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An E-maintenance platform based on SOA and smart sensors

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Abstract

New emerging ICT solutions are providing powerful capabilities for distributed control and monitoring of production plants and machineries. In particular, Smart Sensors and Embedded mechatronics systems are promising intelligence at shop floor level, allowing many decisions taken in real time by decentralizing data analysis. Moreover, such new devices can be exploited by the use of Service Oriented Architecture (SOA), that can allow their interconnection in a kind of flat architecture. Maintenance activities can especially benefit from these technological developments, leading to distributed monitoring activities, faster data analysis, also guaranteeing low cost solution development. The paper presents the potential of a combined use of modularization and standardization to better exploit technology-enhanced solutions for improving maintenance management.

I. INTRODUCTION

Maintenance management is increasing its potential thanks to the ICT (Information and Communication Technologies) that are enhancing shop floor capabilities, by providing new possibilities according to the well-known E-maintenance concept. [1] defined E-maintenance as 'maintenance support which includes the resources, services and management necessary to enable proactive decision process execution'. Different points of view and perceptions of this term exist as discussed by [2] and [3]. Besides, during the last decade, many new technologies have accelerated the development of E-maintenance, enabling also an enhanced role of prognostics and health management in advanced maintenance systems [4]. Firstly, the availability of new sensors has become a relevant mean to capture different types of data available on the shop floor. Secondly, the maturity of technological paradigms in the communication field, such as Service Oriented Architecture (SOA) (see for instance [5]), boosts new possibilities enabling also to ease the integration of data and computational capability within the frame of an existing ICT system. This type of communication architecture properly matches the capability offered by smart sensors and smart devices.

This paper goes across the research stream that considers the potentialities to use the SOA for supporting maintenance activities, as it is already addressed, for instance, in [6] and [7]. Then, the combined use of smart sensors and SOA allow distributing intelligence along the shop-floor, with the possibility to deploy an opportune communication among the devices, supporting maintenance activity. The research idea starts thus from the interest on single technological components: smart sensors and SOA, hereafter described. Indeed, since the beginning of 2000, new sensors have been claimed as boost for E-maintenance paradigm. Nowadays, smart sensors provide more and more functionalities that support the operator in the field [2] and have become smaller, featuring new capabilities of real-time data acquisition, processing, transmission and connection into applications in a networked environment made of transducers and actuators. Indeed, the term "Smart Sensor" is not so recent. It was born in the '80s. The use of smart sensors has been considered together with MIMOSA standard since last decade (www.mimosa.org). The key role of MIMOSA standard for E-maintenance architecture will be later described. Then, evolution of Smart Sensors is proposing a continuous revision of this basic architecture, thus encompassing also the use of web-services, as mentioned, for instance by [8]. Then, the development of information system for data management related to maintenance activities has been emphasized by the adoption of web-services that, since the last decades, have been claimed to play a key role for interoperability [9]. Services are encapsulated in modular blocks which can be published by their provider on the web with their broker's standard interface through which they can be invoked and composed by the requester [10].

From an application perspective, SOA has been used in several research projects oriented to manufacturing plant control [11]. Web based solution and then SOA are today perceived as the proper architecture for E-maintenance solutions [12]. More recently, cloud computing is also bringing new possibilities to implement capacities of self-management or decision making among a network of machines / devices [13], considering also the use of cloud computing together with service oriented architecture within manufacturing domain [14].

2. ARCHITECTURE DESIGN CHOICES

The design choices initially considered for the E-maintenance platform are owing to the business and technology domain [15]. Such choices, in fact, must consider gathered information ranging from requirements (from business perspective) to potentials (from technology perspective). Taking into account this large range of information is nowadays a key aspect in order to pursue higher level of flexibility. According to this perspective, the following issues are advisable.

