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An Introduction of Embedded Infotronics Agent for Tether-Free Prognostics

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Abstract

This paper introduces an innovative approach on embedded infotronics agent (EIA)[1] that will dramatically impact the future diversified industries. The key element of the EIA is a prognostics *Watchdog Agent*™[2] which will transform today's e-business systems (B2B, B2C) into direct D2B™ (*Device-to-Business*) system[3]. This transformation, in junction with the fast changing tether-free technologies, will bring a profound value for the US industry to prosper and to compete globally.

1. Introduction

The revolutionary changes of the information technology (IT) over the last decade have brought about profound changes in modern economics. The effects of these changes have impacted the velocity of our business cycle time and performance, which is evidenced by the level of sophistication of e-business and e-commerce. This transformation is setting new rules for business competition for the next decade. For example, General Electric Company's strategic transformation[4] toward an industry leader in six-sigma service in 1995 has inspired many companies to follow. Many industries, including the aerospace industry (i.e. jet engine, aircraft), the semiconductor industry (i.e. chip making companies and foundry), the power generation industry (i.e. power utilities companies), the transportation industry (i.e. trucking, airlines), the medical equipment industry, and the building system industry (i.e. elevators, HVACs), have been strategically benchmarking smart predictive maintenance and customer service practices globally to maintain their manufacturing productivity and customer's intimacy for a better competitive position. For example, the latest Pratt & Whitney jet engines have an array of sensors and on-board diagnostics that are capable of generating information with sufficient detail to allow the ground systems to forecast repair needs months in advance. This helps the airlines schedule engine removals so that the cost of downtime is balanced against the cost of overhaul. The on-board systems, in concert with the ground based analysis capabilities, also reduce costly unscheduled events such as delays, cancellations, diversion and in-flight shutdowns. Today's automotive industry is also looking for ways to embrace telematics for getting automatic roadside assistant and route guidance into car. GM has set a goal for its OnStar telmatics service of one million subscribers by the end of 2000. By 2005, GM plans to have all of its cars equipped with the hardware and software components for OnStar with enhanced features.[5] For the semiconductor manufacturing industry, one of the major thrusts is e-diagnostics. E-diagnostics is the ability to remotely service equipment and provide application support such as correcting chip-manufacturing errors via the internet. Chip manufacturers use remote diagnostics software instead of having an engineer come out to a site to adjust chip-making equipment. As chips get smaller, production errors rise. Moving to smaller chips can result in 10 times as many errors, even for leaders such as Intel Corp. and IBM Corp. These errors can force a chip company to shut a production line, causing it to lose thousands of dollars. This is one of the biggest problems chipmakers face today. KLA-Tencor foresees that the semiconductor industry will move toward e-diagnostics technologies for integrated diagnostics monitoring. These enabling technologies will impact the entire industry, not just

[1] EIA was first introduced by the NSF I/UCRC Center for Intelligent Maintenance Systems (IMS) at the University of Wisconsin-Milwaukee (UWM) and University of Michigan. www.imscenter.net The Center conducts research in the areas of web-enabled infotronics technologies in partnerships with over 40 companies including Rockwell Automation, Intel, Johnson Controls, General Motor, Ford, United Technologies, Toshiba, USPS, Harley-Davidson, Xerox, etc.

[2] *Watchdog Agent* is a trademark of the Intelligent Maintenance Systems (IMS) Center

[3] *Device-to-Business (D2B)* is a trademark of the Intelligent Maintenance Systems Center.

[4] Jack Welch and GE, Business Week, Oct. issue 1996.

[5] Telematics to the Rescue, pp93, IEEE Spectrum, Jan. 2001

semiconductor business.[6] Further advancements of these smart industrial applications will be dependent upon continuous innovation and the advancement of next-generation web-enabled intelligent systems.

These transitions demand the development of innovative infotronics agent that enables products and systems to (1) learn about their status and environment, (2) predict degradation of performance, (3) reconfigure itself to sustain functional performance, and (4) informate business decisions directly from the device itself. These enabling technologies will impact the entire industry, not just the above mentioned industries. Further advancements of other smart industrial applications will be dependent upon continuous innovation and the advancement of next-generation web-enabled tether-free infotronics agent.

