A Discussion of the Prognostics and Health Management Aspects of Embedded Condition Monitoring Systems

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ABSTRACT

This paper presents a review of embedded condition monitoring research carried out at Cardiff University. A variety of application areas are described, along with a discussion of the evolution of the hardware platforms used. The current operating philosophies of the Intelligent Process Monitoring and Management (IPMM) research group and the deployed hierarchical and distributed architectures are described. The paper sets out to discuss the on-going trend towards such monitoring systems needing to provide more than fault detection and diagnostic capabilities. System requirements such as tracking operational settings, performance and efficiency measures and providing limp-home facilities are seen to be consistent with prognostics and health management ideals. The paper concludes with a discussion of new and future developments and applications.

1. INTRODUCTION

The Intelligent Process Monitoring and Management (IPMM) research group at the Cardiff School of Engineering has 20+ years experience of condition monitoring research. The following sections describe industrially related application areas and track the evolution of technologies and approaches. The associated discussions describe how modern monitoring systems must provide far more than fault detection and diagnosis.

Originally the IPMM research concentrated on machine tool applications used heavily sensor-based techniques, using PC platforms and interfaces, and working with large companies.

With technologies changes, and following an ERDF funded project aimed at SMEs in south Wales, distributed, microcontroller-based systems became the main area of research.

Table 1. Condition Monitoring System Concepts

Distributed,	data acquisition / monitoring nodes linked by a CAN-bus network
Hierarchical,	3 tier approach – higher levels provide data fusion and robust decisions
Remote,	deployed systems linked to remote base via Internet
Intelligent	minimised data communications and storage
Low-Cost	8-bit microcontrollers used, 96% of faults detected locally……
Monitoring Systems	….. only PC is server-side and used to provide higher level analysis… ……. of remaining 4 % of faults.

There was an accompanying diversification of application areas. The machine tool work continued, but with PLC controlled systems, process and environmental / energy systems added to the range of monitoring applications.

Table 1 reflects on the main concepts employed with the latest generations of the microcontroller-based monitoring systems.

The low cost and ease of use of these systems led to their application to a range of monitoring functions for machine tools and process plant, for example as reported by Siddiqui et al (2010) and Siddiqui et al (2007) respectively. Initially limitations, in terms of processing capabilities restricted their application. However, the current generation of microcontroller devices, such as those now deployed has largely overcome such limitations. As will be discussed later, a generic microcontroller platform is often adopted as a starting point.

The monitoring systems deployed by the IPMM group are not exclusively based upon the described microcontroller platform. For example, SCADA based systems have been used for both the monitoring of water treatment plants and cooling towers within a power plant. In other applications, where higher processing capabilities are typically required, PC based systems have been deployed. Examples include the monitoring of crop shear and roughing mill operations in a steel plant, where sensory inputs were constrained to being provided by acoustic microphones. In other applications the microcontroller-based systems have been used to pre-process data, with the aim of reducing the data processing, communications and archiving tasks on predominantly PC based systems. .

2. MACHINE TOOL MONITORING

Earlier research, as summarised by Drake et al (1995), concentrated on the data acquisition and signal processing aspects of machine tool monitoring. In parallel, many of the constituent sub-systems were researched, in a prioritised manner derived from industrial reliability information, from a fault detection and diagnostic viewpoint. Examples included axis drives (Rashid & Grosvenor, 1997), tool changer & coolant sub-systems (Frankowiak et al, 2005) and the cutting tools (Amer et al, 2007).

