WIRELESS DATA GATHERING SYSTEM FOR CONDITION BASED MAINTENANCE

Christopher McLean, Ph.D.
David Wolfe

ABSTRACT: Advances in wireless technology, battery chemistry, and miniaturization have made large-scale wireless CBM data gathering systems practical. Wireless sensing no longer needs to be relegated to locations where access is difficult or cabling is not practical. Wireless CBM data gathering can be cost effectively implemented in extensive applications that were historically handled by route running.

To receive the full benefit of an industrial condition based maintenance program, it is necessary to have up-to-date equipment condition. When compared with route running, return on investment can be significantly higher for data gathering systems that provide machine condition four or more times a day. Most modern manufacturing facilities are not able to fully implement surveillance systems due to the high capital costs, installation difficulties, and the overall complexity of the system. Monthly or weekly route running remains the most common implementation of condition based maintenance (CBM).

The condition based maintenance practice of surveillance monitoring would benefit significantly from intelligent, inexpensive, wireless sensors. The result would be a lower cost surveillance program, easier sensor node placement, simpler data gathering, increased safety, and seamless reconfiguration or expansion of sensor nodes. In short, surveillance programs would be easier to apply to a wider variety of applications.

This publication will detail the major issues surrounding the development of a wireless surveillance system for practical application in the factory environment. A wireless surveillance system must address the reliability of the wireless communication network, cost, battery life, ease of configuration, miniaturization and intelligence, all while retaining the accuracy and bandwidth of traditional sensors. A careful balance is necessary.

1.0 INTRODUCTION:

As organizations are increasingly faced with demands to lower maintenance costs, increase product quality, and reduce backup production capacity, CBM has emerged as a viable alternative to traditional planned maintenance or run-to-failure operation. Within many manufacturing facilities, running routes with data collectors has become a cornerstone maintenance practice. Data is collected on machine vibrations, temperatures, oil, and running speed. With trending analysis software, machine health can be assessed and projected. With the ability to predict failures (in advance) and prevent downtime, return on investment is realized.

1.1 TREND TOWARDS SURVEILLANCE SYSTEMS:

The next step in the evolution of condition based maintenance practices are surveillance systems that provide more frequent machine condition than route running. To receive the full benefit of a condition based maintenance program, it is often necessary to collect equipment condition multiple times per day. Research has shown that less than 20% of equipment follows age-related failure problems, while the other 80% are random and may not be detected through infrequent route running. However, a surveillance system can detect the random failures and provide additional protection (see Figure 1). When compared with route running, return on investment can be significantly higher for surveillance systems that provide frequent machine condition.

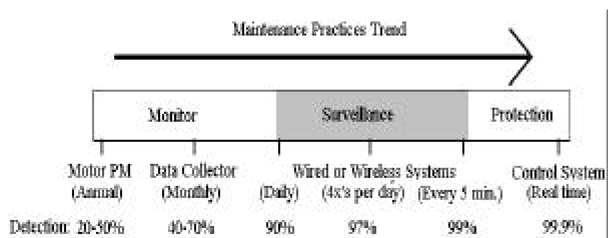


Figure 1, Trends in Maintenance Practice

Most modern manufacturing facilities are not able to fully implement a surveillance system due to the high capital costs, installation difficulties, and the overall complexity of the system.

In addition to monitoring equipment more frequently, monitoring more equipment is another key advantage of a low cost wireless system. Historically, wired systems have only been installed on critical or difficult to reach locations, because costs have been prohibitive to monitoring thousands of points with a surveillance system. However, facilities are missing additional return on investment potential, such as reducing backup production capacity and allocating resources more efficiently. Widespread, up-to-date equipment condition will allow facilities to run leaner, because they will have more confidence in their ability to eliminate downtime.

