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Intelligent Machine Condition Monitoring for Cyber-Physical Systems

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1 Introduction

Modern day Industrial Internet of Things (IIoT) applications are large heterogeneous distributed systems with over 30,000 sensors and 10,000 nodes. Trends indicate a tremendous growth in the number of connected components over the coming years. Gartner Research predicts over 20 billion interconnected devices by 2020, representing a $3 trillion business and technology opportunity [1]. Lee et al. refer to this emerging global cyber-physical network as the *TerraSwarm*, encompassing trillions of sensors and actuators deployed across the planet [2]. These applications will dynamically assemble sensors and computation nodes, aggregate and process large quantities of data, and transfer decisions to actuators and controllers, while meeting tight performance requirements and cost constraints.

Cyber-physical networked systems can generate gigabytes and potentially terabytes of sensor data about the condition and operation of the system. For example, the condition monitoring solution for the Victoria Line of the London Underground rail system yields 32 TB of data every day [3]. In the midst of this explosion of engineering and measurement data, it has become imperative for systems to incorporate a sound management strategy to aggregate the data, conduct diagnostic analytics about the condition of the system, and facilitate predictive maintenance to reduce downtimes and maximize efficiency. Given the cost and complexity of modern cyber-physical systems, it is important that the monitoring solution be scalable and customizable to meet changing application requirements.

Nevertheless, with the advances in sensing and networking technologies, adding measurements to systems has become easier and cost-effective. Intelligence of data acquisition devices and sensors has drastically increased and become more decentralized, with processing elements moving closer to the sensor. In addition to measurement devices getting smarter, smart sensors have emerged that integrate sensing, signal conditioning, embedded processing, and digital interfacing into the sensor node itself.

As processing moves closer to the sensor, innovation in measurement system software is required to efficiently push analytics to the edge. Future software for edge-based systems will be able to quickly configure and manage thousands of networked measurement devices and push a myriad of analytics and signal processing to those nodes. Going forward, systems must transition to smarter, software-based measurement nodes to keep up with the amount of analog data and derive insights about patterns and trends in the operation of the system. The “smart edge” needs specialized software and platform solutions to perform local control and data acquisition and interconnect with entire networks of intelligent “systems of systems” [3].

In this paper, we discuss advances in intelligent machine condition monitoring for cyber-physical networked systems and recent technologies in this area. Section 2 of this paper reviews key components and techniques in a machine condition monitoring solution. Section 3 then presents an industrial tool called InsightCM from National Instruments and discusses an application case study.

2 Machine Condition Monitoring

Machine condition monitoring (MCM) is the process of monitoring the condition of a machine with the intent to predict mechanical wear and failure. Vibration, noise, and temperature measurements are often used as key indicators of the state of the machine. Trends in the data provide health information about the machine and help detect machine

faults early, which prevents unexpected failure and costly repair [4]. The need to eliminate catastrophic downtimes due to unexpected breakdowns and unnecessary maintenance costs has made condition monitoring critical for asset utilization and productivity across diverse industries. The global machine condition monitoring equipment market is expected to grow at a CAGR of 7.6% between 2015 and 2020 from $1.5 billion in 2014 to $2.5 billion by 2020 [5].

MCM provides vital information about the health of a machine. An organization can use this information to detect warning signs early and avoid unscheduled outages, optimize machine performance, and reduce repair time and maintenance costs. Figure 1 shows a typical machine failure example and the warning signs. The user can detect failure signs months before repair is required, allowing for proper maintenance scheduling and shutdown.

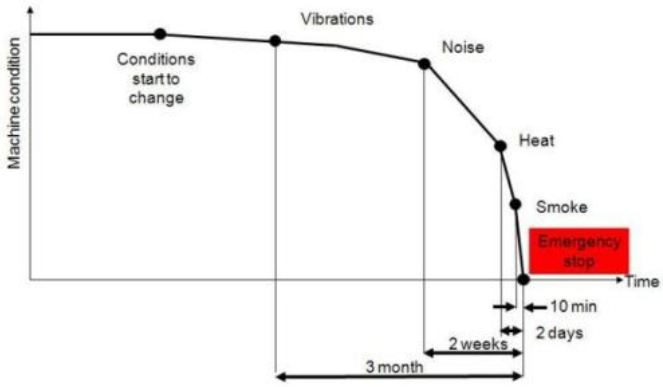

Figure 1: The warning signs of machine failure

As shown in Figure 1, vibrations are the first warning sign that a machine is prone to failure. This warning sign can provide up to three months of lead time before the actual failure date. Monitoring this data with vibration analysis hardware and software helps predict this failure early and schedule proper maintenance [6].