Hess et al (2005) described the constituent functions and processes for Prognostics and Health Management (PHM) systems. In addition the timely and correct acquisition of signals is a vital element of any monitoring and/or PHM system. The approach within the IPMM research is argued to be consistent with these guiding themes. For example, with the machine tool research, the primary aims have been to reduce the downtime of such high capital cost, high utilisation machines. The challenge is to provide sufficient lead time / warning to the operator of progressive faults and to handle the fault detection and isolation of 'hard' (catastrophic) faults with sufficient fault library coverage. A higher level of fault information is then made available to the service / maintenance teams to assist their corrective actions. Further, techniques such as Overall Equipment Effectiveness (OEE) may be used to provide a longer term tracking of the health and performance of the machines. In the context of machine tool monitoring the provision of a scaled indication of the feasibility of continued use is a useful feature. Should the operator immediately halt the machining process, or is there a possibility to complete the existing job or batch (perhaps at reduced cutting speeds and feedrates), or can the machine be run until the next convenient maintenance opportunity?

Rather what has evolved has been the data acquisition, signal processing and computing platforms utilised, along with consideration of the number of additional sensors to be fitted to the machine for monitoring purposes. The data acquisition system (DAS), from the early 1990's work mentioned above, was based on a PC platform and utilised a large number of analog and digital inputs and custom designed interface cards to form the DAS. During remotely sited industrial trials up to 21 additional fitted sensor

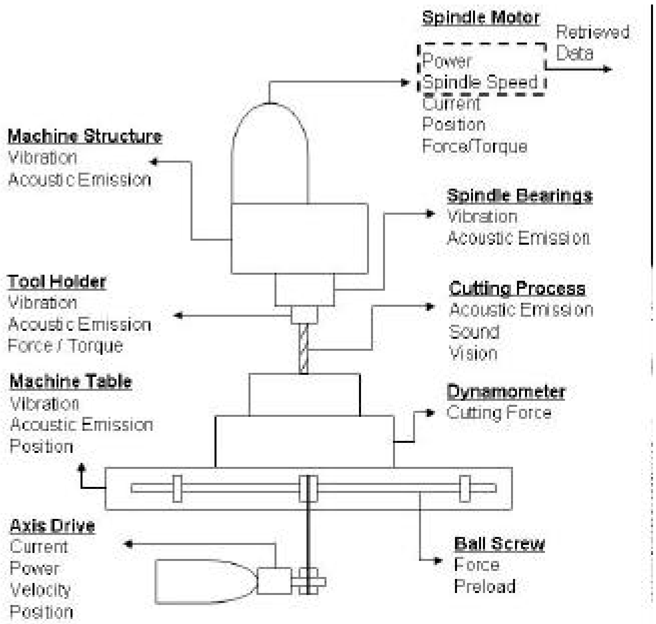

Figure1. Potential Machine Tool Monitoring Measurements

signals, along with 14 signals from sensors that pre-existed on the machine and 46 digital signals were used. The digital signals derived from the CNC and from limit switches etc were used, with a database defined series of diagnostic tests, to provide consistency for trend comparisons and for determining best matches to the established fault library.

Also, to eliminate the variability from all machining operations whilst providing on-line monitoring of the machine tools themselves the database configured tests to capture diagnostic information during all periods whilst the machine was on / moving but not actually cutting metal. The pre-internet enabled communications retrieval from the remote locations and the then limited PC storage capabilities also required a variety of (database configurable) signal processing / data reduction methods. Figure 1 provides a summary of many of the potential measurements that can and have been used in machine tool monitoring.

For the more recent distributed and embedded monitoring systems, and making use of the increased processing power and communications protocols, single chip microcontrollers have been utilised. The number of additional sensors has been dramatically reduced. Continued use is made of any suitable sensors pre-fitted on the machine tool, with their potential for monitoring typically being assessed during an initial auditing phase. Carefully designed monitoring tests then often infer fault conditions from a collection of inputs, which are acquired from the lowest level of the microcontroller based nodes. The next higher level node co-ordinates and provides more robust decision making from the available information. In a more general sense, Jacazio et al (2010) have reported on the role of logical and robust decision making elements of sensor-based PHM systems.

