The Future of Condition-Based Maintenance

Using Wireless Strain Measurement Technology

Dr. Chris Sellathamby, Ph.D., P.Eng. Brian Moore, P.Eng. Steven Slupsky P.Eng.
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SCANIMETRICS

Increased Productivity by Condition-Based Maintenance Using Wireless Strain Measurement System

DR. CHRIS SELLATHAMBY, Ph.D, P.Eng† BRIAN MOORE, P.Eng‡
STEVEN SLUPSKY P.Eng*
†VP Marketing, Scanimetrics, Inc.
‡Director Engineering, Scanimetrics, Inc.
* President and CEO, Scanimetrics, Inc.

Condition-based maintenance is replacing preventive maintenance in many industrial operations as a result of gains in productivity. Preventive maintenance is strictly time-based which means that as long as the prescribed time is sufficiently short, failures are prevented. The trade-offs between shorter cycles and increased downtime is a fine balancing act. Condition-based maintenance is gaining momentum as the more cost-effective and green solution to finding the optimal maintenance cycle and improving overall productivity.

In the many industries, such as mining, oil and gas, and power generation, various parameters of heavy equipment are monitored continuously to provide feedback for maintenance events. However, strain, shock, and vibration, key factors which lead to yielding and fatigue of metal parts, are not generally monitored by built-in systems, mainly due to the complexity of sensor installation and computational intensity of data processing.

Scanimetrics has developed a stand-alone, add-on wireless system for measuring strain, shock, and vibration in heavy equipment and components, the data from which can be directly used to trigger maintenance events. The present system is being deployed in oil sands mining equipment, coil tubing drilling pipe, and power generation equipment. The system consists of a portable display and control unit, a software platform consisting of data management, sensor instrumentation and data analysis, and wireless strain sensor units, which can be easily installed on equipment. Data from the sensors can be gathered throughout the mine site, processed instantly, and used to generate condition-based maintenance events, improving overall uptime of the equipment and overall productivity of the mining operation.

Introduction

Maintenance is critical for all equipment in any industry, but the larger, more crucial, and more expensive the equipment, the higher the importance of optimal maintenance. In the mining, forestry, energy, and construction industries, much of the work relies on large, crucial, and expensive machinery, where minimum downtime is key to generating value from the asset.

This paper is organized as follows: Section 1 describes the two main types of maintenance; Section 2 defines and describes condition-based maintenance (CBM) and discusses the advantages and disadvantages and operational requirements of CBM as a maintenance system; Section 3 shows how CBM can increase productivity; Section 4 describes the limitations of present systems; and finally, Section 5 introduces Scanimetrics' sensor system as a viable means of gathering structural integrity data for CBM systems.

1 Types of Maintenance

There are two basic categories of maintenance systems employed by most industrial companies (see Figure 1): corrective (repair after a failure) and planned (repair to prevent a failure). The type of maintenance used can directly affect profitability: the correct choice will lead to greater profit.

1.1 Corrective

Otherwise known simply as repair, corrective maintenance performs repairs to machinery when the equipment fails.

Although many companies follow the old idiom "if it ain't broke, don't fix it" when it comes to equipment maintenance, when considering long-term cost, corrective maintenance costs are higher than preventive maintenance costs over the long term.[1] Studies have shown that unscheduled corrective maintenance is more than three times the cost of scheduled maintenance repairs.

Although this system will always be used as an emergency measure when a piece of equipment fails unexpectedly or when the equipment in question is non-essential, inexpensive, or physically too small to monitor, operators usually try to plan for failure and repair before it happens. Unexpected failures in the field are often the result of insufficient equipment monitoring.

1 Gokiene, Ruta. "Marginal Break Even Between Maintenance Strategies Alternatives. Ribinis taškas tarp remonto strategijų alternatyvų." Engineering Economics, 2010, Vol. 21, Issue 2, 139.

5120 – 75th Street Edmonton, AB Canada T6E 6W2
Email: info@scanimetrics.com **Phone:** 1-866-747-9441 or 780-433-9441 **Fax:** 780-433-9499

1.2 Planned

Planned maintenance is a system where repairs are made to maintain a machine before it fails. Scheduled repairs allow operators to feel confident in the safety of their equipment operation, schedule the work crew and resource allocation around the repairs, and order parts in leisure.

Planned maintenance includes systems which bring equipment in for repairs every given time period (preventive maintenance) as well as systems which work to understand the equipment to predict when it will fail (predictive maintenance, also known as condition-based maintenance).

