Smart Sensors for Condition Based Maintenance: a Test Case in the Manufacturing Industry

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ABSTRACT

Condition Based Maintenance (CBM) is a well-known concept and it has been demonstrated that it is the way ahead to prognostic maintenance for failure avoidance and for the reduction of maintenance cost.

This paper presents an application for Condition Based Maintenance, with a specific focus on State Detection, according to MIMOSA OSA-CBM reference architecture. The papers aims at presenting peculiarity of development of such a kind of solution when considering the use of Smart Sensors instead of traditional devices.

Indeed, breakthrough in CBM is expected from the development of ICT and embedded systems. This technology supply integrated chips implementing all the necessary circuitry to manage field data capture, data processing, local diagnosis, local feedback (where possible) and information transfer to the upper control levels. These so-called smart sensors exploit new technologies of micro sensors (MEMS, micro electro mechanical systems) and wireless communication together with the computing power of a microprocessor.

In particular, applications related to maintenance and human safety appear to be very promising due to the unstructured nature of these domains, where self-configuring networks of intelligent devices can better comply with an ever changing and partially unpredictable environment.

A test case is deployed on a typical manufacturing equipment: a robot. The objective of the test case presented by the paper is not to develop new diagnostic algorithms, but to implement some statistical analysis within a monitoring infrastructure built with Smart Sensors.

The case of analysis that the paper will present grounds on the use of wireless sensor devices for temperature measures gathered on the electric motors of the robot. Then, data are transmitted through a wireless network to a receiver unit that accomplishes also elaboration by using statistical methods and then, thanks to a web-service communication, results are made available to external requests and users.

An advisory is generated when something is out of the normal behaviour of the equipment. Finally, the user can check this information through the Human Machine Interface available via web-service.

1. INTRODUCTION

In order to reduce the expenses for maintenance, new technologies can provide proper capability to support the decision making process through proper monitoring of the factory to manage maintenance, production and logistic issues. Service oriented architecture (SOA) is a solution that is nowadays analysed by many researchers and that promises an interesting solution for the issues related to controlling of the plant. To this end, some European funded projects related with SOA and the issues related to monitoring of plant condition are mentioned herein. SOCRADES (Cannata et al. 2008, www.socrades.eu) and SODA (www.soda-itea.org) mainly focused on SOA and wireless based communication infrastructures for intelligent embedded systems. AESOP (http://www.imc-aesop.eu/) proposed a SCADA/DCS infrastructure based on a service oriented architecture. This enables a cross-layer service-oriented collaboration between services on the same level and among different levels of the enterprise. Other objectives of AESOP are to investigate the limits of SOA in enterprise architecture and to propose a transition path from legacy systems to SOA based ones. EMMON (www.artemis-emmon.eu) targets the realization of large scale monitoring of huge geographical areas in real time, using wireless sensor devices in specific scenarios (water pipelines, urban quality of life, forest and marine environments, civil protection). While the above-mentioned projects are focused on monitoring through SOA system and embedded devices, the project DYNAMITE (http://dynamite.vtt.fi) targeted maintenance related issues, and in particular it emphasized on predictive maintenance, supporting the concept of e-maintenance with ICT tools such as PDA, CMMS and web services (Muller et al., 2008); the project adopted also the MIMOSA OSA-CBM reference architecture, that is an implementation of ISO-13374 functional specification.

Indeed, the present paper presents a part of a research developed in the scope of a European funded project on this topic, namely eSONIA, that aimed at further developing the results obtained in the above mentioned research projects, while targeting practical implementation issues.

The specific objective of the eSONIA project was to overcome the traditional monitoring activity. Within the project view, traditional monitoring and data gathering techniques have been extended with the ability to elaborate raw data and offer high value information as web services at various levels. This allowed to avoid the use of large centralized systems to collect data where processing is concentrated, while the use of embedded devices improved the data collection possibility. The project demonstrated that Web Services and embedded devices can serve to improve the re-configurability and the interoperation of the monitoring devices while supporting the smooth transition between the legacy device and the new technology ones.

