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Lieutenant-Commander Susannah Chen

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CANADIAN FORCES COLLEGE – COLLÈGE DES FORCES CANADIENNES

JCSP 48 – PCEMI 48
2021 – 2022

Exercise Solo Flight – Exercice Solo Flight

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ROYAL CANADIAN NAVY – TRANSFORMING MAINTENANCE THROUGH DIGITAL TECHNOLOGY ADOPTION

INTRODUCTION

Ready, Aye, Ready – the motto of the Royal Canadian Navy (RCN) that signifies that we are always "Ready". Underpinning this three-word motto are thousands of hours of maintenance to ensure the ships are at optimal technical readiness for deployments and missions. The RCN's maintenance philosophy is conservative, based on planned maintenance after so many hours/periods of operation to attempt to prevent equipment failure, without understanding the actual condition of the equipment or system. Unexpected failures still occur due to various reasons, such as age or overloading, etc, or other reasons that are sometimes difficult to pinpoint despite extensive investigation, then corrective repairs are carried out to fix the problem. Preventive and corrective maintenance consumed significant number of labour-hours for ship personnel, fleet maintenance facilities and contractors, not to mention the time the equipment becomes unavailable while maintenance are being conducted. Depending on the criticality of the equipment or level of redundancy, it may lead to the entire ship being unable to sail or carry out assigned missions.

Preventive maintenance, largely based on Original Equipment Manufacturer (OEM) recommendation, is prevalent among navies and the greater maritime industry, as are the transportation sector until the last decade where vehicles became increasingly 'smarter' with prognostics on when maintenance are required and service life remaining. The consequence of the current maintenance practice in the RCN is that corrective maintenance becomes surprises and often, occurring at the most inconvenient time, such as when the ship is about to depart the jetty or while deployed. Digital technologies, in particular the move towards Industry 4.0 represents an opportunity for conducting maintenance in the RCN. Industry 4.0[1] is in full swing in the 21st century, where data collection, and the application of digital technologies including artificial intelligence (AI) and machine learning (ML) is transforming everyday life. In the manufacturing sector, companies like General Electric are employing robots and automating processes to increase worker productivity while increasing worker health and safety.[2] Toyota uses automation and sensors to collect information on production line movements and processes to develop preventive maintenance strategies and finds ways to optimize its manufacturing process.[3]

The RCN has similarities to large, complex organizations operating sophisticated equipment – albeit with a different mission statement. In 2020, the RCN released the Digital Navy Policy, and its vision related to maintenance is that members of the naval team empowered "by predictive maintenance capabilities made possible through edge-computing capabilities..."[4] This vision is in line with the RCN Strategic Plan 2017-2022[5]

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[1] Industry 4.0 or the Fourth Industrial Revolution conceptualizes rapid change to technology industries and social patterns and processes in the 21st century due to increasing interconnectivity and smart automation. It is an industrial revolution that is powered by big data, artificial intelligence and machine learning to analyze, interpret and synthesize data. https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution.

[2] Chris Thatcher, "Smart Factory: GE Aviation," *Skies Magazine,* 2 August 2017, https://skiesmag.com/features/smart-factory-ge-aviation/.

[3] "Future Manufacturing 4.0," YouTube video, posted by "Futurist Keynote Speaker Patrick Dixon," 2 February 2018, https://www.youtube.com/watch?v=rt65167tZlQ.

[4] Royal Canadian Navy, *Digital Navy: A Strategy to Enable Canada's Naval Team for the Digital Age* (Ottawa: DND Canada, 2020), 9.

[5] Department of National Defence, *Royal Canadian Navy: Strategic Plan 2017-2022 (Ottawa*: DND Canada, 2017), 9.

and LeadMark 2050, RCN's self-assessment on the role it can play in future property and the security of Canada. LeadMark 2050 states there is:

> "the need to optimize warship and submarine maintenance practices to improve the percentage of time…that a warship or submarine may be operationally employed. Shipboard maintenance management systems are expected to become increasingly information-enabled to improve the efficiency of existing maintenance practices and enhance workforce scheduling and management."[6]

The return on investment with improved maintenance processes for the RCN is increased operational employment of warships, or in other words, sea days. This will be due to a combination of higher reliability of the equipment and machinery systems due to fewer unexpected unplanned failures, increased mean time between maintenance and carefully planned and managed maintenance windows that are shorter and less intrusive to a ship's schedule. Another key return on investment is the potentially freeing up 'sailor-hours', in which they could reinvest to the other areas such as training or warfighting where human participation is key, personal development, and better work-life balance. The first part of this paper will discuss the RCN's current maintenance practices, its limitations, and how it affects the technical readiness of a warship. The second part will discuss predictive maintenance that leverages big data, artificial intelligence, and machine learning, and the benefits and opportunities it brings to the RCN. The third part will discuss the U.S. Navy investment on predictive maintenance to highlight the 'edge' military power need to gain. Finally, the last part will look at current RCN initiatives in the current and future fleet, challenges as well as the balance that the RCN needs to strike between leveraging technology, change culture and reliance on new technology.

