SMART CONDITION BASED MAINTENANCE SYSTEM (SMART CBM)

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ABSTRACT

Conventional Onboard Condition Based Maintenance (O-CBM) and Integrated Condition Assessment Systems (ICAS) are concerned with assessing the health of main Propulsion and Electrical systems equipment onboard Marine vessels. Land based CBM (L-CBM), Fleet wide CBM (f-CBM) and Enterprise CBM (e-CBM) are extensions of an O-CBM and provide capability at shore to perform detailed analysis on raw data obtained from onboard the target vessels. Such data could be benchmarked against manufacturers' performance data, as well as against vessels equipped with similar equipment, in order to best identify anomalies and to plan remedial maintenance actions. However, CBM or ICAS should not be limited to main Propulsion and Electrical systems equipment. To achieve higher survivability, higher equipment availability and optimum operations at lower fuel costs, demands the deployment of a smart maintenance management system that provides Integrated Situational Awareness on mission critical equipment related to the target ship(s) Machinery, Combat system, Communication and Navigation systems as applicable. This paper presents an integrated smart CBM suite using advanced analytics that is equipped with Situational Awareness and Fuel Saving features to best assist the crew onboard Naval and Commercial vessels, with appropriate secure interfaces with shore based maintenance centre(s) for situational awareness. The analytics engines of the presented CBM are provided by Caterpillar and are fully integrated and tested with the L-3 MAPPS Integrated Platform Management System (IPMS). The above will ultimately result in lower Life Cycle Cost (LCC)

KEY WORDS

Fuel efficiency, Energy efficiency, Integrated Platform Management System (IPMS), Condition Based Maintenance (CBM), Life Cycle Cost (LCC), Onboard CBM (O-CBM), Land-based CBM (L-CBM), Fleet CBM (f-CBM), Enterprise CBM (e-CBM), Engineering Control System (ECS), Smart Condition Based Maintenance (Smart CBM), Vibration Monitoring System (VMS).

1. INTRODUCTION

Many Navies and ship owners have considered various forms of CBM for their vessels. Some ship owners also obtain limited sensor data from onboard their vessels to monitor various voyage related information, albeit not necessarily through secure communication channels. Yet, less emphasis has been noted on ship wide CBM scheme encompassing equipment beyond Propulsion and Electrical subsystems and as an integral part of their IPMS (ie: Automation System or Engineering Control System).

The Smart CBM complements and broadens the application of a conventional onboard CBM to

Navigation, Communication and, where applicable, to selected Combat System related equipment; whose equipment performance and operational status could be monitored and assessed efficiently and centralized. Smart CBM can include fuel optimization benchmarking based on analyzing engine operational data, that can help planning the most fuel-efficient engine combinations for any underway event or identifying opportunities to fine tune individual equipment to optimize fuel or energy consumption; stack emissions, oily waste separator discharge and ballast systems can all be monitored and integrated with GPS position to provide shipboard operators with the tools they need for environmental compliance. Data on ship position and navigation tracking, route planning, speed and other general ship sensor and situation awareness data related to the target ship are an integral part of a smart CBM. This will include transmittal of guidance and information exchange from shore based locations on multitude of subjects including security and other threats.

Increased operational demands, threats, smaller crews have forced CBM suppliers to become innovative in how they design, integrate and deploy hardware and software for optimum ship maintenance, low cost operations, higher availability and survivability against potential threats and ease of operations. Situational awareness has become an integral part of such deployment strategy and encompasses fuel economy assessment according to speed, sea conditions and engine configuration, predictive maintenance, remote systems and equipment monitoring, remedial action as well as survivability improvement and ship readiness status advisories.

The smart CBM presented in this paper includes consideration for all the above and facilitates integration with desired ship subsystems equipment through the ship's Engineering Control System (ECS). Above all, its main software engine allows the specialists at the Logistics Command/shore based centre to simultaneously compare and assess the performance of a range of ships in the same Class (fleet) or all ships of different Classes (enterprise wide) in order to improve anomaly detection, diagnostics and remedial action.