The paper shows how smart sensors may be adopted for monitoring activities and provides feedback to the scientific community about how they can be used for supporting Condition Based Maintenance (CBM), in particular the State Detection activity. As explained by MIMOSA a CBM program consists, in fact, of the following modules (MIMOSA OSA-CBM, Bengtsson, 2003):

1. Data Acquisition (DA) has the purpose to collect data and properly format them to store/transmit information to upper levels;
2. Data Manipulation (DM) serves to clean and preprocess data, typical operations are: normalization, smoothing, outlier removal, missing data imputation, etc.;
3. State Detection (SD) works to monitor the machine state by checking if the machine parameters are compliant with target ranges; it can generates alarms and warnings when compliancy is not reached;
4. Health Assessment (HA) receives data from the SD module or other HA modules and it detects through an analysis if the health state of the system or sub-system has degraded; moreover, it can suggest possible fault causes.
5. Prognostic Assessment (PA): this module works on the results of the previous modules; it is used to calculate the future health of an asset and the calculation of the Remaining Useful Life (RUL) is possible by taking into account also the future usage profile.
6. Advisory Generation (AG): this module receives data from HA and PA modules, and it generates suggestions on recommended action(s) related to the maintenance how to run the asset under actual conditions;
7. Presentation, this module presents the outputs from the SD, HA, PA and AG modules to the user through a Human Machine Interface (HMI).

At a glance, the importance of Smart Sensors for the maintenance is due to the possibility to build or configure custom devices dedicated to the monitoring and diagnostics of equipment. Furthermore, Smart Sensors are enhanced by the use of MEMS technology that allows including many different types of micro sensors into the device or into a single chip. In this way, the broad spectrum of applications and the power of a comprehensive data acquisition system is made available in the small and self-contained package of the smart sensor (Garetti et al., 2007). This allows concentrating within the sensors the activity of Data Acquisition and first Data Manipulation, leaving to other levels of the architecture the duty of carrying on State Detection.

The paper aims, thus, at demonstrating how this can be achieved practically within a manufacturing environment, considering a test case. To this end, it is structured as follows: paragraph 2 details the benefits for the overall approach proposed by eSONIA project and presents the proposal for an heterogeneous implementation of the mentioned technologies, allowing the integration of new solutions with existing ones. Paragraph 3 explains how the condition-based maintenance management module, which is included in the proposed architecture, is built. Paragraph 4 explains how a demonstrator has been deployed for implementation of the research outcomes, showing the role of the maintenance management functions. Eventually, paragraph 5 concludes the paper envisioning future challenges in this research field.

2. BENEFITS OF THE SOA ARCHITECTURE FOR CONDITION BASED MAINTENANCE

The use of Service-oriented Architecture (SOA) and Web Services (WS) is introducing interesting opportunities in factory automation; in fact, they allow to make incremental adoptions of new application and technologies, while avoiding a green field approach or to make big investments in order to update automation system. Therefore, new automation solutions based on SOA and WS approach could run in parallel to already existing ones.

eSONIA solution grounded on a conceptual description of the architecture. SOA is a flat architecture where all the services can interact together. This consequently makes the control architecture almost flat from an hardware and software point of view, but cannot overcome, of course, a certain hierarchy among the functionalities that the service carries on. Figure 1 shows how embedded solutions communicate with Application tools.

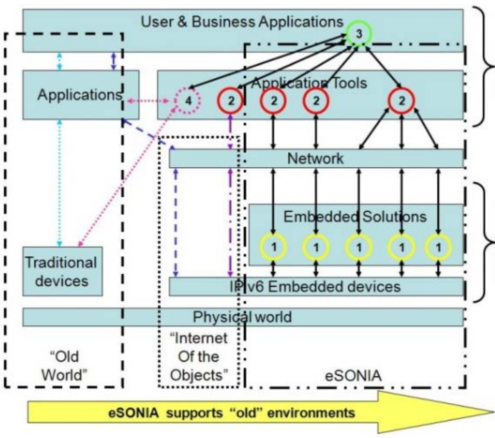

Figure 1. eSONIA conceptual implementation scheme.