For example, a truck taken in for repairs every two months to prevent a breakdown is preventive maintenance, whereas, a truck monitored for strain, shock, and vibration (among other factors), and only taken in for repairs when approaching failure is condition-based maintenance.

Many companies use a combination of the two basic types of maintenance systems. For example, oil sands mining company would use planned maintenance for their large haulers, diggers, and shovels and corrective maintenance when an unplanned failure occurs.

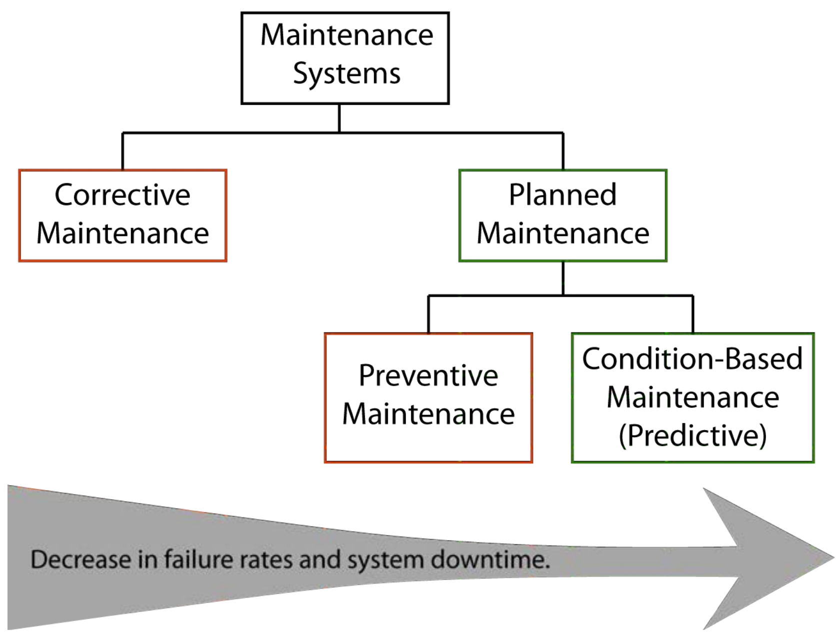

Figure 1: The two basic types of maintenance systems, showing the decrease in failure rates.[2]

2 Koochaki, Javid. "Collaborative Learning in Condition Based Maintenance." World Congress on Engineering 2009 (Volume 1), 2009, 738.

2 Condition-Based Maintenance (CBM)

2.1 Definition

A branch of planned maintenance, condition-based maintenance (CBM) systems repair a machine before it fails by monitoring for signs of fatigue or other precursors to failure. CBM establish an optimal maintenance cycle, generally extending the time between the regular repairs of preventive maintenance, and thus saving costs of un-needed excessive maintenance and downtime.

CBM operates on the analysis of gathered maintenance data (such as strain, vibration, crack propagation, and pressure). Operators gather, process, and analyze the relevant data and observations to make correct and timely decisions regarding the machinery:

- intervene by conducting immediate maintenance on a piece of equipment,
- plan to conduct maintenance within a specified time, or
- continue operating the equipment until the next CBM inspection.[3]

A CBM program, if properly established and effectively implemented, can significantly reduce maintenance cost by reducing the number of unnecessary scheduled preventive maintenance operations.[4] CBM can also anticipate and prevent costly unforeseen failures.

2.2 Disadvantages

HIGH IMPLEMENTATION COSTS

CBM requires often or constant monitoring of systems. To achieve the level of monitoring required, operators need to install many sensors onto their machinery. This initial cost, although not generally repeated, is often inhibiting.

CBM systems are also difficult to implement due to frequent changes of design, technologies, business policies, and management executives.[5]

3 Optimal Maintenance Decisions, Inc. "Introductory CBM Slides." 2010, Slide 6.

4 Jardine, Andrew, Lin, Daming, and Banjevic, Dragan. "A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance," Mechanical Systems and Signal Processing, 2006, Vol. 20, Issue 7, 1484.

5 Jardine, Andrew, Lin, Daming, and Banjevic, Dragan. "A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance," Mechanical Systems and Signal Processing, 2006, Vol. 20, Issue 7, 1500.