In comparison with conventional CBM which lacks historian performance data, the proposed smart CBM provides historical performance data as reference point for main engines, generators and critical auxiliary equipment in order to provide meaningful diagnostics from day one of operations. In additional, it provides rule based diagnostics that improves anomaly identification and assists crew with appropriate advisories.

Ship owners are interested in an effective and technically feasible solution to continuously monitor crew and shipboard operational needs, operational costs, security, and readiness status while their ships are pier side or at sea. The above situational awareness factors are an integral part of the smart CBM. When desired, the above also integrates and communicates images from CCTV, hand held maintenance devices, vibration monitoring as well as reports from target ship to shore based facility.

In this paper, advanced features of the SMART CBM are presented. Implementation of a system with these features would improve analysis and diagnostics, maintenance planning and will ultimately result in an improved Life Cycle Cost (LCC).

2. CBM BACKGROUND

The capabilities of conventional Equipment Health Monitoring (EHM), Condition Based Maintenance (CBM) and Integrated Condition Assessment System (ICAS) applications have continuously evolved. However, the purpose and product capability of each the above subsystems are different and at times not fully appreciated by the end users.

In general, conventional EHM and ICAS products lack capability for providing historical data, detailed or rule based diagnostics & advisories for remedial action. They are mainly concerned about main propulsion engines and electrical generators and perform monitoring and reporting functions. They may be integrated with the Ship ECS (automation system) or, as in most cases, are deployed as standalone systems onboard naval/commercial vessels.

A modern CBM is an integral part of the vessels Engineering Control System (ECS) and interfaces with ship subsystems sensors through the ECS data communication network. This facilitates access to sensor data from main Machinery, Navigation, Communication and Combat (where applicable) systems related equipment. The ECS Interactive Electronic Technical Manual (IETM) provides an added benefit for rapid access to the desired equipment's manuals, drawings, maintenance procedures and diagnostics; all in all providing extra intelligence.

In addition, a modern CBM monitors and predicts machinery failure modes and by taking online and manually entered data, it compares the data with established engineering performance criteria/historical data in support of the condition based maintenance philosophy. It interfaces with ship Navigation related equipment and sensors, radar system, gun/missile mount hydraulics and motors in addition to Propulsion engines & Electrical generators.

Furthermore, a modern CBM should:

- Incorporate editable rule set. Rules for how equipment should operate based on OEM technical manuals or other user-supplied documentation should be developed and configured for each model of equipment. The rule sets should be changeable outside of the CBM system software code so that future changes to the rule set will not necessitate recompilation and redeployment of the base software itself.

- Provide failure mode level information for monitored units. Individual pieces of equipment should be modeled in such a manner that failure modes for each unit are displayed at both the unit level and the system level, and each failure mode can be drilled down to provide actionable information for the user.

- Tablet-based manual log keeping. Equipment readings that are not available on a data bus should be able to be easily logged on an electronic tablet, such as an iPad® that is interfaced with the CBM.

The on board CBM (O-CBM) system ideally should provide all the information required for establishing a condition-based maintenance process. However, the realities of reduced manning, aging equipment and increased repair costs work against the shipboard-only paradigm. A cost effective solution requires getting the gathered data off the ship and into the hands of the maintenance managers in as timely a manner as possible. This has given rise to the deployment of effective Land Based CBM (L-CBM)[1].

It is important to consider an L-CBM that is coherent with and fully integrated with the O-CBM that is deployed on target vessel(s). This is because there is a need for data exchange between the two autonomous systems.

In the next sections of this paper, various features of a SMART CBM are presented.

3. SMART CBM MAIN FEATURES

The need for reducing ship Total Ownership Cost (TOC) through initiatives such as OEM partnering, design improvements, reducing crew size, and remote monitoring has evolved over the years. There is an increased demand for improved preventive maintenance, fuel economy, efficient identification of potential operational failures, improved recovery from failures based on lower MTTR, better survivability, and improved situational awareness under damaged conditions. The above has given rise to a new generation of condition assessment system; SMART CBM.

