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Reactive Prognostic Management of Corrosion with Autonomous Sensors

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ABSTRACT

This paper presents a new technology that holds promise for use in idealized "futuristic" systems for *in-situ* corrosion detection and remediation. New technologies are needed as recent studies show the U.S. Government spends up to $125B per year to detect, protect, and repair damage caused by corrosion. This article is a report on how the US Naval Air Systems Command (NAVAIR) has initiated several Health Usage Monitoring (HUM) and Sentient Health Management (SHM) programs to study and combat chemical corrosion. Because of the corrosive nature of the naval environment, NAVAIR is pursuing new ways to pro-actively detect, prevent, eliminate, and deal with corrosion. In mid-1999, PMA 299, the NAVAIR H60 helicopter program office, funded a feasibility experiment for the development and testing of smart prognostic (Sentient) sensors for HUM and PHM. The Sentients are members of new generation of networked and autonomous reactive sensory computers enabled by microcomputer technologies. The US Navy is investigating the use of Sentients as a new approach to a variety of issues. Sentient devices operate throughout the time between maintenance. Sentients incorporate features for reasoning information gained by combining data from multiple sensors with fuzzy logic and rule based algorithms. Sentients are a first step to having the system be a first line of defense against corrosion.

INTRODUCTION

Defense budget cuts have raised crosscutting issues concerning operations and maintenance. These include safety and environmental pressures associated with the aging aircraft fleet[1]. Corrosion is a term that covers the process of deterioration through the actions of chemical ions and physical stress. The North American Technology Industry Base Organization (NATIBO) estimates that the economic cost of corrosion in the U. S. alone is estimated to be near $126 billion per year. Perhaps $30 billion per year could be saved through in-situ detection of corrosion followed by prevention measures such as the release of anticorrosive compounds.

With Department of Defense funding, Management Sciences, Inc. and Sentient Sensors LLC are developing Prognostic Health Management (PHM) computing and sensors that provide information related to environmental compatibility and provide an early warning of corrosion, potential catastrophic failure of materials and structures. PHM deals with detection, isolation, interpretation, risk assessment, and reactive measures. PHM deals with a broad range of issues such as vibration, wearout, lubrication, as well as corrosion. This paper focuses on the aspects of Sentient Health Management (SHM) related to corrosion.

Corrosion is an electrochemical process. The modes and rates of corrosion for any material are related to environmental parameters, such as the pH and the concentration of hydrogen and chloride ions[2]. Microbiologically induced corrosion may also contribute, in some cases even predominate. Corrosion sensors based upon electrochemical measurement methods have been developed with some success. Many companies and government agencies have developed electrochemical microsensors consisting of an array of electrodes (sensors)[3]. These devices can monitor several corrosion parameters simultaneously. The sensors detect corrosion potential and rate, and the particular environmental factors such as chemical factors, which are known to accelerate corrosion. Computer programs have been written that use the data to estimate and predict damage[4,5].

Because of the corrosive nature of the naval environment, the Naval Air Systems Command (NAVAIR) is pursuing the use of Helicopter Usage Monitoring (HUM), PHM, and SHM programs. HUM and PHM are two complementary approaches that can work to reduce the long-term impacts and cost of corrosion. SHM is a new approach that combines HUM and PHM and adds Reliability Centered Maintenance (RCM) and Probabilistic Risk Assessment (PRA). HUM is to SHM as periodic dental checkups are to daily visits to the dentist. HUM, PHM and SHM are complementary activities. All incorporate the use of sensors; the difference is that HUM is global in nature, while PHM is more focused on local corrosion management. SHM provides reaction such as dispersal of anti-corrosive compounds from within the system.

HUM systems collect sensor and usage data for trend and correlation analysis. The data is unloaded and transferred for statistical analysis. The results of analysis are used by logistics and maintenance teams to develop optimal schedules for fleet maintenance. PHM technology has advanced to the state where data analysis and prognosis is performed for individual systems. SHM addresses the need for quick in-situ reaction to prevent and mitigate damage.