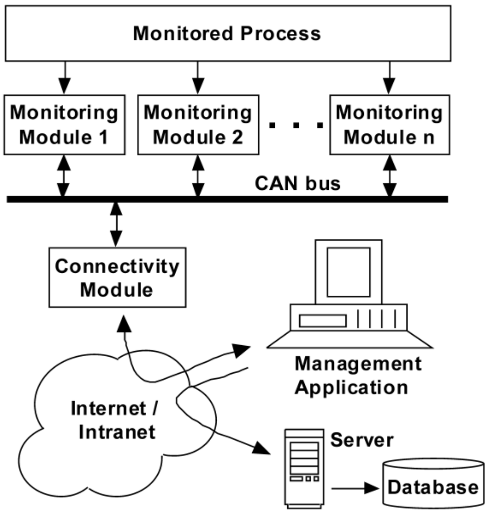

Figure 2. Monitoring System Architecture

The proposed and relatively simple monitoring algorithms are then developed and tested. Research machine tools and / or representative scaled physical models of sub-systems are used to deliberately introduce typical faults. For the case of cutting forces and tool wear / breakage detection the effectiveness of using inferred measures, from motor currents for example, is tested against higher cost dynamometers during this development phase.

Table 1 shown previously describes the overall monitoring system parameters and Figure 2 provides the remote monitoring architecture. A number of (PIC) microcontroller monitoring nodes are deployed on the machine (or process) to be monitored. These are typically capable of detecting 80% of all faults, mainly trivial, low level hard faults. These are connected to each other and to the 2nd level microcontroller via a CAN bus communications protocol. The CAN bus protocol is heavily used and was developed for automotive applications, and its robust performance in harsh and noisy environments make it ideal for machine monitoring applications.

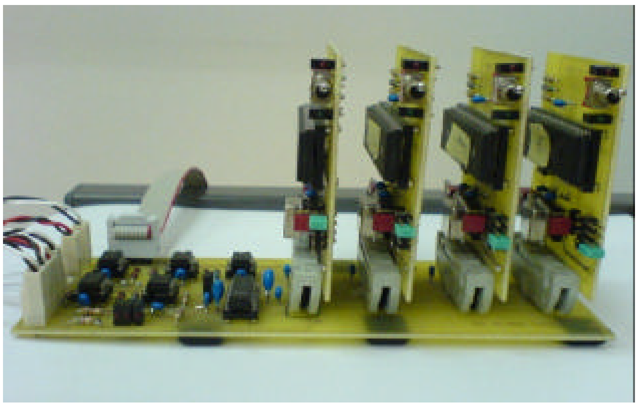

Figure 3. Monitoring Modules Hardware

The level 2 node, as stated, co-ordinates the information from the other nodes and typically 80% (of the 20% not detectable at the lowest level nodes) of remaining fault coverage is provided. These will require more sophisticated diagnostic methods compared to the previously described low level hard faults. More typically the early detection of faults whose level of severity increases with age would need to be detected and diagnosed at this node. The node also provides the internet based communications (at low level UDP protocols) back to the PC-based server. For the 4% or so of faults requiring higher processing capabilities and algorithms the monitored data may be streamed back.

Figure 3 shows the hardware developed, in this case for a batch process application (Ahsan et al, 2006). The 4 vertical circuit boards, each with a PIC microcontroller, are connected to analog signals measuring flowrate, temperature, liquid level and pump power, and are the monitoring modules. The horizontal circuit board includes the connectivity module and CAN bus communications (brought physically close together in this implementation).

2.1 Petri Nets

The group has used Petri Net techniques for a variety of applications, including machine tool monitoring. Initially, and in line with Petri's original concepts, the Petri Nets were used as a graphical user interface. In simple terms, the operator could view the dynamic flow of coloured tokens around the defined Petri Net diagram. A review of the use of Petri Nets in monitoring applications is provided by Frankowiak et al (2009). The approach was then adapted to provide the context and consistency of the defined monitoring tests and to reduce the amount of re-programming of the microcontroller nodes when deployed on new applications. Frankowiak et al (2009) concluded that the extensions provided, to conventional Petri Net representations, facilitated the interfacing and handling of real-life process signals. The addition of thresholded analog inputs and other constructions more suited to monitoring rather than control of sequential process was deemed to be vital to the evolution of low-cost monitoring systems.