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[6] Department of National Defence, *Leadmark 2050: Canada in a New Maritime World (RCN)* (Ottawa: Directorate of Maritime Strategy, 2016) 50.

PART I – CURRENT MAINTENANCE PRACTICES

The RCN maintenance philosophy is based on two traditional types of maintenance: Preventive Maintenance (PM) and Corrective Maintenance (CM) routines. PM, often used interchangeable with Planned Maintenance, is a conservative approach where maintenance is conducted prior to the equipment fails to prevent unplanned maintenance or equipment failure. This maintenance effort is typically conducted in planned, scheduled intervals, occurring as a set regularity such as weekly, monthly or every six months, or based on the number of the hours of operations. These practices attempt to prevent equipment and system failure by keeping them in perceived optimum shape, by periodic inspections, overhauls, and component replacement as detailed by the maintenance order. The backbone of the RCN maintenance philosophy is preventive maintenance. Strong emphasizes is placed on training technicians to conduct the maintenance, to ensure parts are available, dedicating time slots at sea to ensure the completion of PM for those that fall under the responsibility of the ships personnel, as well monthly reporting to the Chain of Command onboard and to Fleet engineering authorities. All maintenance onboard ships are tracked using the Defence Resources Information Management System (DRMIS), where it generates maintenances reminders and schedules, tracks work order completion and generate reports. The PM that are beyond the capability or resources of ship staff and these are scheduled into Fleet Maintenance Facility (FMF) or contractor supported alongside maintenance work periods that each ship are scheduled for several times per year. The underlying understanding in the current RCN maintenance philosophy is that there is a strong correlation between completing PM and reduction in equipment failure, that if PM are completed as per scheduled, then the equipment will be kept in top shape, and should minimize unplanned failure. Of course, despite this effort, there is still no guarantee that machinery won't break and they often do.

PM is expensive and requires significant labour hours including maintenance planning and management, and ship downtime. This is potentially wasteful, doing thing or fixing things before they break. For instance, the ships staff may spend several hundres of hours of PM that may were premature for the condition of equipment. Further, the RCN takes a unified approach, where east and west coast ships have the same maintenance routines, despite their operating conditions being quite different. The Pacific Fleet in Esquimalt, BC has agreeable climate and ships are typically deployed to warmer climate regions, thus generally west coast ships and their equipment fair better and longer. The Atlantic Fleet Halifax, NS, are exposed to colder and harsher climate, and issues such as corrosion are particularly challenging. Yet, the preventive maintenance requirement and frequency do not discriminate between operating environments, which can contribute to waste of resources in conducting maintenance more frequently than necessary or not frequent enough and contribute to early equipment failure.

When equipment fails unexpectedly, corrective maintenance is required. CM is a reactive approach. As the maintenance is unplanned and unexpected, the investigation and diagnostics required to pinpoint the problem(s) that caused the failure is often long and extensive. The repair time is constrained by the parts availability (the supply system), technician availability, and the cost and prioritization to fit into a maintenance work period (when its beyond the ships staff capability or resources). The ordering of parts and scheduling of repairs only starts when the fault is diagnosed. The time required for repairs is further exacerbated by known parts obsolesce issue for the aging Halifax-Class frigates.[7] As a result, the overall equipment downtime could be significant even though the actual repair may be only a fraction of the overall equipment down time while it remains out of operation. Overall, it could have significant impact to a ships schedule and mission success.

Condition Based Maintenance (CBM) is a subcategory of the Preventive Maintenance. It is conducted based on condition of the equipment. The Halifax-Class frigates have real-time remote monitoring of all machinery systems and its critical operating parameters through Integrated Platform Management System (IPMS) onboard the ship. When alarms are triggered, inspections are carried out to determine the condition of the equipment and if PM or CM are warranted. CBM occurs with real-time process data, historical data or analyzing such data is not required.