Following this architectural approach, already existing "Applications" and "Traditional devices" can still be used on a brand new technology-based architecture simply integrating them by ad-hoc gateway services (see number 4 in the circle), thus enabling the co-existence of Web Service devices and traditional devices (e.g. PLC). This approach allows a smooth and incremental transition to an entire Service Oriented Architecture. On such a kind of architecture "Application Tools" (see number 2 in Figure 1) and "User & Business Applications" (see number 3 in Figure 1) are services hosted on computer servers. On "Embedded Device Level", many "Embedded Solutions" (see number 1 in Figure 1) can run web services hosted on embedded devices to provide various functions. SOA, differently from traditional one, allows each Embedded Solution (so the physical device) to interact with other Embedded Solutions on other devices, implementing a low level/distributed monitoring and control capability.

Thus, transformation from raw data to information is accomplished at embedded systems level, then information is transmitted to the higher level of the architecture represented by "application solutions" or "user & business applications" (see Figure 1). The interaction between embedded solutions and, for example, application tools are based on the capability of the service oriented architecture.

3. THE eSONIA CONDITION-BASED MAINTENANCE MANAGEMENT MODULE

Maintenance Management tools in the scope of the proposed architecture are mainly related to condition based maintenance. The main idea of CBM is to use the information on asset health retrieved from on-line sensing techniques (i.e. embedded sensors) to minimize the system downtime and the risk of failure.

The MIMOSA functions, presented in Section 1, can be seen as independent modules that can be built in a Service Oriented Architecture. In this way, each module can be "encapsulated" in a web service.

Scientific contribution provided by this paper on this aspect is related to the proof of concept that eSONIA project guaranteed. Indeed, what is presented herein represents a validation of the use of smart sensors for CBM within an industrial environment. To sustain the use of such technology within an industrial environment, specific attention has been paid to identification of industrial needs and building of a solution compliant with standard (i.e. ISO-13374) and sufficiently easy to be adopted by practitioners. Interoperability issues, communication problems, software development for the smart sensor boards adopted have been tackled in order to achieve a functioning solution that could act as demonstrator, neglecting a specific improvement of the state of the art ICT solutions. Nevertheless effort spent on this should not be neglected by readers interested in replicating the solution proposed herein.

In order to achieve the proof of use of smart sensors for CBM, the MIMOSA modules have been deployed in the eSONIA project in order to build the following functions.

Malfunction advisory generator represents a first function and it is realized on the basis of the State Detection (SD) module. It is deployed to trigger alarms when the value of a parameter overcomes a predefined threshold, then the function provides a list of the related warnings or alarms. Each advisory is completed with certain information and KPIs. The main scope of this function is to show advisories about maintenance problems (i.e. machine malfunctions) and provide related information and KPIs. To this end, proper advisories are generated, providing the operator with the necessary and updated information to understand the problem that is occurring. Operationally, the user can utilize the function as follows:

- He/she configures the malfunction advisories; namely he/she should choose the thresholds of the KPIs on a machine/equipment or section of the plant;
- He/she can read advisories: if a fault happens, the system generates malfunction advisories according to the set thresholds;

- He/she can select a machine/equipment or a plant section and list all the recent and past advisories.

A second function of the eSONIA maintenance management modules is represented by health state reporting. The purpose of the application related to this function is to properly present the health state report of a selected machine or a section of the plant. This tool presents to the user updated health state reports, which are helpful to take a decision on maintenance actions. This function strongly grounds on Health Assessment function derived by MIMOSA framework.

The use of the web service introduces a flexible approach in the realization of an application based on the two presented functions. In particular, it is important to underline that the services are interoperable, in this way it is possible to combine different services to obtain a new and more complete one. Moreover, the access can be granted to all network devices (e.g. other services of computers). Web services can be accessed from machine and from user through a common browser. In the first case the information are transmitted by means of XML data format, in the latter case the information can be included in a html page to obtain an user friendly data presentation (Lastra et al., 2006; Lobov et al. 2009).

The test case presented in the next section 4 focuses on a part of the eSONIA maintenance management module, in particular on the realization of the data acquisition, data manipulation, state detection and health assessment by means of embedded devices.

