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A Condition Monitoring Platform Using COTS Wireless Sensor Networks

Lessons and Experience

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***Abstract*— Developments in Micro-Electro-Mechanical Systems (MEMS), wireless communication systems and ad-hoc networking have created new dimensions to improve asset management not only during the operational phase but throughout an asset's lifecycle based on using improved quality of information obtained with respect to two key aspects of an asset: its location and condition. In this paper, we present our experience as well as lessons learnt from building a prototype condition monitoring platform to demonstrate and to evaluate the use of COTS wireless sensor networks to develop a prototype condition monitoring platform with the aim of improving asset management by providing accurate and real-time information.**

Keywords- condition monitoring; COTS; experience

I. INTRODUCTION

Assets include facilities and equipments used to deliver a desired output. The asset lifecycle can be seen as the succession of five main phases as identified in Figure 1 and described below.

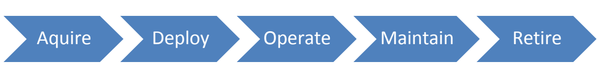

Figure 1. Asset lifecycle.

- *Acquire* includes all activities involved in technical and financial analysis, justification, and planning for acquisition of new assets, as well as in managing the acquisition of assets.
- *Deploy* phase encompasses all activities associated with the installation, testing and commissioning of new and reapplied assets.
- *Operate/Maintain* includes all activities involved in most effectively maintaining asset availability (health), longevity, and capability (quality, performance).
- *Retire* phase covers all activities involved in managing assets that are still owned, but no longer being used, including decommissioning, protection, and disposal [1].

Management of assets is a challenging and complicated task. However, it is important in improving their utility. For instance, decisions such as the scheduling of maintenance events have a critical impact on utilization and overall asset effectiveness and thereby on their output. Careful management of asset usage and asset condition information throughout its lifecycle is also significant in improving value extracted during the retirement of the asset at its end of life as well as the decision made regarding whether the asset should be, for instance, remanufactured, disposed or recycled [2].

Real time information related to the state of assets enables optimization of service and maintenance of assets based on usage instead of scheduled or fault based service and maintenance by understanding and analyzing any deviations from expected operational behavior. Wireless Sensor Network (WSN) technologies have the capability to revolutionize the management of assets through real-time asset condition information.

In this paper we outline the development of a condition monitoring platform aimed at testing new strategies for managing information associated with complex engineering systems [1] throughout their lifecycle. In particular, we have evaluated the use of wireless sensor networks to examine the effectiveness of COTS wireless sensors to improve the management of assets through real-time visibility of asset state variables during its life cycle. We have also summarized a number of important lessons as well as experiences gained through the use and adoption of commercial off-the-shelf wireless sensor networks for a real time application.

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II. Related Work

There is an increasing number of research projects and publications related to implementation of wireless sensor networks for monitoring in different scenarios [4, 5, 6, 7, 8, 9, 10, 11]. Condition monitoring of electric motors was employed in [8] for energy usage evaluations in electric machines leading to improvements in system reliability and maintainability. WSNs were deployed to monitor ecosystems and investigate the bird species recognition using neural networks [4]. Similar attempts to observe sensitive coral sites and to monitor wildlife habitats using wireless sensor networks are reported in [5] and [6]. More recently, asset management applications such as the diagnosis of transformers based on data derived from continuous condition monitoring has been used to build decision support systems that eventually decide if the transformers should be discarded or reused [3]. These growing numbers of applications reflect the capability of wireless sensor networks and their increasing usage in real-time condition monitoring applications.

However, most publications lack the level of detail required to enable a third party to develop a condition monitoring platform without significant effort. There is also a lack of literature on successfully using COTS sensor nodes to build real life applications. More significantly, published material on understanding the underlying problems as well as limitations are also scarce. Consequently, we have provided a detailed guide to developing a prototype condition monitoring application using popular off-the-shelf wireless sensor network technologies provided by Crossbow Technologies (*http://www.xbow.com*). We selected the MICAz technology because it provided a low cost platform suitable for rapid prototyping. Our investigation of commercially available wireless sensor nodes also revealed that Crossbow technologies provided a superior range of development tools as well as libraries to support our work.

