils into consolidated soils identifies the depth of scour.

Company: North American Geotechnical (2 of 4)

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**

  The probe containing the vertical array of filters through which the high pressure air tests the resistance to air flow is permanently installed in the river adjacent to the bridge foundation under investigation.
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

  The electronics for measuring the pressure decay rate and the high pressure air source are portable and are carried to the test site on demand

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**

  The probe can be installed either during construction or post construction.
- **Post Construction**

  Can be installed post construction

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

  Any bridge or structure in the river. The probe is placed in the scour zone adjacent to the structure in the river.

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

  electronics runs on a 12 volt car battery
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Complete system is the probe and associated electronics with laptop computer for data logging and analysis

(9) <u>What is the operating temperature range?</u>

Same as for the laptop computer

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Currently no remote communication due to vandalism problems of the electronics and laptop computer. It is feasible to implement remote communication, but security provisions for the equipment must be provided.

Company: North American Geotechnical (3 of 4)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

None currently. Could be programmed into the system if modified for remote communication

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

User sets up the computer and electronics to record the pressure decay vs depth data. The computer logs the pressure decay data which is graphed for visual interpretation using Microsoft EXCEL.

(13) <u>What services and or support are offered with purchase?</u>

North American Geotech designs the probe and vertical filter array to meet the requirements of each specific bridge from the AS BUILT plans for the bridge. The probe and associated electronics, laptop computer with data logging and data analysis are supplied. The electronics and computer are portable and can be used on multiple probe sites. Operation of the system, including data analysis can be done by the individual DOT personnel after training by us. If preferred, we provide a service to obtain and analyze the data on the clients' schedule. Maintenance and repair of the electronics is available as a separate item on an as needed basis.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

The probe is installed with a conventional pile driver. We act as a consultant to the client, who is responsible for providing the pile driver and inserting the probe into the river bottom. We verify the system is working after installation by running a suite of data. Approximately 3 days of training, including two days of on-site data acquisition generally is sufficient. The 3 days of training is included in the original cost. Extra training time is available at a nominal cost.

(15) <u>What examples/applications of the system are available?</u>

Current installation is at the Kilchis river bridge on Oregon State Hwy 101 several miles north of Tillamook. I am attaching a paper to be presented at the ASNT conference on NDE/NDT for highways and bridges, Sept. 8-12, 2008 in Oakland, CA. This paper describes the installation and testing of our Pneumatic Scour Detection System. The paper is co-authored by Edward Mercado, President, North American Geotechnical Co. and John Woodroof, State Bridge Engineer for Oregon Dept of Transportation

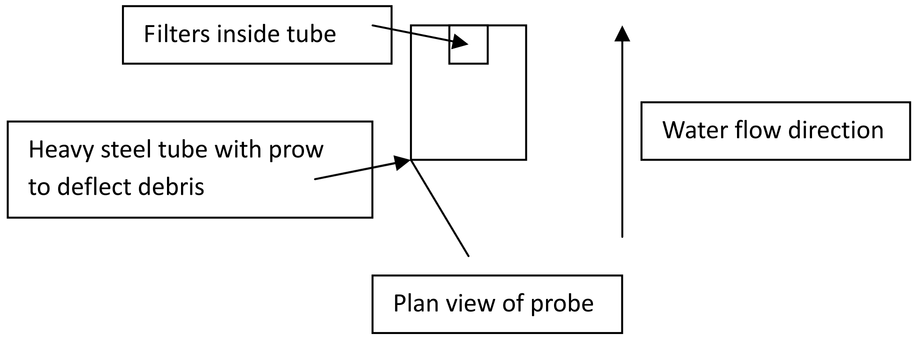
(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

The vertical spacing of the filter array built into the probe controls accuracy of determining the depth of scour. Nominal vertical array spacing is 1 foot, providing 1 foot accuracy of the depth of scour.

System operation is independent of the ambient temperature as long as the laptop computer used for data logging is operable.

The system operates independently of the turbidity, temperature, salinity, or clay/debris content of the river. The strong steel probe protects the filters from river-borne debris, as the probe face containing the filter array is oriented downstream. The steel probe can be reinforced against flood-borne debris by welding plates on the upstream face to form a pointed prow as sketched in plan view here. Additional reinforcement of the probe would be to connect it to the bridge structure to provide additional vertical stiffness.

Company: North American Geotechnical (4 of 4)



Company: Omnisens SA (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  Yes
- **Early warning**
  Yes
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
    Yes
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
  Yes
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Distributed fiber optic strain and temperature sensor: The system is composed of fiber optic cables which are the sensing elements and an interrogator (a single instrument for both temperature and strain). We use a strain sensitive fiber optic cable and a strain sensitive temperature fiber optic cable.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Distributed fiber optic strain and temperature sensor
Distributed strain and temperature measurements leads to the drawing of temperature and strain profiles (i.e. strain and temperature as a function of position)

Company: Omnisens SA (2 of 3)

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**

  Yes

- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

  Fiber optic cables are permanently attached.
  Strain and temperature interrogator is transportable.

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**

  Yes

- **Post Construction**

  Yes

  Note: the answer to this question depends on the application. Fiber optic cable can be embedded in concrete or glued on the surface of the structure.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**

  Yes

- **Steel Truss**

  Yes

- **Cable Stayed**

  Yes

- **Prestress Concrete Girder**

  Yes

- **Reinforced Concrete**

  Yes

- **Other**

  All of them

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**

  Yes

- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

The system is composed of the sensing cables and the interrogator unit. The interrogator unit achieves measurement, signal processing and extract strain and temperature profiles.
The core element of the interrogator is an industrial computed also equipped with communication equipments. It can be connected to another computer/server and transfer information with TCP/IP.

Company: Omnisens SA (3 of 3)

(9) <u>What is the operating temperature range?</u>

0 to 40oC for the interrogator (ideally, it should be in a control room with requirements similar to computer/telecom equipments standards)

-40 to 60oC for the sensing cables.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

The user can operate the system on the field or remotely through a communication network using TCP/IP.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

All sensors can be segmented in zones with alarm thresholds definition. Communication with computer/server in control room is ensured via communication network through TCP/IP.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Software process the measured data and display the results, ensure communication between the remote instrument and a computer/server in a control room.

(13) <u>What services and or support are offered with purchase?</u>

Sensor layout and design by ourselves or by our system integrator partners.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

This can be negotiated but training is required for first time users. For complex installation, our implication or system integrator involvement is recommended.

(15) <u>What examples/applications of the system are available?</u>

Please consult the following case studies:

http://www.omnisens.ch/ditest/doc-news.php?id=210

http://www.omnisens.ch/ditest/doc-news.php?id=205

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Please refer to the attached data sheet.

Company: OSMOS (1 of 10)

(1) <u>What is the purpose of the system?</u>

The *OSMOS Structural Monitoring System was developed in Europe in the late 1980s to provide a method for determining strain (and stress)in structural members in a manner that avoids the limitations (e.g., drift, limited life, very small area coverage, lack of dynamic data) of conventional Civil Engineering monitoring sensors. Its development also included the entire system of sensors; data collection, interpretation and communication components; and warning systems to make it easy to install and immediately available for interpretation.*

The OSMOS system has successfully been used on more than 800 structures over 15 years throughout the world. It is a complete and proven system consisting of a series of patented sensors, software, hardware, and data storage and communication technology to create an incredibly accurate, durable and user-friendly system. Additionally, the OSMOS data management system can accommodate any commercially available analog devise allow for simultaneous interpretation of the results of its sensors and information concerning local strain, temperature, wind, etc

- **Long-term monitoring**

  A primary purpose of the Osmos system is reliable long-term, continuous and real-time monitoring of the global behavior of a bridge or structure. It detects changes in elastic behavior, cracking, and natural frequency shifts as indicators of continuing adequate performance or changing structural conditions that need to be evaluated. Provides continuous dynamic and static data from fiber optic sensors without the need for special sensors for static or dynamic conditions. As an example, the system has been used continuously for 15 years to monitor the effects of load changes, wind, ice storms and temperature on the very important Eiffel Tower. The system has been very stable and accurate for this entire period.
- **Short-term monitoring**

  The system is frequently used for short periods to observe effects of construction, to develop load ratings for bridges, and to quantitatively evaluate inspection results that indicate a deficiency may exist. In the vast majority of cases, the monitoring has shown that a bridge is performing better than anticipated, or has “pin-pointed’ the area where a repair is necessary. The equipment can be readily removed without damage and immediately be used for additional applications.
- **Inspection**

  A major use is to monitor items identified as potential concern during a conventional “visual” inspection. In the majority of cases, the quantitative results show that the structure is behaving better than assumed from the “subjective” visual observations. In those cases, the monitoring can be left in place to continue to verify the structures adequacy. In cases where a problem is confirmed, the monitoring assists in establishing load limits and determining the most cost-effective repair.)