The vision of inexpensive wireless CBM has been in existence for some time. A fully wireless CBM data collection system has distinct advantages over a wired system. No cables are required for power or signal. This reduces the up-front capital equipment cost, and minimizes operating expense, as there are no cables to fail due to chemical erosion, thermal erosion, vibrational fatigue, and accidental destruction. The result will be easier sensor placement, simpler data gathering, increased safety, and seamless reconfiguration or expansion of measurement nodes. This will allow trouble spots to be addressed in a timely manner and permits resource to be allocated more efficiently as equipment history is developed.

Inexpensive wireless sensor technology has the ability to revolutionize the condition based maintenance discipline. The field of condition based maintenance will benefit significantly from newly available wireless sensors with a price under $400. These new products will produce significant cost savings for industrial customers already involved in condition based maintenance and will be easier to apply to a wider variety of applications.

1.2 RETURN ON INVESTMENT:

The relative costs and return on investment for data collector, wired surveillance, and wireless surveillance CBM programs need to be addressed. A summary of the relative costs is shown in Figure 2. While data collectors have lower installed costs, their operating costs are linearly related to the number of points covered, times the number of times per day these points need to be measured. Surveillance systems will have higher installed costs, but the operating costs are fairly flat for any number of points and any frequency of monitoring.

The installed cost of any CBM data gathering system is critical to its financial success. A $100 accelerometer becomes a $600-$1000 sensor when considering installed costs. At these levels, it is common to use hard-wired systems only on critical assets. Wireless systems limit the installed cost to a fraction of that with cabled solutions. A $389 wireless sensor becomes a $425 sensor when installed.

The operating costs of the data collector program accumulate every year including labor, training, and benefits. These methods can have significant operating costs when faced with a high number of points and high frequency of measurement. Surveillance systems, especially wireless systems, have minimal operating costs.

2.0 WIRELESS DATA GATHERING SYSTEM OVERVIEW:

The current embodiment of a wireless data gathering system for CBM is shown in Figures 3 and 4. The system operates up to 65,535 wireless sensor nodes from a single Ethernet networked PC. Repeaters are used where necessary. Data is sampled by individual sensor nodes, internally processed, and wirelessly sent to the access points for upload and storage on a primary control PC. Operators can monitor sensor data, be informed of alarm conditions, and configure parameters from the convenience of a standard PC.

The wireless CBM system addresses scalability, cost, miniaturization, reliability of RF communication, battery life, ease of configuration, and intelligence, all while retaining the accuracy, bandwidth, and robustness of traditional sensors. The wireless CBM system includes accelerometers, thermistors, and laser tachometers. Table I identifies some of the desired characteristics for the CBM wireless sensor network and those available in the current embodiment.