Our prototype application utilizes the condition monitoring capability derived from deploying wireless sensors to capture asset lifecycle data in real-time to improve the quality of information available to decision makers. We have also provided a simple and yet flexible architecture for integrating condition based information to decision making processes or decision support systems.

III. System Architecture

The software architecture used for the condition monitoring platform is based on Moteworks 2.0 from Crossbow Technologies. The architecture enables rapid development and deployment of applications through a layered architecture that can be divided, primarily, into three layers or tiers. In the context of our implementation, the tiers in Figure 2 are briefly described below.

The *mote tier* consists of the physical layer i.e. the different sensor nodes in groups and a base station corresponding to each group. The sensor nodes are based on MICAz, a 2.4 GHz IEEE 802.15.4 wireless measurement system from Crossbow. The sensor nodes form a low-power wireless multi-hop mesh network. The sensor data collected is transmitted to the next tier through the radio stack.

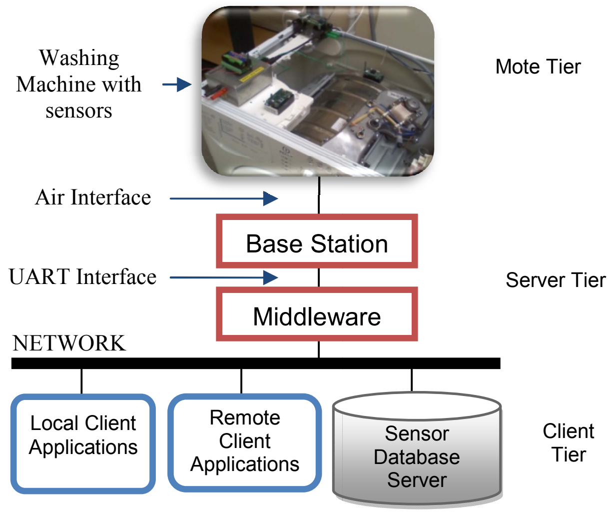

Figure 2. Architecture for condition monitoring platform.

The *server tier* consists of a server running Moteworks middleware, *Xserve*, installation. A local Xserve running on a desktop communicates with the base station over a serial port and interprets the raw binary data obtained from the base station. The interpretation of the data can be configured using a simple Extensible Markup Language (XML) file stored in the Xserve's configuration directory (*/config*). The configuration script provides ample flexibility to control the storage and the pre-processing of the received data, such as converting to meaningful engineering units or simple filtering. The middleware is configured to interpret the binary data to decimal values and to store time stamped sensor data in a defined relational database implemented using Postgresql (*http://www.postgresql.org/*). The sensor data can then be accessed by client applications over the Internet by subscribing to various data streams through a common interface to the database server.

Finally, the *client tier* consists of applications such as decision support systems (DSS) which processes the condition monitoring data for statistical anomalies. The DSS provides tools to visualize condition information (such as plots) and suggest service and maintenance schedules for assets under observation.

IV. Implementation

The condition monitoring platform comprises of four different sensor nodes positioned at different parts of the washing machine forming the assets under observation. The aim is to monitor the critical states of the washing machine as identified in Table 1 and shown in Figure 3.

The sensor nodes used are MICAz MPR2400CA motes with appropriate sensor boards attached to them. Two motes act as base stations and three other motes act as sensor nodes in the wireless sensor network. An illustration of the sensors deployed on the washing machine is shown in Figure 3. The data transmitted from the sensor nodes is received by the tow base stations. The following sections will consider the implementation details of the sensor nodes using various sensor platforms for monitoring the states identified in Table 1.

