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On the use of Wireless Sensor Networks in Preventative Maintenance for Industry 4.0

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***Abstract*—The goal of this paper is to present a literature study on the use of Wireless Sensor Networks (WSNs) in Preventative Maintenance applications for Industry 4.0. Requirements for industrial applications are discussed along with a comparative of the characteristics of the existing and emerging WSN technology enablers. The design considerations inherent to WSNs becoming a tool to drive maintenance efficiencies are discussed in the context of implementations in the research literature and commercial solutions available on the market.**

Keywords—Wireless Sensor Networks, Preventative Maintenance, Industry 4.0

I. INTRODUCTION

Plant maintenance represents a critical component for the success of the modern manufacturing industry. It is estimated that approximately 80% of a companies outlays are represented by correcting chronic failures. It has been highlighted that an effective maintenance implementation can reduce these costs to between 40-60% [1]. The steadily increasing cost of maintenance, due to the automation complexity of industrial plants and a more competitive marketplace, has made maintenance planning an essential strategy to reduce both costs and manufacturing downtime due to equipment failure.

Preventive maintenance is a strategy for planned maintenance of a plant and equipment, the goal of which is to improve equipment lifetime and to avoid unplanned maintenance activity [2]. There are a number of preventative maintenance strategies currently in operation in industry. A traditional approach is to adopt a time-based or periodic maintenance schedule [3]. The methodology predicts the lifetime cycle of the system, considering a bathtub curve and performs preventive maintenance after a fixed period of time, when the probability of failure is above a defined threshold [4]. In this model an initial phase of high failure rate is typically present owing to “infant mortality” and where random failures with constant and lower probability incorrectly characterize the useful lifetime of the product. A key drawback of periodic preventative maintenance is that as equipment ages failure rates increase and the reliability of the planning decreases in tandem.

An alternative to this approach is to intelligently monitor the process so as to trigger maintenance only when a potential failure is about to take place. The strategy known as Predictive Maintenance or Condition Based Maintenance (CBM) is a condition-driven maintenance program that uses monitoring systems to determine the actual mean-time-to-failure, optimizing availability of the process and reducing the maintenance costs. The result is an overall improvement in product quality, plant productivity and ultimately profitability [5].

Given CBM recommends a maintenance action based on information collected through condition monitoring [6], a supporting or supplementary system is a requirement to access and communicate the health status of the process. A practicable solution in this regard is to employ sensors to monitor the critical parameters of the system and to analyse the data provided in real-time. The ultimate goal of CBM being to establish a condition that indicates that a functional failure is about to occur[7]. Industry 4.0 has introduced the concept of the “smart factory”, in which decision making is performed on real data provided by cyber-physical systems. Marr [8] indicates as main characteristics for Industry 4.0 applications: interoperability, information transparency, technical assistance and decentralized decision making.

When considering WSNs in the context of CBM the key advantage is providing an automated monitoring system that does not require regular system checks, avoiding manually performing measurements in potentially hazardous environments. When compared to wired solutions WSNs are easily deployable and reconfigurable reaching areas difficult to access with wiring. In addition there is an associated reduction in installation and the overall condition monitoring costs [9]. However some disadvantages remain in the industrial context including perceived security, bandwidth, latency, processing capability and power resource constraints [10]. Literature surveys to date have focused on the deployment of wireless in industrial applications discussing requirements for industry as well as protocols employed [11]. Other reports detail WSNs technologies and developments in the general industrial context [12] (not focusing on preventive maintenance).

In [13] a state of the art on preventive maintenance techniques (including CBM based on WSNs) is presented from a theoretical point of view, stressing the importance of adopting a predictive online approach. In [14] potential improvements provided by e-maintenance are described, among them remote,

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collaborative and online maintenance adopting the predictive approach based on real time data are cited as the main advantages of this technology. This survey will expand on previous works to detail how WSN technology can be suitable for preventative maintenance deployments taking an application specific point of view, The paper presents real implementations based on commercially available solutions and research in the literature (looking also at the sensors employed), analyzing emerging technologies, and pointing out the importance of WSNs for present and future Industry 4.0 applications.

