Large-scale E-maintenance: A New Frontier for Management?

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***Abstract*—E-maintenance refers to the adoption of ICT to enable the remote monitoring and control of industrial equipment and processes. Traditionally, e-maintenance solutions rely on expensive and proprietary Supervisory Control And Data Acquisition (SCADA) technologies, which present cost and interoperability issues that limit their adoption to large plants and industrial processes. However, recent developments in ICT have broadened the application field of e-maintenance, enabling its adoption for the management of large scale (relatively) small and low-cost machines. This opens up new terrific business opportunities, especially in the increasingly important after-sales services market. This paper aims to draw the attention of the network and service management community on the e-maintenance issue. We hope to provide some helpful information to attract the interest of researchers and practitioners and to stimulate further discussions and research efforts on this topic.**

Keywords: E-maintenance; distributed management.

I. INTRODUCTION

E-maintenance has recently emerged as a key component in the digital factory. E-maintenance is a broad concept that refers to the adoption of ICT to improve maintenance processes in industrial environments. E-maintenance enables the remote monitoring and control of industrial equipment and processes and supports proactive decision making and efficient maintenance operation planning [1].

State-of-the-art e-maintenance solutions usually rely on expensive and often proprietary Supervisory Control And Data Acquisition (SCADA) technologies. Unfortunately, their high cost and low interoperability make SCADA-based solutions impractical for large scale installations of low cost machines, effectively limiting their adoption to the monitoring and control of large plant and mission critical machinery [2].

However, the growing adoption of modern ICT solutions, such as inexpensive off-the-shelf hardware and software components and Internet connectivity, is opening the way to disruptive innovations in industrial process management and maintenance. The economies of scale allowed by modern ICT solutions, as well as the advanced system integration capabilities that they provide, enable the development of e-maintenance platforms for the management of large scale installations of (relatively) small and low-cost equipment [3][4]. In particular, *large scale e-maintenance platforms* seem suitable for the control and after-sales assistance of household and similar appliances[1]. These are automated machines, such as industrial washing or ice cream making machines, that are typically installed in homes, shops, warehouses, light industries, or farms. They usually incorporate motors, heating elements, CPUs, or all of the above, and are designed to be operated by untrained personnel, with no on-site technical support available.

II. LARGE SCALE E-MAINTENANCE

Household and similar appliances are typically managed with a reactive maintenance strategy, based on on-site maintenance interventions scheduled according to a combination of "run-to-failure" and periodic maintenance policies. Since the technical personnel working on the field have little or no knowledge about the problem before performing an on-site machine diagnostics procedure, they often fail to resolve the problem by "Phone Fix" and often it is never a "First Time Fix".

These considerations suggest that e-maintenance platforms could bring significant benefits to the management of large scale installations of household and similar appliances, enabling considerably more effective and more efficient maintenance processes based on remote operations and proactive interventions - especially with regards to the efficient scheduling of human resources that have to perform both remote and on-site maintenance interventions. These platforms can provide advanced remote monitoring and control functions that go well beyond those provided by SCADA-based systems, effectively enabling the proactive maintenance of large automated machine installations.

In order to achieve these goals, large scale e-maintenance platforms should implement four main functions: automated monitoring, self-diagnostics and prognostics, and remote management [1][4].

Automated monitoring is probably the most important function, since the availability of highly informative maintenance data is essential to realize machine health monitoring. Let us notice that the automated monitoring of

[1] As classified by international product standards such as IEC (International Electrotechnical Commission) 60335-1:2010 and IEC 60335-2-75:2002.

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household and similar appliances presents additional challenges compared with the monitoring of industrial processes or networking equipment. In fact, household and similar appliances are typically installed in a wide range of heterogeneous environments and often have discontinuous connectivity (at best). They also have a potentially very large set of highly heterogeneous data to collect, cross-correlate, and visualize. This hinders the reuse of existing software for the monitoring of household and similar appliances and calls for ad hoc solutions.