Sentient Sensors are "thinking machines" that leverage existing technologies. Sentients perform multi-parameter sensor processing and produce health information. Sentients are robust microcontrollers with at least two megabits of non-volatile memory and one megabits of static read only memory. Each Sentient can handle up to twelve electronic sensors. The sensors output an analog signal that is proportional to a change in property that is more or less unique to the condition being measured. The Sentient compensates for errors caused by voltage offsets and non-linearity of response such as caused by changes in operating temperature. For corrosion, the major sensors detect and quantify temperature, pH, moisture, free hydrogen ions, and relative humidity.

Sentient Sensor Interface Unit (SIU)

A Sentient SIU is made up of a microprocessor, a Field Programmable Gate Array (FPGA), a Fuzzy Logic Circuit and other electronics. The SIU interfaces directly with the Sentient module. The SIU can work with any type of sensor that has an analog or digital output from "smart sensors" with internal microprocessors. Sensors come in several sizes ranging from macro-sensors down to meso sensors, micro-sensors, and micro electro mechanical systems (MEMS). Some of the same type of sensors used by HUM are also used for PHM. SHM adds fuzzy reasoning based on RCM and risk.

Health Usage Monitoring Systems (HUMS)

HUM systems install sensors to collect data factors that cause corrosion, e.g. on temperature, humidity, salinity, pH and moisture. HUM systems record the factors of corrosivity and corrosion. Scheduled transmittal or on-request download of information sends the data to a storage media that will hold the information for sending to the analysis site. HUM combines the use of historical data with on board monitoring with subsequent off-board data analysis at designated support facilities. The support facilities combine sensor data with information on corrosion found during repair to estimate the schedule for inspection and repair. The estimates are based on correlations using geographic environmental data and information about damage found in previous inspections and repairs. HUM is meant to improve reactive processes through measurement. HUM is also used to assess the effectiveness of prophylactic chemicals and preventive processes.

Sentient Health Management Systems

SHM is an emerging technology that may hold have significance in combating corrosion in future systems. SHM is a pro-active in-situ process for "self awareness" with "deep reasoning" that considers not only the long-term effects of corrosion, but the possibilities for short term catastrophes. SHM combines sensors, microprocessors, software reasoning, and taking action against causes of problems. SHM sensors differ in the way sensor data is used for detecting early signs of factors leading to corrosion and other problems. SHM is concerned with detecting the onset of conditions leading to corrosion not necessarily measuring corrosivity or measuring corroding of the structure. For instance, when a normally hermetically sealed corrodable area is breached, presence of water vapor with free hydrogen ions means that corrosion will start to occur. Or, when a corrodable surrogate begins to corrode, local corrosion can be assumed. However, SHM can extend detection to include the tracking of fires that can occur if the wiring has polyimid insulation.

SHM works in-situ, at an increased tempo to head off problems through on-board means, to improve situation awareness at local operations. The sensor data and derived information can be a source of data for a HUMS system. The difference is in moving prognosis and management to the local site so that operators and maintainers can be aware of the presence of causes of corrosion and its potential damage. The driving concept behind SHM is to shift from sensing of off board data statistical processing to on-board reasoning of data to prevent and manage rather as well as record for statistical analysis. Several advances in technology have made it possible to move sensing with prognostic reasoning and action into the system.

- Reliable Sensors
- Tiny Robust Processors
- Fuzzy Logic Analysis
- Prognostic Reasoning
- Failure Modes and Effects Criticality Analysis
- Reliability Centered Maintenance
- Probabilistic Risk Analysis

Each feature provides an enabling aspect to SHM. Prognostic reasoning is key to providing information that work to locally prevent and mitigate the Each feature provides an enabling aspect to SHM. Prognostic reasoning is key to providing information effects of corrosion when possible and to provide early warning messaging to the distanced logistics and repair facilities. The "impossible dream" of SHM is to eliminate corrosion and to eliminate the need for structural overhauls due to corrosion.