As a central maintenance management suite, through the ECS and its interfaces, the SMART CBM obtains information from Vibration Monitoring Systems (VMS), and oil debris monitoring system. Both of these are possible in online monitoring configurations (preferred), or via Portable Data Terminal (PDT) and Portable Data Analyzers (PDA). The PDT is a hand-held unit used for manually acquiring engineering plant information. The PDA is a portable, wireless communication, field-use instrument which facilitates machinery condition monitoring by enabling the acquisition and storage of vibration data including vibration spectrum data and other related information.

In addition, the SMART CBM integrates online and offline data sources as well as from plant historians and other reliability applications. It provides users with the ability to "qualify" data for various user-definable machine states such as Online/Loaded, Online/Unloaded, Online/Steady State or Start-up. This qualification capability allows the creation of unique rules and alarm set points for each defined machine state. Any of these data may be trended, alarmed, or used as inputs to rule logic, either individually or in combination, to detect and diagnose machinery failures and drive operational and maintenance decisions.

The SMART CBM provides an effective means of observing equipment performance over time, anticipating failure based on historical data and planning maintenance based on material condition. However, shipboard systems by their nature are constrained to equipment operations inside the lifelines of one ship.

Key to optimizing remote monitoring for a class of ship or a fleet of ships is a central piece that provides the operational and maintenance decision makers with the flexibility to monitor individual ship equipment data fed from the O-CBM systems, aggregate data by ship and by equipment model, and provide a means by which they can feed back maintenance recommendations to the ship's crew in a timely manner.

As shown in Figure 1, through full integration of CBM functions with the ECS and other mission critical ship systems, optimum Equipment Health Monitoring (EHM) objectives are achieved. The SMART CBM can incorporate:

- Combat systems hydraulic, pneumatic and motor systems & other combat related mission critical subsystems
- Stores and ammo elevators and conveyors
- Ballast and deballast systems & Tank Level Monitoring
- Damage control remote operated valves/actuators, water mist and fire door systems
- Organic air asset performance data
- Refrigeration system
- Fuel system related equipment
- Navigation systems equipment & sensors
- Desired Internal and External Communication subsystems equipment
- Aux and Anc. subsystems and systems too specific to a particular class of ship, including pumps, valves & motors.

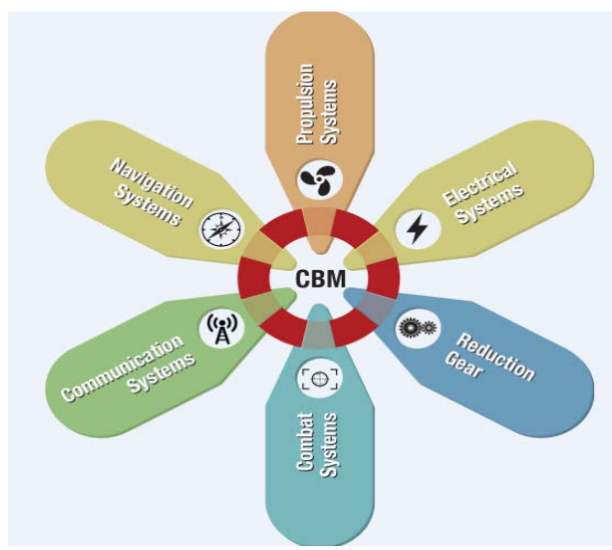

Figure 1 – SMART CBM Applications

3.1 SMART CBM's ANALYTICS AND RULE SET

The most modular and most essential piece of a scalable, extensible SMART CBM is the incorporation of "plug-in" analytics or rule sets mapped to individual model operating parameters and configured to the sensors for each ship in which that model is installed. Graphical rule development is characterized by

- Use of a combination of crisp rule sets and anomaly detection rules to provide early warnings of functional failures
- Rule based logic that can contain but is not limited to time-based evaluation, parameter exceeding limits, and curve-based/parametric performance evaluation
- An anomaly engine that utilizes historical performance data to set baseline conditions against which all future parameters are compared
- Machine state qualification to ensure only relevant data is analyzed for specific failure modes

The rule sets are self-contained in that they can be modified based on the needs of the customer without modification of the CBM core software.