Tether-free technologies deal with non-contact and remote techniques in transmitting, communicating, monitoring, and controlling a physical system and its elements to achieve functional objectives. For the past five years, tether-free technologies have dramatically impacted the advancement of mobile and networked computing and communications industry. With the advent of the fast changing wireless and communications technologies, researchers and practitioners need to get abreast of these continuous developments and develop transformation technologies to impact our manufacturing industry. As the wireless technologies continue to play more of a role in our daily life, communications in manufacturing over the wireless will become more important in allowing companies to compete effectively in a global basis. As one envisions a tether-free world of the future: one sees the monitoring and control of processes being done from anywhere, seamless information transmission and reception from anywhere to anywhere, work and personal tasks being done anywhere, materials, structures, vehicles, and even humans, signaling when they need attention. To stimulate research and education activities in this field, NSF held an Industry/University Panel on Feb. 17, 2000[7] to assess the possibility in launching a potential initiative. In parallel with this, a number of industry consortia and working groups (i.e. bluetooth) have also been formed to develop protocols and standards to accelerate the effective integration and deployment of these developments. Even though with the fast-pace progress on these activities, the manufacturing research community and industry have been staying aloof due to lack of updated knowledge and know-how to improve manufacturing productivity and efficiency through the effective utilization of these potentials.

To further define the research roadmap, an NSF Workshop on "Tether-free Technologies for e-Manufacturing, e-Maintenance and e-Service", was held on October 1-2, 2001 in Milwaukee, WI[8]. More than 150 participants from industry and academe attended the workshop. Details of the workshop, presentations and summaries can be reviewed at www.imscenter.net. As results of the Workshop, three critical research issues were identified as follows:

1. Learning how to predict reliability and performance in enormous systems and ensure robust and dependable operation.
2. Communicating with devices embedded in many kinds of equipment and places, including needs for wireless connectivity and managing sensors and physically active devices.
3. Understanding how to share information and instrumentation among groups of people and equipment, and how to build and best use information technology inside buildings, instruments, and other physical and engineering systems.

This paper introduces an innovative approach on embedded infotronics agent (EIA) that will dramatically impact the future diversified industries. The proposed novel EIA will transform today's e-business systems (B2B, B2C) into direct D2B™ (Device-to-Business) system. This transformation, in junction with the fast changing tether-free technologies, will bring a profound value for the US industry to prosper and to compete globally. Imagine a copy machine with such EIA will enable it to order its toner, prevent jamming and call for services automatically through predictive prognostics technologies and peer-to-peer (P2P) assessment technologies.

2. Technical Approach

To realize the proposed tether-free embedded infotronics agent (EIA), technical breakthroughs are needed to: (1) effectively correlate and compute massive and multi-sensor data from various sensors

[6] Kenneth Schroeder Interviews with Investor's Business Daily, CEO of KLA-Tencor Corp., August 2000.
[7] NSF Tether-Free Workshop Report, Arlington, VA, Feb. 17, 2000.

[8] NSF Workshop Award, DMI-0127513

to predict the degradation and health condition using peer groups and virtual machine models, (2) integrate this dispersed information in a networked environment, (3) synchronize with business systems at an enterprise level utilizing web-enabled and wireless communication technologies. The vision is to integrate an embedded prognostics agent into a tether-free device for achieving a tether-free embedded infotronics agent (EIA). Figure 2 shows a system diagram of a tether-free embedded prognostics agent in a networked machinery environment.

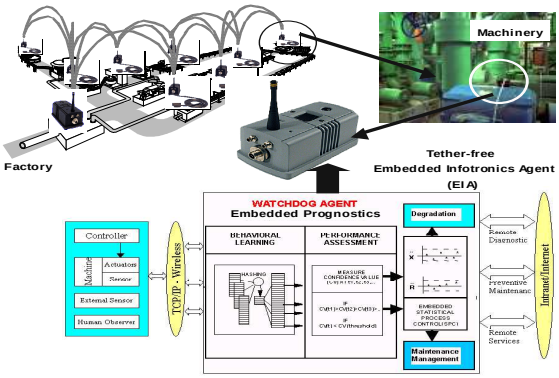

Figure 1: The Tether-free Embedded Infotronics Agent (EIA)[9]

This approach intertwines the hashing, sensor fusion, and wireless communications techniques. Evaluation of the data will be performed locally, and then transferred through the wireless or internet/intranet network. For instance, reduction of data into useable health information through smart prognostics agent would definitely eliminate hurdles regarding the transmission of large data on a given bandwidth capability. Information regarding (a) degradation modes, (b) degradation sections of the machine, (c) degradation frequency, (d) degradation time and place, (e) time required to prevent, (f) cost required to prevent, (g) suggested and/or applied maintenance practices, etc. will be recorded and stored in a database. This information will be used for behavior learning and rule extraction purposes as a part of intelligent expert maintenance system. Hence, a knowledge base system will be achieved through intelligent conversion of data into information, and information into knowledge.

