Shipboard Automatic Watchstander

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***Abstract*—Crew sizes in the Navy and Coast Guard continue to decrease. Optimally or minimally manned crews complete ever more complex and varied mission sets. Accordingly, crews rely on sensors and automatic operation to perform a host of duties formerly completed manually. The Non-Intrusive Load Monitor (NILM) provides a low cost, low-maintenance, rugged, easily installed tool for machinery monitoring from a centralized location. This paper presents a real-world application and case study of a power monitor installed on a USCG Famous Class (270 ft) Cutter's "Engine Room Auxiliary Machinery" panel, monitoring eight key pieces of machinery. The NILM effectively determines machinery status. Comparison is made here to crew-generated logs, demonstrating the NILM's ability to effectively disaggregate equipment operation from aggregate power data.**

I. INTRODUCTION

Modern Navy, Coast Guard, and commercial maritime crew sizes continue to shrink as there is a shift to "optimally" and minimally manned crews completing more complex and varied mission sets. Smaller crews rely on sensors and automatic operation to perform a host of duties once completed manually. This generates a substantial need for monitoring systems to ensure proper operation of equipment and maintain safety at sea [4]. These systems require a significant infrastructure of sensors, wires, and intermediate panels or data collation sites. Because conventional monitoring systems rely on a substantial, distributed hardware installation, communications losses and sensor failures can become commonplace and crippling. Reduced manning may also mean reduced repair hours, and crews with complex but difficult to maintain sensor systems may effectively be left without needed monitoring equipment.

The Non-Intrusive Load Monitor (NILM) determines the operating schedule and health of individual electrical loads with reduced installation effort. NILM systems rely on voltage and current measurements taken at a single centrally located point in a power distribution network. They receive aggregate power usage for all equipment on the system being monitored. Signal processing of the aggregate power data can disaggregate individual machinery transient events, permitting determination of operating schedule and equipment health.

The NILM poses interesting possibilities for shipboard use and maintenance [11]. The NILM system can serve as an "automatic watchstander" for tracking machinery operation. This paper demonstrates automatic watchstander hardware and software operating during underway operation of USCG SPENCER, a 270 foot Famous-class cutter.

II. SHIPBOARD AUTOMATIC WATCHSTANDER

The power distribution network on-board ships could be pressed into dual service, providing not only power distribution but also an energy-scorekeeping and diagnostic monitoring capability. This power system diagnostic monitor would use existing power wiring to monitor loads. We call this approach "nonintrusive" load monitoring (NILM). With remarkably little installation effort or expense (a Pentium-class computer, power converter, and single set of current and voltage sensors), a minimally intrusive power monitor can serve as a Shipboard Automatic Watchstander (SAW). The SAW could assess energy consumption under different operating conditions, determine the need for maintenance, identify fault conditions, find power quality problems, help reconfigure a power system after damage, and provide reliable verification of load operation. The SAW could be installed temporarily or permanently. It could become the basis for an efficient and effective energy-audit service. Information from the SAW could permit "continuous commissioning" - the availability of information necessary to keep the operation of a ship fine-tuned for optimal energy consumption under all operating conditions and as the installation hardware ages.

The NILM offers several important benefits for service as the technical foundation of a SAW, discussed in further detail in this section. First, NILM systems can discern machinery status and automatically generate a log of operation. Second, they can compare machinery operation and sequencing, reflecting the demands of the crew, to a known operational status to relay to decision makers crew fatigue and operational tempo. Third, a SAW based on nonintrusive monitoring technology could ensure that operational procedures are followed and that automatic functions of machinery are operating as designed to improve or maintain the life of machinery. Because NILM systems require limited access from an aggregate measurement in the power system, they provide a single robust monitoring point that doesn't rely on complex networks of sensors.

A. *Automatic Logging*

In the USCG the current method for keeping machinery logs is manual entry. This approach relies heavily on accurate human observation and annotation. Logs are forwarded to maintainers and operational commanders, and accurate log keeping is an important function for the USCG. Logs are critical for recording operational history and supporting maintenance decisions, and are entered as official legal documents. Generally, watchstanders maintain a "rough log" which is a handwritten document containing times of events and operations including fuel transfers, machinery status changes (starts and stops) and other key events. This is then periodically transferred to a typed document, an overall method that is clearly open to flaws. Watchstanders can be extremely taxed while making normal rounds on equipment. Verifying operation, safety, performing maintenance, training new crew members, and performing casualty response are just some of the watchstander's normal duties. Accurate log keeping can become an afterthought in stressful or repetitive situations. Manual logging also poses the possibility of distracting the watchstander from the equally important task of monitoring machinery health, possibly allowing for a casualty to go unnoticed.