The land-based rule sets take the data provided from the ship and display the data as qualified by the rules in the same manner as in the ship-based system, only in the land-based system, the user is able to pull that data for all ships under review. As sensors are added or removed from a system or operational parameter set points are changed, the rule sets can be modified easily to consume the data as required.

3.2 SMART CBM's FAILURE MODE

The failure mode level drill down capability for each unit configured in the shipboard system should also be available for review and troubleshooting on the land-based system. The rules applied to unit sensors provide diagnostic roll-ups for each piece of equipment and can be used to troubleshoot potential problems beyond the ability of ship's force to identify. A system level "stoplight" type display can provide a quick view for supervisory personnel and can be expanded for more serious pathology of machine conditions.

Furthermore, drill down displays, status strips and plots can be configured to show out of limit areas. The plot range should coincide with a selectable number of days passed.

An enterprise tool to view frequency of failure for each failure mode across all ships equipped with a particular model of equipment is considered an indispensable piece of the SMART CBM. Maintenance and lifecycle managers can determine causes for high failure rates on particular ships or for ships deployed to particular areas or even for ships which have had repair work conducted by specific facilities.

3.3 SMART LAND BASED CBM

Another feature of the SMART CBM is the ability for a subject matter expert to review shipboard data, modify statuses and insert maintenance or repair recommendations/advisories that via a report could be sent directly to the ship and its support infrastructure. This is clearly a force multiplier since the pool of SMEs ashore is much larger than on a ship. Moreover, SME remote assessment of shipboard equipment can be a substantial money saver.

For ship owners/operators of mission critical commercial vessels who have remote access to the shipboard control systems (through secure, encrypted or secure non-encrypted media) a cost effective Fleet wide CBM (f-CBM) can further enhance Maintenance Management for a Class or Fleet of ships. As a result, the f-CBM could compare performance of similar equipment across a Class of Ship or over the complete Fleet as applicable.

3.4 SITUATIONAL AWARENESS

As mentioned earlier, it has become essential for navies and commercial ship owners to have improved visibility on their crew's technical support needs, voyage data, fuel consumption, equipment and systems readiness status, maintenance needs, potential operational risks and threats, methods adopted on provision of advisory for ship crew, failures and damage status, etc. However, in most cases today, ad hoc and selected information is exchanged between shore base and target ship(s). The data transmission risks and cyber security issues are also not fully addressed by solutions that are currently deployed by some ship owners. Furthermore, standalone systems are used with minimum system integrations.

Situational awareness is therefore considered as an integral part of the SMART CBM. Being an integral part of the target ship's IPMS solution, the SMART CBM readily obtains intelligence on systems and equipment status from the IPMS and other ship systems:

- Sensor data
- Manually entered data related to equipment status
- Equipment & Systems readiness and availability status
- Equipment damaged status, repair status, failures and expected future failures due to cascading effect
- Desired information from Navigation, Communication and Combat systems equipment
- CCTV images related to incident locations and areas monitored by CCTVs
- Fuel consumption, fuel reserve and fuel economy related factors
- Risks and threats
- Location of key crew
- Equipment Health Monitoring (EHM) data for IPMS related equipment, as well as Navigation, Communication and Combat systems equipment through interfaces.

Figure 2 illustrates Smart CBM integration with the IPMS.