[9] The wireless sensor is the HiDRA™ of Rockwell Scientific.

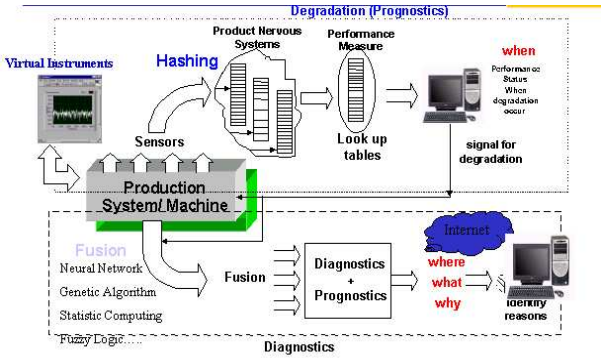

Figure 2. Methodology for prognostics using hybrid sensor fusion and hashing

Watchdog Agent™ Method and Prognostics

Assessment of a machine's performance information to operators in remote sites requires an integration of many different sensory devices and reasoning agents. When aging occurs, the component and machine generally progress through a series of degradation states before failure occurs. If a degradation condition can be measured and detected, proactive corrective maintenance activities can be performed before further degradation or failure occurs. To effectively measure the degradation of a machine, its behavior and associated information from operators and its working environment need to be assessed adaptively.

One method has been known as CMAC (Cerebella Model Articulation controller), first introduced by Albus[10] [11] is a widely known neural network and it is used for robotics, control, digital communication and many other applications. It is normally employed as a method for function approximation with fast convergence. A CMAC is essentially a lookup table algorithm that maps an input space into an output space. As we have seen, Albus's CMAC is a method for function approximation. Lee [12] [13]showed how this algorithm

[10] Albus, J.S., "A New Approach to Manipulator Control: The Cerebella Model Articulation Controller (CMAC)", Transactions of ASME, Journal of Dynamic Systems, measurement and Control, September 1975, pp.220-227.

[11] Albus, J.S., "Data Storage in the Cerebella Model Articulation Controller (CMAC)", Transactions of ASME, Journal of Dynamic Systems, measurement and Control, September 1975, pp.228-233.

[12]Lee, J. and Kramer, B.M., Analysis of Machine Degradation using a Neural Networks Based Pattern Discrimination Model, *J. Manufacturing Systems*, Vol. 12, No. 3, pp. 379-387, 1992.

could be enhanced as a *Watchdog Agent™* - an innovative method for prognostics. As a matter of fact, using the sensor signals of the machine as CMAC inputs, the algorithm learns what the signals are when the machine behaves "normally" and gives a "confidence index" which is a numerical evaluation of how the machine is working correctly.

Watchdog Agent™ CMAC Algorithm has two different periods :

- Learning period: first, given an input vector, CMAC algorithm activates the corresponding association cells and looks for the weights of these cells. The output of CMAC is the sum of these weights. If the output is "different" from the desired output, the weights are adjusted so that next time the algorithm comes up with the same input or a neighboring input, the output will be the desired output, i.e. CMAC learns the desired function.
- Training period: once CMAC has learned the desired function, the algorithm is ready to be used as a tool for robotic, control or other applications.

Basically, CMAC can be described as a computing device that accepts an input vector $S = (S_1, S_2, \ldots, S_n)$ and produces an output vector $P = F(S)$. To compute the output vector P for a given input state S, pair mapping is performed, namely

$$f: \quad S \rightarrow A$$
$$g: \quad A \rightarrow P$$

where A is called the association cell vector, which is actually a large table of memory addresses. Given an input vector $S = (S_1, S_2, S_3, \ldots, S_n)$, the mapping function f points to some memory addresses (location in the A table); these locations are among the association cells A and are referred to as the active association cells. The number of active association cells for any given input is a fixed parameter of the watchdog module selected by the user. Weight(s), or tabulated values that contribute to the output response, are attached to each association cell. One weight if output vector P is one dimensional, and n weight if P is n dimensional, is attached to each cell. Mapping function g uses the weights associated with the active association cells and generates an output response. Function g may be a simple summation if the weights are attached to active association cells, or it may vary during the training and storage process. Any input vector is therefore a set of address pointers, and the output vector, in its simplest form, is the sum of weights attached to these address pointers. Thus, each element of the output $P = (p_1, p_2, \ldots, p_n)$ is computed by a separate watchdog from the formula

$$p(k) = a_1(k) \times w_1(k) + a_2(k) \times w_2(k) + \ldots + a_n(k) \times w_n(k)$$

where $A(k) = (a_1(k), a_2(k), \ldots, a_n(k))$ is the association cell vector of the kth watchdog and $W(k) = (w_1(k), w_2(k), \ldots, w_n(k))$ is the weight vector of the kth watchdog. The value of the output for a given input can be changed by changing the weights attached to the active association cells.