Both HUM and PHM are implemented by sensors that detect and measure the amount of corrosion taking place for transfer to a remote site for subsequent processing. HUM and PHM are evolutionary (PHM has been in use for over seventy years). Using SHM for corrosion is revolutionary; changing the way corrosion is managed. SHM reacts to sensor data according to fuzzy rules stored in its memory. Of course, SHM also takes advantage of any historical HUM information about legacy costs for deferring action for scheduled maintenance. SHM computing devices can be distributed in the wiring system, which is partitioned to match the system architecture6. SHM is centralized because analog data from the sensors is delivered to the Sentient is processed into information before being formed into prognostic knowledge by the sector manager. SHM is federated because the information is routed from smart sensors to the local Sentient; from the suite of Sentients to the sector management unit; and from the sector managers to the system supervisor. Figure 1 shows a diagram of how the Sensors, Reactors, and Sector Health Managers are distributed in an aircraft as part of the wiring system.

Sector Management Unit (SMU)

An SMU is a rugged personal computer that performs as a supervisor for major subsystem sectors. SMU will focus on higher level SHM assessment for one vital subsystem, e.g. engines, communication, avionics, weapons, rotors, and controls. A SMU processes information from the Sentient into knowledge based on trends and events. The knowledge is processed with prognostic reasoning and quantified by probabilistic risk assessment. Actions are taken according to the fuzzy logic rules.

Using Prognostic Reasoning (PR) to Anticipate Effects of Corrosion

A computer program running on the SMU does PR. The program processes several forms of sensor data. Information for prognostic reasoning is also provided by the Reliability Centered Maintenance (RCM) analysis. Prognostic reasoning uses the a-priori information to convert derived sensory information into risk assessments. The risks are used by Fuzzy Reasoning to make recommendations for actions that will reduce the risks. For example, the detection of salt water should call for flushing with fresh water as soon as possible. Constant risk awareness along with considerate preventive action result in reduced life cycle cost. PR does not necessarily detect corrosion, rather to reason the probability of corrosion and the impacts and risk of not taking preventive or pre-emptive actions.

Using Fuzzy Probabilistic Reasoning (FPR) to Assess Impacts of Corrosion

FPR is akin to people knowing that winter is probably near when the leaves turn color. FPR uses information from RCM to perform a Probabilistic Risk Assessment (PRA). Fuzzy logic algorithms process the probabilities that trigger actions. Fuzzy logic is a new area of mathematics that deals with equations and statements that are expressed in terms of "too much", "too little", "too soon", "too late", and other ambiguities. Sets of fuzzy local and global expressions are processed in order to raise concerns, which in turn can be quantified by fuzzy mathematics. The reasoning uses modeling and simulation to obtain confidence intervals on estimates for the time for each step in the progression of events. Fuzzy reasoning uses the confidence intervals to assess the probable course of events. The reasoning uses parametric data derived from probabilistic risk analysis. Fuzzy Logic has been developed to where it plays an important role in control systems and it is especially useful in developing rules for control of chemical processes such as corrosion.

Reliability Centered Maintenance

RCM is a formal accounting process that is the basis for preventive maintenance. RCM examines each element of the Failure Modes and Effects Criticality Analysis (FMECA) which lists the "domino effects" of root causes. RCM considers the FMECA items for economic, safety, and performance issues. The RCM analyst makes a recommendation for each salient failure mode. The RCM database contains the recommended steps to be taken to assure that the failure mode does not occur. The problem is that the RCM process is often forgotten, and not fully utilized. SHM moves the RCM database on board to be used with PRA for safety assessments and for economic analysis.

Probabilistic Risk Assessment

The SMU develop risk assessments by using models, rules developed in RCM, algorithms and time domain simulation. PRA is a well-established mathematical process that quantifies the probabilities associated with a set of events. PRA combines the use of historical data with values derived from relationships defined by materials scientists and values about future environmental conditions. PRA has been used for many years to assess the risk factors found in nuclear power plants. PRA has also been applied to safety assessment of chemical plants. Corrosion is a complex relationship of chemistry, metallurgy, temperature, and physics. For example, the rate of corrosion is more severe in hot summer coastal conditions than inland in the same temperatures.