Figure 1. Typical USCG engine room watch. Notice the logbook, termed the ”rough log,” used to keep machinery operation times and log critical events. Also note the watchstanders monitoring equipment while simultaneously attempting to maintain logs.

This paper presents results from a SAW based on nonintrusive monitoring technology for automatically logging start and stop times of machinery operation. This technology reduces the impact of human error and potentially allows human watchstanders to focus on more important and less repetitive tasks. As budget constraints tighten and technologies increase to allow for remote operation of systems as well as increased automation, crew sizes have decreased, in some cases to 50% of manning on legacy assets. Each remaining crew member performs a new multitude of tasks. It is not uncommon for a single crew member to be responsible for monitoring machinery health through frequent rounds, wipe up oil, complete oil viscosity tests, check oil levels, check temperatures, verify pressures, start generators, pump sewage, refill head tanks, and other duties. A SAW creating automatic logs could improve safety and efficiency by decreasing the amount of time a crew member has to spend logging machinery operation manually. Additionally, precision could be increased through logging of exact times and ensuring that no or relatively few events are missed.

Hourly tracking of operations underlies the USCG's maintenance planning, as many maintenance tasks are based on accumulated operating time, e.g., for major overhauls, oil changes, and other cyclical maintenance. Accurate, automated tracking could greatly improve maintenance planning, decreasing costly corrective maintenance completed after casualties. Also, current systems rely on maintainers receiving aggregated reports from operators on a bi-annual or annual basis. Infrequent information flow easily creates disparities between projected hours and actual operational hours and creates a gap in planning. Automated tracking could ease data collation and access for decision making.

B. *A Bellwether for Crew Performance*

Certain operations pose increased risk. These ”special evolutions” include events such as flight operations, anchoring, maneuvering close to shallow waters, towing, battle quarters, refueling at sea, and law enforcement operations, among other higher risk evolutions. For these evolutions, vessels institute a condition of operation called the Restricted Maneuvering Doctrine (RMD) that sets additional precautions to mitigate risk. This doctrine is a balance, in that a majority of the crew receive complex or additional duties, creating a potentially fatiguing burden. As crew fatigue increases, the likelihood for mishaps increases. Whenever possible operational commanders should be aware of cumulative time spent at RMD to properly evaluate risk when assigning missions.

There is currently no objective metric to measure fatigue. In the surface community, the USCG employs the GAR model which evaluates crew fatigue on a subjective 1-10 scale. This metric is difficult to evaluate objectively. The aviation community, on the other hand, has a more objective metric, accounting hours of operation and requiring hours of rest [5].

C. *Ensuring Compliance with Operating Procedures*

When setting RMD, certain pieces of equipment are generally energized and an equipment status is prescribed. Knowing this status and equating it to RMD, a SAW could sense the amount of time a vessel spends at RMD, providing operational commanders a hard metric for crew fatigue when evaluating risk and gain for missions. Also, the SAW can evaluate compliance with prescribed operating procedures and detect deviations in crew performance. Each piece of machinery has a specified or “standard operating procedure” (SOP). These SOP's contain step by step instructions on machinery alignment and operation. In several systems, the order of operations is extremely important to ensure that catastrophic damage does not occur. For instance, the reverse osmosis feedwater pumps must be started before high pressure pumping commences. Deviations remove cooling and impellers or high pressure pistons could be destroyed. Similarly, diesel engines must be prelubed before starting to ensure lubrication of parts. If a NILM can detect these sequences to prevent or warn an operator when they have missed a step in the sequence, millions of dollars in costly corrective maintenance could be saved across the USCG's 2800 asset fleet. Also, deviations from SOP could potentially serve as an additional indicator of crew fatigue.

D. *Field Experiments*

To explore these possible uses, a SAW system was installed on the USCGC SPENCER (WMEC-905) shown in Fig. 2 from November 2014 to December 2014. USCGC SPENCER is a 270ft Famous Class cutter stationed in Boston, MA. Two nonintrusive systems were installed, one on the #2 Main Propulsion Diesel Engine (MPDE) auxiliary supply panel in the engine room, and another on the main exhaust fan for the engine room. These monitoring systems collected data during underway operations to test the potential for automatic event logging and centralized data analysis from the ship power system to classify the status of the vessel and its machinery.

Figure 2. USCGC SPENCER is a 270ft long Famous Class Cutter whose primary missions include Search and Rescue, Law Enforcement, and Living Marine Resources.

The machinery plant of the 270ft consists of three ALCO V-18 propulsion diesel engines and two electric diesel generators rated for 475KW as well as an emergency generator rated for 500KW. It carries a crew of approximately 100 and maintains a rigorous schedule of over 185 days deployed per year [12].