The coding of the particular Petri net representations was demonstrated for a machine tool changer, a conveyor based assembly process and for a hydraulic press. The coding of the look-up tables within the microcontroller programs allowed for a selective approach to which sequence transition data were recorded and transmitted. This enabled both OEE calculations and the population of dynamic web page displays at the server-side PC. In particular the recording of start and end transitions enabled cycle time calculations. The counting of branched states, for example representing good or bad assemblies (for the conveyor application) enabled a quality measure. The third constituent of OEE calculations was then provided by the time-out / alarms of the Petri Net transitions in faulty conditions. The look-up tables were achievable within the memory constraints of the microcontroller hardware. Each microcontroller node could be interfaced to up to 24 digital inputs, 4 analog inputs and 2 pulse train inputs and could provide 1 digital output.

2.2 Microcontrollers

The PIC microcontrollers used are simple 8 or 16 bit single chip devices, whose features and capabilities have advanced with time. They conveniently handle inputs and outputs and have a variety of communications protocols. Originally the use of CAN bus communications required an additional transceiver chip alongside the PIC. These days PIC devices are available with built-in CAN bus facilities. The simple PIC devices do not have extensive capabilities for mathematical manipulations and/or diagnostic algorithms, although comparison of inputs to pre-determine threshold levels are readily implemented. The considerations for more advanced signal analysis, such as frequency analysis will be discussed here as an example.

Amer et al (2007) reported on the use of sweeping filters for machine tool condition monitoring. A PIC 18 series microcontroller was deployed as one of the monitoring module nodes. It was used to control an analog programmable filter, in the stated application to detect breakage of a 4-toothed milling cutter. The limitations were such that, in effect, a 32 point Fast Fourier Transform (FFT) of spindle load signal on the milling machine was achieved. The filter was swept through the determined and appropriate range of frequencies and enabled the PIC to accumulate sufficient data, with the available timeframe, to determine a limited resolution frequency spectrum. The system was developed though a series of cutting trials, with a range of set machining conditions and for 3 and 2 tooth cutters, in addition to the 4 tooth cutters. The approach was successful, when considered within the context of the first level diagnostics within the hierarchical monitoring system.

The detection of the breakage of milling cutters is a challenging task. In a survey of health management user objectives, Wheeler et al (2010), included considerations of diagnostics and diagnostic metrics. They included detection rates, detection accuracy and detection response time as desirable objectives. For milling breakage detection there is a premium on the detection response time, particularly for high value, long cycle time, minimally supervised machining jobs. The use of better resolution and more sophisticated FFT that was then enable by the next generation of microcontrollers, known as dsPICs, was reported by Siddiqui et al (2007). Figure 4 shows the structure of the dsPIC system.The dsPIC is a 24 bit device and has digital signal processing (DSP) commands along with the established PIC I/O handling and communications. It also has higher resolution analog signal acquisition and