II. WIRELESS SENSORS NETWORKS FOR CONDITIONAL BASED MAINTENANCE

A. Industrial Requirements for WSNs in CBM

A Wireless Sensor Network (WSN) can be defined as a network of nodes that cooperatively sense and may control the environment, allowing interoperability [15]. Typically WSNs employ a supporting infrastructure, consisting of tens to thousands sensor nodes working together to monitor a region or area to obtain data of interest to the application [16].

Wireless systems are often employed given installation and maintenance costs are lower respect to wired ones [17] due to a number of elements including overhead associated with insulation and electromagnetic shielding. While WSNs provide more freedom with respect to wired systems in terms of maintenance, information on the go and possibility of performing measurements on moving objects; elements such as reliability, security, throughput and latency for communication and power, size and accuracy need also to be considered [18].

When considering industrial applications employing WSNs it is worthwhile examining the requirements that are a key component of adoption. These requirements can be domain specific for example an analysis of the technical requirements for WSNs in the case of Oil and Gas industry is performed in [19]. The main issues presented therein are: battery lifetime, stable network performance (susceptible to environment changes), compatibility with pre-existing wireless technologies, security and use of open standardized systems. More general requirements are discussed in [20] where desirable characteristics for wireless networks for control and sensing industrial applications are considered including:

- Range: at least 50m to guarantee full coverage of the industrial plant and robustness to transmit in an environment prone to Radio Frequency (RF) interferences;
- Data Rate: varies by the application, generally low for power saving, but different applications can require higher data rate. Commercially available solutions provide data rates from 250 kbps (IEEE 802.15.4) to 1.3 Gbps (IEEE 802.11) [21];
- Latency: possibility to tune the response at the end node to optimize performance, since low latency is related to higher power consumption. One of the key remaining challenges in research is to improve latency-reliability tradeoff for the Industrial Wireless Sensor Networks (IWSNs) [22] ;
- Security: at a level that ensures protection from node capture, physical tampering, denial of service and other kind of attacks [23] ;
- Operating Frequency: one of the unlicensed bands for operating cost and regulatory reasons (e.g. ISM band). However, due to the increasing usage of this band new technologies working at frequencies different than 2.4 GHz are explored and solutions to mitigate interference issues are one of the main topics in research [24];
- Network topology: increase the number of possible paths to increase reliability and resilience. For example, mesh networking allows hopping from node to node until reaching the destination when finding a blocked path [25];

One of the critical aspects in WSNs for preventive maintenance is the power consumption of the system. Often sensor nodes are battery powered therefore regular maintenance is required when power is discharged resulting in increased costs. An emerging method to reduce maintenance of the WSN is to adopt power generator or energy harvesting systems. This is achieved by harnessing energy in the form of temperature differentials, vibrations and/or electric/magnetic fields generated as a byproduct in the industrial process itself. There are a number of examples of where this has been successfully implemented. For instance in [26] piezoelectric and thermoelectric generator energy scavenging systems are proposed to determine if sufficient energy can be harvested to power a sensor node.. While returns in energy can be small (piezoelectric 2.3 mW peak and thermoelectric 2.67 mW peak in [26]) there is significant opportunity in many industrial applications to leverage energy harvesting to increase battery lifetime.

B. Wireless Protocol Selection for CBM in Industry 4.0

As discussed in the previous section when considering a suitable protocol for CBM in Industry 4.0, there are a number of parameters of interest, which are in turn impact the selection of wireless technology employed for the application. The protocol must also be capable of managing interference in an environment that is likely susceptible to electro-magnetic interferences [27]. Choosing the right protocol, can result to a reduction in power consumption given radio communication is a leading factor with respect to energy efficiency [28]. In Table I a number of network protocols are outlined in the context of CBM applications. One key technology omitted from the table above is fifth (5G) infrastructure. A novel study on the integration of 5G with WSNs is performed in [42] highlighting the opportunities, requirements and the future challenges for research.