The detection, diagnosis, and prognosis provide a way to quickly deal with and mitigate corrosivity and corrosion as a daily process. For example to reapply anti-corrosive compounds that have worn off or otherwise deteriorated. The Sentient module can be tasked to fire a micro-squib that releases the anti-corrosive compound[7,8].

EXPERIMENTAL PROCEDURE

Work on SHM for corrosion (and other risks) began in 1997 as the result of a Broad Agency Announcement (BAA) contract from the Joint Strike Fighter (JSF) program office for PHM. The PHM office issued a broad agency announcement for ideas on how to use PHM to improve the safety, performance, and operations and logistics support of the JSF. The JSF program office focus is on using PHM to provide real-time situation awareness for detecting loss of stealth signature, to improve the probabilities for mission success, and to reduce life cycle costs[9]. The JSF PHM office funded a major study of embedding processors in to the wiring harness and wiring integration units. The wiring is a perfect place to place corrosion detection systems because the wiring is found in virtually every compartment, nook and cranny. Management Sciences, Inc. was awarded a contract to place PHM processing in, on, and near wiring to process sensor data and detect battle damage, vibration, and fires.

The contract also examined the ability to monitor maintenance actions, as well as environmental parameters that cause corrosion. Corrosion in all forms is a major area of interest as corrosion is known to have major impacts on life cycle cost and safety. Corrosion was of particular interest to the Navy, as the JSF will be operated from carriers. Carrier aircraft operate in a very severe corrosive environment because of sea spray and warm temperatures. The JSF program was especially interested in ways that wiring could deteriorate and cause trouble that would ground the aircraft. Corrosion of all types is a major concern.

Since the JSF will not fly for several years, it was necessary to use laboratory experiments to devise a SHM method for corrosion. For the JSF, the researchers built a laboratory test bench. Dr. Vinod Agarwala provided valuable insight into the chemistry and physics of corrosion. Dr. Agarwala has been working with industry to develop a device to measure corrosion with a galvanic circuit [10]. A small microprocessor senses the micro-coulombs of current generated during corrosion of a gold/cadmium spiral pattern on a Mylar strip. The SPEC technology was promoted as a way to provide valuable information about the potential for corrosion.

There are several approaches to corrosion management through spraying locations with a prophylactic material. These materials eventually deteriorate. The SHM approach is to not measure corrosion, but rather to detect the probability that corrosion is occurring in protected or unprotected areas. This requires techniques to detect when the protective coatings have/will deteriorate to a point when a new application is warranted. This can be done by coating the corrosion detecting sensor and detecting when the coating loses its ability to provide protection.

Prototype SHM Units

Several prototype SHM units are being installed into naval helicopters. The first SHM units to be tested contain an advanced instrument controller (AIC), microsensors for temperature and humidity, and an exposed plate with an etched pattern of conductive lines. The pattern of lines, from 3 mils to 12 mils is etched into a copper plate that is 5 mils thick. When exposed to a corrosive environment, the exposed copper wires are eaten away until the circuit is opened. Logically, the thinner wires will be eaten away quicker than the wider wires. The timer of the SHM processor is set when the new sensor is placed into the application environment (an aircraft). At periodic intervals set externally, the SHM processor tests the condition of the multiplicity of wires. When the first wire is consumed a data entry is made. Prognostic reasoning processes the time of occurrence along with environmental data that has been collected about temperature, moisture and relative humidity. The parameters are processed by the "fuzzy reasoning" algorithms which use a pre-stored set of fuzzy rules. The results can initiate actions such as releasing of anti-corrosive agents by the flight line crew.

The project built and tested four ruggedized prototype units. In November 1999, the units will be installed on two navy H60 helicopters. After thirty days, the units will be removed and examined for the effects of corrosion. The data recorded will be unloaded from the non-volatile memory and studied.

In a Phase II NAVAIR SBIR, the Sentient modules and sensors for SHM are being linked via the Internet. In a parallel project, "smart wiring" will house the Sentient Sensors. Beginning in 2000, the project will develop the rule based reasoning and fuzzy logic algorithms that will be used in the Sector Management Units.