Another factor to consider is that currently RCN ships are sometimes operating in the 'known unknown' risk space. There is the Materiel Baseline Standard where life saving, and critical systems preventive maintenance must be completed on schedule at all times before the ship can proceed to sea or while the ship is at to ensure the ship meets a minimum standard in materiel safety and life saving.[8] Other than this, there is more

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[7] "Navy's Aging Warships Getting Harder to Repair: Defence report," National Post, 6 March 2020, last accessed 4 May 2022, https://nationalpost.com/pmn/news-pmn/canada-news-pmn/navys-aging-warships-getting-harder-to-repair-defence-report.

[8] Royal Canadian Navy, NAVORD 3000-0, *Materiel Baseline Standard (MBS) – Surface Ship Policy* (Ottawa: DND Canada, 12 December 2016).

maintenance (PM and CM, first, second and third line maintenance[9]) than there are available labour hours to do them. Often, some of the noncritical maintenance routines are deferred to the next available maintenance work period or until a work period can fit it in, when these maintenance routines are deemed not urgent related to system operation or safety. The planning of a maintenance work period is like a hospital triage where labour hours, parts, expertise need to be prioritized, deconflict with maintenance work within the same ship, as well as deconflict concurrent work periods with other ships. A deep understanding of how deferring maintenance and how it relates to equipment failure or unsatisfactory operating condition is not explicitly tracked or studied.

PART II – PREDICTIVE MAINTENCE AND BENEFITS

Optimal Time to Conduct Maintenance

If preventive maintenance can be seemed wasteful and not optimized, especially depending on the function and criticality of the equipment, but if waited too long and corrective maintenance is required, it is too late. Then the optimal window to conduct the maintenance is before a piece of equipment fails with sufficient early warning so maintainer/technician availability, parts, and opportunity to do the work can be arranged so it will not impact a ship's operation or schedule. The maritime industry is in a

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[9] First Line Maintenance refers to maintenance normally performed under the authority and sponsorship of the ship's Engineering Head of Departments and performed by shipboard naval technicians. Shipboard naval technicians have the skillsets to carry out first line maintenance and they use spare parts that are carried on the ship. (NaMMS, 5-1-2). Second Line Maintenance refers to maintenance performed under the authority and sponsorship of the Formations and achieved through Formation allocated person-hours in Fleet Maintenance Facility (FMF) Cape Scott in Halifax and FMF Cape Breton in Victoria. (NaMMS, 5-1-2). Third Line Maintenance is typically performed by Original Equipment Manufacturer (OEM) as it is a fault or overhaul that neither the ship's crew nor FMF is qualified to handle, or for warranty considerations.

continuous state of digital transformation similar to the manufacturing industry, from reactive to preventive and proactive approaches regarding maintenance,[10] although the manufacturing sector is known to be the forerunner in leveraging robotics and the internet of things (IoT) for its operations and maintenance and is at the head of the curve of Industry 4.0[11]. Predictive Maintenance (PdM) is the proactive approach leveraging cutting edge technology including data analytics, artificial intelligence and machine learning to optimize maintenance to save time and money, and to increase reliability by early detection of problems. Predictive algorithms can compute a prediction that includes a confidence score and the probability of failure such as: Component X has 40% probability of failure within 95 operating hours,[12] or the engine oil has 30% life remaining. PdM algorithms can be tailored to the need of the end user requirement, based on prior knowledge about the component (failure and none failure data), its performance history in relation to other system components, as well as real-time operating conditions.[13] AI based predictive maintenance makes use of intelligent data.[14] The outputs of the prediction models are as good and reliable as the data feeding it as it analyzes historical trends in comparison to real time data to provides early warning on when faults might be occurring to prevent it at early stage.

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[10] Dragos Simion, et al, "Naval Maintenance. From Corrective Maintenance to Condition Monitoring and IoT. Future Trends set by latest IMO Amendments and Autonomous Ships," Proceedings of the International Scientific Conference SEA-CONF 2021, 325

[11] Fudurich, James, et al, "Adoption of Digital Technologies: Insights from a Global Survey Initiative" Bank of Canada staff discussion paper, April 2021, last accessed 4 May 2022, https://www.bankofcanada.ca/2021/04/staff-discussion-paper-2021-7/.

[12] Ben Rosenzweig, "If It Ain't Broke, When Do We Fix It?" Proceedings (by U.S. Naval Institute) 147, no.6 (June 2021). https://www.usni.org/magazines/proceedings/2021/june/if-it-aint-broke-when-do-we-fix-it.

[13] Ibid.

