The Advanced Technology Program (ATP), of the National Institute of Standards and Technology (NIST), held a workshop on Condition-Based Maintenance (CBM) as part of it's November 17-18, 1998 Fall Meeting in Atlanta. The CBM workshop was one of several allowing industry and research communities to define critical R&D investment opportunities with both high technical risk and potential for broad national impact.

BACKGROUND

During the past year, when ATP asked companies where they thought their next critical R&D investment would lie, monitoring and accessing the health of machinery was one area identified. This R&D area, sometimes referred to as condition-based maintenance, was viewed as one of the next great opportunities for product differentiation and successfully competing in world markets.

THE OPPORTUNITY

Discussions with companies identified 3 technical barriers to CBM's widespread implementation:

- the inability to accurately and reliably predict the remaining useful life of a machine,
- the inability to continually monitor a machine, and
- the inability of maintenance systems to learn and identify impending failures for a machine and then recommend what action should be taken.

These barriers could potentially be addressed through innovations in three technical areas:

- prognostication capabilities,
- cost effective sensor and monitoring systems, and
- reasoning or expert systems.

WHAT TRANSPIRED IN ATLANTA

68 people attended the CBM session. Representation was very diverse:

- companies ranged in size from small to Fortune 500;
- with different industrial sector representation including
  - developers of control systems, instrumentation, analytical equipment, and software for management systems;
  - suppliers of analytical equipment, instrumentation, and maintenance systems;
  - machinery manufacturers of turbines, pumps, motors, gear boxes and transmissions, trucks, aircraft and ships, chemical plants and refineries, and HVAC; and
  - end users such as the electric utilities, waste management and manufacturers of steel, aluminum, food products, and paper.

These people discussed their vision of where CBM should be going, what must be addressed to get there, and how this could be accomplished. Technical solutions in the three technical thrust areas were also discussed in the context of ATP investment criteria:

- what makes these innovations risky technical investments,
- why won't these innovations be developed without ATP funding, and
- what significant national impacts should be expected from commercialization of the innovations.

Two keynote speakers did an excellent job of setting the tone for the ensuing breakout sessions. John Mitchell, president of Machinery Information Management Open Systems Alliance (MIMOSA), focused on the ideas that CBM is not a solution to offset the costs of maintenance, but is a viable path to increased profitability through increased plant capacity and / or availability. Getting to this goal would require the CBM community to develop new technologies, prognostication capabilities both technical and business / economic input, and improved data representation. The second speaker, David Thurston, Program Manager for CBM in the Office of Naval Research, discussed the current research and research needs from a Department of Defense (DOD) perspective. While DOD is moving forward in the area of CBM, point solutions are what is being developed while generic solutions are desired. An ATP focus on CBM was thus considered to be complementary to DOD's efforts and highly desirable.

THE WORKSHOP BREAKOUT SESSIONS

Workshop attendees divided about equally into the three breakout sessions addressing prognostication capabilities, cost effective sensor and monitoring systems, and reasoning or expert systems. Technical barriers and risk assessments were discussed and identified below. Economic benefits and requirements for support were also discussed.

1. Prognostication

Prognostication included three components:

- estimation of remaining useful life (or time to failure or time for degraded performance) based on the condition of the equipment;
- development of confidence levels (uncertainty estimates); and
- recording an audit trail of how the estimate and confidence level were obtained.

In developing these three parts of prognostication models, quality diagnostics and sensor information were considered imperative. Data is thus needed not only for use by prognostication models, but also to train and validate the models. The group placed a very high priority on quality and complete data sets that would be publically available for review and use. The models should also be able to incorporate changes in mission compliance, operational environment, economic rules, priority assessments, and functional requirements. The barriers to achieving these goals included:

- Lack of complete understanding of the evolution of faults and how they effect equipment;
- Lack of knowledge of controlling parameters hampers development of accurate models;
- Lack of robust modeling techniques for state-based modeling to develop understanding of physics of failures (reduced order modeling techniques);
- Lack of condition life test facilities, e.g., how to replicate operating environment; and
- Lack of predictive methodologies for unsteady signatures indicative of failure modes which are physics-based.