TABLE I. CONDITIONS MONITORED AND SENSOR BOARDS USED

Condition	Component	Sensor Board Used
Vibration	Drum	MTS310
Tilt	Body	MTS310
Humidity	Water Inlet	MTS400
Temperature	Motor	MDA300
Current	Motor	MDA300

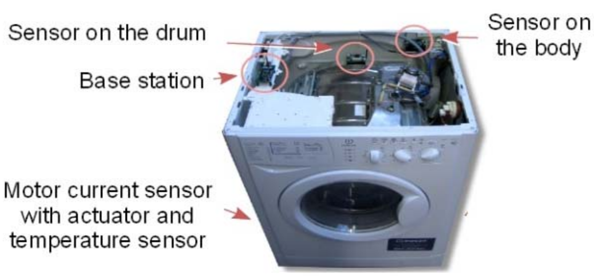

Figure 3. Deployment of sensors on the washing machine.

A. Vibration analysis of the drum

For vibration analysis, the MTS310 sensor node (mote based on using the MTS310 sensor board) is placed on the outer covering of the rotating drum. The raw data denoting acceleration is measured from the acceleration sensor ADXL202E on the MTS310 sensor board along two perpendicular horizontal axes *x* and *y*. These raw values are converted into milli-gravity (mG) units using the equation given below.

$$accel = \frac{data - zerogdata}{onegdata - zerogdata} \times 1000 \quad (1)$$

In (1), obtained from the ADXL202E datasheet, *accel* is the value of acceleration in mG, *data* is a raw data value from the sensor, *zerogdata* and *onegdata* are the raw data when acceleration is zero and one *g* (9.8 ms^{-2}), respectively. By orienting the sensor in the direction of the gravitational force and in a direction perpendicular to the gravitational force it is possible to evaluate the raw data values for *zerogdata* and *onegdata*.

The sensor is sampled at 256 Hz and 8 sampled values for each of the *x* and *y* directions are sent in a single packet, whereby 32 packets are transmitted every second utilizing 12.5 kbps of the communication channel.

However, the sensor data obtained in the time domain must be converted into the frequency domain to provide a frequency spectrum for vibration analysis of the drum during a washing cycle. This is achieved by transforming the acceleration values to the frequency domain using Short Time Fourier Transform (STFT). A rectangular moving window function is used to simulate a digital spectrum analyzer.

$$X(m,k) = \sum_{n=-\infty}^{\infty} x[n]w[n-m]e^{-j2\pi kn} \quad (2)$$

Equation (2) gives the transformation used to convert the time domain acceleration data from the sensor into the frequency domain. In (2), *X(m,k)* are the values in the frequency domain, *x(n)* are the sample values in the time domain, *k* is the frequency index, *m* is time index and *w* is the window function. As the signal is real, the frequency range of our analysis is limited to half the sampling rate (Nyquist frequency) i.e. 128 Hz.

B. Tilt Detection

An unbalanced machine causes excessive and unnecessary vibration and it is a result of improper adjustment of the machine legs or the wear and tear of supports bearing the counter weight of the machine. Hence managing the any tilt of the machine over time is a critical factor that affects the failure of the machine. The tilt of the washing machine body is monitored by a MTS400 sensor node with respect to two perpendicular horizontal axes. This involves measuring raw data from the acceleration sensor ADXL202E on the MTS400 sensor board along two perpendicular axes *x* (horizontal) and *y* (vertical). These values are converted to tilt in degrees using the equation below.

$$tilt = \sin^{-1}\left(\frac{|data - zerogdata|}{onegdata - zerogdata}\right) \quad (3)$$

In (3), also obtained from ADXL202E datasheet, *tilt* is the value of tilt in degrees, *data* is a raw data value from the sensor while *zerogdat*a and *onegdata* are as described in (1). The inherent assumption here is that there is no other external force except gravity. The sensor is sampled and a data packet is transmitted once every second.

C. Humdity and Temperature

Two different sensor boards are used for measurement of humidity and temperature. The MTS400 is used for humidity near water inlets (see the sensor on the body in Figure 3) and the MDA300 for temperature of the main motor. Both boards have the Sensirion Humidity-Temperature sensor (SHT11). The raw data obtained from the sensors are used to obtain humidity as a percentage and temperature in degrees Celsius using (4) and (5), respectively (as outlined in the SHT11 datasheet).

$$H = (T - 25) \times (0.01 + 0.00008 \times d) - 4 + 0.0405 \times d - 0.0000028 \times d^2 \quad (4)$$

$$T = -39.6 + 0.01 \times d \quad (5)$$

In (4) and (5) *H* is the percentage of humidity, *T* is the temperature in ºC and *d* is the raw value obtained from the sensor [15]. The sensor is sampled and a data packet is transmitted once every second.