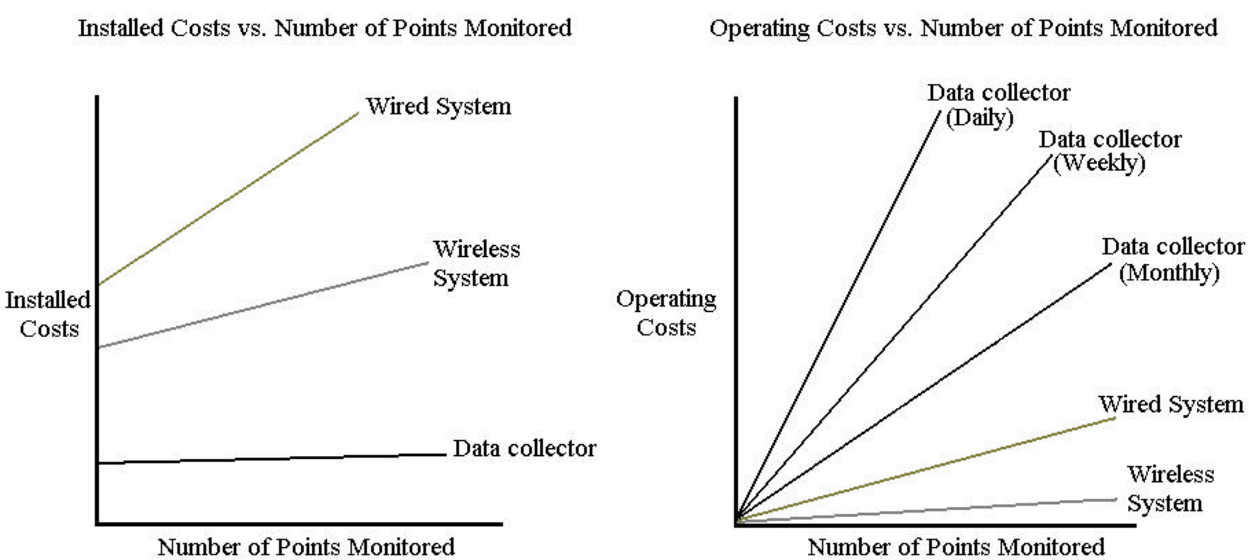


Figure 2, Relative Costs for Data Collector, Wired Surveillance, and Wireless Surveillance CBM programs

Table I
Desirable Characteristics for a Wireless CBM Sensor Network and Current Embodiment

Parameter	Desired Value	Current Embodiment
Number of Sensors Supported	Thousands	65,535 Nodes
Types of Sensors Supported	Vibration, Temperature, Running Speed	Accelerometer, Thermistor, Laser Tachometer
Cost	$200 to $400 installed cost	$389 in volume
Sensor Performance	Same as traditional sensors	Same as traditional sensors
Intelligence	High – internal processing, autonomy	Highly intelligent and fully autonomous
Size, Weight, Environmental Resistance	Same as traditional sensors	Same as traditional sensors
RF Communication Distance	Hundreds of feet	300 feet
RF Security	Encryption	Encrypted
RF Communication Reliability	High – 100% data integrity, EMI resistance	Multipath correction, and 100% data accuracy through error correction algorithm
Power	Self powered for at least 2 years	3 Year life with eight 1024-point FFTs sent per day
Installation	Less than one minute on existing mounts	Less than one minute plug-and-play, ad-hoc networking
Integration with other software	High – CMMS, CBM Software, Open Database Architecture	Open database architecture
System Reliability	High – should not produce additional maintenance	Battery monitor, temperature monitor, ad-hoc networking

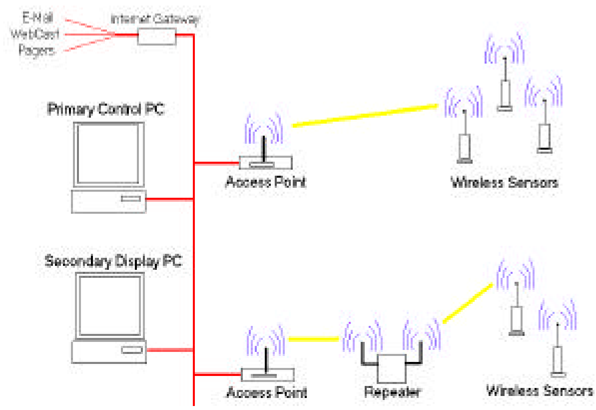


Figure 3, General embodiment of a wireless CBM data gathering system

Figure 4, Modern wireless CBM system including accelerometer, laser tachometer, and temperature sensors

3.0 WIRELESS COMMUNICATION:

Areas of concern with digital radios are cost, size, battery drain, reliability of the transmissions, distance of the transmissions, carrier frequency, wireless protocol for multiple sensor nodes, and compliance with FCC part 15.

A simplified view of digital radio layering is shown in Figure 5. The digital radio begins with the physical layer. The physical layer is the actual radio circuitry. It may be narrow band or spread spectrum, and is the actual transmitter and receiver of information. On top of this layer, a communications protocol is built. The communications protocol defines how information is packetized, how it is routed, whether it is encrypted, and how error checking and error correction are handled. The final layer is the application. The application defines what information needs to be transmitted through the communications protocol and what to do with received information once it is stripped out of the communication protocol.