Large scale e-maintenance platforms should also provide self-diagnostics and prognostics functions, which respectively realize automated fault detection and forecasting. More specifically, the diagnostics function should perform a first-order analysis of maintenance data, usually through the just-in-time analysis of critical working parameters, to check whether the machine is in correct operating conditions. The prognostics function instead should implement a more complex and higher-order analysis, typically relying on the comparative analysis of data collected from all the machines in order to detect deviations, anomalous operations, or conditions favorable to future faults.

The early detection of anomalies and the monitoring of machinery health based on the collected maintenance data are essential to enable proactive maintenance, as they represent the best way to reduce both machine downtime and maintenance costs. This calls for the adoption of advanced data analysis methodologies and tools, significantly more sophisticated than those commonly employed, e.g., in the monitoring of networking equipment. In addition, large scale e-maintenance platforms should provide a remote management function, which would enable to implement effective and proactive maintenance strategies. More specifically, this function should allow to establish on-demand live monitoring and diagnostic sessions to help technical support personnel in quickly identifying the cause of deviations and abnormal operations on the machines under their responsibility and in deciding how to proceed for the resolution. Finally, large scale e-maintenance platform should be capable of integrating with the enterprise information systems to generate value added services, for instance by providing the machines' production data to their customers [3][4].

Large scale e-maintenance platforms leverage on the rapid changes and developments in ICT, which have recently brought disruptive innovations in industrial process management and maintenance. More in details, Components Off The Shelf (COTS) hardware is becoming more and more powerful and affordable. Web-based software technology is allowing to realize sophisticated and highly interoperable communication infrastructures for distributed applications, leveraging on Open Source software that has low barriers to entry and no license costs. Advances in distributed data analysis techniques enable the real-time analysis of large amounts of data, thus allowing to implement sophisticated anomaly detection techniques to proactively identify problems within machines. Finally, the formidable improvements in Internet technology now provide several solutions, e.g., mobile connectivity, that can significantly facilitate the remote access to appliances, with low costs, especially with regard to data traffic [5].

III. INTERESTING RESEARCH TOPICS

Large scale e-maintenance therefore represents a terrific opportunity, which calls for further research. In this context, the network and service management community seems better suited than other communities (most of the literature on e-maintenance comes from the mechanical engineering and the production management research communities) to drive the research effort and push forward the state-of-the-art. In fact, this community developed a remarkable experience with the remote monitoring and control of networking equipment and servers, which would be an invaluable knowledge base for large scale e-maintenance research. Some of the interesting topics of research are detailed in the folllowing.

A. Architectures

Most existing state-of-the-art e-maintenance applications rely on proprietary SCADA systems for the automated monitoring of machines and devices. SCADA solutions are essentially tools for the development of remote monitoring and control stations for industrial automation systems. As a result, they operate at the conceptual level of Programmable Logic Controllers (PLCs), and usually focus on providing tools to read control variables from remote PLCs, to perform simple manipulations on the acquired data, and to display them on a monitoring screen. Remote control functions, where present, are also realized as write operations on PLC control variables.

In addition, to favor the integration with industrial automation equipment, SCADA-based systems are often deployed in master-slave configurations. This arrangement enforces sequential point-to-point communications between devices, with the master periodically connecting to each slave in order to collect data and to issue commands. Since no prioritization is usually enforced, the latency can significantly grow as the number of slaves or I/O operations grow larger. In practical applications, it is not uncommon that an entire loop for a few machines can take up to minutes.

Finally, SCADA-based solutions usually provide very few data analysis tools out-of-the-box, often forcing their adopters to develop their own routines using proprietary languages that prevent the reuse of the high quality commercial and Open Source COTS components available on the market.