Company: OSMOS (2 of 10)

- **Early warning**

  Automatically provides early warnings based on pre-set dashboard thresholds. Warnings can be dual level for any individual sensor or specified combination of sensors. The warnings can be sent to multiple persons by computer, fax, cell phone, warning lights, etc.
- **Other (please specify)**
  Weigh-In-Motion (WIM)

  The OSMOS system is frequently used as a very inexpensive, but accurate method for determining the weight and number of loaded vehicles using a bridge. Usually, the accuracy is at the third level of ASTM standards, suitable for enforcement support

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**

  The OSMOS System provides accelerometers as needed for each application. These devises are generally used to compliment the fiber optic displacement strands.
- **Acoustic Emission**

  While the OSMOS sensor does not directly monitor acoustics, it can be often be used for the same purpose since any small disturbance (e.g., an individual wire breaking) will be observed. The added benefit of the OSMOS sensor is that in addition to the breaking event, the OSMOS sensor will also immediately show if there is a structural behavior change.
- **Strain Gauges**
  - **Fiber-optic**

    Two types of fiber optic sensors are available. One type consists of a macro-bend fiber optic strands that measure sensor displacement over long gage lengths (2m, 5m, and 10 m standard) that can be converted to strain levels by dividing by the sensor length. The other is an extensometer that measure the displacement between two points using a rod fixed at one end and allowed to move with the structure at the other. Both types are accurate to one micron and read either statically or dynamically (up to100 measurements per second). Sensors are available for normal use with silicon sheathing and for embedded use with steel
  - **Electric Resistance**

    The OSMOS data management system automatically allows for any type of analog sensor, including electrical and vibrating wire strain gages to be used in conjunctions with the more accurate and durable OSMOS sensors. This sometimes is useful when data for both longer dimensions and specific small locations are useful for complete interpretation. The system automatically correlates the time sequencing for all connected sensors.
  - **Vibrating Wire**

    (See comment on Electrical Resistance strain gauges)

Company: OSMOS (3 of 10)

- **Load Cells**

  Analog load cells are compatible with the OSMOS system and can be monitored simultaneously with the OSMOS senor readings.
- **Wind Gauges**

  Analog anemometers capable of continuous reading of wind speed and direction are compatible with the OSMOS data management system and are used on all structures where wind is an important loading condition..
- **Tilt**

  One, two or three axis analog tiltmeters capable of continuous reading of angular change are used regularly with the OSMOS System. Generally, tilt meters are used on piers and decks and provide valuable information regarding the global behavior of the structure.
- **Temperature**

  Analog temperature sensors capable of continuous reading of temperature data are always included in an OSMOS installation and are used to correlate the effect of thermal changes in the structure. Collecting the temperature changes over a period of time and at different location within the structure are essential when evaluating the overall behavior of the structure

  The OSMOS system has a special capability to allow for one temperature sensor to be associated directly with each fiber optic strain sensor. This allows the temperature compensation to be made automatically if desired for a particular application. .
- **Displacement**

  (The OSMOS system does not perform these functions directly. But OSMOS USA can monitor this data in parallel if the is a need to correlate global movement with internal displacements. Generally, this is not necessary)

  Optical strand displacement
  Displacements parallel to the axis of optical strands are obtained directly from the OSMOS sensor readings, up to distances of 30 meters. OSMOS optical Extensometers can also measure displacements directly and are used in applications such as crack monitoring and Weigh-in-Motion Systems (WIMS) for determining live load dynamic response that is calibrated to give load magnitude

  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Inclinometer (Optical Caterpillar)

Company: OSMOS (4 of 10)

OSMOS fiber optic sensor for measuring slopes along a path can be used to continuous monitor the deformation of embankment slopes and substructure deformations.

Additional Analog Sensors

(As noted above, the OSMOS data management system has analog ports to specially allow any of the following sensors to be monitored automatically and simultaneously with the OSMOS optical strands or extensometers)

Corrosion sensors

Chloride diffusion sensors

Humidity Sensors

Piezometers

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Performance measures monitored include:

Strain (and stress) measurement for performance evaluation, verifying analytical models, detecting changes in load distribution, or the onset of nonlinear behavior, and crack initiation detection. These are the "first order" parameters for showing how a structure behaves.

Dynamic strain pre-set thresholds to provide alarms and warnings for safety monitoring.

Vibration monitoring to observe accelerations associated with dynamic loads (e.g., earthquakes) and to determine natural frequencies and Fourier Spectra using FFT algorithm.

Histogram analysis of live load magnitude distribution in conjunction with WIMS Dynamic signature change analysis for determining structural damage or stiffness change due to bearing modifications as an example.

Rainflow counting algorithm for fatigue evaluation.

Dynamic crack opening displacement which can have pre-set threshold values for alert and warning actions.

Company: OSMOS (5 of 10)

Corrosion monitoring with compatible corrosion sensors (most all analog sensors are compatible).

Chloride diffusion monitoring with compatible analog sensors.

Direct relative displacement with Optical Extensometers.

Early indication of block movement in rockery retaining walls.

Early indication of block movement prior to concrete spalling.

Early indication of foundation and pier movement due to scouring.

(4) Is the system:

- **Permanent (any piece permanently fixed)?**

  Optical strands placed on the surface can be left in place permanently if desired—or they can be removed and reused at any time. Optical strands embedded in concrete, grouted into the anchor zone of ground anchors are permanently fixed and will function accurately for many years.
- **Reusable (everything can be unattached and moved)?**

  All devises to include the Optical strands and Extensometers can be reused. They can be unattached when monitoring is finished and re-installed elsewhere. Only devises embedded in concrete are not reusable.
- **Portable (nothing attached/installed and are easily moved)?**

  Sensors are installed with simple mechanical devices such as screws, clamps, glue or magnets. When penetrations are undesirable in members being monitored blocks of wood are attached with epoxy and the sensors attached to the wood. Consequently, attaching and detaching are not lengthy processes.

(5) When can/should the equipment be installed?

- **During Construction**

  Benefits result if sensors are installed during construction because they can show the life history of strain in members. Only problems associated with installation during construction is protection from damage. Osmos sensors have been installed in many damage-prone environments from both equipment and personnel, and with protective covers have performed as intended without damage. Recently the OSMOS system has been applied on 10 ABC bridges in Utah which were built off-site and then moved into place. This monitoring showed the entire bridge behavior during lifting, movement and placement.
- **Post Construction**

  Applications following construction are more typical. The most common applications are to: quantitatively evaluate visual observation conditions; monitor behavior during rehabilitation activities, observe behavior after unusual events

Company: OSMOS (6 of 10)

(e.g., column damage due to a barge impact); for WIM; and for accurate load posting.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  Composite materials – Yes

Additional Bridge Related Applications

Embedded in concrete? – Yes

Embedded in anchors? – Yes

Embedded in multiple strand cables? – Yes

Embedded in piles and caissons? – Yes

Embedded in slopes? - Yes

(7) <u>What type of power source is used?</u>

- **Solar**
  Yes
- **Battery**
  Yes
- **AC**
  Yes
- **Other**
  Yes

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

System is complete and consists of the Following:

- Optical sensors (silicon or steel sheathing)
- Analog Sensors

Company: OSMOS (7 of 10)

- Data Acquisition Unit (DAU) (Slave)
    - Inputs for 4 fiber optic sensors.
        - Inputs for 4 slow analog sensors (temperature).
    - Inputs for 4 fast analog sensors.
    - Up to five (5) DAUs can be input to a single master for up to 20 fiber optic sensors and 20 slow analog sensors (temperature) and 20 fast analog sensors per Master.
- SPCU (Signal Processing and Command Unit) (Master)
    - Provides software for displaying, tracking thresholds, and analyzing data.
    - Provide hard disk storage for 20 gigabytes of data.
    - Handles all communications methodologies (see below)
    - Provides two warning levels for pre-set conditions for notification by computer, fax, cell phone, etc.
    - Can have a web site address for internet access to data in real time
    - Up to four (4) Masters can be networked for a total sensor capability of 80 fiber optic sensors, 80 slow analog sensors, and 80 fast analog sensors.
    - Custom designed, weather proof metal et suitable for all weather conditions

(9) <u>What is the operating temperature range?</u>

Optical sensors: -20 deg C to +50 deg C (operating) and -30 deg C to +50 deg C (storage).
DAU and SPCU: -20 deg C to +50 deg C without air conditioning

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

All of the following:
Database connection via the internet.
Direct access to monitoring station via an internet website (observation .and download of data).
Local wireless communication with monitoring station via wireless modem.