TECHNICAL DIFFICULTY OF FAILURE PREDICTION
Translating the raw data from the monitoring systems into useful information is technically demanding and requires expert materials consultation for accurate reliability analysis and failure prediction. Data needs to be intelligently monitored, processed, and mined for valid predictions to be made.

2.3 Advantages

MAINTENANCE CYCLE OPTIMIZATION
CBM's main advantage is the optimization of maintenance cycles. Continual monitoring of key elements of machine failure over a certain period of time allows operators to determine when the machine will fail. This allows the machine to continue operating up until the time it is about to fail, and still have the failure planned for to save on labour, expedited shipping of parts, and rescue operations.

In many situations, especially when both maintenance and failure are very costly, CBM is absolutely a better choice than the conventional (corrective and preventive) ones.[6]

INCREASED MACHINE PRODUCTIVITY
CBM reduces equipment downtime by extending the time between maintenance by knowing when a machine will fail. This lowers overall production costs by increasing production output. Regular maintenance also generally increases the useful lifetime of a machine.[7]

DECREASED MAINTENANCE COSTS
By repairing only what needs repair, CBM eliminates excessive maintenance tasks, as well as decreasing the number of times a machine goes in for repairs and labour time for manual inspections.

IMPROVED SYSTEM RELIABILITY AND INCREASED SAFETY
Monitoring structural integrity improves the readiness, survivability, and performance safety of the machine at the lowest cost by assessing previous failure data.

IMPROVED UNDERSTANDING OF EQUIPMENT
Long-term monitoring of machine behaviour will continuously improve the maintenance process and failure response of the maintenance team.

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6 Jardine, Andrew, Lin, Daming, and Banjevic, Dragan. "A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance," Mechanical Systems and Signal Processing, 2006, Vol. 20, Issue 7, 1500.

7 Gokiene, Ruta. "Marginal Break Even Between Maintenance Strategies Alternatives. Ribinis taškas tarp remonto strategijų alternatyvų." Engineering Economics, 2010, Vol. 21, Issue 2, 137.

FLEXIBLE INTRODUCTION
CBM can be effectively implemented on subsets of the operation and introduced incrementally. Initially, CBM can also be implemented to inform maintenance operations passively.

However, to fully reap the productivity benefits of CBM, it does requires a company-wide maintenance organization changes, such as how a maintenance event is initiated and the relationship between the machine's work, the monitoring of the machines, and the data analysis.

2.4 Requirements of CBM

A successful CBM operation requires the following:

- Knowledge of what has happened: historic data acquired over long periods of time is valuable to determine what the normal state for a particular machine is.
- Knowledge of what should happen: using the historic data and present incoming data, one can determine when a machine is due to fail.
- Knowledge of what is happening: condition monitoring determines present machine health status.

HOW HAS THE MACHINE OPERATED IN THE PAST
This knowledge is built over time; the longer the base of data collected on a machine, the more valuable that data becomes. This data is used to determine machine health and predict failure.

When implementing a CBM system, if there is no previous data, the present sensor readings can still be compared to materials fatigue curves.

FAILURE PREDICTION BASED ON PAST FAILURES

Failures happen randomly, based on a distribution (according to the type of equipment), rather than at fixed times.[8]

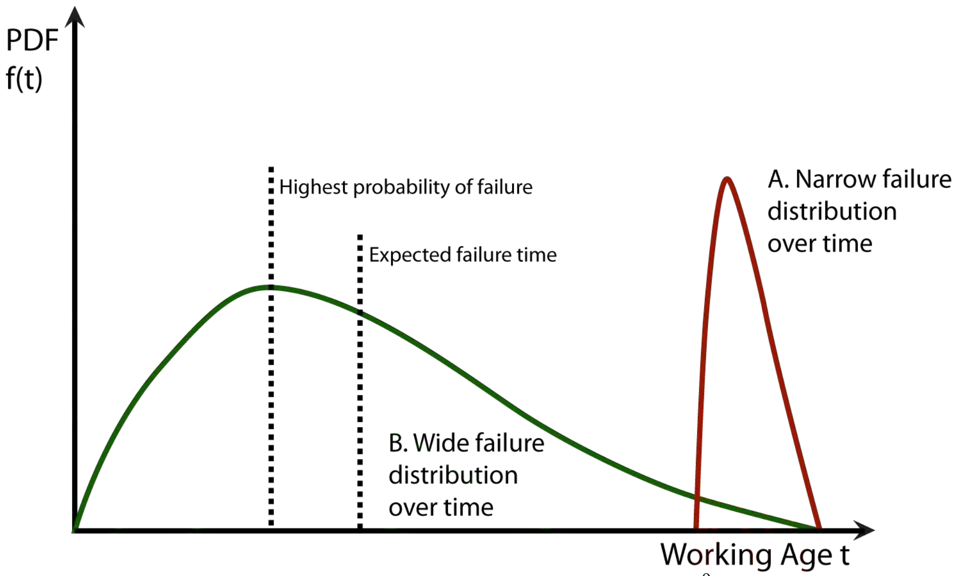


Figure 2: Working age vs. average failure time.[9]

