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Health Monitoring of Marine Equipment

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Abstract—

Commissioning modern military ships and submarines can require significant economic investments in terms of defence budget expenditure. For example a projected £6.3 billion for HMS Queen Elizabeth, and as such these assets are expected to remain operational for decades while being deployed in challenging environments. Health and Usage Monitoring Systems (HUMS) provide a way to monitor the condition of complex equipment, and derive prognostic analysis such as Remaining Useful Life (RUL). This can bring many benefits, such as enabling auxiliary equipment to take over operation of key functions before failure of primary equipment, the increased understanding and insight into equipment being monitored highlighting development opportunities, and anticipation of maintenance and logistical requirements which can reduce maintenance costs. There has been significant growth in interest for HUMS capabilities recently as result of the benefits they bring and in response to increasing demands for Contract for Availability (CfA) and comprehensive supportability, as evidenced by a CfA introduced in 2010 for Trafalgar Class submarines between the UK MoD and Babcock. This interest in prognostics has led to ground-breaking research with considerable relevant expertise at Heriot-Watt University. Furthermore, within the maritime industry there has historically been a view that methods relating to Product Lifecycle Management (PLM) do not apply to bespoke design and manufacture of complex one-off assets. However, advances in technology and analysis strategies enable HUMS capabilities to be integrated into holistic platforms such as Integrated Platform Management Systems (IPMS) therefore providing health monitoring and enhanced insight into the interdependences of components and sub-systems within a complex asset.

The scope of this project was to design and build a first generation condition monitoring system, called the Environment and Health Monitoring System (EHMS), to be deployed onto MacTaggart Scott (MTS) assets of interest. This will enable access to previously unobtainable data to enable condition monitoring and inform the development of prognostic capabilities such as potential RUL derivation. The main technical challenges with regards to system design identified at the outset of the project were firstly fitting the EHMS into spatial restrictions so that it would be compatible with a wide range of MTS mechanical handling sub-systems and equipment, secondly the power consumption of the EHMS with regards to a prolonged lifetime, and thirdly the encapsulation of sensors for subsea environments outside a pressure hull. As a multi-sensor system, the EHMS will collect data on the subsea environment as well as MTS asset measurands, to be stored securely using a well-respected encryption protocol for retrieval. Although operating completely autonomously during deployment, secure wireless functionality has been implemented in order to communicate with the system for maintenance and data reclamation. Also within the remit of the project was the design and build of a Graphical User Interface (GUI) capable of connecting with the system for configuration, maintenance and data retrieval/ interpretation purposes. The resulting prototype system developed throughout this project will not only meet objectives, but is a solid modular platform enabling future development in multiple directions beyond the project scope while overcoming the technical challenges encountered during design.

Keywords- Condition Monitoring, Sensors, Prognostics, Health Management

I. Introduction

Condition monitoring of assets presents many potential benefits in terms of reduced maintenance costs and, critically for submarine assets, higher reliability and availability. Historically, condition monitoring has been used primarily in industrial applications where access to equipment to be monitored is relatively straightforward. Data gathering has either been by periodic manual access to equipment, or through sensors feeding data to a central location as part of a supervisory control and data acquisition (SCADA) type system.

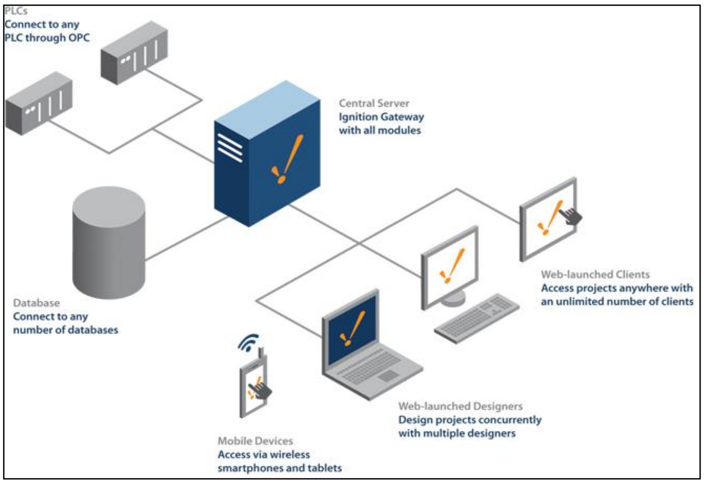

Figure 1. Typical SCADA system architecture (www.free-stock-illustration.com)

Recent platform development programmes have seen the introduction of similar systems to the naval sector, often under the banner of integrated platform management systems (IPMS). Such systems have the capability to provide significant levels of condition related information to the user, but are often restricted to the provision of a ‘system healthy’ or ‘fault’ indication. This restriction is partly due to the complexity already required of the IPMS to provide control functionality over a wide range of systems, partly due to the widely varying levels of monitoring implemented within systems, and partly due to limitations in factors such as available data channels and additional cabling requirements. These latter difficulties are magnified in the event of platform life extension programmes, where retrofit of such capabilities within existing vessels can be a complex, costly and time consuming activity.