TABLE I. COMMUNICATION PROTOCOLS

	CBM Industry 4.0 Compatibility Considerations
ZigBee	• Low power, low data rate (up to 240 kbps) • Line-of-sight technology, less robust in industrial environment [29] [30]
RFID Active	• Wide range of frequencies (from kHz to GHz) • Reader collision can occur when the signals from two or more readers overlap [31]
RFID Passive	• Battery-less low maintenance required • Similar problems to active RFID regarding security and interferences • Typically short range technology
BLE	• Mesh networks in development to meet industry requirements [32] • Very low power, relatively high speed (1Mbps)
Wi-Fi	• Higher power consumption and data rate • High reliability and security with respect to ZigBee [29] • Suitable for real time high data rate applications [29]
Wireless HART	• Very low power, up to 250 kbps data rate • Most used standard in industry [33] • TDMA based with fixed time, self-organizing self-healing mesh network [30] • Simple to apply for the final user [34] • Proprietary meshing protocol [34]
ISA 100.11a	• Used in the 25% of industrial WSN applications alone or in hybrid solutions [35] • TDMA based with configurable time slots [36] • IPv6 compatible adapted to 6LoWPAN, no address limitations, configurable channel hopping [37] • Flexible standard due to customization options [34]
WIA-PA	• WIA-PA products only available in Chinese market, protocol expended internationally after its acceptation as an international standard. [38] • Second most used standard in industry [33] • Reduced traffic and low energy consumption • Proprietary mesh protocol • TDMA based with flexible time slots [36]
UWB	• Low interferences with protocols based on ISM frequencies [39] • Used in industry 4.0 for localization and tracking [40] • Wide frequency range, but at very low energy, overlapping ISM and 2.4 GHz without creating interference [41].

III. CBM APPLICATIONS EMPLOYING WSNS

A. Application Specific CBM Implementations

In the following section sensor technologies employed in preventative maintenance and presented in the literature will be discussed to highlight application specific considerations when making system level decisions in CBM. In particular, the analysis is focused on the cases of vibration, temperature/humidity and sound monitoring.

1) Wireless Vibration Sensing for CBM

In a predictive maintenance program, vibration is widely used for detection and monitoring incipient and severe faults like unbalance, misalignment, bent shaft, rolling bearing faults, eccentricity, resonance, looseness, rotor rub, fluid-film bearing instabilities, gear faults, belt/sheave problems [43]. For instance in monitoring wind turbines [44] MEMS 3-axis accelerometers, according to the frequency range, are employed and connected via Control Area Network (CAN) to the Data Processing System. The ZigBee protocol is employed as the communications backbone and the processed data is sent to a central processing facility which highlights trend graphs and enables the user to monitor and interact with the recorded data.

BP (originally British Petroleum) have also employed wireless accelerometers to monitor the shipboard machine for predictive maintenance by means of multiple Rockwell Automation accelerometers per machine to detect vibrations. The system comprises one sensor for each axis of movement and a tachometer to determine how fast the machine was running and to provide the phase angle [45]. The study highlighted that WSNs operate satisfactorily in hostile environments when sufficient emphasis is placed on transceiver and network architecture design to ensure reliability. In addition the research indicated that WSN platforms are a good match for CBM applications given they can significantly reduce the quantity of data to be relayed by employing processing at the network edge. A study on preventive maintenance used vibration signature to predict equipment failure applied to a semiconductor fabrication plant and to an oil tanker [46]. Two platforms were developed: one based on the Mica2 Mote (Crossbow) and the second on the Intel Mote. The study included an estimation of the costs for an equivalent preventive maintenance implementation without WSN based CBM and it was noted that the resultant systems would be approximately 1.95 times more costly. A WSN based bearing monitoring system is presented in [47] highlighting how conventional piezoelectric MEMS based accelerometers when integrated in WSN platforms are accurate, sensitive and have a frequency range that is adequate for measuring the vibration of electric motors.