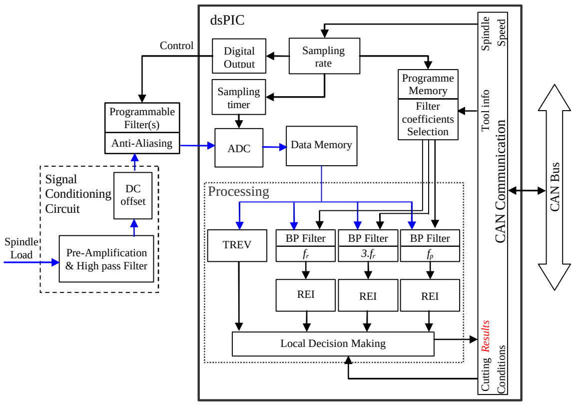

Figure 4. Schematic of dsPIC Monitoring System

in-built FFT routines. Siddiqui et al (2007) implemented an overlap FFT processing scheme in order to address the demanding detection response time requirement. The reported results showed that a robust detection of sudden tool breakage could be achieved within 1.5 revolutions of the spindle (and cutter) post failure. The efficient coding of the software and algorithms meant that detection could be achieved for spindle speeds up to 3000 r.p.m. The monitoring system was designed to be relatively immune to false alarms, even under a range of machining conditions. These included break-in and break-out (these often trigger false alarms in such monitoring systems), variable depth of cut and a range of (operator selected) spindle speeds. For the latter case the sample rate of the dsPIC was changed under software control in order to 'track' the intended and particular frequencies of interest.

Further the derived states of the frequency components, at the spindle rotational frequency (f_r), at 3 times this frequency ($3f_r$) and at the tooth passing frequency (f_p) were fed into a decision maker. The other parameters used by the decision maker were a Tool Rotation Energy Variation (TREV) and a Relative Energy Index (REI). Table 2 summarises the decision making logic. If a clear categorization was not directly possible then either further frames of data could be captured and processed or the raw data could be passed up the monitoring hierarchy for more advanced frequency analysis.

The other aspect of the milling cutter monitoring system that may be of relevance to PHM approaches is the estimation of tool life. Often milling cutters are deployed with a (usually) conservative estimate of expected lifetime. The parameters used with the dsPIC monitoring system are also used to calculate the accumulated usage time of the cutting tool. The energy based monitoring calculations further enable the usage time to be considered in combination with a measure of how hard the tool was used and when it was actually in use, cutting metal. This provides refinements compared to simple logging of the calendar age of the tool or machine-on

Table 2. Decision Making Table

Mean Freq	Magnitude^2			Pattern	Decision
	f_r	$3f_r$	f_p		
0	0	0	0	0	Healthy
0	0	0	1	0	Blunt Tool
0	1	X	X	0	Unexpected : request advanced diagnosis
0	X	1	X	0	Unexpected : request advanced diagnosis
1	0	0	0	0	Wait for next Frame
1	0	0	0	1	Chipped Tool
1	1	X	X	1	Broken Tooth
1	X	1	X	1	Broken Tooth
1	X	X	1	1	Broken Tooth

hours. Potentially such lifetime profiles could be used towards the end of the useful life to determine whether a particular job could be finished, for example at reduced machining rates, with the existing tool.

3. INDUSTRIAL MACHINE / PROCESS MONITORING

3.1 Embedded Monitoring Applications

The previously described microcontroller systems were also deployed, as stated in section 2.1, to monitor a conveyor based assembly process and a hydraulic press. Both of these are good examples of industrial processes whose sequence and logic is controlled by a Programmable Logic Controller (PLC). The conveyor assembly monitoring system was interfaced to 14 digital signals, utilizing both inputs to and outputs from the programmed PLC. The defining Petri Net structure had 63 transitions and was predominately a branched structure. This reflected the various outcomes at the sorting, assembly, overflow and accept/reject stages of the process. The Petri Net was configured to enable OEE calculations and the remote tracking via dynamic web pages of the assembly process performance. Figure 5 shows one example of such performance tracking. The pie chart reflects the counts of well assembled parts, incorrect assemblies or parts and reprocessed parts. The numbers preceding the counted occurrences are the respective Petri Net transition numbers.