Firstly, the selection of the functions supported by the platform should be driven by the business requirements: value creation required at business level must be considered [16]; the selection of functions should indeed take into account the business processes to be supported. The approach starts from 'target value identification'. Then, it is worth to carry out a 'process analysis', that consists of the in-depth analysis of the processes that could be potentially involved in the implementation of the E-maintenance platform, its related equipment and its required functions. In this phase, the study is done following the failure analysis of the equipment. Hence, any technique or tool that allows the detailed study of the functions of equipment and its failure modes could be used in this phase, like criticality analysis (CA), failure root-cause analysis (FRCA), and failure mode, effects, and criticality analysis (FMECA). Then 'value proposition definition' is needed. Following steps proposed by [16] pertain to the activities hereafter listed.

Secondly, the selection of adequate technologies should aim at supporting interoperability and local/remote operations: according to the technological paradigm addressed by this research (i.e. smart sensors and SOA), this implies the selection of a specific type of communication solution to guarantee interoperability between different software applications as well as hardware-software platforms. Last, but not least, attention must be paid in the design of the data storage and the definition of the HMI (Human Machine Interface).

According to the business and technology scope so delimited, the design steps recommended to deploy an E-maintenance platform that matches smart sensors and SOA capabilities are the following ones, addressed by the next subsections. These design choices require a structured approach to be implemented: an acknowledged standard (i.e. ISO-13374 – MIMOSA OSA-CBM documentation) can be considered to this end. The OSA-CBM specification has been in fact adopted by different authors, in order to provide "a standard architecture for moving information in a condition-based maintenance system", facilitating the implementation of maintenance platforms (e.g. [17]). For the selection of proper techniques for data analysis, the concept of maintenance-technology independent service M-TIS [16] may help to understand which kind of analysis is required at this level. The concept of M-TIS can be adopted in order to identify the service without coupling it with the technology that is used for implementation. The concept of M-TIS is inspired by the model-driven service engineering (MDSE) approach that was proposed by [18]. In the MDSE approach, modelling levels such as business system modelling (BSM), technology independent modelling (TIM), and technology specific modelling (TSM) are defined. With focus on maintenance processes: at the TIM level, the above-mentioned M-TISs are considered; at the TIM level, specifications of the structure and functionality of the service are given without technological details. Indeed, the TIM level focuses on the operational details, hiding technological specifications in order to comply with the different technologies [18].

In the present paper, services are related to the mentioned functional blocks owing to the OSA-CBM specification and, in particular, they are "pieces of intelligence", but not yet "pieces of software codes". Building on the key aspect of the conceptual meaning of M-TIS, services are designed as independent from the technology that is used to implement the service. Supported functions and information, that were previously standardized, are leading to the selection of the required techniques. In this regard, it is opportune to classify the techniques which are realizing what required by the different operational functions within the OSA-CBM specification, thus fitting to standard specification. Statistical approaches for CBM are many and their selection is mainly related to the different type of signal statistics may be applied to. In particular, the domain in which the analysis is deployed is a key element to select the proper technique. Most used domains for signal analysis are time-domain and frequency-domain. Time-domain signal can be addressed by calculating the main statistical parameters, such as mean value, standard deviation, skewness, kurtosis and other synthetic parameters [19]. This analysis can be then combined with different signal processing tasks that can be classified under the umbrella of analysis of Probability Density Function (PDF). All in all, these techniques pertain to the Data Manipulation (DM) function. Further on, control charts may be used for State Detection (SD) analysis. On the other hand, when addressing frequency-domain analysis, the data manipulation is related with conversion through FFT (Fast Fourier Transform) and then related analysis focused on spectrum and the pattern of frequencies, cepstrum analysis and wavelet analysis. Once these Data Manipulation is applied, again State Detection may be applied, focusing at glance on the identification of threshold to be placed on amplitude of certain frequency or control chart placed on manipulated data. For Health Assessment, instead, literature proposes many approaches belonging to statistics domain and artificial intelligence domain. Thus the selection, while relying on black box approaches, could be focused on approaches like Artificial Neural Networks (ANNs) or statistical methods such as Principal Components Analysis. They are valid alternative approaches for the efficient support of Health Assessment (HA) analysis.