Company: OSMOS (8 of 10)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

System has an alarm feature. Communication can be via cell phone, relay-controlled devices such as warning lights and gates, http, telnet, SNMP, SMTP, FTP, TCP/IP, PPP, SMS, and Fax. Each alarm has two levels, usually the first is a warning of unusual conditions and the second is for immediate action.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

The Osmos software provides the following capabilities:

- System configuration of dashboard pre-set thresholds and fiber optic instrumentation.
- Real time viewing of data locally or remotely as discussed above. The data can be viewed either in a dash-board form or as an oscilloscope of real-time behavior.
- Data analysis (Formulations of mathematical combinations of sensor data).
- Automatic temperature compensation if desired (otherwise temperature compensation can be accomplish via the data analysis capability).

(13) <u>What services and or support are offered with purchase?</u>

- Consultation on monitoring plan and optimum sensor number and location
- Installation.
- On-site field technical support for complete installation.
- Assistance with data interpretation.
- Permanent data storage on Osmos Database System, accessible by remote communication through the Osmos software.
- Management reports as requested

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

- Power installation and telephone communication may be supplied by the user if desired. If not Osmos can provide both power and communication sources as required.
- A training workshop based on principles of adult learning and technical training fundamentals is available if requested. System is user friendly, but training workshop assists in avoiding learning mistakes.

(15) <u>What examples/applications of the system are available?</u>

Company: OSMOS (9 of 10)

- The Osmos system has been installed on over 800 projects worldwide, better than 420 on bridges. (A file with approximately 250 representative projects is provided as a separate submittal).

- Additional one-page project descriptions are available upon request.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Sampling rate:

- Optical sensors: Up to 100 samples per second programmable.
- Fast Analog Sensors: Up to 100 samples per second programmable.
- Slow Analog Sensors: Up to 10 samples per second.
- Sleep mode when no activity to reduce repetitive storage of data with no meaning. Programmable trigger starts dynamic recording.

Fiber Optic Sensors:
Optical Strands

- Resolution: 1 micron over length of sensor.
- Measuring Path: 10 mm/ 25mm/50 mm for 2m/ 5m/ 10m sensors.
- Accuracy: Plus or minus 2 microns during dynamic monitoring, 2% of final value during long term monitoring.
- Repeating Accuracy: 1%.
- Electromagnetic Compatibility: Insensitive and neutral to electric and magnetic interference.
- Stability and Fatigue Behavior: Greater than 150 million cycles with no drift.
- Connection: Customizable fiber-optic cable with a length of up to 1 kilometer to the OSMOS monitoring station.
- Service Life: Greater than 20 years.

Company: OSMOS (10 of 10)

Fiber Optic Extensometers

- Resolution: 1 micron
- Measuring Path: 5 mm
- Measuring Range: 0.1 m to 10 m
- Accuracy: Plus or minus 2 microns during dynamic monitoring, 2% of final value during long-term monitoring.
- Repeating Accuracy: 1%.
- Electromagnetic Compatibility: : Insensitive and neutral to electric and magnetic interference..
- Stability and Fatigue Behavior: Greater than 150 million cycles with no drift.
- Connection: Customizable fiber-optic cable with a length of up to 1 kilometer to the OSMOS monitoring station.
- Service Life: Greater than 20 years.

Fiber Optic X-Large Extensometers

- Resolution: 0.1 mm.
- Measuring Range: 500 mm.
- Measuring Base: 1260 mm to 1760 mm.
- Accuracy: 0.5 mm.
- Repeating Accuracy: 1%.
- Electromagnetic Compatibility: : Insensitive and neutral to electric and magnetic interference.
- Connection: Customizable fiber-optic cable with a length of up to 1 kilometer to the OSMOS monitoring station.
- Service Life: Greater than 20 years.

Company: PAC (1 of 4)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**

  The Sensor Highway II (SH-II) system is the second version of the original Local Area Monitoring (LAM) system developed under FHWA funding in the mid 1990's (in Chap. 13 of the BIRM). Since that time the SH-II is our company's latest revision that is designed for unattended use in the field, requiring no separate heating/cooling, and is capable of integrating acoustic emission as well as a suite of other sensors (parametric inputs) for long term structural health monitoring applications. The sensors may include: weather stations, strain gauges, inclinometers/tilt, vibration, LVDT/displacement gauges, pressure, load and more. The base system handles 16 parametric inputs, but can be expanded up to 64 or more for customized systems. Last year the SH-II was selected by FHWA for their Steel Bridge Testing program.
- **Short-term monitoring**

  The SH-II is portable and can be used for short-term monitoring before being moved to other locations.
- **Inspection**

  For periodic inspection, PAC provides a µDisp and portable workstations from 8, 16, 24, and up to 56 channels of acoustic emission sensing. The portable systems will handle up to 8 parametric inputs but can be customized to handle additional sensing requirements. Larger systems are available for large applications.
- **Early warning**

  All systems can provide early warning through front end alarms or voltage time gates.
- **Other (please specify)**

  Structural Health Monitoring through sensor fusion and data integration. Can provide Remote Monitoring and access to data 24/7 through a secure website interface.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**

  System can be configured to take readings from accelerometers for waveform analysis or g readings for acceleration, velocity and displacement.
- **Acoustic Emission**

  The SH-II comes standard with 16 channels.
- **Strain Gauges**
  - **Fiber-optic**

    We work with industry partners/suppliers of this technology for integration (typically data integration).
  - **Electric Resistance**

    We work with 3rd party industry suppliers or off the shelf sensors (custom).
  - **Vibrating Wire**

    We work with 3rd party industry suppliers or off the shelf sensors.
- **Load Cells**

  We work with 3rd party industry suppliers or off the shelf sensors (custom).
- **Wind Gauges**

  System already integrates an off the shelf weather station that provides up to 18 weather related parameters (temp, humidity, barometric pressure, wind, wind direction, rain, hail, etc.).

Company: PAC (2 of 4)

- **Tilt**
  We work with 3rd party industry suppliers or off the shelf sensors (custom).
- **Temperature**
  Typical sensor we use now on several applications is a combined temperature and humidity sensor.
- **Displacement**
  Can integrate off the shelf sensors or those provided by 3rd party suppliers or industry partners.
  - **GPS**
    We have not used ourselves, but currently work with a university that has provided differential GPS monitoring on a different projects.
  - **3-D Laser Scanning**
    We have not used ourselves or currently worked with anyone in industry for this type of application.
  - **LVDT**
    We work with 3rd party industry suppliers or off the shelf sensors.
  - **String Potentiometers**
    We work with 3rd party industry suppliers or off the shelf sensors (custom).
- **Other (please specify)**
  Company also provides handheld UT systems for thickness measurements and crack detection/measurement. Company can also provide traditional services using radiography, UT phased array, mag particle, liquid penetrant, eddy current, RFEC, ACFM, and others.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

The information gathered from each type of sensor integrated with the system can be used to evaluate the performance/response of the material. This could include an increase in strain in critical areas (i.e. fracture critical) that leads to active crack propagation detected by acoustic emission sensors, this could be the monitoring of displacements at deck joints and bearing locations to determine if the bridge is expanding/contracting as designed. If performing vibration or differential GPS monitoring, the information could be used in modal analysis of the bridge. Alarming can be set up in the system software to monitor the levels of each sensor and report when designated values are exceeded.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  The AE sensors are typically fixed to the material of interest, but mounting plates can be permanently fixed to the structure and will allow for coupling of the AE sensors using magnetic holddowns. This will allow for the easy removal of the sensors to other locations for periodic monitoring and can then be returned to the original location when needed.
- **Reusable (everything can be unattached and moved)?**
  SH-II system (inside NEMA 4 enclosure).
- **Portable (nothing attached/installed and are easily moved)?**
  Everything is portable (typ).

Company: PAC (3 of 4)

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
  Depends on the application. If monitoring is needed during the construction, the system can be installed then.
- **Post Construction**
  Typical installation is post construction.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes - primarily monitoring for rupture of prestressing wire/strand but can also monitoring degradation of concrete.
- **Reinforced Concrete**
  Yes - primarily for concrete cracking and some cases has been used for corrosion monitoring.
- **Other**
  Suspension bridges, composite

(7) <u>What type of power source is used?</u>

- **Solar**
  Is currently used on several projects.
- **Battery**
  Is currently used on several projects.
- **AC**
  Is currently used on several projects.
- **Other**
  Looking into hybrid systems (wind, solar, flow) and energy harvesting.