4. APPLICATION DOMAIN: AUTOMOTIVE MANUFACTURING DOMAIN

Different use cases have been addressed by eSONIA project and different applications have been analyzed (see Macchi et al. 2011 for further information). Herein, the test case related with the manufacturing application domain is described.

The objective of the test case is to implement proper existing diagnostic algorithms as web services, neglecting to develop new ones.

The application has been implemented on a welding robot with the purpose to support the operator in detecting malfunction state; the robot has been equipped with MB851 wireless sensing boards connected to sensing probes. This solution allowed placing the sensing probes very close to the electric motor windings and the welding actuator. Figure 2 shows the board the probe.

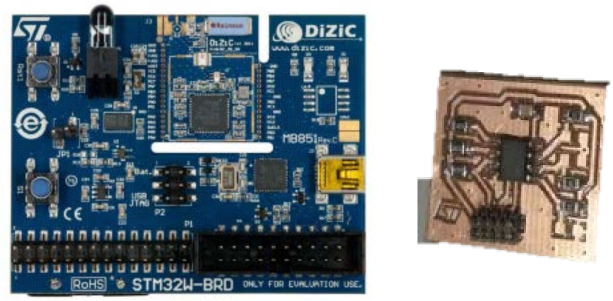

Figure 2. Wireless sensing board MB851 (on the left) and the sensing probe (on the right), please note that images are not scaled.

An overview of the functional architecture is provided by Figure 3. Data are collected from the field through the sensing probes (label number 1), then Data Acquisition function (DA) is performed (label number 2) by wireless sensing boards.

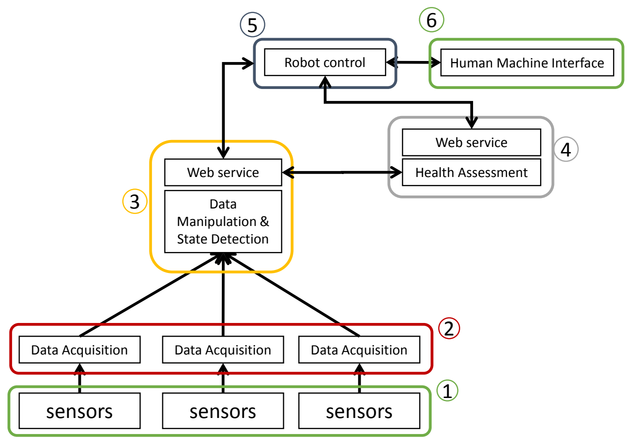

Figure 3. Functional architecture of the test case.

Data are gathered by a receiver node (label number 3) that provides data manipulation (DM) and State Detection (SD), then data are published on the network through web services. Bi-directional flow of information indicated by the arrows in Figure 3 refers to the type of communication between the different nodes, i.e. the requests made by the web-services.

Label number 4 indicates the Health Assessment (HA) function. The operator can access the SD and HA outputs through the HMI device browser (label number 6), which is connected to the Ethernet network through the robot control cabinet (label number 5).

An hardware oriented view of the architecture is shown in Figure 4.

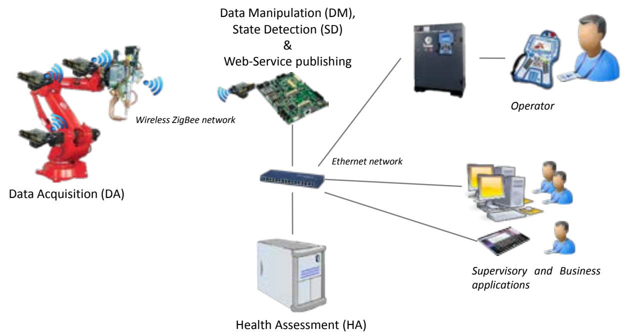

Figure 4. Hardware architecture of the test case.