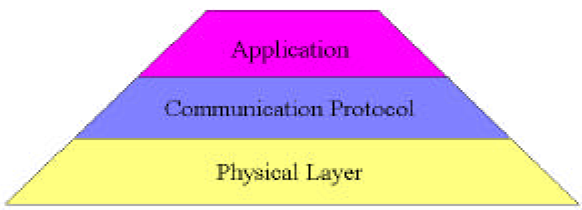


Figure 5, Simplified view of digital radio layering in wireless sensor nodes

3.1 PHYSICAL LAYER:

The two potential choices for the physical layer are narrow band radios or spread spectrum radios. Both can yield good results when properly implemented. Narrow band radios can be classified in two categories; those with only one frequency and those with multiple frequencies. A well-designed multiple frequency narrow band radio with spatial diversity can perform very well in industrial environments. Spread spectrum radios come in two main styles: frequency hopping spread spectrum (FHSS), and direct sequencing spread spectrum (DSSS). Spread spectrum radios improve transmission reliability by distributing (hopping) the transmitted power over a large bandwidth. With FHSS, the hopping rate is slower than the bit rate, but in DSSS the hop rate is faster than the bit rate.

Table II

Relative Performance for Various Physical Layer Solutions

Physical Layer Solution	Cost	Size	Battery Drain	Range	Interference Rejection
FHSS (Bluetooth)	Medium	Medium	Medium	Low	Medium
DSSS (IEEE 802.11b WLAN)	High	Large	High	High	High
Narrow Band	Low	Small	Low	Medium	Low
Multiple Frequency Narrow Band	Low	Small	Low	Medium	Medium

Spread spectrum radios offer better physical layer performance than narrow band radios, but at the cost of increased cost, size, and battery drain. Table II lists some of the relative performance expected with various physical layer solutions.

One of the potential benefits of spread spectrum transmissions is process gain. Process gain can improve receiver sensitivity at the expense of additional battery drain. The process gain is proportional to 20db*log(chirp rate). However, almost all spread spectrum systems employed in wireless sensor networks are frequency hopping spread spectrum (FHSS) that hop too slow to take advantage of the process gain. A direct sequencing spread spectrum (DSSS) radio is necessary to take advantage of the process gain (IEEE 802.11 is an example of DSSS).

Spatial diversity can be used to improve signal reception and transmission. Spatial diversity refers to using multiple antennas and is useful in both narrow band and spread spectrum systems. Simple multiple antenna designs in narrow band receivers can improve spatial resolution by removing the probability of multipath interference. In more sophisticated multiple antenna systems, the antennas are used to provide receiver directional gain through beam forming.

FCC compliance is an issue for wireless data gathering systems. All transmitters within the US must meet FCC guidelines for licensed or unlicensed operation. Since licensed operation is impractical for most industrial users due to the necessary regulatory issues, unlicensed operation is preferred whenever possible. For industrial applications, the ISM (Industrial-Scientific-Medical) bands of 902-928 MHz or 2.4000-2.485 GHz meet FCC Part 15 requirements for unlicensed operation and are popular. Within the ISM bands, narrow band operation is limited to 1mW of radiated power while spread spectrum transmitters are allowed up to 1W of transmitted power. Higher frequency bands provide more signal bandwidth; however, lower frequencies offer better performance in multipath environments where reflections are common.

3.2 COMMUNICATIONS PROTOCOL:

The wireless data gathering network needs to be extremely reliable even in industrial environments where RF interference due to motors, lighting, and other wireless systems is typical. Most industrial interference is limited to intermittent bursts of narrow band signals. Handheld radios common in industrial environments operate at lower frequencies than most sensor networks and cause little interference. For any given instant in time, the wireless link does not need to be reliable, but there needs to be a 100% probability the message will get through within a certain reasonable time. It is also necessary to guarantee that any errors in the message will be detected and corrected. Any lost or corrupt data will show up as distortions and could produce false alarms. Collisions between packets and interference from other radio sources need to be addressed.