All of the above discussion assumes a need for information to be fed back to a central location for processing and interpretation, while ultimately the key requirement is for improved asset reliability and availability, an assertion backed up by the fact that these are the key measures used in through life support and availability contracting. This realisation, along with the relative inaccessibility of the outside pressure hull equipment supplied by MacTaggart Scott, led to the development of the EHMS concept.

The EHMS is intended to operate autonomously throughout the deployment of an asset, gathering data on the environment the asset is exposed to, the usage profile and key operating parameters which provide an indication of the health of the asset. This data is processed locally to the equipment to provide a ready indication to service engineers of the asset condition and remaining useful life when they access the equipment during maintenance periods. This approach makes the equipment suitable for installation during both life extension programmes and new build, allowing condition based maintenance decisions to be made, improving the availability of the asset while maintaining a cost effective approach to maintenance. The equipment also has the capability to capture key operating events, highlighted by the measures, which may assist in refining equipment specifications for future generations and characterising route cause and rogue failures.

Key stages in the development of the EHMS are discussed further in the following sections of this paper.

II. Identification of Key Measurement Parameters

Key to the success of any condition monitoring system is the identification of the correct parameters to monitor. This will vary from system to system, however for the MacTaggart Scott candidate equipment (outside pressure hull mechanical systems) a number of key equipment characteristics were identified. These were:

- Hydraulically driven
- Linear and / or rotational movement
- Failure modes linked with leakage, corrosion and marine growth

From these considerations, alongside the desire to establish to true duty cycle and operating conditions of the equipment, the following monitoring parameters were identified.

A. Hydraulic Pressure

Hydraulic pressure is a key indicator of equipment operation and health. The presence of hydraulic pressure within an equipment supply line indicates that movement is being commanded, and the level of pressure experienced is a key measure of the power required to provide the desired movement. Assuming a relatively consistent load, increasing hydraulic pressure in operation is an indication of decreasing efficiency. With no further indications of problems reduced efficiency may be attributed to fouling of rotating or sliding interfaces, however with other indicators may point to internal component wear or failure. Monitoring of hydraulic peak pressures would also provide an indication of how close to design limits equipment is operating. This measure could be used to influence equipment specification for future generations, as with peak limits properly identified it may be possible to engineer lighter, more cost effective solutions.

B. Hydraulic Temperature

Along with fluid cleanliness, temperature is a key measure of the condition and suitability of a hydraulic fluid. A system which is underrated will tend to run hot, which reduces the lubricity of the fluid and can lead to accelerated component wear. Equally, low fluid temperatures can cause damage as the higher fluid viscosity may lead to cavitation within a system, or improper lubrication in areas of fine tolerance. Fluid cleanliness would be a more effective monitor of fluid condition, however the cost, size and interfacing requirements of equipment required to effectively provide this monitoring was prohibitive for the mounting locations envisaged for the equipment.

C. Vibration

Particularly in rotating equipment, vibration (or structure borne noise) is a key indicator of equipment health. Due to bearing types and locations, number of operating pistons or poles and the nature of the drive mechanism, each type of equipment has a distinct signature. As a crude measure, changes in the overall vibration level of equipment can indicate a fault. The true value in vibration as a diagnostic tool is revealed when frequency based analysis such as Fast Fourier Transform (FFT) is used, and the vibration levels generated at different frequencies are revealed. Correlation of this data with the equipment design such as number of rolling elements in a bearing can identify the component which is deteriorating.

D. Oceanic Pressure

Oceanic pressure is a key indicator in the duty cycle of outside of pressure hull equipment. While the equipment must clearly be able to tolerate exposure to deep dive test pressure, significant influence on the design can be made by understanding the depths the equipment routinely operates at. This is particularly relevant to rotating equipment seals, where selection may be based on pressure energised or other sealing strategies. Understanding the amount of time equipment spends at depth, and the amount of operating time at depth, may be a significant influencer in design for future generation equipment.

E. Oceanic Temperature and Salinity

Oceanic temperature and salinity are key factors in the types of marine growth present, and their rate of growth. Understanding of exposure time to different parameters, along with examination of fouling growth on equipment, is again potentially a key influencer in the specification of future equipment. Understanding the timescales over which growth affects equipment sealing and operating efficiency may influence routine cycling operation periodicity, where equipment is operated regularly even when not required to prevent the build-up of growth. Understanding rates of growth in different conditions could lead to these periods becoming variable depending on mission location, influencing equipment reliability and maintainability.