The installed nonintrusive monitors observed the exhaust fan pictured in Fig. 3 and the #2 MPDE auxilliary supply panel. Mission critical loads fed from this supply panel include the #2 Main Propulsion Diesel Engine (MPDE) prelube pump, the #2 "C" Controllable Pitch Propeller Pump, the MPDE lube oil heater, and the MPDE Jacket Water Heater. The location and placement of the monitoring boxes can be seen in Fig. 4. By observing data from these monitors, the machinery plant status can be reconstructed, as shown in the next section. This reconstruction can be compared with required operating procedures. For example, the exhaust fan should be turned on prior to the MPDE starting in order to ventilate the space. The fan is deactivated when the MPDE is not running to keep the engine warm while offline.

The CPP "C" pump motor is a 3 phase motor nominally rated at 440V, 13.6 Amperes, and 10 hp. Fig. 5 shows the motor. The MPDE prelube pump motor is a 440 V 3 phase 4.9 ampere and 3 hp motor and can be seen in figure 6. The two heaters connected to the system, the MPDE jacket water heater and the MPDE lube oil sump heater, are both 440 V, 3 phase resistive heaters. The JW heater is rated at 9KW and the lube oil sump heater is rated at 12 KW.

The monitored equipment works separately and together to ensure that the MPDE functions correctly. For example, the monitored prelube pump runs continuously when the engine is offline, but does not run while the engine is online. The Lube Oil heater will automatically energize when required and then turn off when temperatures are adequate, maintaining oil temperature between 90 and 120 degrees Faranheit). The jacket water (JW) heater works in the same fashion, automatically energizing when required. When the engine shuts down, the

Figure 3. Standard exhaust fan.

Figure 4. USCGC SPENCER engine room. Nonintrusive monitors are installed forward of the #2 MPDE just above the monitored panel.

prelube pumps turn on, the JW heater turns on, and the exhaust motor should be turned off by the crew. When the engine starts, the prelube pumps turn off, the JW heater turns off and the exhaust motor should be turned on.

The controllable pitch propeller is powered by a hydraulic loop. Hydraulic pressure is sent through a hollow shaft to the blades of the propeller, altering blade angle to quickly alter speed Hydraulic pumps control the amount of hydraulic oil sent to the propellers to change pitch (by changing pitch the speed/direction of ship movement is controlled). The "C" Controllable Pitch Propeller (CPP) pump is unique in that it is energized for "Special Evolutions" that require that RMD be set. By energizing the "C" pumps, the operators are given greater handling performance and faster response.

During special evolutions the restricted maneuvering doctrine (RMD) is set and a prescribed machinery status is initiated. The nonintrusive SAW can detect machinery status by identifying the transients and recognizing equipment used uniquely during RMD. High level mission commanders

Figure 5. CPP "C" pump motor that supplies pressure to vary the pitch on the blades of the propeller. These pumps are energized when RMD is set and the vessel enters a time of increased risk and fatigue for the crew.

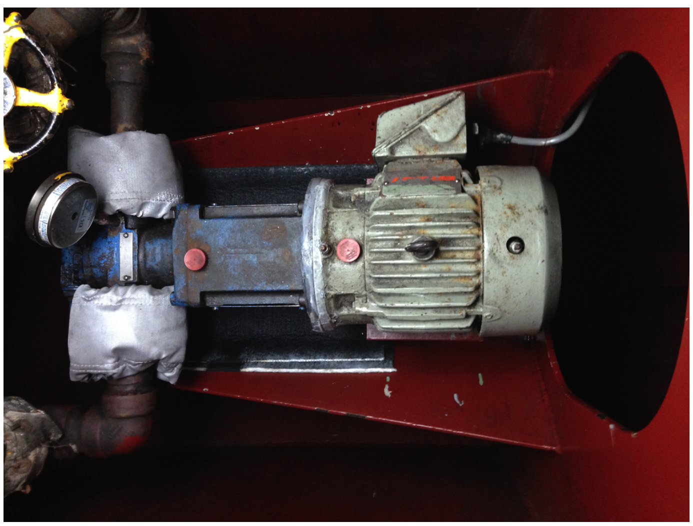

Figure 6. Pictured is the 3 hp motor for the MPDE prelube pump. It is continuously energized when the MPDE is off and automatically stops when the engine is started. By monitoring its status (on/off) the engine's status can be inferred.

could receive automatically logged summaries of times and durations when operational tempo increased. This could move the surface fleet towards the aviation model where given a certain number of hours would equate to a certain level of crew fatigue. It is not uncommon for watchstanders to go without rest due to special evolutions combined with normal routine.

The next section illustrates the findings of a prototype SAW examining underway data obtained from the USCGC SPENCER.

