Using Sensor Data for the Development of Digital Twins in Support of Condition-Based Maintenance

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Synopsis

This article examines how operational data obtained from sensors interacting with the Royal Canadian Navy (RCN) Halifax Class Frigates onboard Integrated Platform Management System (IPMS) could be used to support a shift from schedule-based maintenance to condition-based maintenance. The idea is to use a few years of IPMS data logged by the Equipment Health Monitoring (EHM) software tool to aid in the development of EHM rules (or Digital Twins) that will indicate the current health status of various equipment. The process of EHM rules development consists of several steps. First, the targeted failure modes were selected by carrying out equipment failure modes and effects analysis (FMEA) and reviewing existing operational and maintenance records collected from the resource management system. For each targeted failure mode, relevant IPMS integrated sensors data was identified (when available), extracted, and checked for missing values, low signal to noise ratio and outliers. An equipment digital twin was created using EHM built-in functions and/or Python programming language. Utilization of Python programming language functions allowed implementing EHM approach for wider range of equipment failure modes. Once the EHM rule was developed, it was tested using a different set of IPMS data. The results were analyzed and the digital twin model was reworked until a satisfactory response was confirmed. Numerous Digital twins (DTs) were created for critical equipment on board including propulsion diesel engine, drive train components, pumps, remotely controlled valves, and sensors. This development process demonstrated how sensors meant to support operational needs could also benefit CBM. More value to be expected should the specific needs of CBM be considered early in the ship design. IPMS was proven a valuable source of information to support the development of EHM rules necessary for CBM. In the course of this study, DT engineering process was also validated by Lloyd's Register and received "Digital Twin Ready Approval in Principle" certification. The performance of EHM rules still has to be validated in the field and its value to be confirmed by the end-users, but the work performed so far is promising..

Keywords: Navy; Equipment Health Monitoring (EHM); Condition-Based Maintenance; Data Analysis; Digital Twins (DT); Simulation and Modelling.

1. Introduction

Periodic (time based) equipment maintenance remains a key maintenance approach utilized onboard of navy and commercial vessels. Although it has a number of advantages, such as less equipment downtime, longer asset life, fewer interruption of critical operations, there are major shortfalls, such as high cost. One of the methods to reduce the cost of maintenance is called Condition-Based Maintenance (CBM). The main advantage of CBM is the capability to optimize maintenance schedule resulting in lower cost of maintenance while increasing equipment reliability and availability. CBM heavily relies on equipment monitoring (real-time or frequently updated) and maintenance data. Modern SCADA systems generate large volume of operational data and may serve as a main source of CBM related data.

This paper relates to a study started in 2019 aimed to estimate the feasibility of implementation of a CBM strategy onboard of Royal Canadian Navy Halifax Class Frigates using equipment operational data generated by Integrated Platform Management System (IPMS). For this purpose, IPMS data has been analyzed as per CBM requirements. CBM recommendations were generated for a selected group of equipment and their functions. CBM

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recommendations have been realized through EHM rules (Digital Twins[1]) residing inside of the EHM module of IPMS. Each EHM rule monitors a specified aspect of equipment performance through appropriate equipment models and by using suitable data analytic techniques. In other words, an EHM rule is an algorithm that ingests input data related to a selected aspect of equipment functionality; processes the data according to internal logic; compares the data with corresponding equipment baseline(s); generates an alert if equipment performance significantly deviates from the baseline. Depending on the degree of deterioration and internal rule logic, it issues alerts of different levels (Warning or Alarm). A baseline is a fixed point of reference used for comparison purposes. The baselines are built using key parameters collected during the equipment shop and sea trials. The baselines reflect the best-demonstrated performance of equipment when it is new or brought to "as new condition" followed by equipment major overhaul.