CBM for end-milling has been performed using a WSN platform incorporating a 16-bit MSP430-F1611 microprocessor, a CSMA medium access control protocol for communication and an ADXL 320 digital MEMS accelerometer (Analog Devices) [48]. The paper demonstrated how MEMS enabled WSN platforms are easily deployable for "retrofit" CBM applications. In [49] a system to monitor metal cutting Computer Numerical Control (CNC) machines using a dynamometer, a vibration and a temperature sensor is implemented. For vibration monitoring they used MTS310CA (Crossbow) and a data acquisition board mounting ADXL202JE (Analog Devices). The research demonstrated that an effective WSN based monitoring system can be implemented to enable a CBM system capable of maintaining the condition of machine tools thusly delay the occurrence of tool wear.

2) Wireless Temperature/Humidity Sensing for CBM

Equipment overheating is a significant concern in the industrial setting, and when left undetected, it can result in equipment damage or personal injury. Monitoring and controlling the environmental temperature characteristics is crucial in industrial applications that require specific environmental process conditions. WSNs have been utilised to enable temperature and humidity sensing for a number of CBM applications. In [50] temperature is monitored in a steel mill employing wireless sensors developed by Accutech. The key reasons for deploying a wireless infrastructure were rapid low cost install (only one day for the whole system) and the capacity of the hardware to operate in a high temperature environment. The system operated acceptably in the extreme temperature conditions however battery problems and intermittent data losses were issues that were encountered. A wireless temperature sensor has also been employed to measure cutting tool temperatures in milling [51]. The selection of wireless in this instance was owing to the requirement that the sensors be located on any part of the machine, re-oriented as needed and self-organized into a mesh network. Resistive Temperature Detectors (RTD) were installed on the backside of end-mill inserts and a wireless system transmitted data. The end result was a miniaturized monitoring system integrated with an effective closed-loop control system. Latency and throughput were key tradeoffs to be managed in terms of energy efficiency.

To monitor the temperature of rollers in a continuously annealing line and detecting equipment failures, in the Anshan Iron and Steel Factory [52], 406 sensor nodes using MICL2 were deployed. The platform is based on the AtmeLMega128L, CC1100 as transceiver and DS18B20 (Dallas Semiconductor) as temperature sensor. Energy efficiency, reliability and ability to reconfigure were deemed the most important issues for the wireless network and significant effort was focused in these areas. The network achieved approximately 99% throughput reliability and 15 months of lifetime using 2 AA batteries as a power supply. In [53] Tmote Sky devices (Moteiv Corporation) using a temperature/humidity sensor, SHT15 (Sensirion), are adopted to implement a WSN to monitor a petroleum facility. This system was used to better understand performance for industrial sensor network such as latency, throughput and channel access. Latency was significantly increased when comparing this low power wireless system with a wired one, however, for this specific application, latency and throughput were deemed less important with respect to energy efficiency.

In [54] smart monitoring and control of wind farms is implemented employing WSN technology. The platform incorporated an LM35 (Texas Instruments) for measuring temperature and a MEAS vibration sensor (Measurement Specialities) connected to an ATMEGA328P controller. This system enabled remote monitoring in tandem with control improving the health of the wind turbines. The LM35 temperature sensor is also utilized for monitoring an industrial electric system with dynamic power management in [55]. Intelligent sleep scheduling is employed to prolong the operational longevity of the system. In a battery-free wireless implementation employing UHF RFID technology, Zalbide et al. [56] used an NTC thermistor, IMME 3C 90373 (Vishay), to monitor temperature from -25 °C to +125 °C with an accuracy of ± 1 °C. The system has a communication range of approximately 1.5 m. The application achieved significant savings in size, weight and cost by adopting an energy harvesting approach.

3) *Wireless Acoustic/Sound Sensing for CBM*

Audio sensing is important in the context of preventative maintenance to enable early intervention for equipment particularly machinery with noise producing mechanical components. In [49] a CNC acoustic monitoring system is developed employing the MTS310CA platform (Crossbow). This application highlights how WSNs can be employed for multivariate measurement systems. The sensor used is the LM567 (Texas Instruments). Wireless fault monitoring for wind turbine using periodic sound data is presented in [57]. The protocol employed for the wireless sensors was the IEEE 802.11 at 1Mbps. The versatility of wireless sensors for the displacement allowed monitoring 20 different turbines in an area of 1.6 X 1.2 km area. Reliability, in terms of timely faults detection and notification, achieved a 94% data success rate.