D. Current Detection

The current drawn by the motor driving the drum is monitored using a Fluke i30 current clamp meter which uses the Hall Effect to monitor the current carried by a conductor. The output of the current meter is an alternating current (AC) voltage directly proportional to the current drawn by the motor; hence the Fluke i30 functions as a current controlled voltage source with an output sensitivity of 100 mVA^{-1}.

The resulting voltage is fed to a precision full wave rectifier to obtain a direct current (DC) voltage (it is important to avoid the voltage drop across diodes in full or half wave rectifiers). This output is then fed into the analogue channel, ADC0 of the MDA300 sensor board. The ADC output is read every 250 ms and four values are transmitted in a single data packet every second. These values are converted into current in mA using the equation below.

$$current = 10 \times 1000 \times 2.5 \frac{data}{4096} \tag{6}$$

In (6) *current* is the current drawn by the motor in mA and *data* is the raw value obtained from the sampled analog channel. Equation (6) is based on the format for converting sampled values on the analogue inputs to the MDA300. The factor of 1000 is used to convert the current to mA.

E. Raw Data Conversion

In the preceding sections we have considered the transformation of raw data from sensors to SI units. There are two clear pathways available to a developer to implement the data transformation.

The first approach is the pre-processing of the raw data on the sensor node and the transmission of the transformed data to the middleware. This technique will allow low level decision support such as that described in Section IV and data filtering but any alterations to the details requires editing optimized code and reprogramming the nodes.

The second approach is to carry out the data transformation at the middleware level after receiving the raw data. This is conveniently achieved by configuring the middleware to apply the formulas outlined in (1) and (2) - (6) to the data streams received from the sensor nodes as described in Section III of our paper.

V. System Performance

In the system developed thus far, a number of critical performance issues were identified regarding power consumption of the nodes and the unreliable wireless interface.

The batteries drained quite rapidly. Repeated observations showed that a node transmitting packets at 32 Hz drained the combined voltage provided by two AA 2500 mAh rechargeable nickel-cadmium batteries below the recommended operating voltage of 2.7 V in a couple of days of continuous operation. There is also a significant packet loss of the order of 20% attributed to high data rate, high channel utilization and low SINR by the vibration sensor node (possibly due to interference in the environment caused by two local wireless access points operating in the same frequency spectrum).

Mitigating these issues require the implementation of a modified system that implements power conservation algorithms and end-to-end acknowledgement, thereby increasing the battery life and improving Quality of Service (QoS). These strategies are discussed below.

A. Power Conservation

Power conservation is based on the simple rule that the sensor nodes should only be transmitting data when data gathered is of interest to client applications. Implementing the latter rule requires changing the sensor node state to a '*sleep*' state, if the observed data values are less than defined thresholds (such as a limit value or rate of change of values or both) of interest for a definite period of time (T_{stop}). While '*sleeping*' the node does not perform any sensing or transmitting operations. The nodes remain in '*sleep*' state and periodically enter a '*wake*' state to sense whether the sampled data values are still less than the defined thresholds, if this is the case the nodes remain in the '*sleep*' state. Otherwise, they commence transmitting data once again. The '*sleep*' and '*wake*' algorithm used is illustrated in Figure 4.

However, placing the sensor node into such alternating states may lead to missing important observations. Therefore the T_{stop}, T_{sleep} and T_{wake} time intervals needs to be based on considering the application context, in particular the sensing thresholds and the rate at which the observed conditions can change.