[14] "The Use of Artificial Intelligence (AI) in Predictive Maintenance," Sensorfy (blog), 10 January 2022, https://www.sensorfy.ai/blog/the-use-of-artificial-intelligence-in-predictive-maintenance/

Engine lube oil, for instance, instead of changing it every 3000 hours, if predictive maintenance technique is applied, it would signal that pressure sensor detects X psi at the filter, and based on historical data, it has 100 operating hours before it reaches the preset alarm at X+Y psi. This means the technicians need to find a window of opportunity to change the oil prior to it reaching the alarm stage. Depending on real time oil quality and cleanliness, it maybe be slightly more than 100 hours or slightly less, but predictive maintenance technique would be able to provide that information. Many of the current cars in the market uses algorithms to tell the driver the range remaining in their tank of gas based on the driving behavior of the driver (mileage). This allows the driver to determine whether they need to stop at the next gas station that is 40 kilometers away or the one after 50 kilometers away where the gas is cheaper, and the driver could also choose to improve the mileage by slowing down and may be able to extend the range to 60 kilometers where the gas is even cheaper. Effectively, predictive maintenance combines CBM (measuring real time data) with complex predictive formula that uses big data, artificial intelligence and machine learning techniques to exactly predict when a piece of equipment might fail,[15] thus allowing the ships staff and support personnel to take proactive action to prevent equipment downtime. In turn, PdM will allow the RCN to save labour-hours, parts, management resources, financial resources, and increase ship availability.

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[15] "A Complete Guide to Condition Based Maintenance (CBM)," *Limble CMMS* (blog), 2 October 2018, https://limblecmms.com /blog/condition-based-maintenance/#:~:text=There%20is%20a%20lot%20of%20overlap%20between%20CBM,predict%20when%20a%20piece%20of%20equipment%20might%20fail.

Other Factors for Consideration

Furthermore, there are additional compelling reasons on why the RCN should invest in predictive maintenance. The RCN is challenged with personnel shortages, about 1000 short overall.[16] The navy has faced a particularly difficult time attracting new sailors, as have the Canadian Coast Guard and Canadian marine industry, as older sailors leave faster than they can be replaced and new technology sparks shortages of certain skills.[17] One of the ways to help alleviate the current personnel shortage and to help recruitment is to be smarter on where these personnel are employed. Understandably the issue is more complex than just reduce the crew size and be smarter about maintenance practices, it's a culture change on how/when maintenance is conducted and the type of new skills that would be required for new sailors and in particular those technicians that are part of the Marine Systems Engineering and Combat Systems Engineering Department. The recruitment shortage in the CAF and RCN is not a new problem. In fact, military occupations within the MSE Department and CSE Department have gone through restructuring and amalgamation about 10 years ago to streamline the occupations as a way of reducing some of the personnel shortages. Maintenance consumes a very significant amount of their time, and technology can assist with that. Should they be spending half of their time onboard conducting planned maintenance, simply because x hours have lapsed, but otherwise the equipment health is good? Or when at times swamped with corrective maintenance, should they let some PM lapsed because the

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[16] Berthiaume, Lee, "Canadian Navy Needs to Recruit 1000 Sailors to crew New Warships," CTV News, 30 December 2021, last accessed 4 May 2022, https://www.ctvnews.ca/canada/canadian-navy-needs-to-recruit-1-000-sailors-to-crew-new-warships-commander-1.5723427.

[17] Ibid.

inopportune failure of multiple equipment at similar timeframes? There may be a time in the very near future when the RCN has no choice but to be smarter about how to conduct maintenance due to the shortage of personnel concerns.

Another consideration is external support for maintenance outside of the ship and outside of Department of National Defence (DND). Within DND, there is one Fleet Maintenance Facility that directly supports ship maintenance at each naval base. Their support to the ships are essential, but over the last 20 years the scope and scale of their support have been reduced and tailored, and more contracts have been awarded to the Defence Industry for ship maintenance, ranging from auxiliary vessels, Maritime Coastal Defence Vessels, diving tenders, and certain contracts for the Halifax-Class frigates. The Defence Industry is also quite busy supporting the new shipbuilding projects for the RCN and the Coast Guard, as part of the National Shipbuilding Strategy. With the RCN leveraging technology in its maintenance practice, it will help promote innovation and IoT in the entire Defence Industry and in the service they offer to the RCN.