In Figure 2, the curves represent the likelihood of a piece of equipment to fail at a certain time. The distribution of failure differs for different pieces of equipment. The spread of the distribution indicates the confidence of failure prediction based on an item's age. If the distribution is narrow, as shown on the right, prediction can be made based on an item's age. However, in maintenance, unfortunately, most failure probability distributions are widely spread out, as the curve on the left. This is because age is a mixture that averages in the influences of other more predictive variables, such as crack propagation rate. It is incumbent on the reliability engineer to select variables for analysis along with age that will yield narrow distributions for confident predictions.

If failure always occurs at relatively even intervals (narrow distribution), then preventive maintenance may be more cost-effective. However, if failure occurs at random intervals (wide distribution), condition-based maintenance is more cost-effective.

By analyzing sensor data preceding past failures (or imminent failures) as recorded in the CMMS database, engineers can continually improve the accuracy of their failure predictions.

8 Wiseman, Murray, Lin Daming. "Time to Failure," 2006. Accessed August 17, 2010. <http://www.omdec.com/moxie/Technical/Reliability/time-to-failure.shtml>.

9 Wiseman, Murray, Lin Daming. "Time to Failure," 2006. Accessed August 17, 2010. <http://www.omdec.com/moxie/Technical/Reliability/time-to-failure.shtml>.

2.5 *Monitoring the Present*

The optimal CBM plan includes hardware (such as sensors), preliminary software (to analyze the data from the sensors), and comprehensive software (to initiate and manage work orders), although the analysis and work order management can be done manually as well.

Electronic sensors measure physical quantities (such as strain, temperature, acceleration, crack propagation, pressure, etc.) and convert them into signals read by an instrument (the reader varies depending on the type of sensor).

For example, strain gauges consist of a foil pattern (often in a tight zigzag) insulated in a flexible material and attached to an object under strain. As the object deforms, the resistance of the foil wires changes, allowing a Wheatstone bridge circuit (a measuring instrument used to measure an unknown electrical resistance) to record the variations.

Sensor solutions common in many companies are often labour intensive and expensive:

- Monitoring structural integrity is done manually.
- Wired strain measurement solutions are hard to install, complicated to use, and costly.
- Measured data needs time-consuming analyses and post-processing.

Automating the whole process with CBM decision-making software (called Computerized Maintenance Management Systems or CMMS) and electronic sensors, although initially costly, can prove to be ultimately worthwhile.[10]

Figure 3: Steps of a CBM system.[11]

DATA ACQUISITION

CBM relies heavily on frequent (even constant) data acquisition. The more data one can collect about a machine, the more accurately one can determine when that machine will fail.

As an example, strain and fatigue measurements reveal risks of yield failures and cracking, changes in material properties, and remaining equipment life, making them useful for CBM if

10 Canady, Henry. "Automating Maintenance Planning." Air Transport World, 2008, Vol. 45 Issue 4, 74.

11 Jardine, Andrew, Lin, Daming, and Banjevic, Dragan. "A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance," Mechanical Systems and Signal Processing, 2006, Vol. 20, Issue 7, 1484.

monitored. In the mining industry, strain and vibration are not generally monitored by built-in systems, mainly due to the complexity of sensor installation and computational intensity of the data processing. CBM relies on regular or continuous measurements of parameters that allow operators to determine when the machine will fail (i.e. strain and vibration).

If one can collect constant strain, vibration, and crack propagation data on a machine, techniques exist to predict failures accurately.[12]

DATA ANALYSIS
Once the data has been collected, the raw numbers must be analyzed into a useful format. For example, knowing a truck's rear axle load right now is 7,892 kg tells us nothing about when the truck will next stop working.

CBM can be used to analyze reliability and determine new relationships between failure probability and raw data, and provide these results to operators.