EHM user receives equipment health information at the frequency defined by EHM rules logic. Equipment health information may contain Health Confidence Factor (HCF) value, status of selected equipment or its function and maintenance or operational advisory. HCF is a numerical expression of technical health of equipment or its component. A higher HCF value indicates high confidence that the measured values are normal and a lower value indicates low confidence that the measured values are normal. Depending on the type of DT physical counterpart, its design and its replaceable parts as well as the granularity of its representation by the relevant IPMS sensors, EHM rules may facilitate Anomaly Detection or Conditional Fault Detection functionality. While Anomaly Detection indicates that equipment health deteriorated beyond the preset level, Conditional Fault Detection also points to a group of replaceable parts, the condition of which might be a source of declined equipment performance. The EHM rules (Digital twins) have been deployed on board of one of the Halifax Class Frigates. Upon completion of the trial period, CBM Digital twins' generated data will be analyzed and the performance will be accessed against the recognized quality metrics.

2. Problem analysis

Some of the main disadvantages of Preventive Maintenance (PM), centered on a periodic, time based schedule, are higher maintenance cost and risk of unexpected failure. In the RCN, in addition to operation and maintenance, engine room crew is also involved in the activities related to the mission, military special training and drills. CBM allows optimizing maintenance schedule and reducing overall maintenance cost (labor and spare parts), whilst maintaining a low risk of unexpected equipment failure.

3. Objectives

The long-term goal is to implement a process of continuous optimization of maintenance schedules for selected equipment while maintaining high equipment reliability and availability through the application of a CBM strategy. The main objectives of the study were to 1) confirm that Halifax Class frigates' available operational and maintenance data could be used to facilitate CBM, 2) develop and implement CBM recommendations for selected critical equipment and its targeted failure modes. A derived objective was to provide various stakeholders ashore and onboard information about the technical state of the ship equipment via adapted EHM dashboards.

4. Hypotheses

Existing IPMS sensors installed onboard of Halifax class frigates can support the transfer of equipment maintenance strategy from periodic maintenance to CBM for certain selected equipment, its components or its functions. IPMS sensors produce the data that can be used as the basis for implementation of a CBM methodology. Relevant sensors record the parameters of equipment performance aspects related to the targeted equipment functions. Based on the sensors data, equipment condition or health can be determined with the required level of accuracy. For this purpose raw sensor data would be processed in such a way that current condition of equipment can be estimated. The data produced by the relevant IPMS sensors defines the state of the selected equipment or its level of functional performance adequately and unambiguously. It should allow for development of data driven

[1] As described in Lloyd's Register Procedure for the Approval of Digital Health Management Systems, Chapter 1, Section 1, Article 1.3, Digital Twins (DT) are defined as a digital representation of a specific physical asset, which utilizes data and analytical technique to generate insights on asset health over time (see **References**).

equipment reference model with necessary accuracy, which would continuously monitor the health of equipment and raise a maintenance alert in case of detected anomaly or fault.

5. Limitations

Halifax Class Frigates were built between 1988 and 1996. During the final design stages of the Halifax Class, EHM tools such as Digital Twin, Predictive Analytics and the benefits extant to the platform with regards to near real-time secure cloud and data lake analytics required for fleet wide CBM and operational data based decision making merely did not exist. Using modern data analytics and DT technology available today would clearly enable more efficient and effective resource use. Consequently, the capability to implement specific statistical model based on IPMS data might be limited. Maintenance data residing in the Defence Resource Management Information System (DRMIS) is isolated from operational data. Maintenance data is semi-structured and data mining task is complicated. Synchronization of maintenance and operational data is a tedious process that requires manual steps.

6. Data collection and processing methods

In this work, the following equipment was selected for CBM applicability study: Propulsion Diesel Engine and its components, drive train components (main gearbox, shaft bearings, and controllable pitch propeller system) and auxiliary seawater cooling system components (centrifugal cooling pump, remotely control valves, sensors). EHM rule generation is sourced from the data produced by IPMS integrated instrumentation and recorded by EHM module of IPMS. IPMS/EHM data is gathered from a time-based series of IPMS sensors values continuously recorded at specified sampling rates. IPMS system installed onboard of Halifax Class Frigates contains several thousand connected sensors. The parameters measured by the sensors of interest are pressure, temperature, level, linear and rotational speed, angle, position, proximity, voltage, current, power, torque. The type of signals are analog and digital inputs, analog and digital calculation points.