The wireless CBM communication method must allow thousands of sensors to coexist in a single network. Various techniques are available for dependable coexistence. Some of the more common are time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). The circuit cost and complexity of TDMA is lowest, followed by FDMA, and lastly CDMA. Time domain and frequency domain multiple access are the easiest to understand. In both, the timing or frequency bands separate communications from multiple sensors. In code division, a number of communication channels can be open at the same time as long as the spread spectrum chirping rates are high. For CBM monitoring it is not necessary to have multiple communications. As an example, for a 256 point sensor cell where each accelerometer makes a 1024 point FFT reading 8 times per day, and each communication to the network takes five seconds, the total airtime is 2.84 hours or 12% network loading. Either FDMA or TDMA will perform nicely in these environments.

When thousands of sensors need to exist in a single network, an aggressive networking strategy is necessary. The wireless network must be plug-and-play with ad-hoc network communications.

Wireless standards can offer additional interplay between various sensor manufacturers. Any wireless sensor standard will have to specify the physical layer (FHSS, DSSS, narrow band, etc…), the communication protocol, and significant aspects of the application. In effect, the standard will need to design a universal wireless sensor node and this will be a daunting task. Some work is being done in these areas by the IEEE1451.X working group and Bluetooth SIG with limited progress.

Many possible solutions exist for wireless communications; however, a design must carefully balance performance, cost, size, and power drain. This balance is particularly important in wireless sensors. The wireless performance can be improved through an aggressively designed physical layer, or an aggressively designed communications protocol, or both. As an example, CDMA spread spectrum would be very reliable, but at a significant cost, size, and power drain penalty. A better solution is to use a less reliable physical layer, but improve the communication protocol to achieve higher reliability. Using a narrow band radio with aggressively designed communication protocol can yield impressive results while still meeting cost, size, and power drain requirements. It is important to remember that the timeliness of the CBM data is somewhat relaxed. It is much more important to have correct data that is 10 seconds old than erroneous data that is prompt.

4.0 POWER SOURCES:

The power source for a wireless sensor node is a critical concern. A poor power source can significantly limit the operational life or usefulness of the sensor. Many potential power sources exist. Possible solutions include chemical battery, RF, vibrational energy, solar, heat differential, and AC/DC line. Power sources such as solar (photovoltaic), heat differential (thermoelectric), and vibrational energy (piezoelectric), are too unreliable for the majority of applications. RF powered works well for RFID products, but the range, bandwidth, and auxiliary power are limited for sensor products. Using AC/DC line power significantly limits the freedom of the wireless solution and is to be avoided. Given that the sensor environment is not known in advance, manufacturers have tended to rely on chemical batteries for power sources. Because batteries need to be maintained through either charging or replacement, the battery life is critical. An almost unlimited array of battery choices is available to the designer as shown in Figure 6.

The battery size is directly related to the power drain and the operational life requirements of the device. Simply adding a wireless connection to existing sensor designs is not a good solution from the battery standpoint. Sensor electronic designs and operational methodology must be laid out with battery drain as a primary concern. Power efficient circuit design in conjunction with aggressive battery management (standby modes, duty cycling, etc.) can provide operational lives hundreds of times longer than those without.

Figure 6, Sample of the Various Chemical Battery Possibilities

Chemical batteries come in rechargeable and primary varieties and in either case, Lithium chemistries exhibit the best performance. They exhibit 3.3 Volt output, high peak output, low self-discharge, low weight, high energy density, good cost-to-capacity ratio, and little memory effect. For rechargeable and primary batteries, Lithium Ion and Lithium Thionyl Chloride are superior choices.

Rechargeable batteries are used where recharging is desirable such as in temporary testing. Only two viable rechargeable battery chemistries exist – Lithium Ion, and Lithium Polymer.

Both exhibit excellent energy density, good peak currents, low weight, high voltage, and no memory effect. Lithium Ion tends to be less expensive than Lithium Polymer, but Lithium Polymer tends to be more rugged and environmentally robust. Lithium polymer can be formed into various shapes and lends itself nicely to packaging. Both Nickel Cadmium and Nickel Metal Hydride are poor solutions due to their self-discharge, increased weight, lower energy density, lower voltage, and memory effect. For permanent installations, recharging a battery often is not desirable and primary battery is used.