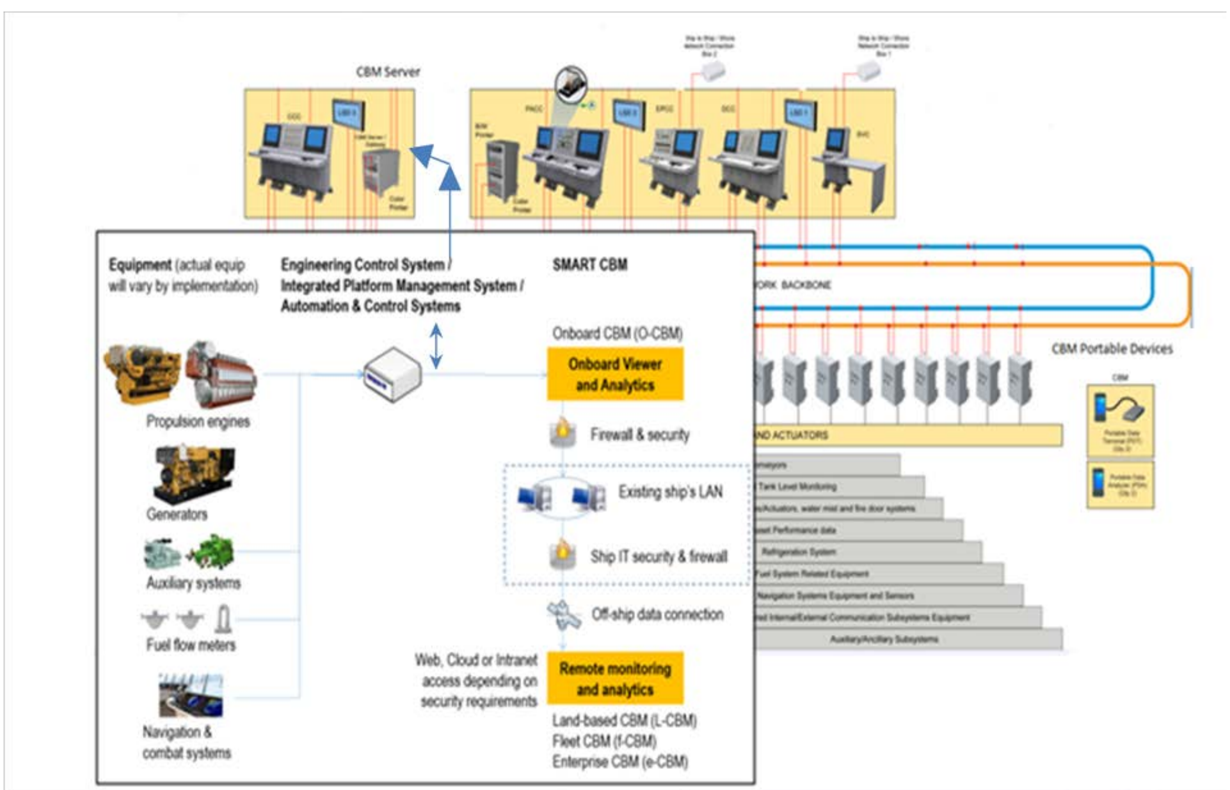

Figure 2: Smart CBM Integration with IPMS

As a result of the SMART CBM deployment as an integral part of the IPMS, the navy's Logistics Command and Commercial ship owners will have full situational awareness. The CBM also will be empowered to provide detailed assessment of equipment availability and conditions in order to provide meaningful maintenance strategy, advisories and information on ship readiness status. When combined with f-CBM or e-CBM capabilities and interfaces, the onboard SMART CBM will cover Fleet and Enterprise schemes.

3.5 BENEFITS OF INCREASED FUEL & ENERGY EFFICIENCY FOR NAVAL VESSELS

Increasing fuel and energy efficiency has shifted from a 'nice-to-have' to a strategic imperative for many Navies around the world. In the current world of increasing defense budgetary pressures yet higher operational tempos, fleet leaders are looking for ways to sustain operations at lower cost. Fuel is a significant cost for every Naval Vessel, often being the second largest lifecycle cost behind onboard crew.