The EHM module is a configurable software that collects, processes, analyzes data and generates customizable reports. The on-board EHM monitors and records any data or processed information pertaining to the on-board machinery equipment monitored/controlled by the IPMS. To achieve this, the EHM acquires data associated with equipment operation and on-line sensors and actuators signals that are continuously polled by the IPMS. The EHM archives this data and then provides the tools to analyze it from a number of different perspectives. The on-board EHM creates a new historical database every month. Available dataset covers several years of operational data for the 12 Halifax Class frigates. EHM data is fully structured in a SQL database. The data contains the following information: time stamp, sensor ID, sensor status, sensor value.

The EHM software functionality allows convenient data querying, data analysis and generation of EHM rules. Preprocessing of raw EHM selected sensors data may include checks for missing values, low signal to noise ratio and outliers removal. The development toolbox includes EHM built-in functions as well as EHM Python programming language tool, which is made available through an EHM Python plug-in. EHM alerts are triggered by EHM rule internal logic using a set of IF-THEN conditions. Specific metrics are used to validate model accuracy (False positive rate or R-square for example) where applicable.

Another large source of data comes from equipment maintenance data, which is stored in RCN DRMIS. This data contains the history of equipment planned and corrective maintenance. This semi-structured data contains equipment ID, running hours, type of maintenance, ship's name and text, describing the findings, details of the maintenance activities, etc. DRMIS database can be queried using several parameters with the resulting dataset saved in MS Excel tables. The data structure allows drilling down to selected component, type of maintenance activity (planned, corrective), maintenance activity description, event date, etc. Maintenance activity description is stored in text format. It contains the details, describing the reasons of corrective maintenance, description of failure, scope of repair, results of inspection and replaced parts.

For selected failure modes, the content of EHM data is examined in regards to its capacity to reflect the symptoms of a failure by the failure descriptors derived from EHM data. Failure descriptors could be directly obtained from EHM data or engineered. If failure symptoms cannot be reflected by Failure descriptors due to instrumentation limitations, i.e. no useful sensors available/monitored, then the corresponding failure mode is excluded from the list of the targeted failures. All equipment failures can be split into three large categories:

1. Failures that actually occurred and therefore failure event is recorded in DRMIS and IPMS/EHM data is available to support further analysis.
2. Failure that actually occurred prior to the installation of IPMS/EHM and no supporting data is available.
3. Failure did not occur, but it may occur in the future if no engineering protection measures are implemented.

For the first category, the associated DRMIS maintenance information is identified and the date of failure noted. With this information, the EHM data covering an ample period leading to the failure, during the failure and up to the time when the failure was rectified is selected. Both data sets are then synchronized by a time stamp to create a subset corresponding to the equipment fault instance. Subsequently, this subset of data is analyzed and failure descriptors are engineered. For the second and third categories, no EHM data existed at the time of the failure. For these cases, failure descriptors are determined by consulting subject matter experts (SME), Original Equipment Manufacturers (OEM) instruction manuals and technical service letters.

All EHM rules can be split in three groups by their functionality:

1. Anomaly Detection.
2. Conditional Fault Detection.
3. Fault Detection.

Anomaly Detection DT alerts an operator in case of a detected anomaly in equipment performance. Anomaly Detection is a condition-monitoring tool, which indicates that the health of equipment is deteriorating without specifying the affected replaceable parts. Related CBM recommendation in this case can contain the recommendation to inspect equipment and identify the affected part(s) or to replace equipment or its component as a unit. Conditional Fault Detection DT is capable to identify a group of replaceable parts while Fault detection is capable to pinpoint the problem to a unique replaceable part.