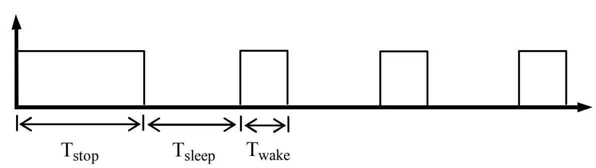

Figure 4. Typical duty cycle of sensor node going to sleep after T_{stop}, sleeping for T_{sleep} and checking sensor values for T_{wake}

B. End-to-End Acknowledgement

End-to-end acknowledgement of packets needs to be implemented judiciously over the normal transmission of packets if a reliable link is required between WSN nodes and the base station. While end-to-end acknowledgement is not necessary for the vibration data given the high sampling rate and the fact that any loss of data would only manifest itself as increased noise in the STFT, it is important for other sensors which only send sensor data packets intermittently.

More importantly, for the vibration sensor we observed that attempting to transmit more data over the channel causes much greater loss of data packets rather than improving the situation. Thus implementing QoS over high throughput data links is not recommended.

Improved QoS is achieved by re-transmission of packets by the sensor nodes when the received packet by the base station is not acknowledged as being received free of errors as determined by a Cyclic Redundancy Check (CRC) value appended to the transmitted data packets. The outline of the protocol is illustrated in Figure 5.

In the event that a mote does not receive an ACK (acknowledgement) within 20 ms of transmitting a data packet, the mote assumes the data packet is lost and reattempts to transmit the same data packet a maximum of five consecutive times unless an ACK is received indicating a successful re-transmission. The re-transmission interval has some significance as it was taken to be near the typical delay for the ACK to arrive in a two hop mesh network and given the small number of nodes as well as their layout, data packets did not make more than two hops before reaching the base station. The packet is considered lost in the event that an ACK is not received after 5 retries.

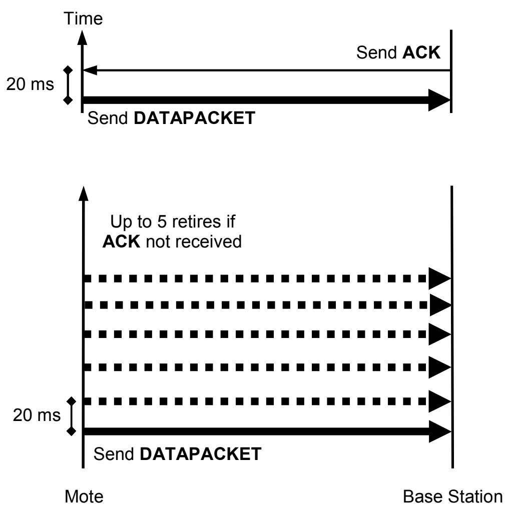

Figure 5. Implementation of the end-to-end acknowledgement. Dotted arrows depict retries when an ACK is not received for a transmitted packet.

VI. ENHANCEMENTS

The platform developed thus far has addressed a number of performance issues. However, the system is too rigid and relies on a number of parameters that would require dynamic adjustment. Such as sleep times, sensor value thresholds and transmission rates. In order to improve the flexibility of the platform as well as to demonstrate the ability to improve asset management through not only condition monitoring but by decision support at lower levels in the architecture, a number of enhancements described below were developed.

A. Autonomous decision making and actuation

Safeguarding the motor was considered a key aspect of the system. Hence the system is required to monitor the performance of the motor and in the event of abnormal operating conditions turn the motor off to prevent any damage. This would allow a faster response than a client DSS application which takes an action with the aid of a human being.

Thus, the motor current profile and the operating temperature range are monitored to set a dynamic operating range for both current and temperature. If the motor draws current more than the expected profile limits or the temperature rises above an expected threshold, the machine is turned off using relay switches on the MDA300 sensor board where the relay is used to control the power supply to the motor.

B. Command processing and remote management

Increased flexibility of the system is achieved by using the *XCommands* library provided by MoteWorks for downstream command processing. Each sensor node implements an application specific version of the *XCommands* set to allow the behavior of the motes to be altered. The end-user can manage the condition monitoring platform by altering different parameters of the active nodes within the network in real time. The various alterations supported by the different nodes are given in Table 2.