The wireless sensing probes collect several kind of data, such as accelerations, angular speed, magnetic field and temperatures; in the presented test case the temperatures were sampled. Wireless sensing board, namely MB851, provides Data Acquisition (DA) functions. The boards are battery powered. In order to avoid a fast discharge due to computation energy demand, it was decided to use them mainly for data acquisition and transmission, so neglecting data manipulation, because data manipulation would request a too high energy demand to such boards. A longer battery operating time has been preferred for this application.

Data Manipulation (DM) is provided down way the data stream by another device. In fact, all data are transmitted through ZigBee wireless network (IEEE 802.15.4) to a receiver node, which is wired to a computing board. This last board is based on the Tsunami Interface Baseboard for TAO-3530 and it is intended to provide a complete data manipulation (DM), a State Detection (SD) function and to provide also web service access to other devices on the network. In particular, the Tsunami board is connected on the Ethernet network and acts as a sort of gateway for the sensors. Hence, Tsunami board can be considered part of the architecture of smart sensors. In this way, the Tsunami board allows to have a sensing network uncoupled from the output requests. Moreover, it has enough computational capacity to provide web service access to each data stream of the nodes. Otherwise, the web services had to be published on each node of the sensing network and this will increase battery consumption, changing the technical requirements of the sensing boards.

Through the web service it is possible to access the collected data simply by means of a browser equipped device. In fact, in the test case, it was possible to connect the operator's HMI to the so-realized sensing network. However, the information provided after Data Manipulation function is not user friendly. In order to overcome this limitation a State Detection (SD) function is used to produce easy-to-read KPIs, so the operators can quickly be informed on the asset warnings and alarms. In other words, the SD function quickly detects abnormal deviation of working parameters (e.g.: an over-temperature status) and/or an abnormal dynamic behavior (e.g.: an heating trend on the equipment), then it produces and indicator to measure "how much" the parameters are in the expected range and, in faulty cases, it generates a warning/alarm message to the operator. As in the DM function, the computing results of SD are published on the network in form of web services. Health Assessment (HA) module is, instead, implemented and run on a high computational device, namely a desktop computer, that is connected on the Ethernet network, in order to get data from SD and DM web services. The desktop computer host HA because computational constraints of the TAO-3530. HA, as SD and DM modules, elaborates data and provides an output through the web service technology. Overall, the operator can easily retrieve information from HA and SD functions from the browser of the already-in-use device, and so have a quick and complete feedback on the robot health state.

Figure 5 shows an example of the web page generated for the HMI, focusing on the information coming from one single sensing probe. State Detection function runs as a web service on the TAO-3550, the graph shows the actual level of the monitored variable while some KPIs are indicated on the page.

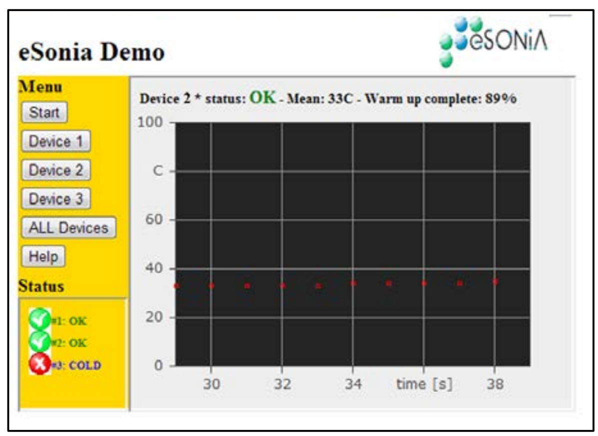

Figure 5. Example of the web page as shown on the robot remote controller (HMI). Information is related with State Detection

The information available on the network are formatted into an html page (see HTML 4.01 Specification) to be displayed in a user-friendly way on a common browser (see Figure 5 and Figure 6).

Figure 6 shows another example of the web page available to the operator. The whole represented area covers all the possible working condition of the robot; an indicator will point out a sub-area so indicating, in a quick and user-friendly way, the fault. In fact, each sub-area is associated to a robot working condition and a fault cause. The HA function is designed based on Principal Component Analysis (PCA) theory and tailored using history sample data on the machine behavior, according to the research presented in Fumagalli et al. (2014).

Figure 7 provides the legenda on how to read the HA information provided on the robot controller.