While these limitations are acceptable in industrial automation systems, where the number of devices and control variables is relatively low, large scale e-maintenance applications operate on a much larger amount of data and call for more sophisticated solutions. More specifically, the essential importance of communications and data analysis operations in large scale e-maintenance suggests to adopt higher level concepts and to leverage on Internet and Web-based architectures.

In particular, our experience suggests that event-based architectures might represent a better suited solution for large scale e-maintenance applications, as they enable to manage independently each machine and allow the on-demand, (soft) real-time transmission of monitoring data and control commands. More specifically, machine-installed diagnostics functions would be able to automatically trigger the transmission of maintenance data to a central monitoring station in case of malfunctions, thus significantly reducing the response time of assistance interventions. Event-based architectures also represent a perfect platform for implementing control interfaces for remote technical support interventions and the periodical transmissions of maintenance data. Finally, event-based architectures cope pretty well with the often-disconnected nature of household and similar appliances.

B. Protocols and Standards

At the moment of this writing there are no standard protocols or service interfaces for large scale e-maintenance. In fact, the interoperability standards developed so far in the industrial computer applications market, such as the OSA-CBM project, (Open Systems Architecture for Condition-Based Maintenance) [6], have not yet delivered protocols and service interfaces well suited for large scale systems integration.

Network management protocols, such as SNMP, could represent an interesting solution for large scale e-maintenance platforms. However, they present a few issues that might hinder their adoption in some applications. In fact, SNMP leverages on UDP, which can be difficult to deploy in the extremely heterogeneous environment of large scale household and similar appliance installations. In addition, the remote management of household and similar appliances calls for the implementation of relatively sophisticated diagnostics and (re)configuration interfaces, which would be difficult to implement on top of SNMP.

Overall, modern Web-based software engineering methodologies and protocols might represent the best suited solution for large scale e-maintenance platforms. Web Services, especially ReST-based ones, provide excellent interoperability and extensibility characteristics, two critically important features for the realization of large-scale distributed applications, such as e-maintenance platforms, that need to be capable of evolving and integrating with other components of the enterprise information system. In addition, Web 2.0 and HTML5-based technologies enable to realize sophisticated graphical solutions for the visualization of data on a wide range of devices and foster the development of innovative applications. Finally, Web technologies have proved very effective on resource-constrained devices, allowing to build distributed applications with embedded components [7].

The development of standard management protocols and interfaces would significantly help the realization and deployment of large scale e-maintenance solutions. However, there is unfortunately still a lot of work to do in order to achieve this objective.

C. Communications

The wide range of deployment scenarios usually found in large scale e-maintenance applications require communication infrastructures that go beyond those supported by SCADA-based systems, which typically rely on industrial automation standards or on ad hoc communication stacks, e.g., private radio over UHF or unlicensed bands. In fact, most practical e-maintenance applications will need to deal with different types of Internet access technologies, such as IEEE 802.3 (Ethernet), IEEE 802.11 (Wi-Fi), GPRS, 3G, and 4G connectivity.

D. Data Analysis Techniques

The development of more and more sophisticated sensors requires large scale e-maintenance platforms to collect and analyze a significantly larger amount of maintenance data. For instance, accelerometer sensors, that generate a large amount of data which is computationally very expensive to analyze, and as a result are currently mounted only on large plant machines, could be installed even on low-end automated machines. At the same time, it is possible to hypothesize that the evolution of sensors could enable significantly more sophisticated process monitoring solutions, e.g., based on biological sensor data acquisitions.

The very large amount of sensors data can significantly improve diagnostic and prognostic in large scale e-maintenance, but requires the development of innovative methodologies and tools capable of analyzing and processing the large array of data streams, of significantly different type and nature, through sophisticated statistical analysis, machine learning, and anomaly detection techniques.

Recent research results and computational advances produced a new generation of data-intensive real-time processing techniques and tools that enable to process large quantities of data, to extrapolate non-trivial features, and to highlight non-trivial (cor)relations among them. Many of the above mentioned techniques and tools were developed in the context of the "big data" application field, which has recently attracted a lot of interest from both the industry and the academia [8].