7. Results

Using the methods described above, it was found that the information provided by the IPMS sensors was sufficient for the analysis of several past failures and supported the design of EHM rules (digital twins) that could provide early warnings. Although some EHM rules for the initially targeted components (e.g. PDE fuel filter, PDE lube oil filter) were not developed due to the absence of the corresponding sensors, numerous EHM rules were designed and implemented into the EHM software. Table 1 summarizes the main EHM rules that were produced in the course of this study and provides a glimpse of the potential CBM coverage that could be enabled by using IPMS sensors.

Table 1: EHM rules

#	EHM rule name	Component/Function	EHM rule descriptor
1	FW PUMP PRESSURE HCF	PDE fresh water cooling system	PDE fresh water cooling pressure deviates from the baselines
2	SW PUMP PRESSURE HCF	PDE sea water cooling system	PDE sea water cooling pressure deviates from the baselines
3	LO PUMP PRESSURE HCF	PDE charge air system	PDE Lube oil circulating system pressure deviates from the baselines
4	CHG AIR PRESSURE HCF	PDE Lube oil circulating system	PDE charge air system pressure deviates from the baselines
5	ENGINE START AIR PRESSURE DROP DEVIATION	PDE starting air system	PDE starting air consumption at engine start is above the expected value
6	TURBOCHARGER A/B SPEED UNBALANCED	PDE exhaust gas system	Difference between speed of PDE Turbochargers A & B is above the expected value
7	FW PRE-HEAT PRESSURE	PDE fresh water pre-heat system	PDE fresh water pre-heat pressure deviates from the baselines
8	TURBINE INLET TEMP A - B DIFF HCF	PDE exhaust gas system	Difference between inlet exhaust gas temperature of PDE Turbochargers A and Turbochargers B is above the limit
9	PDE MAIN BEARINGS DIFF TEMP HIGH/LOW HCF	PDE lube oil circulating system	Corresponding PDE main bearing temperature deviates from the baselines
10	TURBOCHARGERS SPEED HCF	PDE exhaust gas system	PDE Turbochargers (A, B) speed is above/below the expected baseline

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#	EHM rule name	Component/Function	EHM rule descriptor
11	MLO PUMPS PRESS DIFF AVG DEV	Main gear box lube oil system	Difference between MLO pumps pressure is above the limit
12	PLUMMER BEARINGS LO TEMP DIFF AVG DEV	Main shaft line	Difference between corresponding plummer Port and Stbd bearings temperature is above the limit
13	THRUST JOURNAL BRGS TEMP DIFF HCF	Main shaft line	Corresponding thrust bearing temperature deviates from the baselines
14	CPP PRESSURE FLUCTUATION RATE AVG DEV	Controllable pitch propeller hydraulic systems	Corresponding CPP main oil pressure fluctuation rate is above the expected limit
15	FW PRESSURE NOT UPDATING	PDE fresh water cooling system	Corresponding signal not updating
16	FW PRESSURE SNR LOW	PDE fresh water cooling system	Corresponding signal not updating
17	LO PRESSURE NOT UPDATING	PDE Lube oil circulating system	Corresponding sensor's signal to noise ratio (SNR) is above the limit
18	LO PRESSURE SNR LOW	PDE Lube oil circulating system	Corresponding sensor's signal to noise ratio (SNR) is above the limit
19	PDE RAMP RATE LOW	PDE Speed control system	PDE speed ramp rate is below the expected value
20	SUPPLY VALVE TO CHILLER OPEN/CLOSE TIME	Auxiliary system Chillers	Corresponding remotely controlled valve's operating time is longer than expected
21	PDE STEADY STATE SPEED OSCILLATION	PDE Speed control system function	PDE speed fluctuates excessively
22	AUX PUMP TEMPERATURE SNR LOW	Auxiliary system Auxiliary Sea Water Circulating Pumps	Corresponding sensor's signal to noise ratio (SNR) is above the limit
23	AUX PUMP TEMPERATURE GRADIENT HIGH	Auxiliary system Auxiliary Sea Water Circulating Pumps	Corresponding sensor's signal rate of change is above the limit
24	AUX PUMP TEMPERATURE CALIBRATION	Auxiliary system Auxiliary Sea Water Circulating Pumps	Corresponding sensor requires calibration
25	MAIN BEARINGS TEMP SENSOR HEALTH WATCH	PDE Lube oil circulating system	Corresponding sensor's signal rate of change is above the limit
26	TURBOCHARGER INLET - OUTLET TEMP WATCH	PDE exhaust gas system	Difference between inlet and outlet exhaust temperature of PDE Turbocharger is below the limit
27	TURBOCHARGER INLET TEMP WATCH	PDE exhaust gas system	Difference between average PDE bank and inlet exhaust temperature of corresponding PDE Turbochargers is above the limit
28	TURBOCHARGER SPEED OSCILLATION WATCH	PDE exhaust gas system	Speed of corresponding PDE Turbocharger fluctuates excessively
29	TURBOCHARGER SPEED SENSOR FAILURE WATCH	PDE exhaust gas system	Corresponding sensor's signal rate of change is above the limit
30	FW PRE-HEAT TEMP FROM STARTUP WATCH	PDE fresh water pre-heat system	PDE fresh water preheat temperature is not within the limits (Water heater fault)
31	FW PRE-HEAT TEMP CONTROL WATCH	PDE fresh water pre-heat system control function	PDE fresh water preheat temperature is not within the limits (Temperature control fault)
32	FW PRE-HEAT TEMP CHANGE RATE WATCH	PDE fresh water pre-heat system	PDE fresh water preheat temperature increase rate is lower than expected