Some specific examples included:

- *Corrosion and fouling:* inability to detect localized pitting and being able to predict when damage becomes irreversible.
- *Prediction of electronics failure*: how to do failure prediction on the fly and how to reduce the cost associated with doing this.
- *Temperature assessment*s: e.g., condition of hot gas spots and crack formation, what signals important to diagnosing these problems, and how to make infrared systems survive.

2. Sensors and Monitoring Systems

This group identified technical barriers preventing development of sensors and monitoring systems with features needed by CBM. The barriers can be broadly grouped into:

- *Sensor Characteristics:*
  - embedding intelligence and data-to-information-to-knowledge processing for sensors;
  - data validity and reliability;
  - robustness as a trade-off with greater sensor capabilities (ruggedness verses complexity);
  - lack of real time sensors based on semiconductor designs (as opposed to more expensive ASIC designs); and
  - lack of knowledge about the design of sensors, sensor operating conditions and supporting infrastructure leading to the inability to design systems up front.
- *Measurement Capabilities:* direct, real time sensor measurement of many condition parameters is not feasible today, e.g.,
  - corrosion data for metal fatigue;
  - lubricants state;
  - micro-cracking in ceramics / composites; and
  - volume of coal dust in fossil power station.
- *Interface Barriers:*
  - wireless interfaces systems (complexity varied between industries due to transmission and frequency interference in a remote oil field or an urban high traffic area or rooftop location) which in turn impacted system power requirements and other system sub-component design specifications;
  - battery/energy storage and generation technology too immature to support wireless interface
  - inability to integrate sensor with other parts of the CBM infrastructure (sensor with sensor processing electronics, database, and human operator's monitor, e.g., STNC); and
  - lack of flexibility to work with various sensor and data interpretation platforms.
- *Environmental Barriers:* Non-intrusive design of sensor that can be embedded in the final product with the ability to operate in harsh environment, and thus reduce the importance of sensor placement based on sensor requirements as opposed to CBM system requirements.
- *Economic Barriers:* Life cycle costs are highly dependent on design complexity, which in turn impacts the longevity of sensor. For example, the automotive industry has very low up-front costs and requires little maintenance while the aerospace industry has more intelligence (read as cost) designed into the sensor with the understanding that it will be continually checked for calibration and data validity given the potential for the cost of catastrophic failure. However, cost is not confined to just the sensor. The cost to develop and maintain the infrastructure to transmit, interpret and analyze data, and designing for operator friendliness is more than one company can justify.

3. Reasoning or Expert Systems

This group identified technical gaps in the software tools and infrastructure available for CBM. The group found that CBM needs generic software tool capabilities and software infrastructure which is not currently available. Because the same generic software capabilities could apply across all manufacturing processes, there is substantial opportunity for leveraging research results in this area; however, actual application of the software tools requires careful tailoring through specific data sets, rules, models or other mechanisms to make the generic tools effective in addressing a particular CBM application. This group concluded that industry would not develop these generic capabilities on its own because substantial resources are tied up generating point solutions to each new problem.

The group identified the key technical capabilities needed in this area as tools and infrastructure for generic applications which automatically analyze features, extract features from data, identify critical features and generated system models. Successful CBM needs this generic data mining capability for application to a broad range of data sets and models. The manufacturing industry has the capability to generate the data sets and models needed, but without the tools to exploit the data, has not had the incentive to collect the data. Currently, this is an area dominated by point solutions or custom tools.