The technological decisions considered by the present research stress the concept of modularization. SOA and the use of web-services, in fact, allow to think about portion of independent software. Nevertheless, such technological capability does not mean that these pieces of software are really built according to a proper modularity. In fact, the modularization should take into account an encapsulation of operational functions into modular units that could then act also independently and according to different possible arrangements of the modules.

3. THE PROPOSED ARCHITECTURE

Keeping MIMOSA OSA-CBM ISO-13374 as reference standard, three mentioned design steps are used to explain the proposed solution of a web-service based E-maintenance platform within an experimental industrial case, where role of smart sensors has been tested.

The proposed architecture has been built starting from an experimental industrial case, derived from a research activity carried out in the frame of the FP7-Artemis research project eSONIA (www.esonia.eu), where different applications have been analyzed. Herein, the experimental case related with the manufacturing application domain is reported to show the proposed architecture that can be realized following the steps mentioned in previous Section 2. The application has been implemented on a welding robot with the purpose to support the operator in detecting a malfunctioning state (as also previously presented in [20]). The welding robot has been thus selected as critical equipment for the proposed case and focus of the analysis.

The requirements to be considered for the experimental case have been related with the business use of the platform. Such business/user requirements can be summarized by the following points: the user (i.e. shop-floor operator) must access data retrieved by the sensor and analysis made on it by means of a browser equipped device; as requirement, this device must be i) a generic mobile device and a ii) dedicated robot teach pendant where a browser is installed; data collected by sensors and some first analysis that is possible to apply to such data are proven to be not user friendly; in order to overcome this limitation, the platform must provide the user with easy-to-read Key Performance Indicators (KPIs), so the operators can quickly be informed on the asset warnings and alarms; data and information should be provided with different level of details (e.g. aggregated or not aggregated information) in order to cope with the need of having a general perspective of the shop-floor status or an in depth report of data collected by a specific sensor. These requirements have been matched with the functions, according to the framework defined by MIMOSA OSA-CBM functional blocks, previously mentioned in Section 2.

The selection of techniques should, first of all, follows a Technology Independent Modelling. Within this modelling scope, it is worth making a first classification, in regard to two alternative types of approach: "White-box" and "Black-box" [21]. The former concerns the physical modelling of an equipment behavior in order to have a basis for the diagnostic analysis. The latter concerns mathematical modeling based on statistical data. For the proposed solution, a first main decision at technology independent modelling level is to adopt a "black-box" approach. This solution is to be preferred in all the cases when physical system models are not available. Indeed, the statistical approaches – representative of a "black-box" approach – do not require support of physical modelling. The proposed case exploits a black box approach; the case, in fact, is based on an industrial context where many physical model are available (e.g. model for kinematics of robots), but they are not suitable for the specific case of monitoring the status of motors based on their temperature. Additionally, this decision allows to develop and test a solution that can be easily generalized to other similar asset (i.e. robots) of a production line.