The life of the battery is critical, especially when considering the expense associated with either replacing or recharging. A chemical battery should be designed to last 2+ years under fairly heavy sensor usage. The current wireless accelerometer is designed to operate on a ½A Lithium battery with a capacity of 1000mAh. With a standby current draw of only 3 ìA and an operational current of 20mA including the sensor, microcontroller, and transceiver, significant battery life results. For such a battery, the standby life would be 38 years and is neglected in this analysis, as it is longer than the shelf life of the battery. The sensor should be able to perform 9000 operations (assuming 20s duration) over its life. If the wireless sensor monitors eight times per day, this leads to a projected battery life of 3.08 years. The life is scalable, so for monitoring four times per day, the projected life would be six years. When performing battery projection, the network traffic and reliability of the physical layer must be taken into account. Additional transmissions caused by errors or collisions will reduce the battery life. By contrast, if the sensor were operating continuously (20 mA drain) the sensor would operate for only 50 hours (2.08 days).

For maximum confidence, wireless CBM sensors should be designed to perform periodic self-test diagnosis of power fluctuations, or low battery.

5.0 EASE OF CONFIGURATION AND USE:

The wireless data gathering network must be designed for easy installation and easy use. The sensor nodes must be plug-and-play with ad-hoc networking capability. For thousands of sensors, anything less would be a significant installation and upkeep effort. This capability will allow additional sensor nodes to be added easily and allow existing sensor nodes to be reallocated quickly.

Of the existing enterprise networks available on the factory floor, Ethernet provides the most flexibility. Modbus, DeviceNet, and Fieldbus are more specific and do not offer the flexibility of Ethernet. The sensor nodes will communicate with access points on the enterprise network. Once on the enterprise network, the information can be easily sent to anywhere in the world. Factory condition can be viewed on site or on the other side of the globe.

It is necessary for applications software to be multi-user. Typically, the sensor node data would be stored in an ODBC compliant open architecture database using SQL language. Figure 7 shows a typical client database engine that can display sensors on network, events, and raw data as needed.

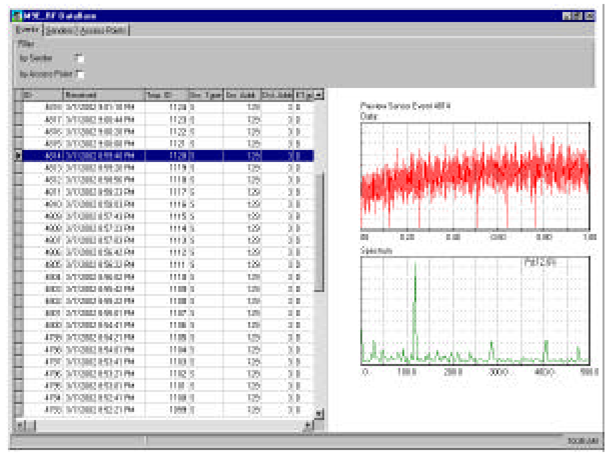


Figure 7, ODBC compliant database client displays sensors on network, events, raw data, and spectrum

6.0 MINIATURIZATION TECHNOLOGY:

Several miniaturization strategies are available for wireless sensors including system-on-a-chip, MEMS, and ASIC. There are five main areas of volume consumption in a wireless sensor. They are the battery, the radio, the sensor element, the circuitry, and the package. The radio, accelerometer element, and circuitry can be reduced in size through hybrid, MEMS, or mixed-signal ASIC design. The battery and package must be dealt with separately.