For the hydraulic press application 22 digital signals from the PLC were used along with 3 analog signals used to measure the motor currents on each axis of motion. The Petri Net representation had 29 transitions and the only branching required depended on whether a left hand or right hand pallet was selected for pressing actions by the press

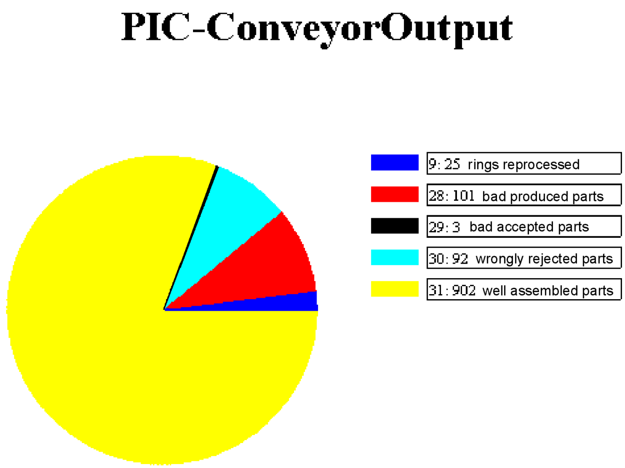

Figure 5. Dynamic Webpage Example for Assembly Process Application.

operator. The movement of the vertical axis provided a good example of where context based (provided by the Petri net structure) thresholding of signals was required. The vertical motor currents, for normal fault free operations were different for upwards and downwards movements. The monitoring system was again configured to provide cycle times, loading times and fault diagnostics.

Prickett et al (2010) reported on the monitoring of pneumatic systems, such as linear actuators and grippers. These are widely used in the automotive, manufacturing and food packaging industries. The dsPIC microcontroller system was used to detect the presence of parts and indentified their size in real time during gripping operations Key timing in measured pressure response profiles during a gripping cycle were identified. A modelled 3D surface that described the actuator movement and the effect of air supply pressure and stroke length was then utilised. The timings could then be used to confirm that the correctly sized component had been gripped and that it had not slipped or had been dropped during the actuation cycle.

3.2 Monitoring Applications Using Other Platforms

Sharif and Grosvenor (1997) used a PC based system in the monitoring of pneumatically actuated process control valves. In this application the monitoring system was used to complement the built-in diagnostics and test cycles of the valve's digital position controller. A test rig was established and the fault diagnosis capabilities were assessed following the introduction of simulated faults. It was reported that a range of fault conditions and their levels could be detected with the addition of 1 extra pressure transducer. The faults were deemed to be representative of harsh and arid type pipeline conditions. The faults were vent hole blockages, diaphragm ageing & cracking and damage to the valve stem seal due to accumulated deposits on the valve stem. The problem of internal leakage through the valve was separately investigated and was found to require the addition of acoustic emission sensors.

Eyers et al (2005) considered the monitoring of a robotic welding station. The industrial application began with the deployment of a commercial system that interfaced up to 4 sensor signals from the machine on the factory shopfloor to an office based location. This device used Bluetooth class 1 communications but was found to be inflexible in terms of file storage. This rendered the viewing of longer term trends difficult and required large file storage capacity. The developed PC-based monitoring system was accordingly focussed on intelligent data management and reporting. Web-based OEE statistics were generated and a 99% reduction in the daily traffic of monitored information was achieved. Significant differences in completed welding operations across the 3 shifts per day were observed and the industrial partner was then able to instigate performance improvement measures. The shift-by-shift reports and the weekly and monthly trends were reported via a number of mechanisms and technologies.

4. OTHER MONITORING APPLICATIONS

Edwards et al (2006) considered monitoring techniques for determining lamp condition in lighting applications. The proposed approach required the measurement of a combination of lamp characteristics in order to accurately determine remaining life. Testing was carried out with filament lamps, low pressure discharge lamps and UV sterilization lamps. In the case of filament lamps it was found that strong correlations existed between initial characteristics and lamp life. A short duration (30 seconds) test of each lamp could then be used to predict the remaining useful life. A multi channel PC based test rig was used to test multiple lamps and to gather the data used to establish the correlations.