The most obvious benefit of maintaining and operating equipment to drive energy and fuel efficiency is the reduction in fuel consumption. These direct fuel savings can be measured and attributed to specific actions, whether maintenance or operations.

In addition to the cost of the fuel that is saved, there are the costs of delivering that fuel to the vessel. In many situations, this fuel is being delivered to where operations are occurring, potentially via Naval replenishment vessel or to a remote or potentially troubled area. The costs involved in distribution should not be underestimated. The US military estimated that the cost per gallon of fuel to be delivered to remote areas of Afghanistan to be up to $400 per gallon[1] and delivery at sea can cost between five and fifty times the market price[2]. While these costs are real, they are often not immediately apparent, but should be included. Eventually, a decrease in fuel logistics services demand could lead to lower required capital investment in fuel distribution resources (Naval supply vessels, etc).

A tertiary impact of better fuel efficiency and fuel conservation is the resulting increased vessel range. Whether coming off-station for underway replenishment or going completely off-station for in-port refueling, these gap periods must either be covered by another vessel or there is a potential gap in the mission coverage. Increasing fuel efficiency enables greater time on station as a percentage of total time, less time off-station in underway replenishment or transit to a fueling location and therefore greater fleet readiness and higher likelihood of mission accomplishment. With extended range and time on station, the same mission could either be accomplished with fewer assets, greater redundancy of assets on station or decreased crew deployment time. This increased fuel efficiency provides fleet commanders with increased options for how to achieve mission success while balancing other objectives.

Lastly, in addition to the fuel savings, fuel logistics savings and the increased range/time on station, optimizing operations for fuel and energy efficiency usually results in less equipment online at a particular time (while ensuring appropriate redundancy for mission requirements). This in turn, slows the wear on equipment, enabling deferral of maintenance (and associated cost) and extension of equipment life – both of which reduce TCO and WLC.

3.6 OPPORTUNITIES AND VALUE OF USING A FLEETWIDE SMART CBM TO REDUCE FUEL AND ENERGY COSTS

The marine industry brings together the complexity of both power generation assets (main engines, generators) and energy consumption assets (shaft, thrusters, compressors, cranes, air conditioning, water production, electronics, etc). While many industries focus their efforts on just one piece of this, a ship has to focus on both the energy production and consumption sides of the equation. This complexity underscores the value that collecting operational and condition data in real-time and automatically analyzing can have above what an onboard operator

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[1] http://thehill.com/homenews/administration/63407-400gallon-gas-another-cost-of-war-in-afghanistan-

[2] Grace V. Jean, "Greening the Fleet: Navy's Energy Reform Initiatives Raise Concerns among Shipbuilders," National Defense (April 2010), p. 37.

can do with simple spreadsheets. Driven by rising fuel costs, many owners and operators have already acted on many of the 'low hanging fruit' opportunities for energy efficiency. The next wave of increased efficiency will require optimizing the entire vessel as a system, instead of just a single asset.

A. Equipment tuning and maintenance to drive efficiency savings

Optimizing how equipment is maintained and tuned can enable dramatic fuel savings. This white paper walks through a few examples of different types of fuel efficiency opportunities; these are not meant to be exhaustive, but rather illustrative examples of a larger opportunity across a wide range of equipment. Opportunities are usually found across both energy producers (engines, generators, etc) and energy consumers (air conditioning, water desalinization, refrigeration, etc). These can drive 10-30% percent energy or fuel savings for a piece of equipment, which can then add up across an entire vessel for significant efficiency gains.

Diesel engine example: Faulty fuel injectors identified to save fuel

For a vessel with two high speed diesel engines, the condition of the fuel injectors was also able to be monitored using onboard sensors and data analytics as part of the Caterpillar Marine Asset Intelligence (MAI) technology platform. The analytics were able to identify when the fuel injectors were likely fouled even before their scheduled replacement by analyzing the exhaust temperatures, engine speed, and fuel consumption. The analytics identified specific fuel injectors that were likely fouled and were costing an extra $175 per day in excess fuel consumption (equivalent to $52,500 per year); all of which would not be able to be identified by the onboard crew because the engine appeared to be operating normally. In this case, the fuel injector replacement paid for itself in approximately three days as well as reduced wear on the engine and avoided a potentially catastrophic engine casualty had this not been addressed when it was.