There are five main types of machine condition monitoring. *Route-based monitoring* involves a technician recording data intermittently with a handheld instrument. This data is then used to determine if more advanced analysis is needed. *Portable machine diagnostics* is the process of using portable equipment to monitor the health of machinery. Sensors are typically permanently attached to a machine and portable data acquisition equipment is used to read the data. *Factory assurance test* is used to verify that a finished product meets its design specifications and to determine possible failure modes of the device. *Online machine monitoring* is the process of monitoring equipment as it runs. Data is acquired by an embedded device and transmitted to a main server for data analysis and maintenance scheduling. *Online machine protection* is the process of actively monitoring equipment as it runs. Data is acquired and analyzed by an embedded device. Limit settings can then be used to control turning on and off machinery.

Direct machine condition monitoring is accomplished via sensors, of which the most prevalent types are: accelerometers, tachometers, and proximity probes.

- *Accelerometers* are used to monitor vibrations of a machine. These are transducers for measuring the dynamic acceleration of a physical device, and are important to machine monitoring because they monitor system vibrations, which can be used to predict the life cycles of parts and to detect faults in machinery. Among the most common transducers are piezoelectric accelerometers, unbonded strain gage accelerometers, vibrating element accelerometers, and Hall effect accelerometers.

- *Tachometers* are used to determine the rotational speed of a shaft to provide phase information for the vibration data. These are transducers for measuring the rotational speed of a physical device, and are important to machine monitoring because they provide rotational speed as well as phase information, so that frequency components can be matched to shaft speed and position. Drag torque tachometers are among the most common.

- *Proximity Probes* are used to monitor the movement of a shaft. These are transducers for measuring the displacement of a physical device, and are important to machine monitoring because they monitor the movement

of a rotating shaft. Proximity probes are usually found in 90-degree offset pairs to map an X-Y plot of the shaft movement. Then imperfections such as misalignment of the shaft, faulty bearings, or other external factors preventing perfect rotation can be prevented.

Most machine condition monitoring sensors require some form of signal conditioning to optimally function, such as excitation power to an accelerometer. Filtering on the signal is also common, to reduce both line noise and unwanted frequency ranges. Once the signals have been acquired, software-based signal processing is used to analyze and display the data from rotating machinery. The analysis can include calculation of overall vibration level (RMS, peak, crest factor); integration from acceleration to velocity or displacement; operation of online order analysis such as order tracking, order extraction, and order spectra computation; processing of digital and analog tachometer signals; application of limit testing on time data or power spectra; and drawing of a variety of plots ranging from spectral maps to time based plots.

3 Condition Monitoring Tools

There are many commercial tool offerings for machine condition monitoring. Major players in the marketplace include Brüel & Kjær Vibro, ClampOn AS, Data Physics Corporation, DLI Engineering Corp, Emerson Process Management, FLIR Systems Inc., GE Energy, Honeywell Process Solutions, among others [5]. We now introduce one such MCM tool; National Instruments' (NI) InsightCM^{TM} Enterprise [7]. InsightCM is an online MCM tool for monitoring health of critical rotating machinery and auxiliary rotating equipment. The goal is to optimize machine performance, maximize up-time, reduce maintenance costs, and increase safety. This solution allows maintenance specialists to acquire, analyze, visualize, and manage sensor data throughout the life cycle to draw diagnostic conclusions, manage alarms based on calculated features and sensor measurements, remotely configure, monitor, and manage acquisition devices, as well as authenticate users and devices to address network security concerns. By integrating into the IT infrastructure the tool can interact with existing databases and enterprise software.

Figure 2 illustrates key components of the InsightCM solution: monitoring systems, server for data management and analysis, data explorer clients, and management infrastructure.