Raw strain data can be collected using uniaxial or rosette strain gauges. Rainflow analyses can be used to determine strain cycles, strain vectors, and fatigue. Knowing the current fatigue cycles and comparing this value to the average for the particular component enables prediction of the next failure event.

INTEGRATION INTO DECISION MAKING PROCESS
After the data has been analyzed, reliability managers can make informed decisions about when a piece of equipment goes in for repairs. The CBM data is inserted into the company decision-making process, whether that process is done by a human or a computer.

These processes manage the data analysis and create maintenance events. They grow reliability knowledge by creating new or revising old maintenance records from daily experience. They monitor asset performance through time: does the maintenance pattern need to change?

3 CBM Increases Productivity

Equipment downtime, both scheduled and unscheduled, is an important factor of production loss. According to a study by Optimal Maintenance Decisions Inc. (OMDEC), a leader in condition-based maintenance (CBM) management solutions, failures in the field are three times more costly to repair

12 Cui, Weicheng. "A State-of-the-Art Review on Fatigue Life Prediction Methods for Metal Structures." Journal of Marine Science and Technology, Tokyo: 2002, Vol. 7, Issue 1, 44-50.

(considering overtime, rescue, and expedited shipping of parts) than scheduled (or preventive) maintenance operations.[13] Add in the cost of the repair, the cost of equipment downtime (loss of production), penalty costs of environmental or safety violations, loss of markets, loss of reputation, etc. and one has a very expensive breakdown.[14]

Unscheduled downtime will occur as a result of mechanical problems, unanticipated repairs and other slowdowns.[15] CBM can extend the time between repairs, allowing operators to operate the machinery for longer periods of time.

4 Limitations of Existing Solutions

Existing CBM solutions for predicting structural integrity failures have been historically inaccurate, are expensive or non-viable, and/or produce poor signal transmission and short battery life. Dr. Michael Lipsett of the University of Alberta says, "By employing a condition based maintenance program, it is possible to achieve as much as a 10% increase in machinery uptime for some of the major equipment and processes for oil sands mining operations."[16]

CBM's reliance on high data volume dictates a need to monitor continuously (or at least often) strain and loading. This also creates a need to intelligently manage the volume of data and reduce it to intelligence useful to operators. To understand fully a machine's state requires monitoring of fatigue cracks and crack growth. However, monitoring the thousands of meters of cracks spread throughout the hundreds of machines used every day in a mining operation requires many sensors and many more wires, which are difficult and expensive to install and maintain.

Many solutions have not reliably predicted when a machine will fail. This parameter is probably the most important when it comes to CBM, since CBM relies on accurate predictions of failure. The inability to predict correctly when a machine will fail can have grave consequences on unplanned downtime as well as operator safety.
Some solutions offer accurate predictions, but at high costs, whether in the stages of installation and setup, longevity and data collection, or analysis and data post-processing.

Yet other solutions offer poor signal transmission due to low range or lack of direct line of sight. Power supplies dictate operating conditions and longevity of the solution. Most solutions require too

13 Optimal Maintenance Decisions, Inc. "Sample Assessment Proposal." 2007. Accessed August 19, 2010. < www.omdec.com/wiki/tiki-download_file.php?fileId=34>. Slide 27.

14 Optimal Maintenance Decisions, Inc. "Mining Sustainability and OMDEC." 2010. Page 2.

15 Canadian Oil Sands Trust, "2009 Annual Report." February 2010. Accessed August 1, 2010. <cos-trust.com/Theme/COS/files/COS_2009_eAnnnual/index.html>. Page 19.

16 Lipsett, Dr. Michael. Personal interview. 17 April 2010

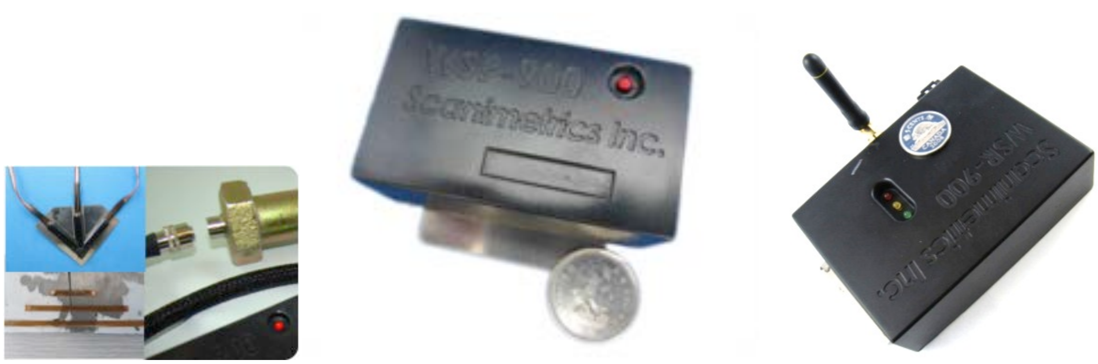
much power to operate for long periods of time, or are too delicate to operate in the harsh conditions of mining operations. Conditions can include extreme temperatures, constant vibration, and quick acceleration. These environmental conditions preclude the use of laboratory-type instrumentation.

