Sensors – the Eyes and Ears of Ship Automation

If your vision or hearing became impaired, it would definitely change the way you interpret and interact with the world. Sensors are the eyes and ears of your automation. Their health (i.e. accuracy and reliability) is essential to all shipboard monitoring and control functions that require reliable data to synthesize decisions, which pretty much includes everything. What is surprising is that, even with this critical role in machinery control, sensor health has received scant attention in the marine industry. In fact, they represent the weak link in modern automation and control systems, from both a safety and a health monitoring perspective.

In this two-part series, we are going to present some real-world data from modern ships that demonstrate the magnitude of the sensor reliability problem prevalent in the world fleets today. This may be, in fact, the only marine data publically available on the subject. Even though a bad sensor can cripple a control system, remediation strategies adopted by other industries, such as physical or analytical redundancy, have yet to be incorporated into ship machinery control systems. In the context of machinery health monitoring, if we can’t trust what the sensors are telling us, it’s impossible to assess the health of the equipment being monitoring. Sensor health monitoring and diagnostics should be first on the list of CBM targeted-items, but unfortunately never makes the list at all. Sensors should be treated the same as any other critical equipment whose health we wish to maintain.

In Part 1 of this series, we will look at some real-world examples of sensor problems from data collected aboard ships with our DEXTER system installed.

Part 2 will present how MACSEA is addressing the sensor problem through advanced research in sensor diagnostics. It presents a summary of our work involving two multivariate machine learning algorithms, nonlinear state estimation and support vector machines, applicable to shipboard sensor diagnostics.

Our hope is that the next generation of microprocessor-based shipboard machinery control systems will incorporate these or similar algorithms for real-time sensor diagnostics and accommodation (software-generated signals used as substitutes for failed sensors).
The importance of sensor accuracy and reliability cannot be over-emphasized when discussing CBM systems, including diagnostic/prognostic systems like DEXTER. The ability to accurately monitor the current state of your equipment relies solely on individual sensors distributed across your equipment. Modern machinery control systems incorporate an enormous amount of measurement instrumentation, including temperature sensors, pressure sensors, flow sensors, vibration sensors, current sensors, and the list goes on and on. They come in the form of mechanical gauges, electrical meters, transducers, thermocouples, resistance temperature detectors (RTD), etc. All of these devices provide valuable information to operators and are also essential for controlling equipment operation, providing alarms, or triggering equipment safety features, such as automatic shutdowns.

A sensor failure, in the worst case, can have a damaging impact on your equipment, perhaps even the environment in the case of lost propulsion control. To a lesser degree, a sensor failure will restrict your ability to assess your equipment’s operational health. This will have a negative cost impact, since maintenance actions cannot be based on equipment condition (CBM) if the
current condition of the equipment cannot be accurately determined. Equipment Health Monitoring (EHM) systems cannot properly function to detect and predict problems without accurate and reliable input from the sensors being monitored. The old saying of “garbage in = garbage out” speaks perfectly to how CBM and EHM systems are reliant on good sensor inputs.

As much as EHM systems can be negatively impacted by bad sensor data, they can also be a valuable tool in identifying sensor issues. They will respond to a high temperature or low pressure input regardless of whether the cause is a failed sensor or an abnormal equipment condition. Either way, they can alert operators that an anomalous condition exists in the machinery plant that should be investigated. However, if operators are inundated with what are considered as “nuisance alarms” from whatever cause, they will soon start to ignore them. The dangerous mentality becomes “… that thing is always triggering alarms, it doesn’t mean anything”. The mentality needs to be “… my EHM is making a fault call, what is it trying to tell me?” This requires proper training, top-down acceptance of the CBM concept, and confidence that the EHM is providing accurate information.