PART III – OTHER NAVIES LEADING THE WAY

U.S. Navy Condition Based Maintenance Plus (CBM Plus) Initiative

At a recent Surface Navy Association symposium, Rear Admiral Casey Moton of the program executive officer for unmanned and small combatants at Naval Sea Systems Command, U.S. Navy, made the following remark, “AI/ML is one of those watershed technologies in the history of the Navy. It is going to fundamentally change what we do."[18] The U.S. Navy has demonstrated leadership in experimenting with AI and ML for naval applications, including maintenance. In particular, the U.S. is experimenting with predictive maintenance techniques on its ships, with the goal of leveraging new technologies to support sustainment and increasing naval ship readiness.[19] U.S. efforts include both maintenance capabilities and combat related systems. Like the RCN, the U.S. Navy is taking a cautious approach and is far from adopting AI and ML more broadly on ships at sea.[20] On the maintenance side, the U.S. Navy performs CBM, but has begun a pilot project called Condition-Based Maintenance Plus (CBM Plus), which adds AI and ML to their software architecture.[21]. The U.S. Navy has embedded sensors to collect data that is then processed by the AI and ML in the software architecture. This experiment uses the power of data analytics to enable predictive maintenance and provide U.S. Navy maintainers with the ability to get ahead of potential impending failures"[22] In a simplistic way, the CBM Plus project is providing predictive data analysis that would allow will provide prognostics that 'this equipment will have X number of hour before it's going to fail."[23] This experiment has allowed the U.S. Navy to look for ways to keep its ships equipment and systems running longer and improve the operational availability

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[18] Mikayla Easley, "Surface Navy Building Digital Infrastructure to Harness AI," *National Defense* (magazine), 18 March 2022, last accessed 4 May 2020. https://www.nationaldefensemagazine.org/articles/2022/3/18/surface-navy-building-digital-infrastructure-to-harness-ai.

[19] Jon Harper, Jon, "Navy to Deploy New Tech to Prevent Maintenance Problems," *National Defense* (magazine), 11 March 2021, last accessed 22 April 2022. https://www.nationaldefensemagazine.org/articles/2022/3/11/navy-to-deploy-new-tech-to-prevent-maintenance-problems.

[20] Ibid.

[21] Ibid.

[22] Ibid.

[23] Ibid.

at the system level.[24] If successful, the U.S. will consider expanding the experiment, to develop a holistic applications of AI and ML to maintenance, where logistics support is also integrated into the system to allow for seamless and accurate supply and store of spare parts. The integration would bring several benefits to the U.S. Navy, including a better understanding of spare requirements prior to deployment and reducing unexpected failures. In addressing the CBM Plus experiment, James Moser, Director of fleet readiness, U.S. Navy Office of the Chief of Naval Operations has stated “They don’t want to be surprised and if they are surprised, they want to surprised early before something breaks down.”

The U.S. Navy has chosen an Arleigh Burke Class destroyer as an experimental test bed for the first phase of the CBM Plus initiative, expected to run through late 2022. In their experiment, the U.S. Navy will apply the AI and ML technology onboard the destroyer on at least nine critical systems, as a test case to validate its utility.[25] As the experiment rolls out, the U.S. Navy is challenging the tenets of preventive maintenance approach against predictive maintenance. The follow on for the U.S. Navy would be to expanding the AI and ML software architecture, including the algorithms and data analytic tools, across the Arleigh Burke Class destroyer fleet by late 2023.[26] In a move that may be bold, the U.S. Navy is keen to expand the future of ship maintenance approach across the fleet, suggesting their ‘pilot program’[27] is unlikely to have an end

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[24] Jon Harper, Jon, “Navy to Deploy New Tech to Prevent Maintenance Problems,” *National Defense* (magazine), 11 March 2021, last accessed 22 April 2022. https://www.nationaldefensemagazine.org/articles/2022/3/11/navy-to-deploy-new-tech-to-prevent-maintenance-problems.

[25] Ibid.

[26] Ibid.

[27] Ibid.

date. As a sign of the U.S. Navy commitment to digital technology adoption, it has plans to integrate their AI and ML technology into new ships, starting with the Constellation-Class guided missile frigates that begin assembly in 2023

Belgian Navy Saves Money with Predictive Maintenance Philosophy

The Belgian Navy was one of the earlier users that adapted and embraced predictive maintenance practise, and it has resulted in saving them money. No doubt the technology from 15 years ago when the Belgian Navy began this path was not as sophisticated as they are today, but with a small navy comprised of only 1600 personnel, two frigates, six mine hunter and six support ships[28], being optimized and cost saving was very important consideration. Specifically, they began vibration analysis using machinery health analyzers from an U.S. company Emerson. Vibration measurements and data from various equipment and machinery such as gas turbines, pumps, motors, and other rotating equipment on the ships were collected, analyzed by the program to determine trends and failure patterns, and repairs and maintenance are conducted as necessary. It was reported that the over a seven year period, this program had save the Belgian Navy €1.5 Euro by extending the gas turbines overhauls on seven ships from 2500 hours to 4000 hours.[29] The vibration and oil analyzes program had determined overhaul of the gas turbines did not need to take place at 2500 hours. The RCN has a very basic vibration analysis program that is part of the preventive maintenance routine onboard. It comprised of ship staff manually recording the vibration measurement of the

[28] Military Wiki, last accessed 4 May 2022, https://military-history.fandom.com/wiki/Belgian_Navy.