III. Signal Processing and Transient Identification

The SAW's functionality is critically dependent on it's ability to disaggregate and identify transients of interest. This signal processing problem of extracting individual transients from aggregate data is an intellectually exciting and mathematically tractable problem for power systems of the size found on SPENCER, for example. Aggregate power data for a window of time aboard the SPENCER is shown in Fig. 7. The data clearly shows a complex mix of events occuring on the ship power system, and hints at the challenges in disaggregating transients.

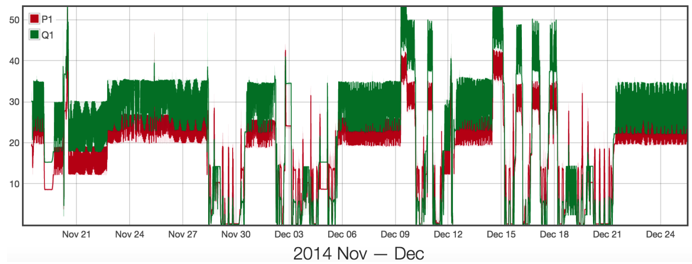

Figure 7. One month of total electrical power consumption data on-board USCGC Spencer.

Careful examination of the ship's data reveals that start/stop events can be identified given exemplars representing individual load transients. During the cruise summarized by Fig. 7, the cutter participated in an extended training period during which it made frequent port calls. This made monitoring interesting, with many transient load activations. The data from 10 December 2014 is one example, shown in Fig. 8 below.

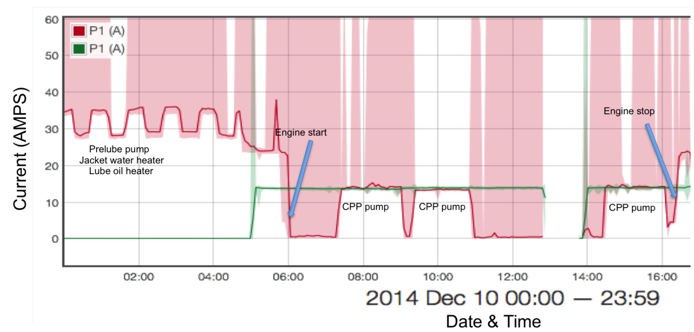

Figure 8. Data retrieved from monitoring on 10 December, 2014.

For example, on this day from 0000 local time until 0600, the ship is in-port on shore power, with a collection of loads operating that would be typical for "bravo status," i.e., the ship is active but not underway. The step function in power is the jacket water (JW) heater turning on and off. The prelube pump is also running. Fig. 9 shows the first crew action for getting underway, the starting of the engine shown in Fig. 9 at 0601. At this time, the prelube pump is deactivated in preparation for engine start.

At 0601 on SPENCER, nothing on the observed panel is operating. The MPDE is on at this time, providing its own lubrication with an attached shaft-driven pump. The electrical support loads are off, therefore, at this time. As described earlier, also on this panel is the CPP "C" pump which is energized when the cutter enters a special operational status of perceived higher risk, or RMD. The first "on" event for this can be seen at 0720 where the pump energizes as shown in

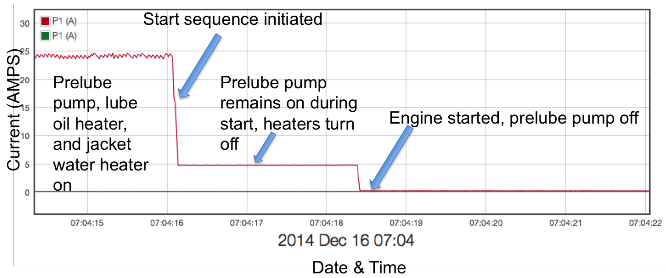

Figure 9. The MPDE starting as observed by the nonintrusive SAW. Note that there is a progression as the heating elements turn off once the start sequence initiates. The prelube pump remains energized until after the start sequence is completed to ensure lubrication during start (approximately 2-3 additional seconds).

Fig. 10. This corresponds to the cutter leaving port, and RMD condition.

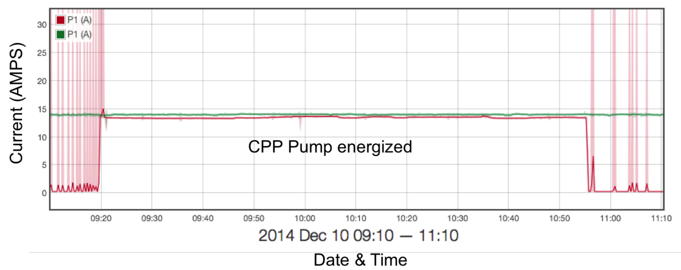

Figure 10. Characteristic CPP on and off event. The CPP motor is rated for 13.6A.