Therefore, the supported functions and information, previously standardized, are leading to the selection of the required techniques for statistical analysis. Statistical approaches that are suitable for the presented case are, in principle, many and their selection is mainly related to the different type of signal statistics may be applied to. The domain in which the analysis is deployed is a key element to select the proper algorithm/technique. Most used domains for signal analysis are time-domain and frequency-domain. The temperature signal analysis considered in the experimental case proposed is a typical time-domain. Considering Data Manipulation (DM) functional block, time-domain signals can be addressed by calculating the main statistical parameters, such as mean value, standard deviation (in order to evaluate data dispersion), skewness (in order to measure the deviation from distribution from symmetry), kurtosis (as an index of "peakedness" of distribution) and other synthetic parameters [22]. This analysis can be then combined with different signal processing tasks that can be classified, for seeking of simplicity, under the umbrella of analysis of Probability Density Function (PDF). For the State Detection (SD) functional block, while working with time-domain signals, a simple solution to be applied is owing to the control charts [23]: this is a well-known approach, applied for condition based maintenance [24] and more in general in the scope of engineering applications for quality control. For Health Assessment (HA), instead, literature proposes many approaches belonging to statistics domain and artificial intelligence domain. Many techniques/algorithms are today available at the state-of-the-art and the selection of this algorithm is sometimes also facilitated by the availability of certain library of techniques/algorithms, as the concept of Watch Dog Agent [25] and its subsequent evolution made available on National Instruments website (www.ni.com), even enhanced by providing prognostics capabilities. Thus, for what concern Health Assessment, while relying on black box approaches, the selection can be focused on approaches like Artificial Neural Networks (ANNs), Fuzzy logic and Support Vector Machines. Moreover, Principal Components Analysis (PCA) is another valid approach for the efficient support of HA analysis. Indeed, the mentioned techniques are very different in nature, and cannot be applied alternatively on the same input data. For the proposed case, PCA is applied, thus maintaining the class of selected techniques in the statistical domain.

The Principal Component Analysis may be used as tool for the classification of variables, individuation of outliers and the indications of anomalies in the data structure [26]. Formally, it is a technique of multivariate nonparametric analysis that is used to simplify the original data with the purpose of reducing the number of variables to be considered. In fact, PCA applies a linear transformation to the original data matrix, in order to find a new set of variables (principal components) that express the maximum variability of data, with a reduced dimension than the original data, allowing anyway losing the minor quantity of information. By applying PCA, it is possible to get a good trade-off between simplification of the analysis and information loss, and the right number of principal components to be considered is crucial to this end.

A set of data, collected for maintenance purposes from sensors, may be confused, namely may be redundant (i.e. with correlated variables) and with a lot of noise. PCA serves, indeed, to eliminate such redundancy of the information, namely self-correlation [26], by creating a new reference system. The advantage in using a new reference system is to allow the possibility to highlight more easily the structure of the data. The first axis, thus, represents the variable with higher variance, the second axis the one with the second higher variance and so on. PCA has been used within the proposed architecture for an elaboration of the information to identify a proper reference space to allow fault identification within such space: this means supporting an activity required for making the Health Assessment function. Physical meaning of monitored variables (i.e. temperature) is thus lost, but proper meaning for the final user (i.e. status of the asset) is provided thanks to PCA.

To support the development of such solution, the following hardware configuration has been considered. 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. Three sensors have been installed in order to monitor simultaneously the temperature of the motors and retrieve the overall status of the robot. The sensing probes collect several kind of data, such as accelerations, angular speed, magnetic field and temperatures; in the presented experimental case the temperatures were sampled and these data were used. The wireless sensing boards (STM MB851) are battery powered and collect (by wire) the data coming from sensing probe. The use of these two boards have been considered in order to recreate the functionalities of a complex smart sensor within an experimental environment. These two boards could be substituted by a unique board incorporating all the functionalities (i.e. a Smart Sensor with the same type of accuracy in temperature and an opportune probe to be located on the surface to measure). Data collected by the STM MB851 boards located on the three motors can be transmitted through ZigBee wireless network (IEEE 802.15.4) to a receiver node (i.e. another STM MB851 board), which is wired to a computing board. This last board is the TAO-3530, which provides also web service access to other devices on the network. This board is then connected on the Ethernet network and acts as a sort of gateway for the sensors. Hence, TAO-3530 board can be considered part of the architecture of smart sensors. In this way, the TAO-3530 board allows having the sensing network fitting the configuration needed to consult data acquired by sensors through web-services.