[29] "Begian Navy Saves Big Money with Predictive Maintenance Based on Vibration Montioring and Oil Analysis." https://www.emerson.com/documents/automation/case-study-belgian-navy-saves-big-money-predictive-maintenance-based-on-vibration-monitoring-oil-analysis-ams-en-38550.pdf

specified equipment at predetermine frequency, typically monthly, and the data are sent to the FMF vibration subject matter expert for analysis.

PART IV – CURRENT AND FUTURE RCN FLEET

With the release of the Digital Navy Policy in 2020, and within it states the direction that RCN will advance toward relating to maintenance, that is predictive maintenance.[30] Later in December 2020, it was announced that BAE System's Integrated Data Environment (IDE) will be deployed on RCN ships.[31] It is a shored based management system that will focus on configuration management, obsolescence management and digital twin, aiming to enable effective and efficient shore-side support the Halifax-Class frigate. This in turn sets the environment and groundwork that the Future Fleet will operate in.

Through the Innovation for Defence Excellence and Security (IDEaS), industry partners receive funding for new predictive maintenance technology[32]. The Department of National Defence research branch, Defence Research and Development Canada (DRDC), has an ongoing research focus to determine to what degree the sensory data from the frigates IPMS and Equipment Health Monitoring Systems can be used for

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[30] Royal Canadian Navy, *Digital Navy: A Strategy to Enable Canada's Naval Team for the Digital Age* (Ottawa: DND Canada, 2020), 9.

[31] Defence Advancement, "BAE System's Integrated Data Environment (IDE) to be Deployed on Royal Canadian Navy Vessels," 23 December 2020, last accessed 29 April 2022. https://www.defenseadvancement.com/news/bae-systems-integrated-data-environment-ide-to-be-deployed-on-royal-canadian-navy-vessels/.

[32] "Gastops Recevies IDEaS Funding for New Predictive Maintenance Technology," last accessed 4 May 2022, https://www.gastops.com/news-resources/gastops-receives-ideas-funding-for-new-predictive-maintenance-technology/.

predictive analytics and extract useful information.[33] The Halifax-Class frigates are expected to operate until 2040s, until its replacements the Canadian Surface Combatants (CSC) are built and in operation. This means despite its age, digital advancement and technological investment in the frigates would still have very good return on investment for the RCN considering the years of service remaining.

For the Future Fleet, the RCN currently has three major shipbuilding projects in the work, the Joint Support Ships (JSS), the Arctic Offshore and Patrol Vessels (AOPV), and the Canadian Surface Combatants (CSC). The JSS and AOPV are more advanced in their project where there are already two AOPV in the water (one already in service and one conducting trials) and first JSS is expected to be delivered to the RCN in 2023/2024. Neither the JSS nor AOPV have predictive tools that are part of the current ship design. However, as their technology is 'new' and the ships are young in their operational life of several decades to come, it would be the most opportune time to invest predictive analytics for these new ships. The CSC is currently in the design phase, Health and Usage Monitoring System (HUMS) and predictive analytics is being explored and is expected to be part of the design. The CSC project team will also investigate how it will fit into the IDE model that will already be active by the time CSCs are built, as well as concepts of the 'digital twin' and 'common source database' relate to the IDE.[34]

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[33] Defence Research and Development Canada and National Research Council Canada, DRDC-RDDC-2019-L124, On the Use of the Integrated Platform Management System data to develop Predictive Models: Summary of initial results and finding for supervised learning (Ottawa: DND Canada, May 2019).

[34] Sargeant, Andrew, Cdr, "The Canadian Surface Combatant – Starting a New Conversation on Canada's Major Warship Replacement Project," Maritime Engineering Journal no.93 (summer 2020), https://www.cntha.ca/static/documents/mej/mej-93.pdf.