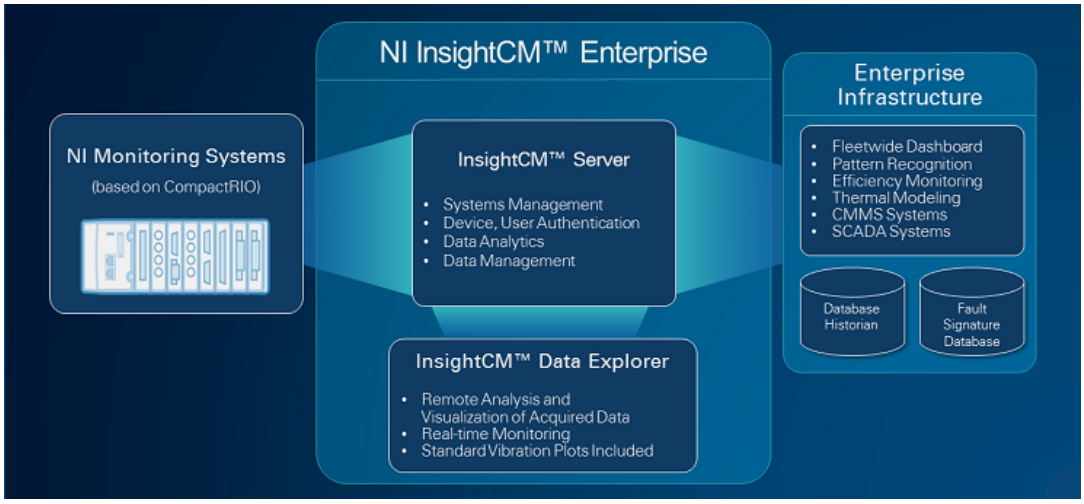

Figure 2: NI Insight^{TM} Architecture

The monitoring devices at the edges of the system are NI CompactRIO platforms [8]. These devices, in addition to sensors and I/O modules, have processing and reconfigurable components for inline data processing, control analytics, network communication, and timing. The CompactRIO devices supports a range of analog and digital sensors, such as proximity probes, accelerometers, pressure sensors, voltage and current sensors, thermocouples, and temperatur detectors. The monitoring system supports periodic monitoring as well as observation of important

transient events such as start-ups and coast-downs. The *periodic recorder mode* allows data logging based on configurable time intervals, measurements, and user triggers. Dynamic waveform and static measurement sensors account for 80% of measurements in a predictive maintenance program, suitable for replacing traditional, manual diagnostic rounds. The *transient recorder mode* streams time waveform data during transient events at run-up and coast-down until steady state is maintained, and includes support for accelerometers, velocity meters, and proximity probes.

The server delivers analytics coupled with management of CompactRIO systems, data, and alarms. The server software manages reliable, loss-less communication across the entire architecture and includes capabilities to configure, view, and manage the remote acquisition systems. The software processes dynamic waveform data and analyzes RMS, peak-peak, true-peak, derived-peak, DC gap, crest factor, and spectral bands. It also supports custom measurements like bearing, gear, and other fault frequencies. Additionally, the server provides a security layer to authenticate and protect sensor and server data.

The data explorer provides interactive visualization and analysis of real-time and historical offline data stored in the server. The software package helps in remotely analyzing raw time-series data and results, drawing comparisons and viewing historical trends with support for standard vibration plots. The data explorer provides two modes: one for viewing periodically acquired data and one for viewing previously captured transient events. Users can detect imbalances, bent shafts, misalignment, bearing defects, and other faults in rotating machinery, and determine actions that need to be taken as part of diagnosis and maintenance procedures.

InsightCM has been widely used across multiple industrial domains including traditional power generation, oil and gas, renewable power generation, transportation and aerospace, heavy equipment, and manufacturing [9]. We discuss the use of InsightCM for a power grid monitoring application.

Duke Energy [10] is the largest power generation holding company in the US with a diversified energy portfolio mix and the capability to generate 58GW across 80 plants. Data used to be collected manually in periodic rounds on assets such as turbines, transformers, boilers, radiators, valves, motors, pumps, fans, and generators. The typical measurements include motor current, lube oil level, vibration, pressure, performance, and thermography. In this approach, 80% of the effort was spent on data collection, and 20% on analytics. Besides being labor intensive (about 60000 rounds/month), this approach has limited instrumentation and inconsistent diagnostics, which severely constrains the analysis. By employing InsightCM for condition monitoring, Duke Energy was able to phase out manual collection and spend more resources on the analysis. The system solution consists of one monitoring and diagnostic center for 80+ power plants controlling 30,000+ sensors distributed over 10,000+ assets. The monitoring architecture uses 1200 CompactRIO systems, generating and analyzing over 600 GB of data each week [11].

4 Summary

Machine condition monitoring (MCM) for large scale Industrial Internet of Things deployments will be critical for enterprises owning such systems. The need to eliminate catastrophic downtimes due to unexpected breakdowns and unnecessary maintenance costs has made condition monitoring critical for asset utilization and productivity across diverse industries. It has become imperative for such MCM systems to incorporate a sound management strategy to aggregate the data, conduct diagnostic analytics about the condition of the system, and facilitate predictive maintenance to reduce downtimes and maximize efficiency. According to a September 2015 report from Frost & Sullivan on Global Big Data Analytics Market for Test & Measurement, product development costs can be reduced by almost 25%, operating costs can be reduced by almost 20%, and maintenance costs can be reduced by 50% if big data analytics is applied for testing [3]. In this paper, we discussed the roles of enterprise MCMs and presented a representative tool, NI InsightCM™, which has been used for controlling and monitoring large scale distributed systems like a modern power generation network. To push the boundaries and maintain a competitive edge, the engineering community must provide MCM tools that find new correlations based on the monitored data to predict key future behaviors and even automatically take preventative actions with little human supervision.

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