A procedure for entering a function in a watchdog agent is as follows:

1. Assume F is the function we want the watchdog agent to compute. Then $P = F(S)$ is the desired value of the output vector of each point in the input space.
2. Select a point S in input space where P is to be stored. Compare the current value of the function at that point $P^* = F(S)$.
3. For every element in $P = (p_1, p_2, \ldots, p_n)$ and $P^* = (p^*_1, p^*_2, \ldots, p^*_n)$, if $l\ p_I - p^*_i\ l < e_i$, where e_i is an acceptable error, do nothing; the desired value is already stored. However, if $l\ p_I - p^*_i\ l > e_i$, add to every weight that contributed to p^* the quantity $M_i = (p_I - p^*_i) / N$, where N is the number of weights that contributed to p^*_i.

The mapping function points are some memory addresses; these locations are among the association cells and are referred to as the active association cells. The number of active association cells for any given input is a fixed parameter of the watchdog module selected by the user. Weight(s), or tabulated values that contribute to the output response, are attached to each association cell. One weight if output vector is one dimensional, and weights is attached to each cell. Mapping function uses the weights associated with the active association cells and generates an output response. Any input vector is therefore a set of address pointers, and the output vector, in its simplest form, is the sum of weights attached to these address pointers.

[13] Lee, J. (1999) "Machine Performance Assessment Methodology and Advanced Service Technologies, Report of Fourth Annual Symposium on Frontiers of Engineering, National Academy Press, pp.75-83, Washington, DC.

The values of a set of inputs act as pointers to a table of random numbers. These numbers are hashed to form a set of addresses in a weight table. The values in the weight table pointed to by these addresses are summed to yield an output. Training consists of adjusting the values in the weight table based on the error between their present summation value and the desired output for the particular values of the input that resulted in these addresses.

A very important point of CMAC is generalization. In this algorithm, it is not necessary to assess all the possible inputs since once CMAC has learned the desired output for an input vector I_1, another input I_2, close to I_1, will give the same desired output or a "similar" output as CMAC activates almost all the same weights.

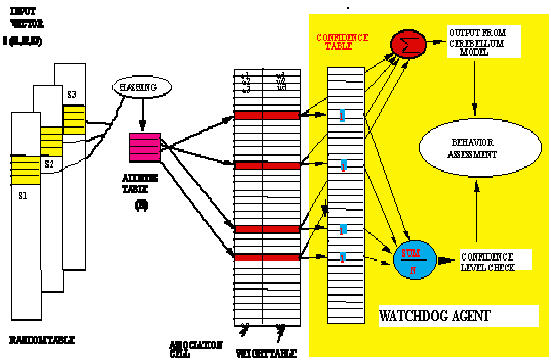

Figure 3 : Watchdog Agent™

As we have seen, this algorithm can be used to assess the performance of machines and it satisfies the prognostics requirements:

- It yields a quantitative performance index
- It enables multiple sensor fusion
- It uses generic algorithms for data processing in order to make it available for use on wide range of applications.
- It is robust to the input type.

To enable a robust prognostics function, we can improve the algorithm by adding the following elements:

- It should capture the dynamic behavior of the performance index in order to predict the necessary maintenance.
  → This can be done with dynamic models such as ARMA.
- It should be robust to the sensor noise and sensor failure.
  → This can be done in a pre-processing module.
- The signals must be pre-processed into a significant domain.
  → This can be done with FFT and/or time frequency analysis

Device-to-Business (D2B™) Platform

The D2B™ Platform provides transformation of raw data (or information through EIA) from device level to widely compatible web-enabled formats (e.g. XML) so that many web-enabled applications can be performed. Once, device information is available at this level, users from various part of the network users in different geographical locations can share the same information for different but synchronized applications. Figure 4 illustrates the overall structure of the D2B™ Platform.