Challenges

As attractive as predictive maintenance is to the future of naval ship maintenance, there are some significant challenges the prevents the RCN from taking aggressive and immediate actions to adopt these technology and practices, namely the lack of or limitation of data to enable machine learning and capital investment. The biggest challenge in setting up AI in predictive maintenance is the shortage of accurate, available data, in order to populate and test mathematical predictive models.[35] It is critical to determine which data sets are required and then implementing the correct sensor solutions to collect the data.[36] Sufficient amount of data, both non failure data and failure data, then needs to be collected and stored, which could translate to months and years of data collection. Failure data is particularly challenging to obtain,[37] and in general there are insufficient amount of failure data. Though the Halifax-Class frigates, JSS, and AOPVs are equipped with the Equipment Health Monitoring onboard that collects and stores equipment operating data, it was designed with limited trend analysis function only and not with big data analytics in mind. Further, RCN ship maintenance data such as likely/actual causes of faults or failure, investigation details, corrective action taken, parts replaced, etc, are documented on the Defence Resource and Information Management System (DRMIS). DRMIS, however, does not have any sensory data and its data are

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[35] Veronica J. Jimenez, et al., "Developing a Predictive Maintenance Model for Vessel Machinery," *Journal of Ocean Engineering and Science* 5, no. 4 (December 2020): 384, https://doaj.org/article/4af279eeb66b46f3bc61bb37700cac63.

[36] "The Use of Artificial Intelligence (AI) in Predictive Maintenance," Sensorfy (blog), 10 January 2022, https://www.sensorfy.ai/blog/the-use-of-artificial-intelligence-in-predictive-maintenance/.

[37] Veronica J. Jimenez, et al., "Developing a Predictive Maintenance Model for Vessel Machinery," *Journal of Ocean Engineering and Science* 5, no. 4 (December 2020): 384, https://doaj.org/article/4af279eeb66b46f3bc61bb37700cac63.

manually entered by the ship or fleet maintenance personnel. DRMIS currently does not include maintenance work conducted by contractors. DRMIS data, if any, that is useful for data analytics or machine learning is likely to be an extremely time-consuming effort to vet and extract. Factors, such as OEM recommendation on component operational time and maintenance interval, coupled with expertise from ship personnel and Fleet subject matter experts will aid in modelling the data required for failure events.[38] Once these data are available, techniques such as trend analysis and pattern recognition can be used to identify situations that have occurred in the past, to produce warnings and maintenance requirements.

The capital and recurring costs to invest in AI technology to enhance ship maintenance practices will be significant, from deploying sensors and IoT systems to machinery systems to collect, sort and store the necessary data, as well as to develop the algorithms and architecture to analyze the data and produce the necessary output and interface with the end user. Adapting predictive maintenance as a singular approach (i.e. one or two or three equipment systems) is not ideal and not practical, given the best AL and ML systems consume multiple datasets. A singular approach will not allow the RCN to reap the desired benefits from predictive maintenance, thus the return on investment will likely be low or unsatisfactory in this case. The scale of application needs to carefully considered. The U.S. Navy CBM Plus pilot program will be conducted in a phase approach, where the first phase will activate the predictive maintenance technology

[38] Veronica J. Jimenez, et al., "Developing a Predictive Maintenance Model for Vessel Machinery," *Journal of Ocean Engineering and Science* 5, no. 4 (December 2020): 384, https://doaj.org/article/4af279eeb66b46f3bc61bb37700cac63.

on at least nine critical systems onboard a DDG-51 Arleigh Burke Class destroyer, as a test case to validate its utility.[39] It will then scale up.

Finding Balance with Technological Change

What is balance that the RCN needs to strike or factors to consider when adapting predictive maintenance practices? The RCN Digital Navy Policy promotes a culture of innovation at all levels, aiming for a full-scale shift to digitalization and leveraging modern technology for the ships and their crews. The vision is that sailors will be digitally connected with mobile devices to cloud based services, ships will have predictive maintenance capabilities, digital twinning, onboard 3D printing for parts, integration of the technology across all domains, becoming a more risk-tolerant, experimental navy, and staying ahead of the digital curve.[40] The adoption of new technologies and predictive maintenance approach would need to consider how it impacts the personnel, and change management. Engineers and technicians with decades of hands on, valuable experience in operating and maintaining ship systems have tremendous knowledge that is at the core of the RCN's strength. Their pride in their work and service is an important part of the culture of the RCN that may be perceived as being threatened as new technologies are considered. Those who join the RCN as marine technicians, for example, want to be hands on to work on the engines or generators or hull equipment, depending on their subspeciality. It would be vital for the RCN

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[39] Jon Harper, Jon, "Navy to Deploy New Tech to Prevent Maintenance Problems," *National Defense* (magazine), 11 March 2021, last accessed 22 April 2022. https://www.nationaldefensemagazine.org/articles/2022/3/11/navy-to-deploy-new-tech-to-prevent-maintenance-problems.

