Teorema: an E-maintenance Platform for Ice Cream Machines

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Abstract

In modern manufacturing, the integration of ICT in the maintenance process, led to the development of e-maintenance, that automates management operations. E-maintenance, that initially interested only large plant machinery, is now becoming affordable for mass-produced equipment, thanks to the recent advances in ICT. This paper presents Teorema, an innovative e-maintenance solution for Carpigiani ice cream machines, which provides several services: remote monitoring of machines, automatic notification of malfunctions, diagnostics and prognostics functions, remote assistance interventions, and automated reporting of production data. Teorema is already in production and it is significantly improving the after-sale service to Carpigiani customers.

1. Introduction

In the last decade, industrial engineers have applied ICT-driven automation to improve every step of the manufacturing process [1]. In particular, many research studies have focused on the development and deployment of e-maintenance, that aims to automate management operations, like diagnostics and prognostics, by exploiting the remote monitoring and control of manufacturing devices [2] [3]. E-maintenance aims to enable and foster the adoption of more efficient proactive management processes that can reduce failures and unscheduled maintenance shutdowns.

So far, e-maintenance solutions have been developed mostly for large and expensive machines, for instance in the energy industry and in the heavy one, because of the high costs of remote monitoring technology [4]. The cost, size, and revenue of these devices justify the deployment of 24x7 remote monitoring technologies that leverage on automated computation-intensive data analysis and relatively high bandwidth ad hoc proprietary communication stacks, e.g., private radio over UHF or unlicensed bands.

Novel Internet technologies enable e-maintenance application to the market of lower cost machines, such as the ones usually called "household and similar appliances", mass-produced equipment that is commonly found in homes and offices, which present significant constraints, e.g., in terms of cost and size. In fact, recent advances in Internet-based communications, embedded computation capabilities, and software technologies now offer remote management solutions that are becoming affordable even for low cost equipment [5]. This enables the adoption of innovative e-maintenance solutions, that could bring significant benefits to the after-sales assistance of these machines, which typically operate unattended. Since there is no on-site technical support available, remote monitoring and diagnosis are crucial to organize and schedule timely assistance operations for household and similar appliances.

This paper presents the Teorema e-maintenance platform for the management of the ice cream machines produced by Carpigiani Group (one of the leading industries in the market). Ice cream machines are complex and high-duty systems with a long life cycle, during which the machines require many maintenance interventions. Since ice cream machines are often installed in many locations within large geographic areas, on-site interventions for maintenance operations is usually very expensive, for both technical personnel costs and (possibly long) machine downtimes with related revenue loss.

Teorema permits the remote monitoring of each machine operational state and stores, aggregates, and processes the collected data in order to provide several services, that include: automatic notification of malfunctions; synoptic visualization of maintenance data; automated reporting for monitoring and diagnostics purposes; prognostics functions to identify machines and components that are likely to fail; remote assistance interventions such as interactive diagnostics analysis, reconfigurations, and firmware updates. The Teorema remote management functions allow significant savings in maintenance operations. In addition, Teorema provides Carpigiani customers with a reporting service for the real-time access to the production data of their machines, which represent a disruptive innovation in after-sales services within the ice cream machines market.

2. The Teorema Project

Teorema is the innovative e-maintenance solution for the ice cream machines produced by Carpigiani Group. Carpigiani's ice cream machines are complex and high-duty systems which perform critical food processing operations and have a long (usually more than 10 years)

life cycle. As a result, notwithstanding their high-quality construction, during their lifetime ice cream machines require numerous maintenance interventions, which are performed on-site and are scheduled according to a combination of run-to-failure and periodic maintenance policies. However, Carpigiani's ice cream machines are usually installed in many locations within large geographic areas, and on-site maintenance interventions can be very expensive, in terms of both machine downtimes (and consequently loss of revenues) and significant travel expenses for the technical support. Teorema enables the remote monitoring and control of Carpigiani ice cream machines and offers several e-maintenance services that have changed the after-sales process of ice cream machines.

2.1. Teorema Operations

Teorema provides four main functions: automated monitoring, self-diagnostics and self-prognostics, remote management, and customer data access.

The automated monitoring function permits periodical and on-demand reporting of operational state (including failure notifications), from the ice cream machines to a centralized management application. Teorema supports the synoptic visualization of the machine state (programming table, firmware version, analysis of alarms, diagnostics of failures, events, machine access log), updating values in real-time. It supports also the graphical representation of time-varying metrics (number of ice cream served, hours of work for the refrigeration engine, temperatures, density of the served ice cream, etc.). In addition, the system provides an advanced reporting mechanism, that sends to each registered technician a daily report on the state of the machines under his responsibility.