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

The complete system includes the DAQ board, sensor boards, CPU, compact flash/industrial hard drive, sensors, cabling, power, software and communication. The SH-II systems are completely customizable and based upon the needs of the client.

(9) <u>What is the operating temperature range?</u>

-30C to 70 C (-86 F to 158 F)

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Data can be retrieved manually or through Telephone, DSL, Fiber, Cellular, Wi-Fi.

Company: PAC (4 of 4)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

There are several different alarm features. There are Front End Alarms that can be set for warning and alarm levels (I/O); ASL (average signal level alarms); Cluster Rate Alarms – checks to see if the number of events in the defined time period has been exceeded; Alarms can be set for audio, screen based (default), digital I/O (buzzer, warning light), and can implement email/text/phone notification.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Software provides the interface for the collection of data, integration of data (data fusion), data processing, alarming, download/upload of data, remote monitoring (periodic statistical information) and communication.

(13) <u>What services and or support are offered with purchase?</u>

There are a variety of warranties/services available and depends on the type of equipment and application. Services may include, but not limited to: software upgrade support; technical support (onsite/office/phone); maintenance and material upgrade/replacement services; training; online monitoring; remote access; data analysis; research/feasibility studies and reporting services are available. All design, engineering, production, manufacturing, research and software engineering services are headquartered in Princeton Junction, NJ.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Depends on the application and type of access. Most training is provided at our facility in Princeton Junction, NJ but can also be provided onsite if needed. Our in-house training provides for SNT-TC-1A Qualification/Certification courses in AE and other NDE/NDT methods. Certification per SNT-TC-1A is done by the employer who has a Written Practice developed for this purpose. Installation is typically not provided unless requested by the client.

(15) <u>What examples/applications of the system are available?</u>

Several types of installations include offshore oil platforms, bridges (steel, suspension, cable), nuclear power plants, coal plants, transformers and oil and gas plants. Each system customized to meet the needs of the clients.

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Please see the attached specification sheet for the SH-II. Limits, resolutions, ranges, accuracy will then be governed by the sensor(s) connected to the system.

Company: Pinnacle Technologies (1 of 4)
Please note that Applied Geomechanics is a division of Pinnacle Technologies and the source for 3D Tracker™ GPS Software and many other related systems for bridge monitoring.

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**
  Applied Geomechanics provides monitoring systems and solutions for all of the purposes described above including others such as load testing (static and dynamic). We offer 3D Tracker™ GPS monitoring as well as systems that utilize various sensor types alone and in combination with each other and GPS.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  At Applied Geomechanics we provide a broad range of different sensors and equipment depending on the specific monitoring issues for any particular bridge. While 3D Tracker™ is primarily a real-time high-precision GPS monitoring system, many systems combine multiple different sensor types as required for a particular monitoring application. In addition to GPS, we currently provide bridge monitoring systems that use all of the sensor types above except acoustic emission, fiber-optic strain and 3-D laser scanning.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Applied Geomechanics motto "Is it moving?" generally describes how our monitoring systems are helpful to bridge monitoring engineers. By understanding the specific and relative movements of the relevant bridge components, engineers are able understand and identify structural problems, their causes and potential remedies. The performance measures primarily include displacement, tilt, strain and temperature alone or in combination.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

While 3D Tracker™ is a permanent system requiring fixed installations for optimal performance, the components are reusable. Other types of sensors such as tiltmeters, strain gages, and displacement transducers are usually installed in a permanent or semi-permanent manner although they can be reused, installation fixtures may require replacement. We also offer a portable tiltmeter system and portable manual readouts for tiltmeters and vibrating wire sensors although these utilize permanent or semipermanent installations of reference plates or sensors. In most cases the primary system components are reusable once a monitoring project is complete.

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

Depending on the purpose for monitoring installation during construction is not always an option though it is preferred. In general we recommend installation of monitoring equipment as early as possible before any significant construction activity in order to characterize baseline behavior. While it is not always possible, up to one week or more of baseline data is best.

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

Applied Geomechanics monitoring systems and equipment can be used on all of the bridge types above as well as others.

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**
- **Other**

In general Applied Geomechanics monitoring systems operate on 12 Volt DC power. These systems typically include a charging source either Solar or AC and a 12-volt battery backup supply.

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Company: Pinnacle Technologies (3 of 4)

Applied Geomechanics monitoring systems are customized to our clients needs and requirements. Typically different sensor types and quantities are accommodated as needed using data loggers, multiplexers, and wireless transmitters. While a basic system typically includes sensors, data collection, communications and software, the details vary significantly. We can provide full service turn-key systems including installation, maintenance and data service for the project duration or ship a system ready for the customer to install and operate.

(9) <u>What is the operating temperature range?</u>

While specific product temperature ranges vary, most of our products are rated for operation from -40 to +85 degrees C or better. Please refer to individual product data sheets for product specific information.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Applied Geomechanics offers options for system communications with the user ranging from direct wired systems, to wireless spread spectrum radio and Wifi for line-of-sight applications, to telephone, cellular, satellite phone and Internet.

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Alarm outputs are communicated based on system communications options described in the question above. Alarm communications with the end user often include backup and duplicate notifications. The system generated alarm outputs can also be used to trigger on-site audible and visual alarms and/or provide telephone, e-mail or control panel notification to specific or multiple users.

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Various software programs are used depending on the nature of the system. Software is used for communications with the systems, the control and operation of automated system features as well as data analysis, storage and post processing. 3D Tracker™ is specifically Differential GPS data processing software.

(13) <u>What services and or support are offered with purchase?</u>

Every Applied Geomechanics system includes technical support during installation and operation as well as a one year warranty on parts and labor. We also offer full turn-key service including installation, maintenance, training, data collection and reporting or any combination thereof per the customers requirements.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Depending on the specific components included in a system, the users experience and level of service provided by Applied Geomechanics, the training and installation requirements for the user vary significantly. We strive to provide engineers with the measurement data required to perform their work without needing to become experts in sensors, communications, computers or system operation. Most basic sensors and data collection systems can be installed by field crews with moderate technical construction skills and knowledge of basic electrical and computer systems after reading the manuals. GPS/3D Tracker™ systems and integrated monitoring systems typically require factory installation and some level of training. In most cases operational training can be completed within one day.

(15) <u>What examples/applications of the system are available?</u>

Please review the case histories for various 3D Tracker™ and Bridge Monitoring applications on the internet at the locations listed below and on our web site. As

Company: Company: Pinnacle Technologies (4 of 4)
instrumentation and monitoring specialists, our examples include specific bridge monitoring applications as well as examples where the same systems and technology are used for monitoring other structures such as dams and buildings. Many other projects have been completed but are not included in the publications below. http://www.geomechanics.com/appcats.cfm?appcatid=11 http://www.geomechanics.com/casehistories.cfm http://www.pinntech.com/pubs/CS/CS04_RD.pdf **(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>** Individual product specifications and details are included in our catalog and on data sheets available on our web site www.geomechanics.com . Additional details regarding 3D Tracker™ and a link to the data sheet are available at this location http://www.geomechanics.com/dspproduct.cfm?prid=101 . Applied Geomechanics' 3D Tracker™ Differential GPS Software is capable of measuring three-dimensional position change with 1 mm sensitivity after processing using conventional GPS hardware. We offer tiltmeters that are capable of sub micro radian resolution though resolution of 0.0006 is usually more than sufficient or bridge monitoring applications. Physical displacement (non-GPS) and strain can be resolved to 0.01 mm and 1 micro strain or better, respectively. Our equipment excels are measuring small movements in relatively static structures such as bridges and dams. Typically these measurements require a narrow range but with high resolution. Additionally while high sample rates are utilized to improve the resolution of measurements, there is a direct tradeoff between speed of response and high resolution. Our equipment works best for monitoring movements that occur at frequencies of 1 Hz or less with typical data recording and alarm checking rates in minutes or hours for most bridge monitoring applications although higher rates are possible for specialized purposes. We have systems deployed from the equator to the arctic and our equipment is build to operate in all weather conditions. Please contact Etienne Constable at etienne.constable@geomechanics.com or (415) 462-3200 x3330 if you have additional questions or need more information.