The data from the CPP can be highly telling as it relates directly to a condition of steaming of the vessel, the setting and securing of RMD. From the data, one can extrapolate that the cutter was at RMD from 0720 to 0903, 0919 to 1055, and 1426 to 1607. For that day alone, the cutter was at a heightened state of readiness for 5 hours. This is a telling metric for mission commanders and planners and shows that there is a high probability of fatigue for this crew on this day. In evaluating the risk for an additional potential evolution, this metric could be crucial to weighing the risk and gain of a proposed mission. These start and stop times match manually logged start and stop times. Fig. 11 shows the data on MPDE start and stop times as well as CPP times taken from the NILM box sensing of the prelube pump status and the CPP pump status.

Nonintrusively acquired and interpreted power data can be more reliable than human entry. Human entry relies upon an already overtaxed watchstander to log items. This leaves a high probability that during high stress or high tempo times, the log becomes an estimate at best, at worst a distraction to a watchstander trying to maintain equipment. An example of this is missed entries in the log. Taking the log from 10 December for an example, the SAW was able to identify two key events (the setting of RMD denoted by starting the CPP "C" pumps) that were not logged in the watchstander's log. Thus the NILM offers a way to deconflict the work of the watchstander while still providing an accurate log, in this case more reliable than one created by human entry. It is important to note that the

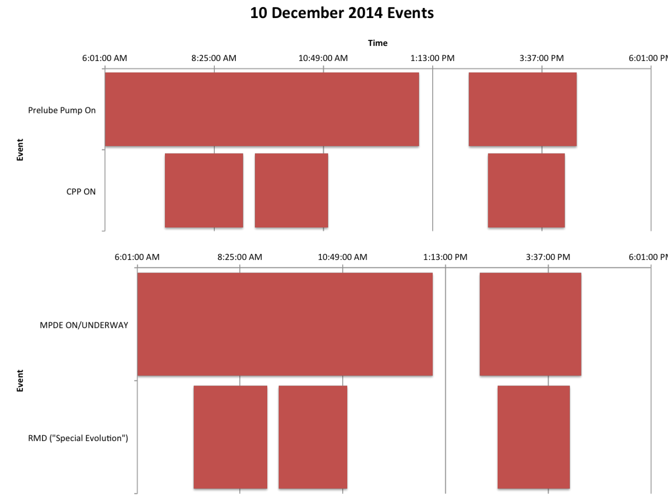

Figure 11. This figure shows the data taken from 10 December 2014 from the SPENCER SAW.

NILM also provides exact time data whereas the logs were off from the NILM data by up to 15 minutes.

When the MPDE is stopped, there is a similar sequence of relevant transients and load activations. The prelube pump should start immediately upon engine stop. Other loads associated with the MPDE (JW heater and lube oil heater) will not start immediately as these are controlled by temperature thermostats. The engine stopping can be seen in Fig. 12. Then, approximately 15 minutes later, the heater loads activate as shown.

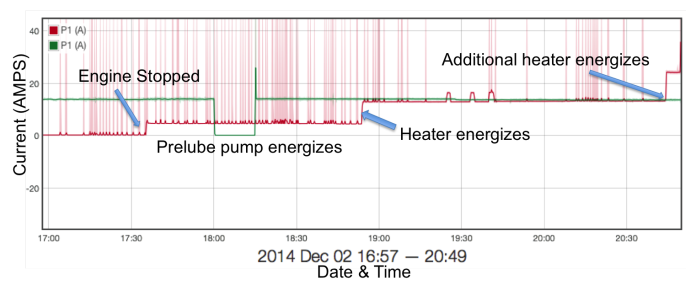

Figure 12. MPDE Stop Sequence

The SAW is able to identify sequences and ensure prerequisites for proper load activation and operation are met. On Famous Class cutters the prelube pumps are continually running. However on many ships, such as the USCG 210ft Reliance Class cutters, prelubing must be done manually before starting the MPDE's or increased wear will develop on the MPDE. This requires a human input that may be skipped if the operator is not following the SOP correctly. An installed NILM would be able to sense the prelube pump and ensure it is started before starting the MPDE. This has many applications as many systems work in this manner where prerequisites should be met before other steps are taken or damage can occur to the system. On newer ships, many of these failsafes are built into the systems. For example, on the newest USCG cutter, the WMSL, the controls software will not allow start of the MPDE without prelube to a specified pressure; however on legacy class cutters this function does not exist and they rely on human input, which, especially during high stress situations, can result in errors. The SAW can be used to ensure proper steps are followed, producing a warning signal if proper sequencing is not observed.