Next-generation e-maintenance solutions will also have to deal with a very wide range of data types to analyze. In fact, in most cases the maintenance data currently analyzable consists of discrete data sets, also known as "value type" monitoring data in maintenance literature [9], which essentially limits the monitorable quantities to temperature, pressure, etc. Discontinuous value type data are significantly more difficult to handle than continuous ones, for which a large number of well-tested and sophisticated tools (based, for instance, on Fourier analysis, wavelet analysis, time-series analysis, etc.) is available, and present some limits to the applicability of automated anomaly detection mechanisms for real-time monitoring systems [10].

In addition, many types of automated machines also record a list of events, including events related to the normal operating conditions of the machines such as commands issued by the machine operators, completion of manufacturing process, etc., and transfer them to the central management station. This information, also known as "event data" in maintenance literature, is used to realize higher-order detection of malfunctions or incorrect machine usage through complex event correlation techniques [11].

E. Integration with the Enterprise Information Infrastructure

Modern ICT solutions provide large scale e-maintenance solutions with system integration capabilities that go well beyond those of SCADA-based system, which are hampered by a low-level information model designed to interoperate with industrial automation equipment. This enables the development of new and highly innovative features on top of the e-maintenance platform.

More specifically, large scale e-maintenance platforms could easily integrate maintenance and production data collected from the automated machines in the enterprise information systems of both the manufacturer and the purchasers' companies. In fact, the aggregation and cross-correlation of data from both e-maintenance and Customer Relationship Management (CRM) subsystems would provide the manufacturer with the full history of its relationship with his customers. This would enable a better informed decision making and a more efficient contracting, which could result in a strategic advantage over the competition. At the same time, the real-time access to the machines' production data would enable the customers to perform better informed business strategy decisions.

The integration of maintenance data with enterprise information systems is becoming a key concept in the e-maintenance discipline. In fact, experts agree that e-maintenance is not simply the integration of earlier maintenance procedures, such as predictive maintenance and condition-based maintenance, in an ICT-driven framework. Instead, e-maintenance also involves the synchronization of manufacturing and maintenance operations with business management systems [12]. Unfortunately, so far this research topic has been mostly unexplored.

F. Security

Compared with industrial control systems, large scale e-maintenance installations raise even more security concerns. In fact, the automated machines need to have Internet access in order to enable their remote management, thus significantly increasing their exposure to attacks.

It is therefore necessary to adopt security measures that prevent malicious access to the machines in order to protect confidentiality of data transfers between appliances and external monitoring stations, as maintenance data is an important industrial secret, and to avoid the unauthorized changing of critical configuration parameters of the manufacturing process, which could lead to machine malfunctions (and potentially damage).

However, from the security perspective, modern ICT solutions represent a considerably better platform than SCADA-based systems, which operate at the industrial control system level. In fact, Industrial control systems have recently become the objective of a large and growing number of malicious attacks. Several episodes, such as the Stuxnet attack, have raised significant concerns about the inherent security of these systems [13].

IV. CONCLUSIONS

The purpose of this paper is to draw the attention of researchers from the network and service management community towards the compelling research opportunities provided by large scale e-maintenance. In fact, theoretical and applied research on the large scale management of household and similar appliances would significantly benefit from the experience that this community developed on the remote monitoring and control of networking equipment and servers. In addition, large scale e-maintenance presents peculiar challenges that could stimulate researchers to develop new management methodologies and tools.

The considerations presented in this paper emerge from the authors' experience in building an highly innovative large scale e-maintenance platform, called Teorema, for the management of the ice cream making machines produced by Carpigiani (one of the leading industries in the market). Teorema currently controls about 4000 machines distributed all over the world, thus allowing for significant savings in maintenance operations, and represents a disruptive innovation in after-sales services within the ice cream machines market [3][4].

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