Company: Practical Technology LLC (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**
  Specifically the purpose is to notify motorists of a catastrophic failure that has already happened, but they are not yet aware. This is especially important for bridges with significant curvature, such as the Queen Isabella Causeway, or I40 Arkansas River Bridge, where by the time the motorist sees the collapsed span, sufficient stopping distance is no longer available. As far as we are aware, no fatalities would have occurred in either of these cases if approaching motorists were immediately told to stop.

  A bridge collapse breaks a fiber opric cable, a controller immediately flashes warning beacons placed along the bridge, and proper authorities are notified by phone.

  The system is designed to be simple, reliable and affordable. Out of service systems do not save lives, and drain funds from other important projects.

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
    Very specialized form
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Collapse sensing system - Fiber optic cable is run over the span of the bridge and anchors placed several spans apart. Cable breakage triggers alarming features. Anchors are not required on every span, as minimal elongation will break the fiber. Electrical cable powers flashing red signal beacons spaced periodically over the structure.

Company: Practical Technology LLC (2 of 3)

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Catastrophic collapse

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  Yes
- **Reusable (everything can be unattached and moved)?**
  The fiber cable is delicate and not reusable. The fiber anchors, beacons, controller, etc. are reusable.
- **Portable (nothing attached/installed and are easily moved)?**
  No

(5) When can/should the equipment be installed?

- **During Construction**
  Yes
- **Post Construction**
  Yes

(6) On what types of bridge can it be used?

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  All types should work
  Bridges with limited visibility of collapsed span – yes
  Bridges with clear visibility of a potentially collapsed span - no

(7) What type of power source is used?

- **Solar**
  Pptional, very low normal power consumption
- **Battery**
  Yes, sized to operate all beacons during a power failure
- **AC**
  Yes
- **Other**

Company: Practical Technology LLC (3 of 3)

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

Wires
Anchors
Signal beacons
Control Unit W/ Autodialer

(9) What is the operating temperature range?

-40C (optional) to +70C

(10) How does the system communicate remotely with the user (if at all)?

Autodialer

(11) Does the system have an alarm feature and how is it communicated?

A bridge collapse breaks a fiber opric cable, the controller immediately flashes warning beacons, and proper authorities are notified by phone.

(12) What does the software do (data processing, interface, communications, etc.)?

The system is self-contained, software is not apparent to the end user. Software to detect loss of signal through the optical fiber and actuate the beacons and autodialer is embedded in the controller.

(13) What services and or support are offered with purchase?

Additional services are available as required by the DOT.

(14) What training/installation is required of the user or are these included (ease of use)?

The installer must be able to follow simple included instructions as to attaching the optical fibers to the anchor. All other aspects should be familiar.

(15) What examples/applications of the system are available?

Queen Isabella Causeway Bridge

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

The fiber is continuously monitored for breakage.

The resolution is a pass/fail for catastrophic collapse.

Optical fiber does stretch, a few anchor points are required per mile, dependent on bridge fall height.

Company: Roadmap GPR Services (1 of 3)

RoadMap GPR Services. They are a service provider while Sensors & Software Inc. is a GPR manufacturer. RoadMap GPR Services performs bridge deck deterioration surveys using ground coupled ground penetrating radar technology. The surveys do not require lane closures. GPR can be used to evaluate the condition of concrete bridge decks overlaid with asphalt using a methodology outlined in ASTM D 6087–07. In this test method the GPR signal attenuation of the section of the deck above the upper rebar mat is measured. This attenuation is correlated with the chloride content and/or moisture content. Zones with high chloride and moisture are indicative of probable areas of current or incipient delamination induced by rebar corrosion processes. In practice, a set parallel GPR profiles are collected over the bridge deck, the amplitude of the reflections from the steel reinforcing bar (rebar) are computed and converted to a deck deterioration index. A color scale image of the deterioration index and of the rebar depth over the deck surface is provided to the client. In addition the individual rebar locations can be provided.

(1) What is the purpose of the system?

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**
  Yes
- **Early warning**
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Ground Penetrating Radar (GPR)

Company: Roadmap GPR Services (2 of 3)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

  Used on bridge deck that is either reinforced concrete or reinforced concrete with asphalt overlay.

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

  Yes
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Van with control units and data collection computers and trailer with mounted GPRs, GPS, DMIs for data acquisition.

(9) <u>What is the operating temperature range?</u>

GPR : -40 C - +40C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

NA

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

NA

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

NA

(13) <u>What services and or support are offered with purchase?</u>

NA

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

NA

Company: Roadmap GPR Services (3 of 3)
(15) <u>What examples/applications of the system are available?</u> NA (16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u> NA

Company: Roctest Ltd (1 of 3)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  No
- **Early warning**
  Yes
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
  Yes
- **Acoustic Emission**
  No
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
    Yes for all strain gauges
- **Load Cells**
  Yes
- **Wind Gauges**
  No
- **Tilt**
  Yes
- **Temperature**
  Yes
- **Displacement**
  - **GPS**
    Yes
  - **3-D Laser Scanning**
    Yes
  - **LVDT**
    No
  - **String Potentiometers**
    No
- **Other (please specify)**

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

- crack formation and propagation
- strain & global displacement
- rotation

Company: Roctest Ltd (2 of 3)

- acceleration
- temperature
- loads & forces
- water level
- tilt & slope
- concrete corrosion
- vibration

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  Yes
- **Reusable (everything can be unattached and moved)?**
  Partially (depending on which system)
- **Portable (nothing attached/installed and are easily moved)?**
  Yes, should be

(5) When can/should the equipment be installed?

- **During Construction**
- **Post Construction**
  Both

(6) On what types of bridge can it be used?

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**
  No limitation: every bridge should be monitored with our systems

(7) What type of power source is used?

- **Solar**
  Permanent monitoring, just in particular conditions
- **Battery**
  Portable reading unit
- **AC**
  Permanent monitoring
- **Other**

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

It's a complete system and includes everything:

- Sensors
- Control units
- accessories

Company: Roctest Ltd (3 of 3)

- Software
- Communication

(9) What is the operating temperature range?

Approximately from -20°C (with heating system) to +70°C (with cooling system)

(10) How does the system communicate remotely with the user (if at all)?

RS232 ; TCP/IP; Ethernet; Modem, GSM, Radio

(11) Does the system have an alarm feature and how is it communicated?

- Not as standard, but available as application software on demand
- The communication should be by SMS, Web and other on specific request

(12) What does the software do (data processing, interface, communications, etc.)?

Everything you need, according to the level of implementation you required, Roctest Group can provide a specific application software

(13) What services and or support are offered with purchase?

Remote support is included in the first application: on demand we can also quote and offer on-site service and support, data post-process and interpretation with detailed reports

(14) What training/installation is required of the user or are these included (ease of use)?

Our systems are generally “user friendly”: we organize free training courses twice a year, but we can also offer support on-site, including training courses for the best use of our technology

(15) What examples/applications of the system are available?

Please point to the SMARTEC website www.smartec.ch , under:
http://www.smartec.ch/reference_projects.htm#Bridges
The latest monitoring project in the US is the ongoing monitoring of the I35 bridge in Minnesota

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

Hereunder, you find just the features you have mentioned:
For specific features of the different systems, please refer to our web site.

- sampling rate: Up to 10 KHz
- resolutions: Temp: up to 0,01°C – Strain: Up to 0.01 µm
- data ranges: No limits
- temperature ranges: Depending on the temp. sensor: from -50°C, up to 300°C and more
- measurement accuracy: Temp: up to 0,05°C – Strain: Up to 2 µm

Company: S + R Sensortec GmbH (1 of 2)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
- **Inspection**
  Yes
- **Early warning**
  Yes
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  corrosion sensors to monitor the durability of reinforced concrete and/or prestressed concrete structures (normally exposed to chloride containing conditions)

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

Corrosion and indirectly the depth of depassivation front

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  Yes
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

5) When can/should the equipment be installed?

- **During Construction**
  Yes
- **Post Construction**
  Yes, but during construction is better

Company: S + R Sensortec GmbH (2 of 2)

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
- **AC**
- **Other**
  it is a passive sensor, which is measured once or twice annually, using a handheld measuring instrument (CANIN LTM)

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Sensor and measuring device is necessary

(9) <u>What is the operating temperature range?</u>

Approx. -10 to 40 °C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

There is a possibility of remote system, but this is not recommended (annually measured!!)

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

there is a software comparing the results with limit value and giving green or red light.

(13) <u>What services and or support are offered with purchase?</u>

We normally fully support in the design of the monitoring system and in the assessment of the data.

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

We recommend an installation trainee

(15) <u>What examples/applications of the system are available?</u>

Please find examples of applications in the text

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Please find further information in the enclosed text.