Sound monitoring can be also employed to retrieve information about the temperature. In [58] a monitoring platform based on Surface Acoustic Wave sensors is proposed for CBM in industrial plants. Velocity of the sound wave was found to be proportional to the temperature and a second order equation derives temperature for the application. Passive wireless sensors powered by the interrogation unit are employed to reduce maintenance and deployment complexity. Leakages in pipelines can be monitored by analyzing acoustic/vibration data [59]. The application used WSNs to increase the spatial and temporal resolution of the operational data and thusly addressed the near real-time monitoring requirement. The monitoring system was based on the ADXL203EB accelerometer (Analog Devices). Leaks were signified by high magnitude noise in specific frequency bands of interest. Throughout the deployment the sensor measured to within acceptable tolerances under environmental extreme conditions. A number of problems relating to connectivity and data processing were encountered.

B. *Commercial off the shelf solutions*

WSNs have achieved significant growth with IDTechEx research in 2014 [60], estimating that the market (defined as wireless mesh networks) will have grown to $1.8 billion by 2024. According to a more recent market research report [61], this market was valued at 29.06 billion dollars in 2016 and is expected to reach 93.86 billion dollars by 2023. A key driver for growth being the multi-sector applicability of the technology including industry 4.0, structural health monitoring, agriculture and healthcare [16][62]. A number of companies offer dedicated WSN CBM solutions along with a services component to encourage and support the uptake of the technology in industrial settings. The following table includes a number of companies operating in this space:

TABLE II. COMMERCIALLY AVAILABLE WSN ENABLED CBM SOLUTIONS AND SERVICES

	Services provided
iQunet (www.iqunet.com)	Complete wireless solution that monitors asset health (vibration, temperature, pressure, inclination, proximity, etc.) and offers online servers to monitor data and change sensors settings remotely.
Waites Wireless (www.waiteswireless.com)	Robust wireless vibration condition-monitoring services and tools to prevent unexpected downtime. Hardware with advanced analytic software..
OneProd EAGLE (www.oneprod.com)	Continuous monitoring system for rotating machinery employing wireless sensors
EastWay (www.eastwaytech.com)	Conditioning monitoring services, including vibration analysis, thermography and continuous online monitoring
Sensor Works (www.sensor-works.com)	Temperature and vibration sensors, data collector, data analysis and BLE communication
ABB Ability (www.new.abb.com)	Condition monitoring solution for low voltage motors
K Power (www.kpowerglobal.com)	Smart Vibration Sensor and data analysis
Inertia Technology (www.inertia-technology.com)	Vibration monitoring system including sensor network (V-Mon 4000), gateway and software for data monitoring and network reconfiguration
ZetLab (www.zetlab.com)	Multichannel Vibration Control System and Software for test performance

It is also worthwhile exploring companies offering wireless sensor nodes which are key enablers for service providers and industry partners looking to internally drive efficiencies employing CBM. Table III illustrates that there has been significant growth in the number of providers including new entrants providing CBM sensing technology with integrated wireless capability. This move toward a system based approach would indicate that WSNs are therefore likely to play a central role in future CBM systems for Industry 4.0 applications.