TABLE II: SUPPORTED ALTERATIONS IN BEHAVIOUR OF SENSOR NODES

Sensor Node	Sampling rate	Sleep time	Wake up	Reset	Actuate	Set Threshold
Vibration	✓	✓	✓	✓		✓
Tilt	✓	✓	✓	✓		
Humidity	✓	✓	✓	✓		
Temp		✓	✓	✓	✓	✓
Current		✓	✓	✓	✓	✓

VII. EXPERIMENTAL RESULTS

After the system integration and the installation of sensor nodes on the washing machine, the entire system was run in repeated experiments under different scenarios to simulate faults and extreme sensor values. All the conditions tabulated in Table 1 were recorded during test runs. The following sections provide an analysis of the data obtained from the platform.

A. Vibration

The frequency spectrum obtained for the vibrating drum is shown in Figure 6. The spectrum clearly shows the dominant frequency of vibration noted by the large magnitude peak at 55 Hz. There are other relatively smaller frequency components at 4.5 Hz, 11 Hz, 44 Hz, 88 Hz and 100Hz (see Figure 6). However, the peaks at 44 Hz, 55 Hz and 88 Hz can be considered as harmonics of 11 Hz. But this cannot be ascertained for certain from our implementation.

Nevertheless the performance of the sensor node proved adequate for monitoring frequency components less that 128 Hz. Unfortunately we were not able to transmit data packets over the mesh network faster than 12.5 kbps, therefore 128 Hz remained an inherent limitation of using the COTS devices. Certainly this was expected as wireless sensor networks are not designed for high throughput applications. However, we were able to establish an upper bound on the best possible transmission rate for our application.

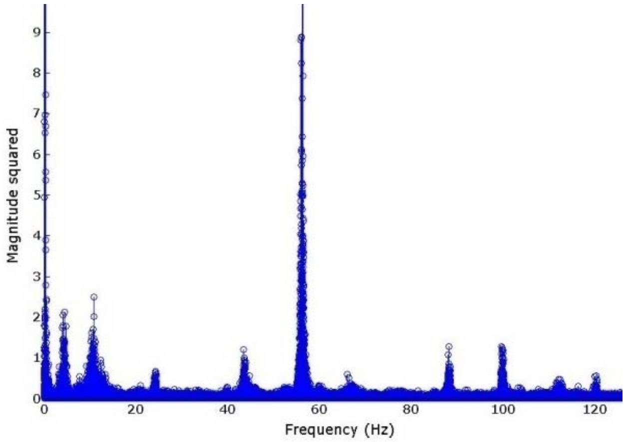

Figure 6. Vibration spectrum of drum from acceleration data obtained in a single washing cycle.

B. Tilt

Our relatively short experimental time fame coupled with the fact that we used a new machine did not allow us to obtain meaningful results to test the tilt functionality. The machine remained fairly upright and straight throughout our experiments. However the system was tested by obtaining the tilt (*pitch* and *roll*) from the 2 axes (x and y) of the acceleration sensor while moving it over a measured range of angles and then comparing the results as shown in Table 3.

The last three rows in Table 3 depict the saturation of the sensor values when the angle between the accelerometer axis and the direction of the gravitational force is less than 10 degrees. This is an inherent limitation of the sensor.

TABLE III: ACCURACY OF THE TILT VALUES REPORTED FROM THE SENSOR

Pitch (X - Horizontal axis)		**Roll (Y - Vertical axis)**	
Measured	***Sensor***	***Measured***	***Sensor***
0°	0°	90°	90°
10°	10°	85°	85°
30°	30°	80°	80°
45°	45°	60°	60°
60°	60°	45°	45°
75°	75°	30°	30°
80°	*90°*	*10°*	*0°*
85°	*90°*	*5°*	*0°*
90°	*90°*	*0°*	*0°*

C. Humidity

The humidity measurements depicted that the humidity level near the water inlet was essentially equal to that of the atmosphere. This can be attributed to the condition of normal functioning without any leakage. A rise in humidity level was artificially created and the response of the humidity sensor is shown in Figure 7.