Davies et al (2009) used a SCADA based system to obtain PLC information for water treatment plant and cooling tower applications. The water treatment plant monitoring mainly consisted of detecting pump and piping blockages and of determining the performance of the programmed schedule of filter bed backwashing actions. The Citect SCADA software that was utilised acted as an OPC server and was hosted on a PC platform. The initial detection of potential faults was triggered if a raised speed request from the PLC continuous PID control loop was detected. This could indicate the controller 'working harder' to maintain the set flowrate of water for treatment in the filter bed. This could be in reaction to either single or combined blockages, of the upstream or downstream pipework or could indicate that the filter is in need of backwashing. A diagnostic program then ran and manipulated the speed request signal to create a test cycle. The flow and pressure signal profiles

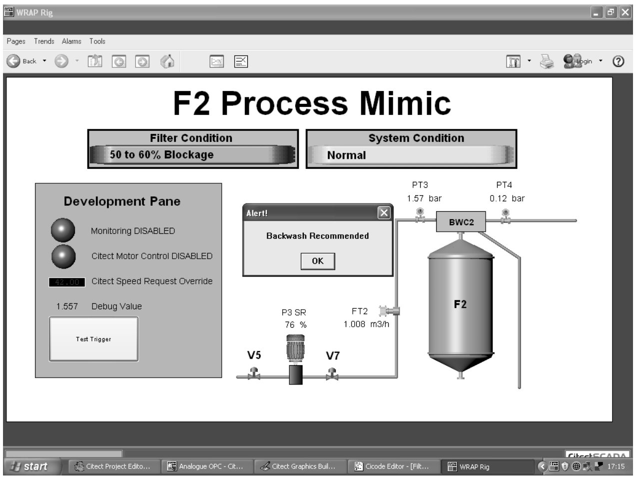

Figure 6. Process Mimic Screen for Water Treatment Plant.

obtained were then used to determine the fault conditions. The diagnostic program could estimate blockage levels for both single and multiple fault scenarios and could distinguish pump and pipework blockages from filter bed fouling. The triggering of filter backwashing was implemented when required. The system however was also used to optimise the duration between scheduled backwash operations. The operator was provided with a process mimic summary screen, an example of which is shown in Figure 6.

For the cooling tower application the monitoring system was also required to track the chemical dosing regime. The system also helped to co-ordinate and optimise the selective operation of 3 cooling towers in varying operational conditions. The system also provided accurate real time information on the energy usage and efficiencies and provided the manager with a financial costing screen.

5. DISCUSSION OF FUTURE APPLICATIONS AND PHM TECHNIQUES

5.1 New and Future Monitoring Applications

One example relates to the emerging technologies for tidal turbines and renewable power generation. In many cases the proposed monitoring schemes are deemed to be analogous to those deployed on wind turbines. Owen et al (2010), for example, have reported on a multi-mode structural health monitoring system for wind turbine blades and components. Certainly in considering typical generic designs that are emerging for tidal turbines there are, at the sub-system level many similar components to wind turbines. The operating conditions and medium are vastly different. The IPMM group is considering the monitoring and PHM requirements that are likely to be embedded within tidal turbines. As a starting point a Failure Modes and Effects Analysis (FMEA) provides a vehicle for the systematic

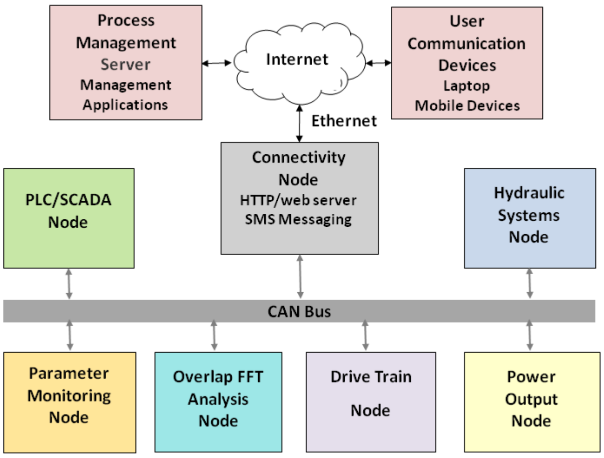

Figure 7. Representation of the Marine Tidal Turbine Condition Monitoring Architecture