The nonintrusive SAW also offers opportunities for tracking machinery health. There are characteristic start up and steady state signatures associated with each piece of machinery. If these signatures change, then there may be an idenifiable maintenance issue. For example, pump damage can occur when pumps are run without a pumping medium (run ”dry”). This situation occured with a CPP pump onboard SPENCER during the cruise under observation here. After performing maintenance, the CPP pump was started and run without a medium for several seconds (system was purged of fluid during maintenance). Fig. 13 shows power fluctuations possibly caused by loss of suction in the pump. By identifying these events, the nonintrusive monitor can be used for health monitoring.

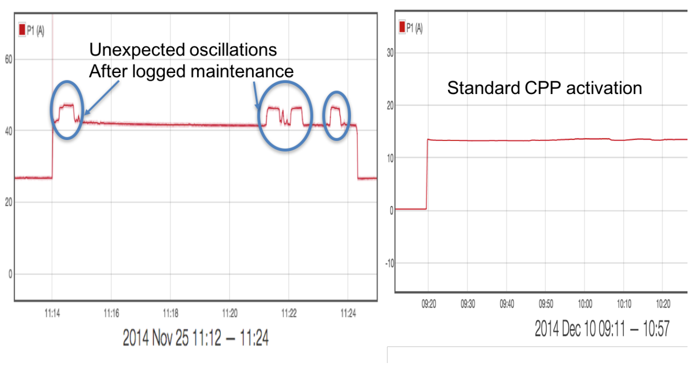

Figure 13. Image of unusual readings from CPP pump after maintenance.

Another example of this is when the cutter moors (enters port) or leaves port. During these evolutions, there are rapid calls for rudder and propeller commands. These rapid movements can be seen in unusual patterns in the CPP’s power draw as the motor is worked aggressively. This can cause damage to the pump or motor beyond normal expectations and, depending on conditions, could indicate that operators should be encouraged to decrease command frequency. At a minimum, these records can be used as a kind of “odometer” to indicated the potential need for maintenance. Fig. 14 shows these heavy use patterns.

IV. Automatic Watchstanding on USCGC SPENCER

Using the ”Wattsworth” program described in References [6] and [10] describe the “Wattsworth” computer monitoring environment for nonintrusive monitoring. This cloud-based application permits flexible review and analysis of power monitoring data, sampled at 8 Khz at a target site like SPENCER, anywhere in the world. One of the benefits of the Wattsworth system is that it places minimal demands on required network bandwidth. All data is stored locally at the target site, in this case, SPENCER. Requests and analysis are performed by an inexpensive monitoring computer at the

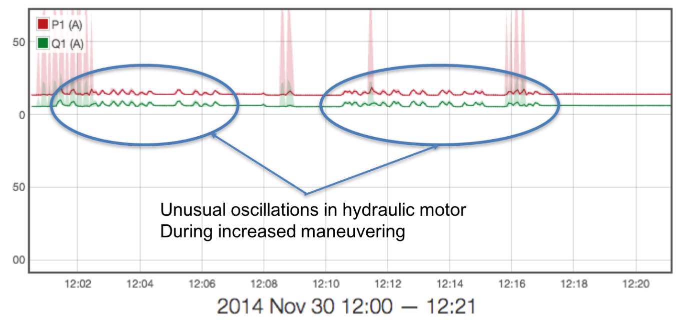

Figure 14. Image of unusual readings from CPP pump during mooring; oscillations indicate aggressive operation of the pump motor.

site. Results can be reported anywhere in the world with low bandwidth data connections. New analysis code, written in a programming language that is an extension of Python, can be uploaded over low bandwidth connections to the SPENCER nonintrusive SAW running Wattsworth to expand and add new analysis capabilities.

Each piece of machinery on the ship can be characterized on initial installation of the SAW during a training phase. There are a variety of methods for acquiring training data. During the training phase, for example, readings are taken on three phases A-B-C while loads on-board the ship are activated or observed during dock-side operation. Power signatures are recorded in real and reactive power and higher current harmonics, associated as fingerprints for each load of interest. Different machinery draws different amounts of real and reactive power and harmonics consistent with the different physical tasks performed by different machines. Each piece of equipment may also exhibit unique turn-on transients. For example, Fig. 15 shows the real and reactive power demanded during the startup transient of a CPP pump. For comparison, Fig. 16 shows the turn-on transient of a lube-oil heater. These distinctive, predictable, and reproducible waveforms can serve as fingerprints for recognizing and disaggregating load operating schedule by examining the aggregate power feed to the loads, even when several loads are operating at the same time.