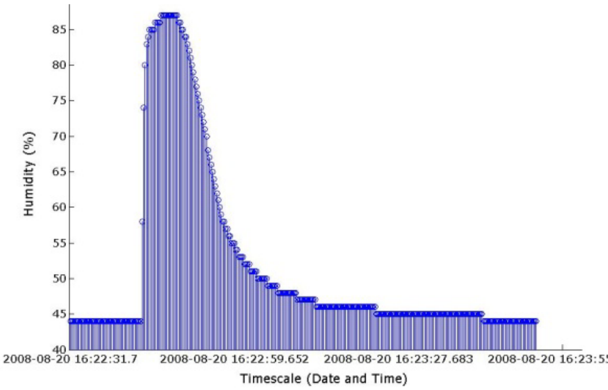

Figure 7. Humidity variation: The humidity suddenly rises to 85% and then falls down gradually to the humidity level (44%) of the surrounding.

D. Temperature

The temperature profile of the main motor is shown in Figure 8. As expected, it can be seen that the temperature of the motor increases towards the termination of the wash program when the machine is in its spin cycle requiring the continuous operation of the motor to drive the loaded drum of the machine.

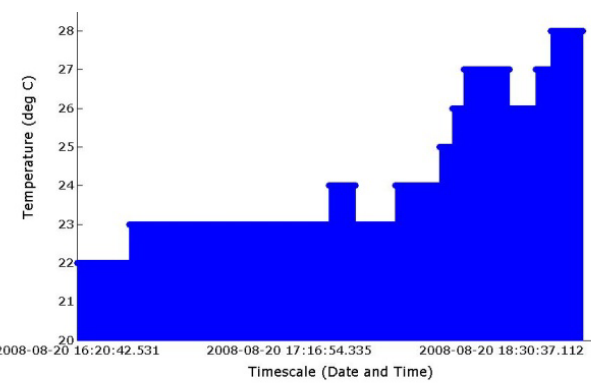

Figure 8. Temperature variation of the motor for a continuous run of the washing machine comprising of 6 washing cycles.

E. Current

The current drawn by the motor during the washing cycle can be analyzed as a function of time. The results are shown in Figure 9. The current profile of the motor during the washing cycle portrays the motor performance, where the peaks indicate the intermittent operation of the motor during the execution of the washing program. Monitoring the current drawn provides a more reliable cue for detecting malfunctions than the temperature of the motor.

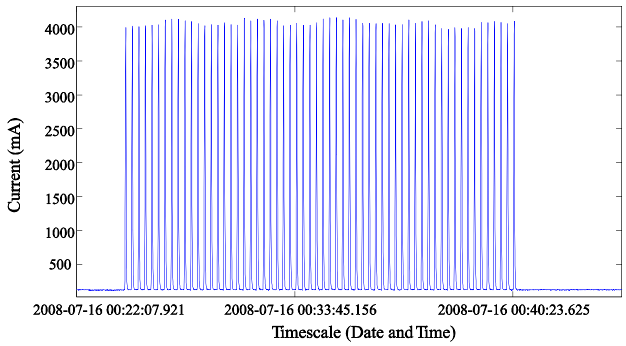

Figure 9. Current drawn by motor in mA for a complete washing cycle

F. Power Conservation

The analysis of the battery voltage profile of the sensor nodes demonstrates the effect of implementing the power conservation algorithm. The voltage profile for the sensor node monitoring vibration (see Figure 10) indicates significant conservation of battery power as a result of the node going into *'sleep'* by implementing the power conservation algorithm. It can be seen from Fig. 10 that during continuous transmission by the node for a period of approximately 6 hours, the decrease in battery voltage was 120 mV and when the node was in *'sleep'* state for the same duration, the decrease was 46 mV. This is a reduction of power consumption by 62%.