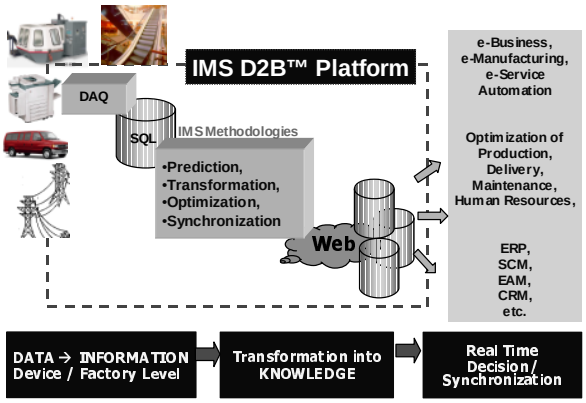

Figure 4 Overall structure of D2B™ Platform

Three fundamental features of this D2B™ can be described as follows:

1) Data *transformation*: abilities to transform data from machine or device level to reconfigurable web-level application formats (SQL, XML, HTML, etc)
2) Product performance *prediction:* abilities to predict the degradation of machine or process performance for prognostics via EIA
3) *Synchronization* with supply chain systems: abilities to synchronize manufacturing performance with e-business tools and supply chain systems.

Data Transformation

The IMS Center has developed an IMS Platform for e-Manufacturing implementation. The IMS Platform serves as a transfer function between the manufacturing data acquisition system and SQL server. It correlates data from different formats and transforms them to a web-deployable information system. These data can be gathered from traditional control I/O or through a separate wireless data

acquisition systems using different communication protocols, including 802.11, 802.11b, bluetooth, etc..

Figure 5 shows how data and information are transformed from machine and device level to a web-enabled environment. At this level, many web-enabled applications can be performed. For example, we can perform remote machine calibration through telescopic Ball bar in a different location. Experts from machine tool manufacturers can assist users to analyze machine measurement data and perform prognostics for preventive maintenance. Users from different factories or locations can also share this information through these web tools. This will enable users for high-quality communications since they all sharing the same set of data formats without any language barriers.

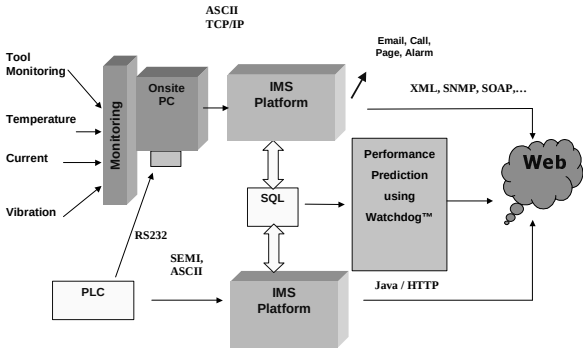

Figure 5. Data transformation through D2B™ in a web-enabled environment

Performance Prediction

Degradation prediction of products is achieved through the use of EIA described in the previous section. Its output represents the quantitative measures of the performance of the product or equipment at a given state. By comparing performance value at different states, it can predict and assess the condition and performance of complex and sophisticated machine systems. To effectively apply this methodology in various kinds of products and machines, its integration with the working environment (i.e. sensors, actuators, controllers, and human interfaces) needs to be further developed. Figure 6 shows how multiple signals are hashed, and transformed into a performance confidence index.

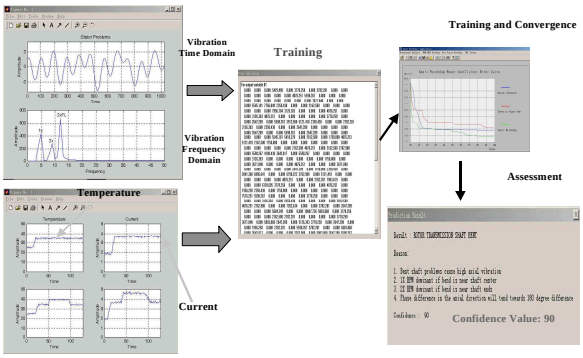

Figure 6 Data transformation through D2B™ in a web-enabled environment

Synchronization with e-Business Enterprise

The synchronization element provides the required integration with e-business systems including Customer Relations Management (CRM), Supply Chain Management (SCM), B2B e-Commerce systems. For example, by knowing the degradation of machines in the production floor, the operation supervisor can estimate its impacts to the materials flow and volume and synchronize it with the ERP systems. The revised inventory needs and materials delivery can also be synchronized with other business tools such as the Siebel CRM system. For example, when tools worn out, the information can be directly channeled to the tool providers and update the tool needs for tool performance management. In this case, cutting tool company are no long selling cutting tools, instead, selling cutting time. In addition, when the machine degrades, the system can initiate a service call through the service center for prognostics. This will change the practices from MTBF (mean-time-between-failure) to MTBD (mean-time-between-degradation).

Potential Impacts

The introduced technologies will enable products to achieve near-zero-downtime performance and as well as enable a product that orders its own parts through direct Device-to-Business (D2B)™ technologies.

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