5 Scanimetrics' Wireless Sensor System

5.1 Description

HARDWARE

Scanimetrics has developed a complete solution for assessing structural integrity on heavy industrial equipment, which includes installation, measurement, monitoring, data analysis and report generation, enabling optimal maintenance decisions. The small, stand-alone, add-on wireless system measures fatigue, strain, crack propagation, bolt tension, shock, and vibration on mobile and stationary equipment, such as haul trucks, shovels and pipelines. The system combines sensors (see Figure 4a) with wireless sensor modules or “Motes” (see Figures 4b) and a master data capture unit or “Gateway” (see Figure 4c) connected to the Internet. The data is transmitted to a server where it is processed by software that allows operators to trigger maintenance events.



Figures 4a, 4b and 4c: Scanimetrics sensors, wireless sensor modules (Motes) and master Gateway.

The Gateway can be up to ten meters from the Motes to receive the strain data being transmitted in normal non-direct line of sight operating environments. It enables sensing in hard-to-reach places and is non-intrusive to normal machine operation. Wireless repeaters can be used to extend the range between the Gateway and the Motes.

The wireless sensor modules operate as a mesh network and can relay data between the master and units which are not directly reachable by the master. This enables sensor modules to be placed deep inside machinery and still be accessible by the master.

Different RF frequencies are available for the Motes. Currently, 900 MHz has been implemented in oil sands mining, which eliminates interference with Wi-Fi 2.4 GHz signals.

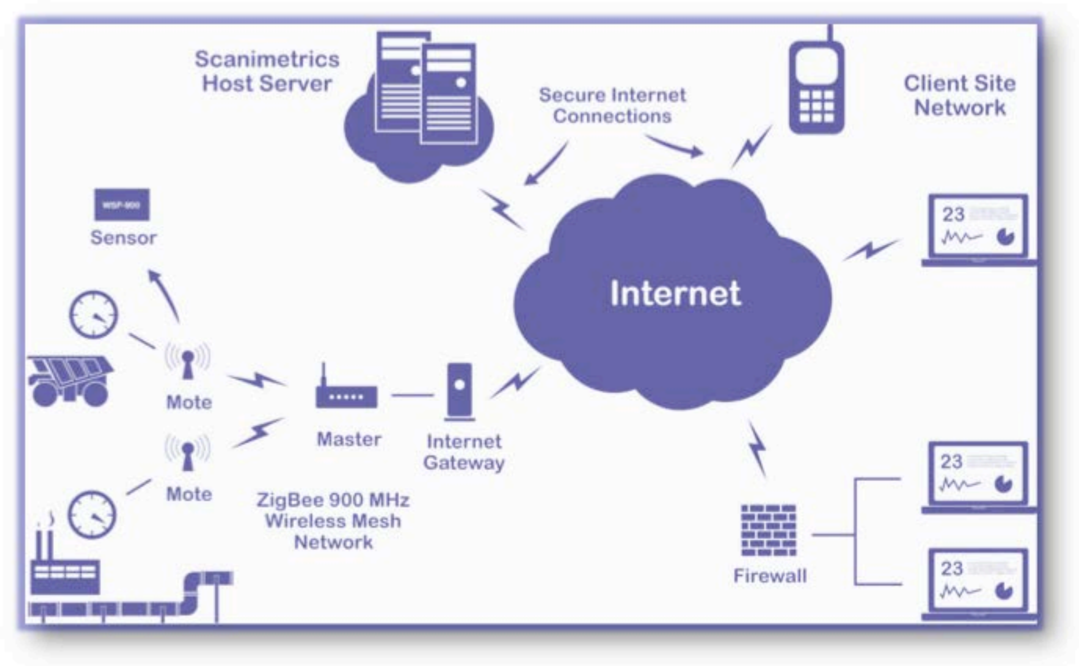


Figure 5: The interaction of the entire Scanimetrics wireless sensing and data acquisition system.