Additional technical gaps came up during the group's discussion that reflected the needs of manufacturers to integrate CBM systems with manufacturing systems and with enterprise-wide systems:

- *Technology to model economic benefit to the CBM user:* In integrating CBM with broader asset management systems or enterprise integration systems, the manufacturer could use a more exact representation of the value of selecting a CBM strategy and components of a CBM strategy for a particular machine. Implementing this technology would require extending expected value assessments or models to CBM applications;
- *Knowledge fusion:* Individual models and data analysis techniques are often not enough to analyze a complex system. The user would like to combine diagnostic results from multiple techniques in order to determine a CBM strategy. This would facilitate the integration of CBM systems with each other and with enterprise resource planning capabilities;
- *Infrastructure for assuring the reliability of the CBM system:* For an operating manufacturing line, integrating any new system (including a CBM system) requires technology to assure that it will be reliable, will exchange knowledge seamlessly with the existing system and will not perturb plant operation. Assuring the reliability of large, expert systems in particular is a technical challenge which this community has found inadequately addressed by current research and tools; and
- *Development environments:* Integrating generic knowledge systems capabilities into CBM systems requires the introduction of very specific data and models about the systems under maintenance. For a CBM system to operate, engineers who understand the manufacturing system requirements, data sets and models, must be able to customize the knowledge system part of the CBM to meet operational needs. These engineers need user interfaces and software development environments designed for CBM.

Economic Benefits

While there was not a specific breakout session for this topic, discussions of economic issues werre threaded through out the three breakout sessions. The general consensus of these discussions was that the economic benefits of CBM in general are hard to quantify. Corporate management often does not appreciate the value of CBM, often only seeing the up-front cost of upgrading to CBM sensor and supporting infrastructure, loss in productive capacity when the plant is down to install and test CBM upgrades, or potential liability and warranty issues associated with CBM product failures caused by poor sensor or infrastructure performance.

Other industries, such as the automotive industry that uses 30-35 electronic sensors under the hood of the automobile at $300 per vehicle, are used in response to government regulatory requirements, not market pull. This is not the situation for CBM.

An example of the dollar value of CBM was discussed in the context of refinery plant corrosion. If corrosion could be measured directly at a refinery plant, down time for maintenance could be reduced from every year to potentially every 3 years. Since a typical maintenance period is two weeks to a month (about 10% of available operating time), an economic value can be assigned to a reduction in down time. However, offsetting maintenance costs is probably not the primary economic driver for CBM. Instead, it should be looked at as an integral part of a corporate business strategy for profitability. In the case of CBM, *it contributes to maximum up time (capacity) with reduced operating costs.*

IN SUMMARY, WHERE'S THE TECHNICAL SWEET SPOT?

For ATP, the "technical sweet spot" is defined as a focus on those R&D investments that are characterized as

- innovative ideas with very high technical risk that address the technical challenges of CBM,
- which cannot be done by the company alone (and thus require partnering with the government and/or others), and
- have the potential for significant national benefits.

The general consensus of this workshop was that the core R&D challenges for CBM required highly multi-disciplinary solutions focusing on system level issues. A potential technical sweet spot for ATP's investment in CBM, as defined by this workshop, involves developing the capability to confidently recognize the onset of a failure process, and then to track and predict the evolution of that failure process to a point that economic, engineering or other business criteria determine it is appropriate to repair or replace the equipment. To achieve this goal,

- modeling capabilities need to be improved (both to extract the pertinent physics as well as new model formulations);
- improved are needed in data mining, processing, handling and availability; and
- developments are needed in reasoning systems that include, in addition to the traditional CMMS capabilities, information on economic impact of decisions, training and how to perform maintenance tasks, and interfaces to other maintenance (existing) systems.

While this sweet spot definition captures the technical and business views of this workshop, it is not viewed by ATP as the only representation of CBM's technical needs. For example, two other challenges were considered very important to the development of CBM. The first looked at specific solutions to very narrowly defined technical challenges. Specific sensor performance and design issues would be one example. The second addressed the need for comprehensive and complete data sets characterizing equipment failure processes. Current data sets are incomplete (don't include postmortems of equipment failures), may not track all the pertinent parameters, or are proprietary. The group's consensus was that a public repository for such information was needed if CBM was to make critical advancement that could be accepted by industry and companies. It was recognized that such technical activities that could not form the core of a strong ATP program.

CLOSING REMARKS

It is hoped that one outcome of this workshop will be continued discussions by industry and the research community to identify additional critical R&D efforts that are central to the development of CBM. These discussions should lead to eventual business decisions on what the best path for developing these ideas is, and that, when appropriate, ATP participation will be a path that is given strong consideration.

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