Faulty or inaccurate sensors can:

- defeat equipment safety designs by improper activation of safety controls,
- mask existing equipment problems, resulting in inefficient or unreliable operation
- cause costly unplanned equipment down time
- waste crew troubleshooting time and effort
- trigger excessive nuisance alarms,
- desensitize operators and slow their response time to real problems

Sensors failures can occur in many forms. Some common examples are:

- sensing line clogs, voids, leaks, or loose mechanical connections
- electrical opens or shorts
- loose or high resistance terminal connections
- inaccurate calibration
- transducer data communication issues
- electrical interference or line noise
- signal loss or corruption

There is no guarantee that any of these issues will be immediately identified by even the most diligent of operators. Absent an actual alarm condition, these sensor issues often go unnoticed. Intermittent problems can easily be missed; if the issue isn’t present when the physical gauge, meter, or control panel screen is viewed, then the operator doesn’t see it. This is where the graphical displays of the EHM system can really shine. Looking at sensor data on historical
graphs makes it easy to detect sensor issues. The following three graphs show clearly when a sensor problem is present.

The graph to the right shows an example of a healthy sensor, with all values falling within the normal band.

This graph shows an erratic sensor, sometimes appearing normal, while at other times drifting well beyond the normal low limit with large variation.

This graph shows an obvious failed sensor. All data is “flat-lined”, with a constant reading across the engine’s entire load range.

EHM systems require accurate and reliable data to function properly. The typical EHM system does not perform sensor diagnostics. It simply responds to the machinery sensor information supplied to it, as if it were always good data. When bad sensor inputs are introduced, erroneous equipment fault calls are generated, since the EHM system has no way on knowing whether an actual equipment problem exists or whether there is a bad sensor. An abnormal input is always assumed to be equipment related.

In the following paragraphs, we will discuss some real-world examples of sensor problems from data collected aboard ships with our DEXTER system installed. These results are not unusual; in fact, they are typical for every installation MACSEA has done to date. In most cases, the ship crews are not even aware of these problems until after system commissioning.
In this case study, shortly after DEXTER commissioning on this particular vessel, the customer reported that a large number of fault diagnostic calls were being generated and tasked us to perform a forensic analysis of the diagnostic data. A detailed analysis conducted in May 2011 revealed some startling results. A summary of that analysis is as follows:

Total number of Fault Calls – 291
- Engine Faults: 36
- Improper Standby Pump Operation: 93
- Calls due to failed sensors: 162

For the data sample provided, there were a total of 291 diagnostic fault calls generated. Surprisingly, fifty-six percent of these (162 diagnostic calls) were clearly the result of failed or erratic sensors (similar to the graphs shown previously).

Thirty-two percent of the diagnostics generated in the data sample (93 fault calls) were due to improper operation of a standby lube oil pump. A specific diagnostic had been included in DEXTER to detect when the standby pump was being operated in non-maneuvering situations when it shouldn’t be, hence consuming additional energy and creating excessive oil pressure in the lube oil system. Clearly, the crew was ignoring this energy conservation and maintenance avoidance directive.

In this case study, the customer was shocked to learn of these results. Although they had been involved in CBM-type systems for some time, they had never seen data like this before and had no formal remediation procedures in place to address either the sensor or the energy conservation problems. Besides fixing the bad sensors identified from our analysis, crew training would obviously need to be an important part of their future energy conservation program.

This case study illustrates another very important point regarding the implementation of EHM systems. There is a maturation process involved with all EHM systems and ship-specific grooming is required in order to fine-tune system performance for maximum diagnostic robustness. Excessive alarm generation will desensitize operators to legitimate fault calls, leading them to ignore important diagnostic calls that are “buried in the noise” of sensor-related
calls. In the case study, over 88% of the fault calls where a result of either a bad sensor or improper equipment operation. The EHM system did exactly what it was designed to do. In fact, the sensor and standby pump issues were previously undiscovered deficiencies in the material readiness of this vessel. However, subsequently to initial EHM system commissioning, the operators were overwhelmed with a large number of fault calls and tended to ignore the valuable information the system was providing.