Company: Sensors & Software, Inc. (1 of 3)

Sensors & Software Inc. provides ground penetrating (GPR) instruments that can be used to perform a variety of inspections of bridge decks and bridge structural components. Typical products useful for this application are the Conquest system, TR1000, Noggin SmartCart and the Noggin SmartHandle configurations.

- GPR can be used to image steel reinforcement, concrete and asphalt thickness and other structural elements within concrete bridge structures.
- GPR can be used to evaluate the condition of concrete bridge decks overlaid with asphalt using a methodology outlined in ASTM D 6087–07. In this test method the GPR signal attenuation of the section of the deck above the upper rebar mat is measured. This attenuation is correlated with the chloride content and/or moisture content. Zones with high chloride and moisture are indicative of probable areas of current or incipient delamination induced by rebar corrosion processes. In practice, a set parallel GPR profiles are collected over the bridge deck, the amplitude of the reflections from the steel reinforcing bar (rebar) are computed and converted to a deck deterioration index. A color scale image of the deterioration index and of the rebar depth over the deck surface is provided to the client. In addition the individual rebar locations can be provided.

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
- **Short-term monitoring**
- **Inspection**

  Yes
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

  Ground Penetrating Radar (GPR)

Company: Sensors & Software, Inc. (2 of 3)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
- **Post Construction**

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

  Used on concrete bridge structures and decks

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**

  Yes

- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Systems typically consist of logging computer, control unit, GPR sensor, Flash data storage, wheel odometer, GPS mounted on a cart along with acquisition and viewing software for field collection and post processing.

(9) <u>What is the operating temperature range?</u>

GPR : -40 C - +40C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

NA

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

NA

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

NA

(13) <u>What services and or support are offered with purchase?</u>

Often training may be included.

Company: Sensors & Software, Inc. (3 of 3)
(14) <u>What training/installation is required of the user or are these included (ease of use)?</u> Optional training can be provided. **(15) <u>What examples/applications of the system are available?</u>** There are many published case studies on the use of GPR for bridge applications. **(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>** The systems provide a wide range of sampling rates and resolutions depending on the measurement frequency employed.

Company: Strainstall Ltd. (1 of 3)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
- **Inspection**
- **Early warning**
  Yes
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Fatigue usage Monitoring by crack growth in coupon.

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

The sensor system monitors the growth of a crack in a coupon and relates the crack growth with the amount of design fatigue life used for specific welds in a structure

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  The sensor is permanently installed
- **Reusable (everything can be unattached and moved)?**
  The battery and logger can be reused once a sensor has given all the information required.
- **Portable (nothing attached/installed and are easily moved)?**

(5) When can/should the equipment be installed?

- **During Construction**
  Yes

Company: Strainstall Ltd. (2 of 3)

- **Post Construction**
  Yes
  The system can be used most effectively on new build but will also give extremely useful information if attached to existing structures

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes if contains welded steel in deck
- **Prestress Concrete Girder**
- **Reinforced Concrete**
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
- **Battery**
  Yes
- **AC**
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Yes complete system contains
Sensor
Protective enclosure containing logger/electronics
Battery enclosure for extended battery life
Indicator for instant reading (as alternative to data logging)
Wireless comms (currently being developed)
Software for download and analysis
Tools for installation

(9) <u>What is the operating temperature range?</u>

Ambient... -25 to 60 Deg C

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Three alternatives

1) Manual reading on an indicator
2) Downloading logged results to laptop PC
3) Download logged results via wireless to laptop

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

No alarms... the consumption of fatigue is slow and future fatigue life can be predicted

Company: Strainstall Ltd. (3 of 3)

(12) What does the software do (data processing, interface, communications, etc.)?

Set up logger
Set up comms
Download data
Presents crack growth details in table form
Presents crack growth details in terms of fatigue life consumed in graphical form with explanations
Allows a what if capability for changing weld classes
Allows for stress factoring between sensor position and weld location
Data archived and available for further analysis

(13) What services and or support are offered with purchase?

Training in installation method or installation carried out by Strainstall or agent supply of all installation tools
Training in downloading data and use of software

(14) What training/installation is required of the user or are these included (ease of use)?

If it is economically viable... based on number of structures and number of sensors... the training could be carried out to the bridge owner or a nominated contractor. Alternatively the installation can be carried out by Strainstall or by its. Agent

(15) What examples/applications of the system are available?

24 sensors have been installed on Avonmouth Bridge, UK.
Other sensors have been installed on dump trucks, excavators, and ships

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

The sensor has 12 tracks, which will be brocken as the crack grown. For a UK class F weld the 12th track is broken when 81% of the design fatigue life is used. For class F2... 119%. For class E 49%

For a bridge structure it is suggested that the sensors are inspected every 2 years.

The accuracy of absolute percentage design fatigue life consumed is estimated conservatively at 10%. The change in percentage design fatigue life is more accurate.

Company: Structural Monitoring Systems Ltd. (1 of 6)

(1) What is the purpose of the system?

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) What types of sensors or equipment are used?

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**
  Crack detection and propagation monitoring

(3) What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?

(4) Is the system:

- **Permanent (any piece permanently fixed)?**
  Yes – Sensors, pneumatic connectors and self-contained measurement device(s) together with communications device. Optional use of solar power combined with cells
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) When can/should the equipment be installed?

- **During Construction**
  Yes
- **Post Construction**
  Yes

Both are Beneficial when applied to known critical areas

Company: Structural Monitoring Systems Ltd. (2 of 6)

(6) On what types of bridge can it be used?

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Not explored
- **Prestress Concrete Girder**
  Under Development
- **Reinforced Concrete**
- **Other**
  Will detect cracks on any solid surface – not dependent on conductivity of material – Example: composite repairs

(7) What type of power source is used?

- **Solar**
  Yes
- **Battery**
  Yes
- **AC**
  Yes
- **Other**
  Yes

Any of the above – power usage is minimal – less than 100W for multiple unit with comms device

(8) Is it a complete system and what does it include (sensor, control unit, software, communication)?

Sensors, pneumatic network, measurement device, power source, communication device

(9) What is the operating temperature range?

Nominally 50C- +100C. However range can be increased through material selection as required (sensors developed for aviation sector originally)

(10) How does the system communicate remotely with the user (if at all)?

Output of measurement equipment is high or low voltage – any comms device can be used – demo unit uses GSM network to send status to remote centre(s) at pre-programmed intervals as well as any change to status

(11) Does the system have an alarm feature and how is it communicated?

See above

(12) What does the software do (data processing, interface, communications, etc.)?

No software

(13) What services and or support are offered with purchase?

Development of appropriate sensor geometry and material, training, installation and lifetime support

Company: Structural Monitoring Systems Ltd. (3 of 6)

(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>

Very easy to use – no post processing or noise control – training provided

(15) <u>What examples/applications of the system are available?</u>

System in use on aircraft full scale fatigue tests with Airbus, Embraer, Bombardier – system also used

(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>

Continuous monitoring of a structure enables surface cracks to be detected at very small sizes. The result is deterministic and not subject to noise suppression, post processing or statistical analysis

Please find below and extract from a paper

Comparative Vacuum Monitoring – CVM™

CVM™ has been developed on the principle that a small volume maintained at a low vacuum is extremely sensitive to any ingress of air. A sensor with fine parallel grooves on the underside (Figure 1) is placed directly onto the component to be monitored and a vacuum applied. If and when a crack breaches the galleries, the vacuum is breached and detected by either pressure transducer or a pressure switch.

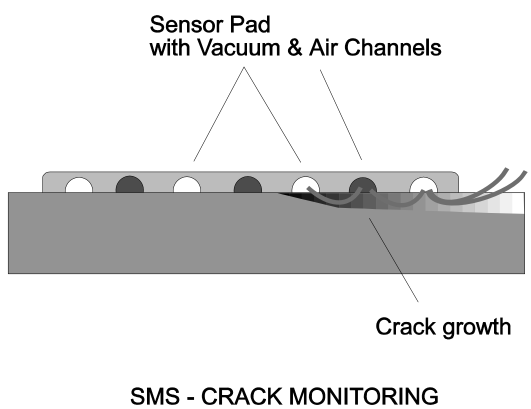


Figure 1: CVM sensor schematic showing airflow caused by crack

CVM™ works on any material to detect and monitor surface cracks including common structural materials such as steel, aluminum, composites and concrete. Current applications include full scale fatigue tests on airframes with Airbus, Bombardier and Embraer, component testing for auto parts maker Bosch. Trials have been completed for these sensors to be fitted permanently to civil aircraft so that they can be used as an Alternative Means of Compliance for some inspections currently requiring extensive time periods for gaining access to inspect with HFEC or visual techniques. Work at Sandia Laboratories in Albuquerque to verify detection capabilities of these sensors has been completed. Figure 2 shows the progression of a crack in aluminum which was continuously monitored using CVM™ via a pressure transducer as part of this work.