analysis of potential failure modes to reduce and if possible prevent failures. An effective FMEA can identify critical points within the design, manufacture, installation and operation of components, characterise failure modes, actions also direct the specification and configuration of condition monitoring systems that can support the successful operation of marine tidal turbines. Values for the severity, occurrence and detection ratings for constituent sub-systems are multiplied to produce risk priority numbers (RPN). The group plans to implement an embedded monitoring system and to initially test and develop the system on scale models of the turbines. These are being used in water flume testing for the validation of computational fluid mechanics (CFD) mathematical models. An outline of the system architecture is shown in Figure 7. A representation of the main constituents of a generic tidal turbine that will require monitoring is provided in Figure 8.

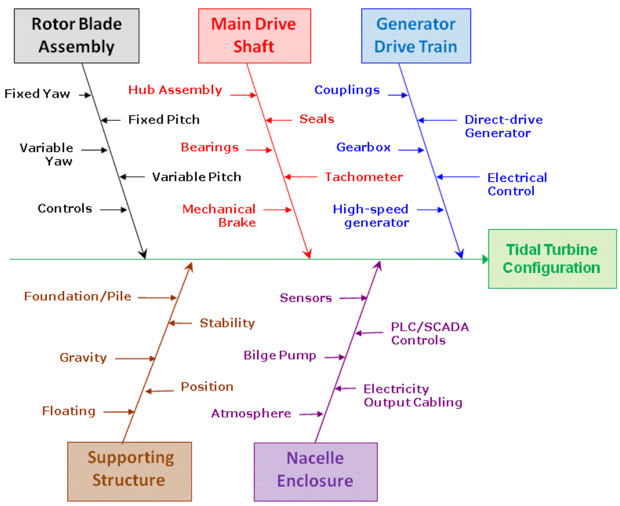

Figure 8. Representation of Possible Turbine Configurations.

5.2 Discussion of the Need for Condition Monitoring Systems to Embrace PHM Techniques.

The authors believe that the modern and future generations of monitoring systems need to provide more than just condition monitoring and fault diagnostic functions. It is hoped that the range of monitoring applications reported in this paper already contain some of the PHM philosophies and techniques. The dsPIC based embedded and distributed monitoring architectures reported are believed to provide a potential platform for future developments.

It is hoped that the experiences reported may be of use to other PHM practitioners when they initially consider which approaches and platforms for their applications.

When working with multiple distributed applications and/or small resource limited organizations the lower cost microcontroller platforms and the selective use of key additional sensors will almost inevitably be a constraint or be of fundamental importance. Further consideration should be applied to which of the available range of techniques is most appropriate. For example, the simple comparison of an analog signal level to a set threshold will have low microcontroller resource implications. It would not be over demanding in terms of sample rates, processing power or data storage and communications. In other cases, for example machine tool or rotating machinery applications, the ability to provide FFT processing would almost certainly be a vital requirement. A more detailed analysis of the microcontroller resources would be needed.

The IPMM group is, as stated, applying such considerations to the monitoring of future generations of tidal stream turbines. It is envisaged that ruggedized commercially available modules, such as the compactRIO system from National Instruments will be investigated in conjunction with some of the reported microcontroller modules.

It has been reported that PHM involves interdisciplinary research with a broad range of application areas. The detection of impending faults remains a key objective and in a wider PHM system allows logistical decision making. This along with the concept of transforming data into information and onwards to decisions is consistent with the condition monitoring approaches reported in this paper.

There is potential to expand the monitoring research to have more explicit links to reliability predictions and to more fully consider lifetime management of components and systems.

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