TABLE III. OFF THE SHELF SENSOR NODES

Type	**Producer**	**Part Number**	**Description**
Vibration	Parker	SN-VSN-1	Wireless Sensor Node
Vibration	OneProd	EAGLE System	Sensor, Signal Processing and Gateway
Vibration	PCB Piezoelectronics	670A01	Sensor, Receiver, Wireless Junction Box
Vibration	Wilcoxon	PCH420V Family	WirelessHART Sensor Node
Vibration	Yokogawa	LN01 and FN510 module	Accelerometer and Field Wireless Multi-Function module
Vibration	BeanDevice	AX-3D XRange	Wireless accelerometer with built-in data logger
Vibration	Auroras	AU03-55C8G	Wireless Vibration Sensor
Vibration	Signallink	-	MEMS and CPU processing the real time FFT
Vibration	LORD MicroStrain	G-Link-200	Wireless node processing also vibration parameters
Vibration	Valmet	WVS-100	Industrial wireless WLAN sensor for mechanical CBM
Vibration and Temperature	Banner	QM42VT and Q45 Sensor Node	Sensor and Wireless Node
Vibration and Temperature	Emerson	AMS 9420	Vibration and temperature transmitter (WirelessHART)
Temperature	RFMicron	RFM3250	RFID Smart Passive Sensor
Temperature	Yokogawa	YTA510	ISA100.11a temperature transmitter
Temperature	BB Smart Works	Wzzard Node	BLe Sensor Node
Ambient Temperature and Humidity	Episensor	TES-11	Zigbee Sensors, Gateway and Server
Temperature and Humidity	Banner	M12FTH4Q amd Q45 Sensor Node	Sensor and Wireless Node
Temperature and Humidity	BeanDevice	ONE-TH	Wireless temperature and humidity data logger
Temperature and Humidity	Advantech	ADAM2031Z	Wireless Temperature and Humidity Sensor Node
Ultrasonic	Banner	K50UX1RA and Q45 Sensor Node	Sensor and Wireless Node

IV. DISCUSSION

In accessing how WSN technology will contribute to CBM applications in future Industry 4.0 applications the existing implementations available on the market and in the research literature provide some insight on likely future research direction and consumer sentiment. As has been highlighted there are a number of key advantages afforded by WSN enabled CBM that will enable ease of deployment and a reduction in commissioning and instrumentation costs. When addressing the wireless interface there is evidence of a clear migration from traditional WSN protocols such as Zigbee to protocols such as WirelessHART and ISA100.11a that are specifically designed to operate more efficiently and reliably in the industrial environment. This trend is likely to continue for future Industry 4.0 applications. However as the number and diversity of the wireless CBM applications grow, there is still the necessity to continue to improve protocol robustness particularly in the mobile scenario. Couple this with an inherent need for improved security and latency and there remain a number of potential hurdles to wide scale adoption of WSN technology for CBM. Enhanced industry specific protocols along with new physical layer technologies such as

UWB and 5G could be key contributors to solving this problem. WSNs enables advanced edge processing and while research has begun to address the simultaneous management of energy efficiency and decentralized decision making, further work is required before the balance is struck between operational longevity and the reliability of the equipment failure detection. One potential avenue for further exploration is energy scavenging in the industrial setting and this research space is has received significant recent attention. When considering sensing modality a significant number of the case-studies in the literature, along with the commercially available solutions focus on vibration and temperature monitoring. This trend is driven by a significantly lower overhead in processing and a wider range of faults that can be detected. Improvements in memory and processing capabilities of the integrated WSN CBM platforms are enabling alternative sensors including acoustic sensing to be employed more readily. Future applications may adopt alternative and emerging sensing technologies, such as magnetics and optical sensing, to enhance equipment failure detection accuracy. In addition it is likely that sensor fusion methodologies, whereby multiple sensor technologies will be employed to improve response time and detection accuracy, will play a key role in new CBM applications.

V. CONCLUSIONS

This paper has outlined the current role that Wireless Sensor Networks (WSNs) play in preventative maintenance and more specifically Condition Based Maintenance (CBM) in the context of Industry 4.0. Fundamental requirements that will drive the adoption of WSN technology have been identified. A number of key enabling technologies and protocols have been analyzed and their compatibility and suitability for Industry 4.0 was discussed. Existing applications from the literature, including vibration, temperature, humidity, and acoustic monitoring, were discussed highlighting some key advantages and limitations to employing WSN technology as a communications mechanism. This discussion was expanded to include commercially available off-the-shelf end-to-end solutions and services. In addition integrated wireless sensor node CBM platforms were included for completeness. The work highlights the technological trends that are emerging in the WSN enabled CBM application space and key areas where ongoing and new research will likely focus.

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