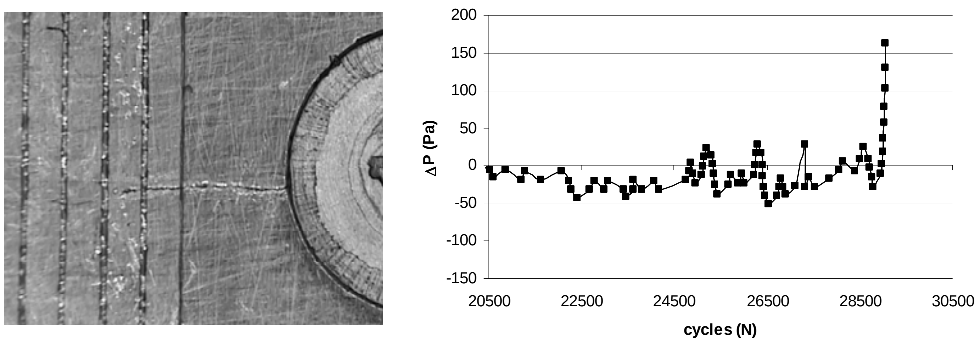


Figure 2: Fatigue Crack Crossing Into CVM Galleries;
(Pressure increase caused by crack reaching a gallery is clearly indicated)

CVM™ Performance on Thick Steel Structures

To assess the performance on typical bridge materials, CVM™ sensors were installed on a 0.375" thick steel (ASTM 572) plate with a fatigue crack seeded along the edge of the specimens. These test specimens were then exposed to tension-tension fatigue tests in order to propagate the crack into the CVM™ sensor. Figure 3 shows the overall test set-up along with the equipment used to monitor the CVM sensors.

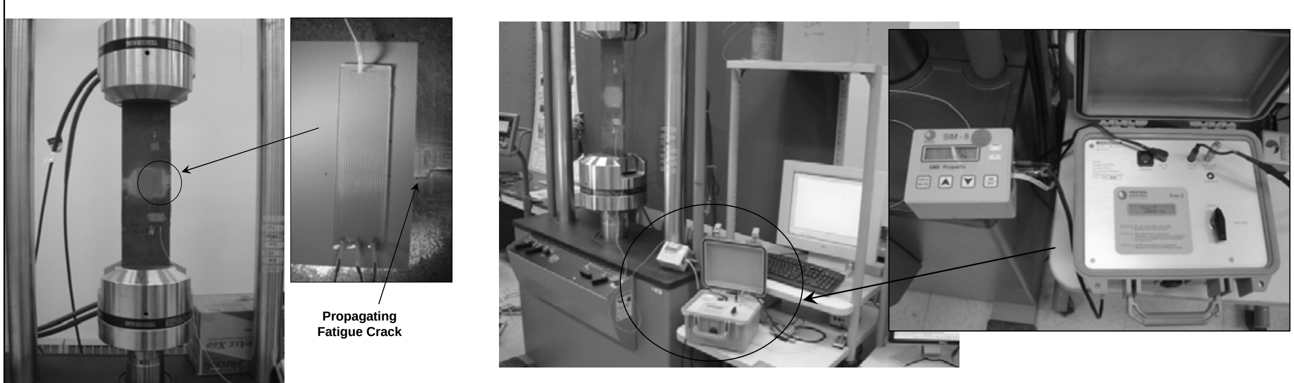


Figure 3: Arrangement of steel component fatigue testing with CVM™ sensor

Company: Structural Monitoring Systems Ltd. (5 of 6)

CVM Set-Up					CVM Crack Detection with No Load			
Test Specimen	Sensor	Initial Crack Length (in.)	Initial Sensor Location [Distance from Specimen Edge] (in.)	Baseline CVM Pressure Reading [No Crack Engagement Condition] (Pa)	Cycles at Initial CVM Crack Detection [Under Load]	CVM Pressure Reading at Crack Detection [Under Load] (Pa)	Total Crack Length at Initial CVM Crack Detection [Under Load] (in.)	Crack Growth for CVM Crack Detection [Engagement with CVM Sensor] (in.)
SYN FAT 24	1	1.10	1.10	1,580	2,137	16,500	1.15	0.050
SYN FAT 24	2	1.48	1.52	1,435	9,451	19,600	1.57	0.050
SYN FAT 24	3	1.90	1.92	1,460	10,698	12,250	1.99	0.070
SYN FAT 19	4	1.17	1.22	1,488	115,000	11,610	1.29	0.065
SYN FAT 19	5	1.55	1.63	1,500	139,843	17,000	1.68	0.050
SYN FAT 19	6	1.81	1.87	1,500	145,800	19,000	1.92	0.045
SYN FAT 22	7	0.94	1.15	1,740	150,839	7,000	1.20	0.050
SYN FAT 22	8	1.48	1.53	1,363	184,412	17,800	1.59	0.060
SYN FAT 22	9	1.70	1.76	1,530	191,315	17,000	1.80	0.045
SYN FAT 21	10	1.00	1.09	1,510	44,800	3,000	1.15	0.060
SYN FAT 21	11	1.50	1.53	1,433	88,100	19,000	1.60	0.070
SYN FAT 23	12	1.45	1.50	1,457	2,000	11,000	1.56	0.060
SYN FAT 23	13	1.81	1.84	1,570	6,400	20,000	1.88	0.040

Table 1: Crack Detection Produced by CVM Sensors on Steel Plate

CVM™ crack detection occurred when the fatigue cracks ranged from 0.040” to 0.070” in length (Table 1). This would correspond to the ability of the CVM sensor to monitor cracks in real-time while the structure is in use and is well within the requirements normally associated with crack detection on bridges.

Proposed CVM™ Switch based system for remote bridge monitoring

Structural Monitoring Systems Ltd has developed a simple system for CVM™ based on a pressure switches which can continuously monitor structures remotely via a transmitting device.

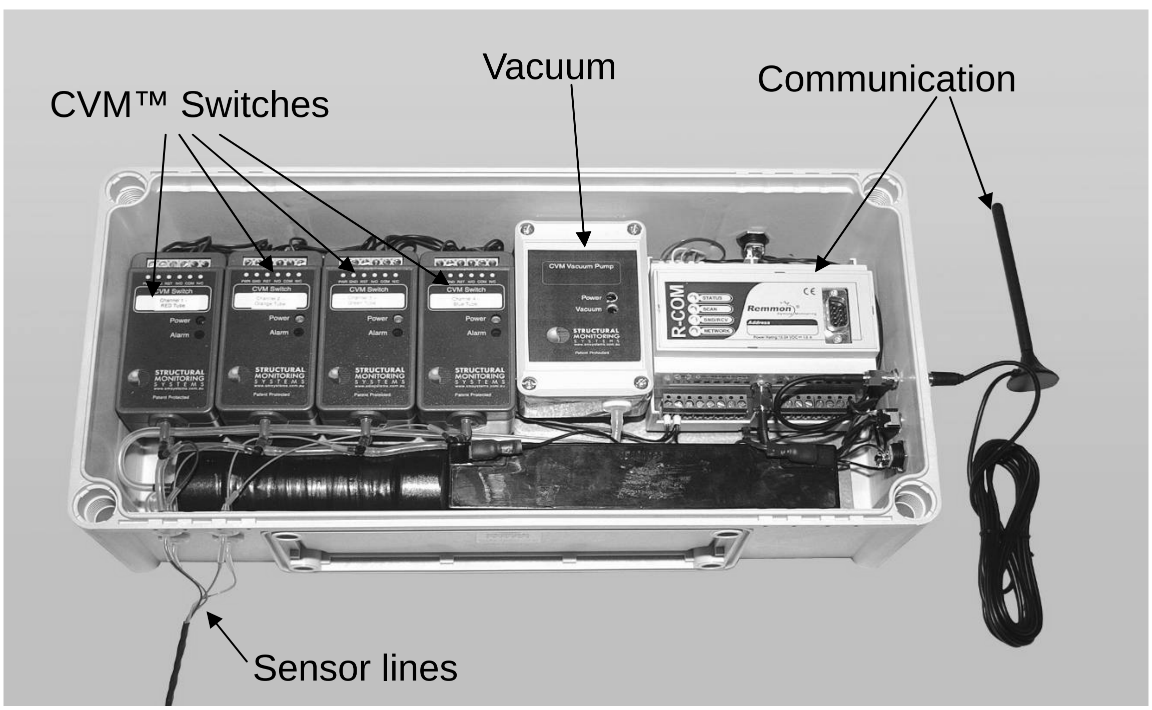


Figure 4: Proposed remote monitoring system

Company: Structural Monitoring Systems Ltd. (6 of 6)
Sensors are placed in known fatigue critical locations on bridges. When a crack breaches a sensor, the pressure switch will be opened which in turn triggers a message to be sent to a central maintenance center. Up to 50 switches can be powered by one vacuum pump. Sensors can be made in almost any shape and out of a material to suit the required environment. Multiple sensors can be arranged to monitor the growth of a crack. It may be that there is a known crack and a sensor placed ahead of the crack will be triggered if the crack grows. Often there are known critical locations at joints or welds that require monitoring. **CVM™ as part of a comprehensive sensor package** Together with acoustic, vibration, corrosion, strain sensors, CVM™ can form a suite of sensor types that will enable the state of a structure to be better understood in real time. Furthermore, implementation costs can be minimized through common power and communications packages for groups of sensor types.