Air Conditioning example: High Superheat, Fouled Condenser and Capacity Control

Air conditioning plants are essential to keeping critical combat systems operational, and they are also typically large consumers of energy onboard (and therefore driving increased electrical generation and associated fuel burn). There are many examples of where improving the maintenance and condition of air conditioning plants results in significant savings for Naval Vessels. In one example of a Naval vessel with four 200 ton air conditioning plants, the plants were monitored by the Marine Asset Intelligence (MAI) analytics package, which when analyzing discharge saturation and condenser liquid line differential temperature, compressor suction superheat, compressor suction pressure and compressor discharge pressure was able to identify high superheat. This issue was causing $159,000 in excess energy costs per year that were avoided by fixing the issue.

In another situation, the MAI analytics were able to identify a fouled condenser before it was scheduled to be cleaned by analyzing compressor oil temperature, chill water outlet temperature, discharge saturation liquid line temperature, liquid line temperature and the sea water outlet temperature, resulting in savings over $200,000 in energy costs on an annualized basis. This also was putting 50% more wear on the equipment than necessary, resulting in a shortened remaining useful life.

Reverse Osmosis example: Fouled membranes

Optimizing maintenance and operations of other equipment can also trigger large energy savings. In an example onboard a Naval vessel, the MAI analytics were able to identify reverse osmosis membranes that were getting dirty faster than scheduled replacement. This was causing $3500+ per year in increased energy consumption, as well as decreased water production (which could impact operations).

B. Vessel Operations Improvement to Reduce Fuel Consumption

Not only can equipment be maintained in a better manner to increase fuel efficiency, the equipment, and the entire vessel can be operated in a manner to enable better fuel efficiency.
In the case of a harbor tug that was monitored using the MAI analytics platform, the optimal speed was determined based on incorporating the actual engine data, fuel consumption and vessel performance data. Transiting to and from operations at the optimal

speed versus what 'feels right' equated to up to $110,000 per year in fuel savings for this particular tug. A monthly report was also established to create transparency into vessel performance and fuel efficiency for the future.

In another situation, the MAI analytics platform was able to assess the overall vessel efficiency and the impact of hull fouling on the vessel in order to optimize when the hull should be cleaned. This saved the vessel owner approximately $300,000 per year in decreased fuel costs compared with just doing hull cleanings on the previous scheduled basis.

C. Optimizing equipment configuration

There are many systems onboard Naval vessels that have multiple equipment installed, both for combat redundancy, as well as the ability to scale up and down to meet current requirements. Examples of these are generators and air conditioning plants. Ensuring that not only the correct number of assets are online for the required load (outside of mission requirements) can drive significant savings. These can be even greater if the specific permutation of equipment is online based on its actual condition.

In the first example, a vessel with four generators, with a highly variable load, was able to use MAI analytics to not only ensure the correct number of generators were online, but also to ensure the optimal specific generators were online based on their current condition (assessed automatically by the MAI analytics) for that specific load level. By ensuring that the right number of generators was online, savings of $50-250 per hour were achieved. Compared with the historical operating profile, this equated to approximately $250,000 per year in savings. In addition to just identifying whether there should be one, two, three or four generators online, identifying the specific combination for a given load level based on the analyzed condition was able to save up to $50 per hour in fuel costs – equating to over $100,000 per year in savings based on their historical operating profile.

In a second example, analytics were used to improve the energy efficiency of air conditioning plants where too many plants were kept online for the required load. This resulted in the air conditioning plants being operated in a sub-optimal configuration, resulting in an annualized $350,000 in additional energy costs had this issue not been identified and corrected. Similar to the fouled condenser, not only were there very clear and immediate energy savings, by identifying this issue, unneeded air conditioning plants could be taken offline, thus reducing equipment wear and extending the remaining useful life of these assets.