[40] Royal Canadian Navy, *Digital Navy: A Strategy to Enable Canada's Naval Team for the Digital Age* (Ottawa: DND Canada, 2020), 9.

leadership to involve the engineers and technicians of today in decisions and planning for acquiring and adopting new technologies and predictive maintenance procedures. This approach would have the benefit of an easier buy in with the technical teams, as well as ensuring RCN fleet maintenance objectives are reflected in any new approaches.[41] The opportunity for the RCN would be to use the new technologies to enhance the work of the technicians and maintainers, and by extension, continue to strengthen a vital part of the RCN's culture.

Maintenance is not only for mission success, but also crucial to ensure that risk is mitigated so that the crews are safe from injury if machinery breaks.[42] From ship staff and Fleet Maintenance Facility technicians and engineers, to contractor support, have demonstrated a strong record of maintaining a mission ready fleet to serve Canada and the RCN. However, with the prognostics provided by predictive maintenance techniques and carrying out the maintenance as specified, the equipment can be expected to become more reliable during operation. Timely maintained machinery and equipment, based on their materiel state and historical trend, is less likely to fail. Ensuring personnel safety is an important priority onboard the ship, the early warning preventing catastrophic failure from occurring creates a safer operating environment for the ship's personnel and equipment. The Halifax-Class frigates have passed their mid life and are expected to continue to serve as the work horse of the RCN until the CSC ships come into service in the early to mid 2030s. By that time, the frigates will be over 40 years old. Ageing

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[41] Royal Canadian Navy, *Digital Navy: A Strategy to Enable Canada's Naval Team for the Digital Age* (Ottawa: DND Canada, 2020), 9.

[42] Naval Association of Canada. "Keeping Navy Ships/Boats At Sea – Maintenance," Naval Affairs Program Briefing Note #31. Last assessed 3 May 2022. https://www.navalassoc.ca/naval-affairs/briefing-notes/.

vessels require more maintenance and upkeep as well as the increased likelihood for equipment failures to occur, thus the RCN will be increasingly operating in known and unknown risks space and the requirement to mitigate those risks. It is critical for the RCN to accurately understand the materiel state of the equipment onboard, at the component and system level.

CONCLUSION

The RCN's current maintenance philosophy has proven that it works in maintaining the technical readiness of Canadian warships as they can be seen being deployed all over the world supporting the Government of Canada's missions and objectives, but it has its limitations. It comes at a significant cost in terms of labour-hours, spare parts, equipment unserviceability, funding and the management of it all. Equipment unserviceability directly impacts the technical readiness of warships and impacts the operational schedule. Preventive and corrective maintenance has and continues to work, but looking forward, the RCN needs to optimize ship maintenance by leveraging digital technology and predictive maintenance practices that will bring the maintenance 'culture' into the 21st digital century.

Ship maintenance can be greatly improved with data analytics and artificial intelligence to predict when maintenance really needs to occur to prevent equipment failure, based on the current condition of the equipment, and provide sufficient time for the maintenance to be scheduled aligning the availability of parts, technician/subject matter experts, tools, etc. Companies such as Toyota[43] and GE[44] in their automotive and manufacturing industries respectively are forerunners of leveraging IoT including artificial technology, machine learning, and robotics to optimize their processes, and now the U.S. Navy is full steam ahead to get there as well. Advanced analytic and prognostic tools will allow ships personnel to accurately understand the materiel state of the ship, to take proactive action to prevent unexpected downtime and increase ship availability for sailing and missions. When equipment is offline for maintenance, it will be down for less time because the fault would have been diagnosed and prognostics provided for optimal planning. Additionally, equipment or system failing catastrophically have been avoided. It is important that note that not every single failure will be avoided because even AI and ML are not perfect.

Big data and predictive analytics will bring huge dividends to the RCN, the men and women in uniform, the current fleet of Halifax-Class frigates, but especially the Future Fleet of CSCs, JSS, and AOPVs. Predictive maintenance practices provide the opportunity for RCN ships to choose the time and place that fits best into its operational schedule to conduct the maintenance prior to equipment failure and extend a ships operational window. Now is the time to lay the groundwork and invest for the Future Fleet and generation of sailors of the RCN.

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[43] Chris Thatcher, "Smart Factory: GE Aviation," *Skies Magazine,* 2 August 2017, https://skiesmag.com/features/smart-factory-ge-aviation/.

[44] "Future Manufacturing 4.0," YouTube video, posted by "Futurist Keynote Speaker Patrick Dixon," 2 February 2018, https://www.youtube.com/watch?v=rt65167tZlQ.

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