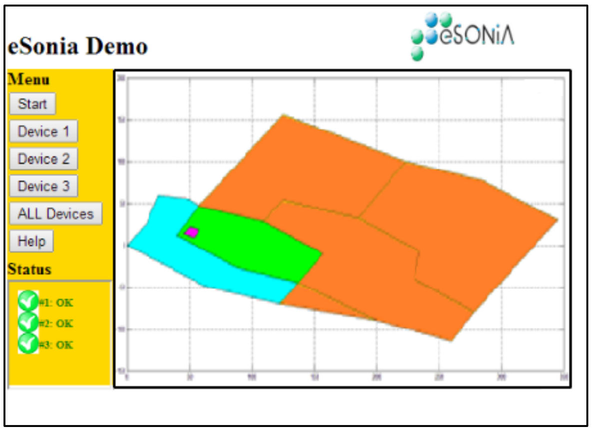

Figure 6. Example of the web page as shown on the robot remote controller (HMI). Information is related with Health Assessment.

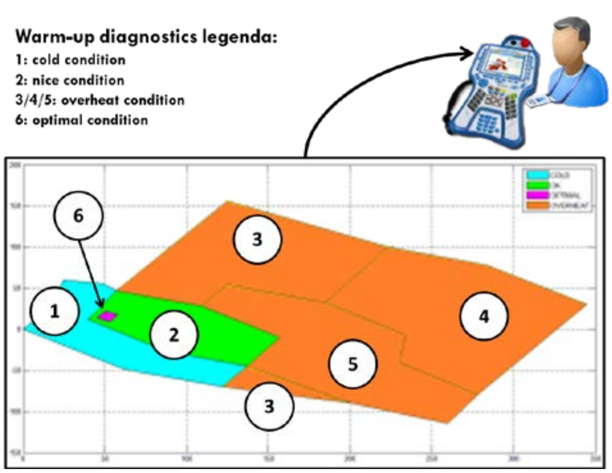

Figure 7. Explanation on how to read the result showed by HA functionality.

Within the presented test case, the setting of the parameters of the Smart Sensors was done by the researchers involved in the eSONIA project. This represents one key issue to be considered when the proposed solution is transposed from a test case within an industrial environment to an operating environment, when real production is performed. In the latter case, in fact, maintenance operators would be the ones called to deploy such architecture within the specific application context. In this case, the key aspect for setting up of the system is the identification of the right physical or statistical model to be used for state detection and health assessment, considering the specific machines where smart sensors are installed.

5. CONCLUSIONS

The paper presented the condition-based maintenance management module within the context of the eSONIA project, in particular it focused on the developed tools, based on smart sensors and web services. The tools have been adopted in the eSONIA Service Oriented Architecture and it was demonstrated how it is possible to smoothly introduce the presented technologies in a real industrial environment. In fact, the tools have been designed considering that they can be used in an already-working environment, so new functionalities can be introduced in the system with a minimum effort to configure the legacy system. Moreover, the tools consider the possibility to interact with IT systems that are external sources to the proposed architecture. To this end, it was shown how it is possible to easily share information on the network from machine to machine and that it is also possible to properly format the information to obtain a machine to human communication.

Overall, the monitoring architecture presented within eSONIA project and, in particular, the condition-based maintenance management module discussed in this paper, demonstrate a smooth migration from an existing monitoring architecture towards a new one, based on new technologies (i.e. smart sensors), while avoiding deep and high cost upgrades of the existing infrastructure. The test case provides feedback to the scientific community about how smart sensors and Web Services can be used for supporting CBM.

Further research can be envisioned on the improvement of configurability of the upper layers of MIMOSA (i.e. SD and HA), enabled by the use of smart sensors that cover lower layers (i.e. DA and DM). Configurability of the upper layers may depend on an analysis of diagnostic and prognostic techniques. Such analysis should consider the definition of diagnostic and prognostic techniques, their functional features and how these features can be exploited in the MIMOSA architecture. MIMOSA, in fact, is a good guideline that can be further enhanced with such analysis, in order to get an easier adoption by industry.

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