Company: Vienna Consulting Engineers (1 of 4)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**
  Yes
- **Short-term monitoring**
  Yes
- **Inspection**
  Yes
- **Early warning**
  Yes
- **Other (please specify)**
  Fatigue assessment, life-time assessment and prediction

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
  Yes
- **Acoustic Emission**
  No
- **Strain Gauges**
  - **Fiber-optic**
    Yes
  - **Electric Resistance**
    Yes
  - **Vibrating Wire**
    No
- **Load Cells**
  Yes
- **Wind Measurement**
  Yes
- **Tilt**
  Yes
- **Temperature**
  Yes
- **Displacement**
  - **GPS**
    Yes
  - **3-D Laser Scanning**
    No
  - **LVDT**
    Yes
  - **String Potentiometers**
    Yes
- **Other (please specify)**
  Cameras, Laser displacement, Magneotrestrective sensors, ultrasonic,…

Company: Vienna Consulting Engineers (2 of 4)

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

Accelerometers (measuring accelerations in three dimensions) give the dynamic properties of the bridge including frequencies, mode shapes, and damping ratios. Measuring dynamic properties of cables allows force in cables to be measured.

Cameras monitor the traffic volume for the bridge to compare traffic volume and dynamic properties.

Magnetostrictive sensors measure displacements with a resolution of 0.01 mm, max. range 2.5 meters.

Ultrasonic sensors are used for displacement.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  Yes
- **Reusable (everything can be unattached and moved)?**
  Yes
- **Portable (nothing attached/installed and are easily moved)?**
  Yes

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
  Yes
- **Post Construction**
  Yes

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
  Yes
- **Steel Truss**
  Yes
- **Cable Stayed**
  Yes
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**
  All Types

Company: Vienna Consulting Engineers (3 of 4)

(7) <u>What type of power source is used?</u>

- **Solar**
  Yes
- **Battery**
  Yes
- **AC**
  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

Complete Systems: Portable Systems, Permanent Systems, Software, Web-interface, Databae

(9) <u>What is the operating temperature range?</u>

Temperature range for portable systems: -22 to +140*C; permanent systems: almost unlimited because of installation in box with air condition.

(10) <u>How does the system communicate remotely with the user (if at all)?</u>

Modem, GPRS, UMTS, Password secured web-interface
SMS & E-mail alarm system

(11) <u>Does the system have an alarm feature and how is it communicated?</u>

Internet
SMS Text Message
E-mail
Optic and acoustic alarms on site

(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>

Data collection
Data processing & analysis
Graphical User Interface
Sensor calibration
Alarm

Company: Vienna Consulting Engineers (4 of 4)

(13) What services and or support are offered with purchase?

General monitoring training
System training
Web interface
Support hotline
System design
System installation
System maintenance

(14) What training/installation is required of the user or are these included (ease of use)?

For simple systems training not required, however, for more complicated systems it is required.

(15) What examples/applications of the system are available?

Over 2000 Structural Health Monitoring projects worldwide, with projects completed on bridges and other structures.

(16) What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?

Depends on system, each system is designed for the individual application according to the requirements

Our product is BRIMOS. You can find information on www.brimos.com. Please find our catalogue enclosed. This system covers everything you have on your list. We can fulfill any purpose, use any sensors you want and make the system permanent, portable or whatever it is. It is applied during construction and for assessment. We don't mind which kind of bridge it is. All kind of power sources have been tried.

Company: Virginia Technologies (1 of 3)

(1) <u>What is the purpose of the system?</u>

- **Long-term monitoring**

  Yes
- **Short-term monitoring**
- **Inspection**
- **Early warning**
- **Other (please specify)**

(2) <u>What types of sensors or equipment are used?</u>

- **Accelerometers**
- **Acoustic Emission**
- **Strain Gauges**
  - **Fiber-optic**
  - **Electric Resistance**
  - **Vibrating Wire**
- **Load Cells**
- **Wind Gauges**
- **Tilt**
- **Temperature**

  Yes
- **Displacement**
  - **GPS**
  - **3-D Laser Scanning**
  - **LVDT**
  - **String Potentiometers**
- **Other (please specify)**

The ECI-1 is a sensor array capable of measuring 5 different properties, primarily related to the corrosion of steel re-bar in the system.

To measure Linear Polarization Resistance and Open Circuit Potential the ECI-1 has a steel working electrode, a stainless steel counter electrode, and a manganese dioxide reference electrode.

There are also four stainless steel electrodes to measure the concrete resistivity surrounding the sensor array.

A silver/silver-chloride ion sensor, in conjunction with the manganese dioxide reference electrode is able to measure the concentration of chloride ions.

(3) <u>What performance measures are monitored and how are these helpful (e.g., crack formation and propagation, strain, displacement, corrosion, vibration, chloride content)?</u>

The Linear Polarization Resistance and Open Circuit Resistance measurements are useful in that as LPR values go up and OCP values become increasingly negative, the corrosion rate increases.

Company: Virginia Technologies (2 of 3)

The general resistivity measurement in the area surrounding the concrete gives the operator and idea of the moisture content in the concrete

The chloride ion concentration is an important piece of information as it relates to the corrosion of steel re-bar

The temperature and moisture data can be useful as the concrete is curing, to ensure that the curing process is behaving according to plan.

(4) <u>Is the system:</u>

- **Permanent (any piece permanently fixed)?**
  Yes, embedded in the concrete
- **Reusable (everything can be unattached and moved)?**
- **Portable (nothing attached/installed and are easily moved)?**

(5) <u>When can/should the equipment be installed?</u>

- **During Construction**
  Yes
- **Post Construction**

(6) <u>On what types of bridge can it be used?</u>

- **Steel Girder**
- **Steel Truss**
- **Cable Stayed**
- **Prestress Concrete Girder**
  Yes
- **Reinforced Concrete**
  Yes
- **Other**

(7) <u>What type of power source is used?</u>

- **Solar**
  Yes
- **Battery**
  The batteries are rechrged by either the local power grid or by solar power
- **AC**
  Yes
- **Other**

(8) <u>Is it a complete system and what does it include (sensor, control unit, software, communication)?</u>

The company itself only manufactures the sensor array (known as the ECI) and the NetCon-10 communication module (which helps organize large ECI networks, however, the data logger, cellular transceivers, and solar panels are provided through Campbell Scientific, Inc.

(9) <u>What is the operating temperature range?</u>

Not Available

Company: Virginia Technologies (3 of 3)
(10) <u>How does the system communicate remotely with the user (if at all)?</u> Information can be downloaded via a cellular modem or wireless transceiver **(11) <u>Does the system have an alarm feature and how is it communicated?</u>** No alarm feature is evident **(12) <u>What does the software do (data processing, interface, communications, etc.)?</u>** Not clear **(13) <u>What services and or support are offered with purchase?</u>** Calibration and test data provided for each ECI-1 unit, integrated software automatically compensates for calibration. **(14) <u>What training/installation is required of the user or are these included (ease of use)?</u>** **(15) <u>What examples/applications of the system are available?</u>** Used by CalTrans on some bridges **(16) <u>What specifications/performance measures for the equipment can you provide us (e.g., sampling rate limits, resolutions, data ranges, temperature ranges, measurement accuracy)?</u>** The data is converted near the source into a digital signal, which the data logger is capable of reading at 1200 b/second Temperature sensor has data range of -40 C to 70 C