6.1 HYBRID:

Thin-film-hybrid technology or chip on board technology can be used to significantly reduce the size of wireless sensors. A standard 4”x4”x0.25” printed circuit board with surface mount components can be reduced to approximately 1”x1”x0.25” by using chip dice, subminiature components,

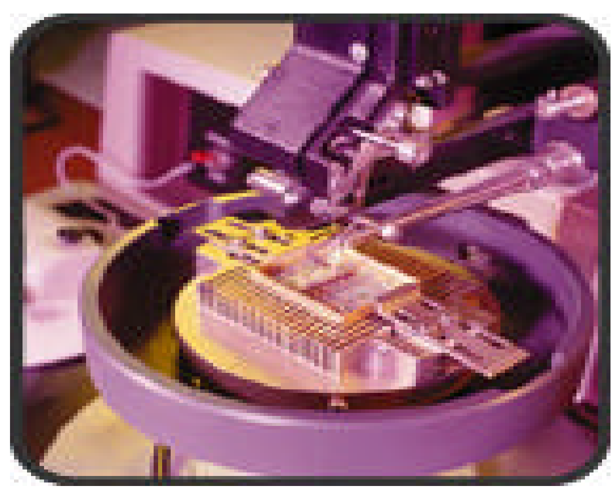


Figure 8, Automated thin-film hybrid production equipment for chip on board manufacturing.

and thin film hybrid technology.

Combining the radio, accelerometer element, and circuitry in a thin-film hybrid will not be a simple matter. As packages shrink, interference problems and power dissipation increase. Packaging the radio in such a small space with the microcontrollers and accelerometer elements involves significant analysis.

6.2 MEMS:

Micro-Electro-Mechanical-Systems (MEMS) system-on-a-chip capabilities are just beginning to reach reality. While the components of MEMS have been around for some time (microsensors, microactuators, microelectronics, and microstructures), the ability to combine them in a reliable cost effective manner has been lacking. With today's MEMS technology, combining the radio transceiver, accelerometer element, and circuitry is still a research area. MEMS accelerometer elements are nothing new, however MEMS accelerometer technology tends to have low frequency response and be more sensitive to shock. Special attention needs to be given to account for these shortcomings. Industry is just beginning to produce viable MEMS accelerometer-radio combinations. Work being done at Georga Tech (Chahal, Bhattacharya), DARPA (Tang), Carnegie Mellon University (Fedder, Luo, Xie), Berkeley (Bilic) and others is furthering the advancement of MEMS accelerometers and radios.

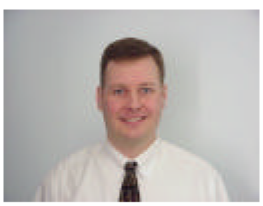
6.3 ASIC:

Historically mixed signal ASICs are limited to large volume solutions and are sensitive to layout. Only when dealing with volumes in the millions of pieces can ACICs become cost effective.

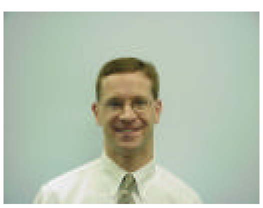
7.0 SUMMARY:

Advances in wireless technology, battery chemistry, and miniaturization have made extensive, wireless CBM data gathering systems practical. Through careful design and balance of technology, inexpensive wireless data gathering systems are currently available. These wireless systems will allow condition based maintenance to be easily applied to a wider variety of applications resulting in improved machinery health monitoring.

BIOGRAPHIES:



Christopher McLean, Ph.D. is the Division Manager for the Techkor Division of Advanced Conversion Technology Inc. Dr. McLean has been involved in the design of instrumentation products and software for over 12 years. His experience covers vibration, stress-strain, thermal, and fluid dynamics. Dr. McLean can be reached by phone at 717-939-2300, ext 256, or by e-mail at cmclean@techkor.com.



David Wolfe is the Head of Industrial Sales for the Techkor Division of Advanced Conversion Technology Inc. Mr. Wolfe has over 10 years of sales experience in various areas including CBM, industrial controls, and process heating. David Wolfe can be reached by phone at 717-939-2300, ext 204, or by e-mail at dwolfe@techkor.com.