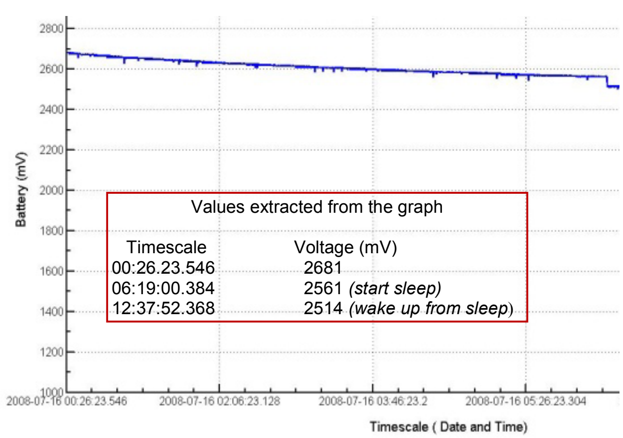

Figure 10. Decrease in Battery voltage for Humidity sensor.

Analysis of the data depicted in the sections above along with external sensor measurements showed that the condition monitoring platform functions reliably. The various plots also showed the high degree of accuracy of the platform and its ability to provide crucial information about the condition of the machine components.

VIII. CONCLUSIONS

One of the critical aspects of asset information management, 'condition monitoring', is successfully implemented using a COTS wireless sensor network technology and tested for a specific application. Test results shows that the performance of the commercially available sensor technologies for real life applications are satisfactory. We were able to improve the performance through easily integrating greater system flexibility, low level decision support and QoS guarantees.

Our initial efforts to develop a condition monitoring platform lead us to the realization that there is a lack of implementation details in literature despite the body of research on WSNs. Most publications described results extensively. We have sought to address this through better dissemination of knowledge that is often assumed known. On the contrary for those wishing to use or carry out research into the field are often faced with the absence of that knowledge in the literature.

Our second objective was to develop a platform that would provide real time information regarding the condition of an asset in its usage phase. This data is then expected to be analyzed and used in decision support systems that predict failures and allow the creation of optimal maintenance routines. This work will be carried out in the future.

Through our experiments and usage we are able to report a number of limitations posed by the hardware and the development platform provided by this popular COTS WSN technology. These limitations are outlined below.

- Time synchronization protocol leads to an inherent delay between transmissions of two packets and thus limits transmission rate to about 32 packets per second.
- Higher data rates more than 32Hz result in larger degradation in performance through significant (in excess of 20%) packet losses and CRC errors.
- Single channel functionality limits a node to transmit on only a single fixed and preprogrammed channel. Compared to frequency hopping techniques, this method severely limits the performance of the network as a result of external devices (such as WiFi, Bluetooth, Z-Wave, etc.) functioning on the same ISM (Industrial, Scientific and Medical) bandwidth.
- It has not been possible to implement inter-node communication; nodes are only able to communicate with the base station. However such communication was reported as being possible in the COTS documentation.
- Using the same base station for vibration and other sensors prevented the latter from occupying the channel and thereby transmitting data to the base station at an acceptable success rate. As a consequence two base stations were used for the simple implementation at an additional cost.
- The current drain from the batteries on the sensor nodes, even with the implementation of the power saving mechanism, is not beyond a week of operation.

As was expected the WSNs are unsuitable for high throughput applications. However we have been able to establish an upper bound for throughput through experiments.

A key improvement we propose is to transfer the STFT evaluation onto the node itself. This will reduce the bottleneck caused by the need to transmit large amounts of vibration data by only transmitting large magnitude vibrations of interest to client applications. Our investigations will also focus on the benefit of processing acceleration data on the mote as opposed to being carried out at the sever tier in terms of power consumption. We expect our proposed technique will greatly reduce the power consumption of the node responsible for collecting vibration data.

Unfortunately, there is little pre-processing that is possible with other types of condition information since only low level decision support is possible on the node itself and more sophisticated techniques can only be implemented on more resourceful hardware.

In summary, based on the authors' experience, it can be concluded that the Crossbow sensor node platform, Moteworks is not suitable for applications with high data throughput. This is an inherent limitation of the ZigBee protocol and cannot be altered since the protocol was designed for low data rate applications. Hence, for applications with low data rates, typically those which do not need transmissions of sampled sensor data at high rates or in real time, the platform is ideal and convenient to use. However, we are of the view that the power consumption of the COTS nodes, even in low data rate applications, provided the most significant bottleneck for their usability in real-world applications.

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