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#	EHM rule name	Component/Function	EHM rule descriptor
33	THRUST JOURNAL BRG LO TEMP SENSOR HEALTH WATCH	Main shaft line system	Corresponding sensor's signal rate of change is above the limit
34	CPP PRESSURE WATCH	Controllable pitch propeller hydraulic system	Corresponding CPP main oil pressure is above the expected low/high pressure warning/alarm limit

8. Discussion

The result of this study shows that IPMS data contains the necessary information that allowed building EHM rules for many targeted equipment components, subsystems and their critical functions. Implemented EHM rules monitor equipment health from the various perspectives. The systems and components described in Table 1 make up for a larger part of machinery, devices and systems related to corresponding equipment. It shows a high degree of coverage of related systems and components by the EHM rules. The results also demonstrate that IPMS based EHM rules can be applied to various types of equipment, systems and their functions. Consequently, the footprint of CBM can be expanded beyond the group of equipment selected for this study.

Some EHM rules, which were initially developed for specific components, such as remotely controlled valves, can now be easily applied to all similar components across the ship systems. For remotely controlled valves, the range of applicable equipment includes vent flaps, fire dampers, quick closing valves and watertight doors assuming the required instrumentation is connected to IPMS.

Some processes and functions of selected equipment were relatively well represented by the integrated sensors, such as Propulsion Diesel Engine (PDE) turbochargers where the list of IPMS related sensors included Turbocharger speed, Turbocharger inlet and outlet temperature, Average banks exhaust temperature. Some components or subsystems were underrepresented, for instance there is no IPMS integrated PDE main fuel filter pressure differential signal. As a result, the initial list of targeted failure modes was revised and for some of them the attempts to generate corresponding EHM rules were abandoned.

For many failure modes, a selection of a unique set of features, which could unambiguously identify specific failure, was deemed unfeasible given the data features. Thus, the available integrated sensors reflect the state of a whole component or a group of replaceable parts and not a unique part. Consequently, applied DTs functionality was limited to Conditional Fault Detection or Anomaly Detection. For instance, PDE LO PUMP PRESSURE HCF DT maintenance warning would point to several PDE Lube Oil Circulating Pump replaceable parts as a potential source of failure, including pumping element assembly, pump relief valve and a loss of LO piping integrity. In order to reduce the uncertainty as to what equipment part is causing the observed performance deterioration, EHM DT maintenance advisory should be amended with recommended additional troubleshooting steps.