RESULTS

Sentient technology has been laboratory tested with sensors for measuring temperature, humidity, vibration, and moisture. Sentients have been tested for corrosion sensing by detecting open circuits caused by loss of conductivity. SHM brassboards have been tested with serial and parallel ports for wire communications. The Sentient instruments have been tested with Boolean rules. Sentients have been tested for self-calibration, noise blanking, detection, diagnosis, statistics, messaging and excitation. Flight tests on H60 helicopters began in November 1999, and testing will continue for the next two years.

CONCLUSIONS

Recent advances in microprocessors, and micro-sensors have facilitated the development of in-situ Prognostic Health Management. Sentient technology can be used with sensors to detect incipient corrosion and take pro-active measures to inhibit corrosion with prophylactic coatings[11]. Sentient technology can also provide exciting new opportunities for other types of corrosion detection, prevention, and control. Further research and development is needed to develop the prognostic algorithms for particular situations, especially those related to deterioration of protective coatings.

Sentient technology is still in its infancy. When matured, Sentient technology used for SHM can result in dramatic reductions in life cycle cost. The savings can be further enhanced by combining in-situ SHM with other means such as the use of prophylactic coatings. Placing SHM devices in and on wiring can be an effective way to place prognostic sensors throughout the areas at risk due to salt-water corrosion.

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REFERENCES

1. G. Smith, J.B. Schroeder, S. Navarro, D. Haldeman, "Development of a Prognostics & Health Management Capability for the Joint Strike Fighter" Proc. of AUTOTESTCON, September 1997, pp. 676-682.
2. M. Tullmin and P. Roberge, Royal Military College; M.A. Little, DND; "Aircraft Corrosion Surveillance in the Military", 1997 NACE Corrosion Conference, New Orleans, Paper No. 97527, NACE International, Houston
3. R.G. Kelly, S.H. Jones, W. Blanke, J. Aylor, A. Batson, J. Yuan, and W. Wang, University of Virginia; A. Wintenberg, Oak Ridge National Lab; G. G. Clemena, Virginia Transportation Research Council, "Embeddable Micro-instruments for Corrosion Monitoring", 1997 NACE Corrosion Conference, New Orleans, Paper No 97294, NACE International, Houston
4. T. Hakkarainen, VTT Manufacturing Technology, "Transferring Corrosion Knowledge to Computers: Models for Predicting Corrosion", 1997 NACE Corrosion Conference, New Orleans, Paper No 97396, NACE International, Houston
5. G. D. Harris, Phillips Petroleum; C.D. Adams, CDA Corrosion Consultants; J. D. Garber, University of SW Louisiana, "Use of a Corrosion Prediction Program as an Engineering Tool", 1997 NACE Corrosion Conference, New Orleans, Paper No 97607, NACE International, Houston
6. G. Smith, J. Schroeder, Air Force Research Laboratory (WPAFB); R. McMahon, Raytheon, K. Blemel, Management Sciences, Inc., "Prognostics for Wiring: Managing the Health of Aging Wiring Systems", Third Joint FAA/DoD/NASA Conference on Aging Aircraft, Albuquerque, September 1999
7. V. S. Agarwala and F. Pearlstein, Naval Air Warfare Center, "Trivalent Chromium Treatment for Aluminum Corrosion Resistance and Paint Adhesion", 1997 NACE Corrosion Conference, New Orleans, Paper No 97546, NACE International, Houston
8. R. Walter and L.M. Cooke, The Dow Chemical Co., "2-(Decylthio)Ethaneamine Hydrochloride: A New Multifunctional Biocide Which Enhances Corrosion Inhibition", 1997 NACE Corrosion Conference, New Orleans, Paper No 97410, NACE International, Houston
9. K. G. Blemel, "Dynamic Autonomous Test Systems for Prognostic Health Management", JAWSS Symposium, Las Vegas, 1998
10. V.S. Agarwala, Naval Air Warfare Center, "Aircraft Corrosion in the Military: Maintenance and Repair Issues", 1998 NACE Corrosion Conference, New Orleans, Paper No 98597, NACE International, Houston
11. K.G. Blemel, "Prognostic Health Management with Sentient Technology", JAWSS Symposium, San Diego, 1999