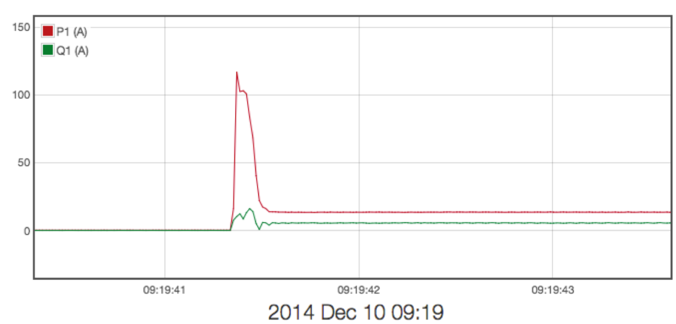

Figure 15. Startup transient for CPP pump.

Some machines operate with strong periodicities, such as heaters that have a period of operation where they are on for a relatively constant amount of time and then off for a constant and relatively predictable amount of time for certain underway

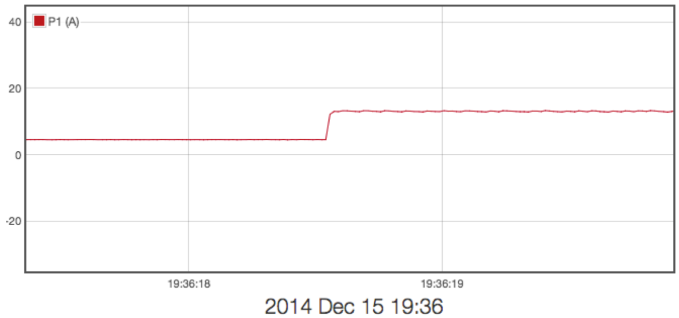

Figure 16. Startup transient for SSDG lube oil heater.

conditions. Other machines follow a predictable sequence of events, e.g., if one piece of machinery starts, another should start at a given interval later, e.g. the pumps in a reverse-osmosis water system. Through knowledge of proper system operation and prediction of events, an expert system can be developed that uses non intrusively observed power transients to identify not only particular loads but also particular cycles of operation or ship state, such as an engine start. The Wattsworth programming environment can be used to flexibly implement an expert system that analyzes and summarizes ship state and condition based on observed load transients and operation. First, by running a load identification filter over an incoming set of data, load events can be identified and tagged. Streams of tagged events can be further analyzed to identify sequences of load operation that correspond to correct or improper use of a multi-load system. These analyses can be summarized automatically as log reports, providing high accuracy automated replacements for human generated logs, unburdening the crew of this labor. For example, Fig. 17 shows an actual log report from a SPENCER watchstander during a recent underway cruise. The SAW onboard SPENCER automatically generated the log shown in Fig. 18. Note the similarities and the more exact times found by the NILM system.

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MACHINERY LOG

U.S. Coast Guard Cutter SPENCER (WMEC 905) **Date:** 10 Dec 14

WATCH OFFICER'S REMARKS:

0000-0400

Vessel is moored at the above location. Ship's status is B-12. Electrical power, potable water, and sewage discharge are being supplied via shore-tie. Reviewed Tag-Out Log and the following machinery is listed as OOC: Oily water separator system, Bridge window heater STBD center, #2 MG set, VCT suction valve, Clutch control PLTHS pushbutton and STBD CPP L/O Heater. All other machinery is IAW the Midnight Machinery Status sheet. **0345** Carried out the watch routine.

0400-0800

Vessel is moored as before. **0425** Energized the pre-lube pumps for both SSDG's. **0430** Started both SSDG's and secured the pre-lube pumps. **0500** Shifted from shore power to ship's power. **0501** Paralleled the #1 SSDG to the main bus. **0535** Conducted round of the ship and the pier, all secure. **0545** Conducted round of the ship and the pier, all secure. **0550** Conducted blow downs of BMDE's. **0600** Started BMDE's. **0630** Shifted BMDE's from E-MAN to ECC Auto. **0700** Completed Light-Off Schedule. **0720** Set the Special Sea Detail. Set RMD in the Engine Room. **0735** Clutched in BMDE's, placed in PHC Auto. **0745** Carried out the watch routine.

0800-1200

Vessel is moored as before. **0814** Vessel U/W. **0825** Conducted round of the E/R, all secure. **0855** Secured from Special Sea Detail, secured from RMD in the E/R. **0905** Secured BCPP C Pumps. **0906** Energized BMDE and BSSDG L/O spinners. **0921** Set Restricted Maneuvering Doctrine and Set GE. **0922** Energized BCPP C Pumps. **0924** Energized #1 and #2 Fire Pumps. **1055** Secured from GE and Secured from Restricted Maneuvering Doctrine. **1056** Secured #1 and #2 Fire Pumps. **1057** Secured BCPP C Pumps. Carried out the watch routine.

Figure 17. The machinery log generated manually by the ship's crew by logging events and times.