III. Energy Management

The EHMS unit was designed to operate autonomously outside the submarine pressure hull between periods where it could be accessed, across a number of submarine platforms. For Nuclear submarines this requirement meant the unit must operate for periods of up to seven years between major docking periods, when the boat would be in dry dock. This requirement made energy management a critical parameter, in order to achieve a power source with acceptable space requirements. Power requirements were established with reference to the following considerations.

A. Sampling Frequency

Sampling frequency is important when determining the suitability of data for condition monitoring activities. Ideally continuous monitoring should be implemented to ensure that developing trends are detected as early as possible, however this strategy is incompatible with the design intent of a compact unit operating under battery power for long periods. Under these conditions periodic sampling is more appropriate, however there is an additional need to verify that the equipment is actually operating when sampled, otherwise data could easily be reporting external influences rather than the condition of the equipment. Additionally, memory for results storage is space intensive, partly in provision of physical memory for storage, but most significantly in terms of power required to operate a larger amount of memory. This led to the requirement to carry out on board data processing and categorisation, storing only trend data for normal operation, but retaining raw data for significant events to allow further interrogation offline. These requirements led to the need to develop triggering criteria for different sensors, and data categorisation strategies to determine which raw data to retain.

B. Sampling Strategy

Sampling strategy must be varied for different parameters within the system in order to provide useful data. Oceanic conditions require regular sampling throughout a deployment in order to develop a picture of equipment exposure. It is also important to obtain these conditions at the time of a significant event in equipment operation to help determine how great a contribution the environmental conditions played in that event. This has led to a strategy where oceanic conditions are periodically sampled and raw data recorded (this is relatively light on resource requirements), and additionally sampled and recorded whenever a significant hydraulic event is detected. Hydraulic and vibration data for MacTaggart Scott equipment cannot usefully be taken on a periodic basis as the equipment is frequently idle for long periods between use, therefore a different strategy is required in order to record useful data. Overall usage is important, as is the recording of significant events. Both of these scenarios can be identified through interrogation of the hydraulic pressure – presence of pressure above a certain level indicates the equipment is in use, while overall hydraulic pressure provides an indication of how hard the equipment is working. Hydraulic pressure is therefore continuously monitored in a low power mode, with a threshold value set to enable the wider functionality of the recorder when an operating pressure level is detected. Depending on the pressure level experienced different recording modes may be enabled, either simple overall vibration level or a burst of raw accelerometer data which is then internally analysed using FFT, with the FFT result being stored for further interpretation. All data is timestamped, allowing a use profile to be developed for the equipment, and offering the potential to correlate extreme loading events with boat activities, should access to log data be available.

IV. Communication

It is envisaged that the EHMS may be deployed directly attached to equipment outside the pressure hull of a submarine. As such the EHMS may be difficult to access, with space to physically connect cabling for data download being particularly difficult, due to the physical size of suitably rated waterproof connectors. For these reasons a wireless communications solution has been implemented, allowing remote connection to the EHMS for download of data. Due to the physical location of EHMS deployment a long range wireless connection is not anticipated, thus it is considered acceptable to include a requirement to physically access the equipment to activate the wireless communication mode. This enables power saving within the unit as the wireless system can be completely disabled when not required, and also increases data security by ensuring the device cannot be accessed unless physically enabled by personnel with authority to access the equipment. Data security is also enhanced by the military standard encryption protocols employed in transmission Once the wireless transmission is enabled the unit can be left to download data unattended, while service engineers carry out physical checks and other tasks.

Due to the space, interfacing, processing and power limitations of the EHMS device, data transfer rate through the wireless connection is limited, therefore careful design of the communication modes has been required to ensure the highest priority data is readily accessible to the service engineer, and that further data can be suitably structured so that only desired data need be transmitted. This approach has increased the processing required of the EHMS from that of a simple data recorder, however has reduced overall power consumption and memory required significantly.

V. DATA RECOVERY AND INTERPRETATION

The operator interface for data recovery and display is a laptop computer running a dedicated LabView application. LabView was selected as the overall interface due to the ability to easily define a graphical user interface in addition to it featuring an easy to interpret and modify programming interface. Significant areas of functionality have had to be developed from the ground up, including implementing scripts in various programming languages within the LabView environment to achieve specific requirements such as interfacing with SQL database functionality (allowing future interpretation of data within other applications) and the wireless communication hardware.