The system is intrinsically safe (sealed in an epoxy compound built to IP67 standard) for explosive and other harsh environments. It uses innovative power management techniques and small batteries and is sealed into a ruggedized unit. With the possibility of three sensor channels and the built-in accelerometer and temperature sensor, the applications for the units are numerous.

The wireless modules can operate in temperatures from -40°C to 85°C, have up to three input channels and sufficient memory and battery power to operate for over a year. They can be attached to most electronic sensors including strain, crack propagation, vibration, ultrasonic thickness, temperature, thermocouple, accelerometer, and pressure sensors.

DATA ANALSYSIS AND REPORTING

Data from the sensors can be wirelessly gathered throughout the mine site, transmitted to the host server, processed in a timely manner with data analysis software, and used to generate condition-based maintenance events and reports, improving overall uptime of the equipment and overall productivity of the mining operation. MoteScan software on the server performs data analysis (including rainflow analysis for fatigue measurement and remaining useful life estimation). Maintenance staff can receive alerts and reports automatically or can log into a secure portal to view the condition of the equipment at any time from any remote device connected to the Internet.

5.2 Benefits

"The small size, versatility, ease of installation and ruggedness of Scanimetrics' solution opens up many new applications where monitoring of structural integrity was not previously timely or cost effective," says Dr. Lipsett.[17]

The Scanimetrics Mote is small and wireless, lowering installation costs, enabling sensor access to hard-to-reach places, and reducing labour cost (no operator intervention is needed during logging). It is reliable and packaged in an integrated unit for operation in harsh or dangerous environments.

Timely data analysis provides information for predicting failures and the data is easily integrated into event and historian systems to improve process reliability.

Although the present system is being deployed in oil sands and hard rock mining equipment, the system is not limited to these applications. Power generating equipment, drillings rigs, pipelines, power transmission systems, and even urban structures such as buildings and bridges can benefit from direct monitoring. The Scanimetrics Mote system offers industrial and plant operations the data needed to manage their risk of equipment failure. The benefits are many, range from economic to environmental to human safety.

For more information, please contact:

Chris Sellathamby, Ph.D., P. Eng.
Vice President – Sales and Marketing
Email: csellathamby@scanimetrics.com
Bus: (780) 433-9441 ext. 300

17 Lipsett, Dr. Michael. Personal interview. 17 April 2010.

References

Canadian Oil Sands Trust, "2009 Annual Report." February 2010. Accessed August 1, 2010. <cos-trust.com/Theme/COS/files/COS_2009_eAnnnual/index.html>.

Canady, Henry. "Automating Maintenance Planning." *Air Transport World*, 2008, Vol. 45 Issue 4, 73-75.

Cui, Weicheng. "A State-of-the-Art Review on Fatigue Life Prediction Methods for Metal Structures." *Journal of Marine Science and Technology*, Tokyo: 2002, Vol. 7, Issue 1, 43-56.

Gokiene, Ruta. "Marginal Break Even Between Maintenance Strategies Alternatives. Ribinis taškas tarp remonto strategijų alternatyvų." *Engineering Economics*, 2010, Vol. 21, Issue 2, 136-141.

Jardine, Andrew, Lin, Daming, and Banjevic, Dragan. "A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance," *Mechanical Systems and Signal Processing*, 2006, Vol. 20, Issue 7, 1483–1510.

Koochaki, Javid. "Collaborative Learning in Condition Based Maintenance." *World Congress on Engineering 2009 (Volume 1)*, 2009, 738-742.

Lipsett, Dr. Michael. Personal interview. 17 April 2010.

Optimal Maintenance Decisions, Inc. "Introductory CBM Slides." 2010.

Optimal Maintenance Decisions, Inc. "Mining Sustainability and OMDEC." 2010.

Optimal Maintenance Decisions, Inc. "Sample Assessment Proposal." 2007. Accessed August 19, 2010. < www.omdec.com/wiki/tiki-download_file.php?fileId=34>.

Wiseman, Murray, Lin Daming. "Time to Failure," 2006. Accessed August 17, 2010. <http://www.omdec.com/moxie/Technical/Reliability/time-to-failure.shtml>.