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Date: 10 Dec 14

MACHINERY LOG

U.S. Coast Guard Cutter SPENCER (WMEC 905)

0000-0400

Vessel is moored as before. Watch properly relieved, carried out watch routine.

0400-0800

Vessel is moored as before. 05:01: Started #2 SSDG. 07:20 :Set RMD. Watch properly relieved, carried out watch routine.

0800-1200

Vessel is moored as before. 07:37. Secured Inport ASW pump. Vessel Underway. 09:03: Secured RMD 09:07: Secured #2 SSDG. 09:21: Set RMD. 10:55: Secured RMD 11:29: Started #2 SSDG. Watch properly relieved, carried out watch routine.

1200-1600

Vessel is underway as before. 13:56:Started #2 Main Propulsion Diesel Engine Prelube Pump 14:01:Stopped #2 Main Propulsion Diesel Engine Prelube Pump 14:04: Shifted to Underway ASW pump, Underway. 14:04: Started #2 SSDG. 14:26: Set RMD Watch properly relieved, carried out watch routine.

Figure 18. Automatic machinery log generated by a SAW onboard SPENCER.

Additional metrics can be parsed from this data. For example, fuel oil transfer pumps periodically transfer diesel fuel to a ready service tank feeding propulsion and power generating prime movers. These fuel pumps deliver a relatively consistent flow rate. The SAW is capable of tracking the operating time of the fuel pump electrically, and then deriving the implied fuel transferred to the service tank, essentially automating the tracking of fuel consumption. Currently, fuel transfer amounts are discovered through manual soundings or an Automatic Tank Level Indicator (TLI) on newer vessels. This approximation from the SAW can be a check of these readings. In heavy weather, manual soundings and TLI readings are extremely unreliable and difficult to achieve due to the motion of the vessel. In rough seas the NILM is capable of providing the most accurate fuel consumption estimate. Several other metrics like this can be developed as well, including machinery hours (an important maintenance factor), crew fatigue from hours at heightened alert, proper sequencing and alignment of multi-pump systems like RO, and metrics on days underway. An example of a dashboard of data from the SPENCER SAW for maintainers and operators is shown below in Fig. 19.

The robust nature and simplicity of the NILM system offers several advantages to the distributed sensor network currently used by USCG, USN and commercial fleets. Communications losses are common place in distributed systems with long cable runs, large numbers of complex sensors, and complex communications systems involving repeaters. Compared to these systems, the nonintrusive approach requires much less maintenance, requires less equipment, and is a fraction of the price to purchase and to install.

V. CONCLUSIONS

Observation from the USCGC SPENCER field data indicates that nonintrusive power monitoring can have an important role in ship operation and maintenance. Here, we observed a single important breaker panel with eight systems

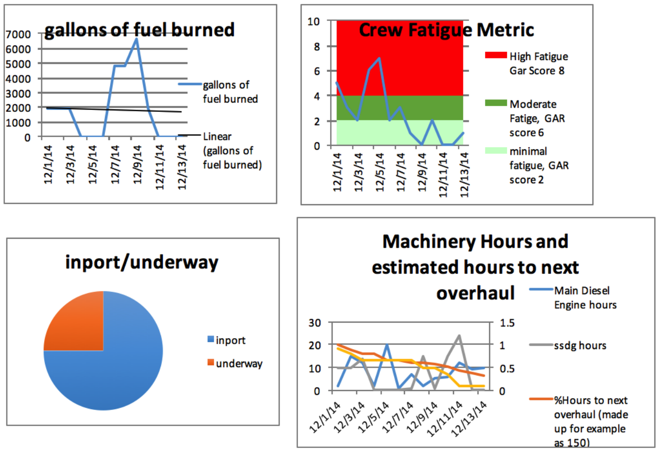

Figure 19. A dashboard for operators and maintainers.

during a month of underway operation. The nonintrusive SAW accurately tracked all systems. The SAW also developed derived metrics using "expert" knowledge of the combined operation of ship systems. For example, the SAW tracked MPDE auxiliaries to determine when the MPDE was online and offline as well as track the usage of the CPP "C" pumps. By tracking the auxiliaries systems of the MPDE, order of operations can be verified to ensure health of the machinery as well as proper start up and securing procedures.

Using this information, top level commanders can easily see the exact state of the vessel, underway, at RMD, or other modes of operation. We are currently installing a NILM system on USCGC SPENCER to monitor the entire, ship-wide machinery status by installing the SAW at a central power distribution point for the entire ship. That is, in this installation, sensors will be installed on the main switchboard. In preliminary observation, loads were observed turning on and off, similar to the observations from the single panel experiment described here. Future work is aimed at expanding the ability of the nonintrusive SAW to detect events in more complex aggregate data streams, and produce comprehensive logs and reports for the entire ship.

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