Both of these opportunities required no maintenance to be conducted or parts to be installed, but rather operators using better information to decide which assets to have online in a given situation.

D. Enterprise resource prioritization and best practice identification

Similar to improving maintenance and reliability, data analytics can also be used to look across a fleet or an enterprise to improve fuel efficiency. Using data analytics can identify the vessels that are most efficient as well as the vessels that are least efficient. Resources can be focused on the least efficient vessels to improve the fuel and energy consumption, while the organization can learn from the most efficient vessels as to what is enabling their reduced fuel consumption. This enterprise view can also enable analysis regarding vessel design and equipment choices; by analyzing multiple vessels of multiple designs and equipment profiles, managers can make better future design and equipment selection decisions.

The preceding examples are all focused on a individual vessels. The value of data analytics and its impact on maintenance and reliability increases significantly when used across a fleet of vessels. For example, traditionally, each chief engineer works through the issues on his vessel individually. Those same problems may be evident on other vessels, yet he likely is not aware and is not able to leverage the learning of the other crews (especially if the vessels are not geographically concentrated). Leveraging data analytics across the fleet can help identify common issues, which can be elevated above the individual ship level and be solved at the enterprise level.

4. CONCLUSION

This paper presented a comprehensive approach to using the analytics that can be added to a SI-CBM, O-CBM and L-CBM system to improve fuel and energy efficiency for Naval vessels. The savings can easily be in the hundreds of thousands of US Dollars per year, based on equipment analyzed, operating profile, etc. In an age of increased defense budgetary pressure, this represents an excellent opportunity to increase fleet efficiency, while also driving increased readiness, reliability and availability of the fleet.

BIOGRAPHY

Dr. Reza Shafiepour obtained BSc in Electrical Engineering from Newcastle Polytechnic (Northumbria University) in 1980, MSc in Power Transmission and Distribution from UMIST (Manchester) in 1982 and PhD in Power Systems Control & Monitoring from Durham University in the UK in 1986. His expertise in Control Systems is as a result of working at Industrial Companies in the UK and Canada; including Westinghouse Systems Ltd (Schneider- UK), National Grid Company (UK), CAE Inc (Canada), L-3 Communications MAPPS (Canada). He is currently a Regional Director at L-3 Communications MAPPS Inc. in Canada with involvements in Business and Product development. He has contributed to various product evolution initiatives, including Battle Damage Control System, Condition Based Maintenance, Situational Awareness, and integration of Smart Technologies to Engineering Control System applications.

Mr. Ken Krooner, Operations & Technology Manager for Caterpillar Marine Asset Intelligence, is a graduate of Old Dominion University (BS Engineering Technology). He has over fifteen years of experience in operations, planning, and program management in the marine engineering field. He has over 15 years experience with designing, developing, and implementing condition based maintenance (CBM) and condition based operations (CBO) strategies within the Navy and commercial industry, using the Shipboard Level and Enterprise level Performance and condition monitoring technologies. Caterpillar Marine Asset Intelligence was formed in 2015 after the acquisition of Engineering Software Reliability Group (ESRG), which Mr. Krooner founded in 2000.

Mr. Rob Bradenham is the Global Sales and Business Development Manager for Caterpillar Marine Asset Intelligence. Marine Asset Intelligence helps owners and operators use analytics and expert advisory services to reduce downtime and improve total cost of ownership. Mr. Bradenham has spent most of his professional career in maintenance and operations of industrial equipment, both as an Associate Partner with McKinsey & Co, the global management consultancy, where he served a wide-range of large industrial organizations on their operations and maintenance, and as officer in the US Navy, where he managed maintenance and operations on surface ships. Mr. Bradenham has a Bachelor’s Degree in Finance and a Master of Business Administration from the University of Virginia.