The lesson to be learned in this case study is that successful CBM implementation begins with the “eyes and ears” of the machinery plant. Bad sensors cannot be tolerated – it’s an “all-in” game. Ignoring sensor issues because the CBM budget didn’t anticipate this need will only result in failed projects and none of the benefits that CBM can provide.

A Short-Term Solution

During the EHM system maturation process, particularly immediately following initial shipboard commissioning, it is imperative that each diagnostic fault call be reviewed and investigated. If a fault call is due to a failed or erratic sensor, then the sensor should be fixed as soon as practical. If the sensor cannot be repaired in a timely manner, then the sensor should be disabled so that it doesn’t impact the equipment health diagnostic analysis. DEXTER provides a feature to enable or disable individual sensors. Disabled sensors will be ignored by DEXTER’s neural network-based diagnostic reasoner. After sensor repair, it can be enabled through the user interface shown below. This feature dramatically reduces the number of sensor-related fault calls.

![Figure 2 – DEXTER Sensor Enable/Disable Screen](image)
This is another case study in which the EHM system was reporting an excessive number of fault calls and we were asked to investigate. Our forensic analysis revealed that the machinery control system (MCS) would intermittently lose communications with its own sensor Data Acquisition Units (DAU). The communication loss only lasted a few seconds but, during the loss, all sensor values associated with the lost DAU would drop to zero. A few seconds later, they would return to normal values. This problem occurred at random intervals and on different DAUs. When these data drops occurred, the EHM system reported numerous fault calls based on bad data from the MCS.

One of the worst cases occurred when the DAU associated with the engine room ambient temperature sensors dropped to zero (see figure 3). In this application, DEXTER corrects a number of air and exhaust gas temperature measurements to a standard ambient air temperature before performing diagnostics. Since engine room ambient temperature is used in the temperature correction calculations, each time this input dropped to zero because of the DAU problem, all related temperature-corrected values were impacted.

Because of the age of the MCS and the cost involved, the customer chose not to fix this communication issue. MACSEA provided an inexpensive software work-around to detect and ignore these “data drops” when they occurred. Interestingly, most of the engineers aboard were completely unaware of the issue. Because the data drops were of such short duration, the MCS signal delays kept the issue from affecting its alarming function.

The graph in figure 3 shows the phenomenon very clearly. The historical data was archived at one minute intervals and covers a one-month time period.
During a short sea trial, the ship in the case study experienced a gas turbine lube oil sump tank low level alarm. The ship took immediate action by taking the engine off line and investigating the issue. After a detailed inspection of the system, no leaks were identified and the actual tank level was found to be normal. The ship reviewed DEXTER’s historical data (see figure 4 below) and found that the tank level indication had been showing signs of erratic behavior for over a month.

In this case, there was no diagnostic fault that used this parameter, but it was being recorded along with other salient machinery data. (DEXTER can also be used as a “Black-box” data recorder.) If it had been, the sensor issue would have easily been identified without having to drill down into historical data. The onset of erratic behavior, where the tank level values fluctuated significantly beyond normal values, would have triggered immediate diagnostic alerts.

This is a scenario where the EHM system could have provided significant value to the ship operator. The ship had to unnecessarily take an engine off line, reduce their propulsion capability, and scramble to investigate what was happening - all due to a single sensor’s erratic behavior that had gone undetected for over a month. Investigating an EHM-generated fault call would have identified the onset of the sensor problem and allowed the ship to repair the problem on their schedule with no upset to operations.

Figure 4 – Faulty Tank Level Indicator that Triggered Manual Engine Shutdown
In order to achieve reliability and robustness, all EHM systems must address the sensor issues outlined in this paper. In Part 2 of this series, we will present how MACSEA is addressing sensor health through advanced research in sensor diagnostics. It presents a summary of our work involving two multivariate machine learning algorithms, nonlinear state estimation and support vector machines, applicable to shipboard sensor diagnostics. Our goal is to introduce these advanced sensor diagnostic techniques into future versions of DEXTER to improve diagnostic robustness and the accuracy of our predictive analytics.