On initial connection to the EHMS, the data recovery and interpretation (DRI) application verifies the status of the EHMS (active, any sensor faults detected etc.) and provides a 'traffic light' based health indication. This is based on interpretation of measured parameters against preset threshold levels. Focusing particularly on vibration, this measure provides a good indication whether anything other than routine service work is required. Within the DRI panel it is then possible to select particular data records based on search parameters (records between certain dates or when certain parameter values are exceeded for example) and display resulting records both numerically and graphically. Operating modes of the EHMS and various parameters can also be set, allowing the EHMS to be configured to different equipment types.

Within the EHMS, as previously mentioned, data is already interpreted for significance, and the level of retained data determined based on this interpretation. Further development of this data interpretation is planned for the unit, in order to unlock the next generation of condition monitoring, through prognostics. In prognostic monitoring, data is interpreted against both known failure data and parameter trends within the equipment being measured, in order to identify data characteristics indicating the equipment is approaching failure. Studies [1,2] have shown a high degree of reliability is now attainable in failure prediction for systems without reference failure data, based on the deviation of parameters over time from a known good system. Development of this capability will be pursued in collaboration with Heriot Watt University following proof of concept deployment of the EHMS to demonstrate that data can be reliably recovered from the harsh environments in question.

VI. CONFIGURATION AND PACKAGING

Key to the success of the EHMS project has been the development to technology to enable deployment of sensors within the harsh submarine environment. While relatively sophisticated systems operate subsea within the oil and gas industry, their length of deployment and reliability are significantly lower than that experienced in defence submarine applications. This difficulty has been highlighted in recent years, where attempts to employ oil and gas technologies in the marine renewables sector, particularly the aggressive nearshore wave environment, have met with limited success due primarily to the longer exposure times required.

The MacTaggart Scott approach has been to select standard sensors and develop custom packaging approaches to provide resilience for the environment. Primarily these packages have relied on resin encapsulation to produce completely monolithic devices which are therefore impervious to pressure effects. This packaging approach has proven to be highly space efficient in comparison with traditional casing protection, and is increasingly used in packaging of commercial off the shelf (COTS) equipment for use in harsh environments. Developments in enabling this technology for use in the EHMS have included developing the use of additive manufacturing (3D printing) techniques for mould and assembly tools and material selection and vacuum degassing techniques for casting resins to ensure void free encapsulation.

Packaging design has resulted in an EHMS system formed of three elements, an equipment sensor package consisting of a hydraulic pressure and temperature transducer and two orthogonally mounted accelerometers, a battery pack consisting of two separate Lithium Ion battery packages for the different voltage levels required and the EHMS unit itself, which includes the external environment sensors. This packaging design was determined through ranked evaluation matrices and addresses the need to access confined spaces around equipment to allow connection to existing hydraulic system test and sampling points while accommodating the batteries required for extended operation. The subsystems are connected via traditional subsea electrical connectors, which additionally allows for the option to attach a different equipment sensor package for different applications, such as electrically driven equipment.

VII. FUTURE WORK

The first generation EHMS system has recently completed functional evaluation and is being packaged for deployment trials. Initially the fully packaged unit shall be subject to environmental testing for shock and electromagnetic compatibility (EMC) to prove it worthy of sea trial. MacTaggart Scott are currently seeking candidate platforms to conduct at sea trials for the system, which will be conducted in parallel with development of the further prognostic capabilities available through the DRI.

It is envisaged that for certain critical systems the EHMS capability may be desirable in real time. Such a second generation device would require direct communication through the submarine pressure hull, however the embedded intelligence already developed would serve to reduce bandwidth requirements, potentially allowing pairing with other existing or required communications. Power could be fed to such a device from within the submarine, making the overall unit more compact and the developing prognostic capability could be hosted within the submarine, allowing ready upgrade as further capabilities are developed.

VIII. CONCLUSION

Condition monitoring for outside pressure hull submarine equipment has historically been unachievable due to the need for environmentally capable, power efficient sensing technology with the capability to operate with little or no interaction with the internal submarine environment. Development of the EHMS system enables meaningful data on system performance and operating environment to be gathered throughout a vessel deployment, in a package that requires no pressure hull penetrations. The first generation system offers monitoring and indication capabilities of direct application to planned maintenance strategies and offers insight into equipment use which may influence future equipment specification.

Potential development of the EHMS system could implement current state of the art prognostic health monitoring techniques, allowing equipment health over time and expected remaining useful life to be predicted.

[1] Dr. David Flynn, "Health and usage monitoring systems: Enabling the future prediction of remaining useful life for submarines," Proceedings of the 12th International Naval Engineering Conference and Exhibition (INEC) 2014, pp. 850-860

[2] S. Cheng, K. Tom, L. Thomas, and M. Pecht, "A wireless sensor system for prognostics and health management," *Sensors Journal, IEEE*, vol. 10, pp. 856-862, 2010.