At technology specific modelling level, the decision to be taken regards how to deploy the selected techniques and algorithms, considering where the supported functions are located within the distributed architecture. SOA provides an infrastructure allowing each embedded solution (hence the device) to interact with other embedded solutions (on other devices), thus implementing a distributed monitoring and control capability. In order to fully exploit this possibility, each device must be provided with the proper functional block of the MIMOSA architecture; this means that each component of the hardware architecture is provided with the proper function that allow deploying the overall E-maintenance architecture. Functions are not univocally assigned to a single device, but, instead, more than one device can welcome the same function as it happens, in the proposed case, for the Data Acquisition on the Wireless sensing board. The specific algorithms have been then deployed considering computational capability and type of operating system running on each device. All in all, data are then gathered by a receiver node that provides both data manipulation (DM) and State Detection (SD). Besides, data are published on the network through web services. Eventually, Health Assessment (HA) function is applied on the data.

The operator can access the SD and HA outputs through the HMI device browser, which is connected to the Ethernet network through the robot control cabinet. SD and HA services are conveyed to the robot control cabinet and can be accessed from here. This is done in order to allow a unique access point, avoiding the publication of SD and HA web-services directly in the entire company network. SD and HA services are consulted through the HMI that encapsulates them. Use of web-service guarantees flexibility and composability of the HMI screen.

4. BENEFITS OF THE ARCHITECTURE

The use of Service-Oriented Architecture (SOA) and web services is introducing interesting opportunities in factory automation: new automation solutions based on SOA and web services approach could run in parallel with already existing ones; moreover, the cost of such solution is smaller than alternative traditional approaches. The specific objective of project was to overcome the traditional architectures, the project demonstrated that using web services and embedded devices could serve to improve the re-configurability and interoperation of the monitoring devices within an existing architecture.

Summarizing this experience at a glance, the importance of Smart Sensors for the benefits achieved in maintenance, namely CBM, is due to the following reasons: i) the possibility to build or configure custom devices dedicated to the monitoring and diagnostics of equipment; ii) the possibility to enhance Smart Sensors in their capabilities by using MEMS technology; in fact this technology allows including many different types of micro sensors into the device or into a single chip, and this provides further potential for enhancing the smart sensing in a plant or machinery, as demonstrated in Section 3 by the use of board MB851 that shows how such platform can be integrated with different sensor: in the case with the sensing probe STLM75.

Considering now the architecture level, SOA is a flat architecture where all the services can interact together. This consequently makes the control architecture almost flat from a hardware and software point of view, but cannot overcome a certain hierarchy among the functionalities that the service carries on.

5. BENEFITS OF THE ARCHITECTURE

Shifting from an experimental environment to a real operative one, some remarks are worth to be provided. 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 / cost to configure the legacy system. Moreover, the tools consider the possibility to interact with IT systems that are external sources to the proposed architecture.

Lessons learnt derive also from the type of industrial environment where the solution has been deployed. The case strongly grounds in the automotive sector that is worldwide recognised as one of the most mature industrial sector. Moreover, the asset selected in the case was a robot, for which technological advancements are continuously proposed by manufacturers. Then, due to the type of asset, automotive sector employees well trained personnel to manage such type of machine (i.e. automation engineers). To this end, the context was fertile for the deployment of such technological solution. Furthermore, the specific need of the type of asset to be equipped with agile systems make the solution very interesting. The wiring of robots, in fact, is one of the main concern of the designers nowadays and it is also related with maintenance problems during operations. Normally in an automotive plant, there are several robots and the proposed solution plays a key role in providing simple and concise information that could be also grouped into a dashboard with all the installed assets. Cost is also a key aspect in automotive sector and thus the type of proposed solution gains other positive remarks also for that. All in all, it could be state that the proposed solution might be suitable for all the cases when: i) smart sensors wireless based solution provides a competitive advantage compared with other solution due to the less problems it causes (i.e. related with wiring); ii) number of equipment to be monitored is large; iii) capability to manage such technology is available among company staff; iv) solution cost must be kept as lower as possible.

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