The considerable number of failed IPMS sensors instances was observed in IPMS datasets. Failed sensors might be a source of EHM rule false positive alarms. Therefore, a verification of the technical health of equipment-associated sensors should become a prerequisite for any EHM rule.

During the reference models building process, various techniques and tools related to the definition of equipment steady states, transients removal, detection of outliers, as well as determination of the components, constituting specific operational conditions were designed and implemented. For instance, in order to determine the PDE steady state the following descriptors were utilized: PDE speed and its fluctuation, PDE speed setting change, difference between achieved PDE Speed and PDE speed setting value, PDE fuel rack fluctuation. In some cases, the rudder angle position and its maximum values were added to the list of conditions to be met in order to confirm that PDE is in steady state.

The EHM rules developed during the project have been deployed on one of the Halifax Class frigates. At the time of writing this article, the author obtained access to EHM logs produced by the implemented rules during 1 month of their trial period. A brief review of the EHM logs has been carried out. Although certain rules require some adjustments, the preliminary results seem to indicate that the rules can be effective.

9. Conclusion

In general, the objectives of this study were achieved. IPMS/EHM proved to be a useful source of data to support an eventual shift from PM to CBM. Capabilities of existing IPMS configurations in regards to its capacity to support the shift to CBM strategy were better understood. Further benefits were also identified as possible if the CBM requirements are considered at the time of the IPMS design. The basis of digital twin ready control systems design was developed. It can be applied to future generations of IPMS to ensure that they will be built keeping CBM requirements in mind.

During the course of this study, Digital Twins engineering process has been developed and analyzed by Lloyd's Register. As a result, Digital Twin engineering process received "Digital Twin Ready Approval in Principle" certification.

This study helped to supplement already existing RCN data analytic tools and procedures with EHM rules. It is anticipated that EHM rules will assist in maximizing the success of IPMS data utilization. This study also determined the main phases of data driven CBM strategy implementation.

Further work on Halifax Class CBM is necessary to evaluate the validity and usefulness of the CBM recommendations in more detail. Additional efforts should be taken to apply EHM rule to other critical equipment, their components and systems. Potential process enhancements include reduction in EHM rules development time, streamlining EHM rules implementation process of similar components (such as pumps, sensors, valves, and heat exchangers), completion of Lloyd's Register certification of DT development process.

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This paper has been reviewed in accordance with the International Traffic in Arms Regulations (ITAR), 22 CFR PART 120.11, and the Export Administration Regulations (EAR), 15 CFR 734(3)(b)(3), and may be released without export restrictions.

References

Lloyd's Register. ShipRight Design and Construction Digital Compliance Procedure for the Approval of Digital Health Management Systems. Lloyd's Register Group Limited, London, United Kingdom, 2018.

Glossary

Table 2: Abbreviations/Acronyms

Abbreviation/Acronym	Description
AUX	Auxiliary
BRGS	Bearings
CHG AIR	Charging Air
CBM	Condition-Based Maintenance
CPP	Controllable Pitch Propeller
DIFF	Difference
DRMIS	Defence Resource Management Information System
DT	Digital Twin
EHM	Equipment Health Monitoring
FMEA	Failure modes and effects analysis
FW	Fresh Water
HCF	Health Confidence Factor
IPMS	Integrated Platform Management System
LO	Lube Oil
MLO	Main Lube Oil
OEM	Original Equipment Manufacturer

Abbreviation/Acronym	**Description**
PDE	Propulsion Diesel Engine
PM	Preventive Maintenance
PRESS	Pressure
RCN	Royal Canadian Navy
SCADA	Supervisory Control and Data Acquisition
SME	Subject Matter Expert
SNR	Signal to Noise Ratio
SW	Sea Water
TEMP	Temperature

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