The self-diagnostics and self-prognostics function realizes both the automated diagnosis at the machine side and the centralized just-in-time analysis of data collected from the machines to detect failures, anomalous operations, or machines and components that are likely to fail. In case of unexpected behaviour in a machine, Teorema immediately notifies the technician who is in charge of its management.

The remote management function allows to establish on-demand real-time remote monitoring sessions to help technicians in quickly identifying the cause of faults and in deciding how to proceed for the resolution. In addition, Teorema provides a remote reconfiguration function which enables the automation of firmware and configuration upgrades for ice cream machines.

Finally, Teorema provides Carpigiani customers with a direct access to production data, such as machines productivity (number of served ice cream cones, ingredient exhaustion, etc.), reliability, and geographic location (see Figure 1 as an example). Customers can access Teorema information and services anywhere, anytime, and from a wide range of devices with different screen sizes, CPU capabilities, and input interfaces, e.g., laptops, netbooks, PDAs, and smartphones. In fact, Teorema provides a Web-based, multi-modal interface

that tailors data visualisation according to the characteristics of the user terminal device.
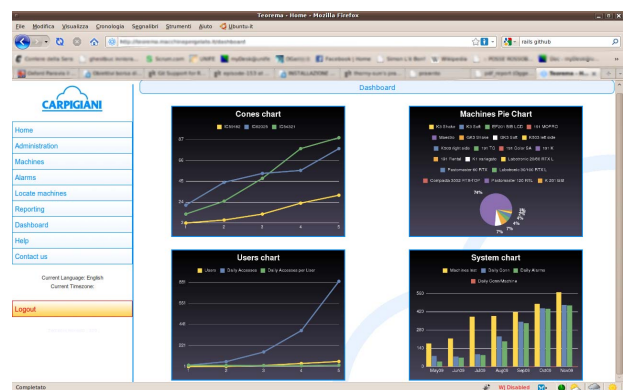

Figure 1. The Teorema customer interface.

2.2. The Teorema Architecture

Teorema adopts a client/server Web-based architecture, with machine-installed kits that integrate with the ice cream machine hardware and act as clients sending maintenance data to the Teorema server, a centralized data monitoring and control station (currently located in the Carpigiani headquarters). Figure 2 depicts the interactions between the components of the Teorema platform.

Different Teorema operations are executed at either the client or the server side, with a carefully designed placement that is decided considering the requirements in terms of computational capability and communication costs. For instance, the diagnostics operation is distributed across both client and server components, while the monitoring follows a centralised approach.

Diagnostic functions are split between the ice cream machines and the central monitoring station, because the limited CPU power available on the machines requires to run locally only simple self-diagnostic functions (based on either predefined threshold values for monitored variables or alarm triggered by machine-installed sensors) and to transmit maintenance data to the central monitoring station for aggregation and further processing. On its turn, the Teorema central station performs just-in-time analysis of the received data via computationally expensive diagnostics and prognostics algorithms, further increasing the capabilities to timely detect failures and unexpected behaviours.

The monitoring of machines is, instead, centralized. In fact, only the central management station has the storage capacity to record all the management data and the computational power to process them to provide aggregation and visualization functions. The transmission of maintenance data from the ice cream machines to the central station occurs according to several conditions. The machine-installed diagnostics functions automatically report to the central station in case of malfunctions. In addition, periodical transmissions of maintenance data are also scheduled. Finally, the machines also provide a control interface for remote

technical support interventions, enabling on-demand, real-time transmission of monitoring data.

Most of the data received by the central station consist of discrete data sets, also known as "value type" monitoring data in maintenance literature [6], which are more difficult to handle than continuous time series data and present some limits to the applicability of automated anomaly detection mechanisms for real-time monitoring systems. Teorema leverages on multivariate statistical analysis for fault detection, as it represents a powerful diagnostics solution [7]. In addition, ice cream 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 processes such as pasteurization, 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 [8].
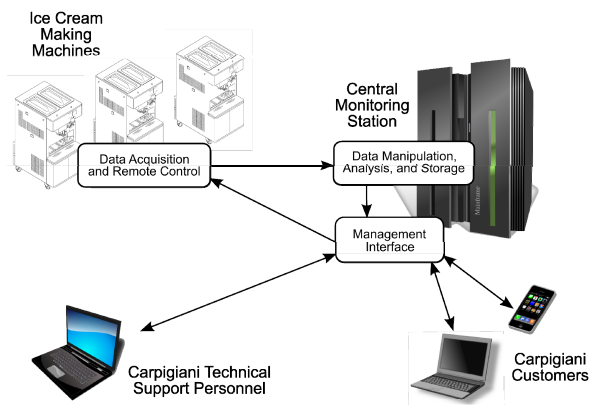

Figure 2. The main components of the Teorema platform and their interactions.

3. Teorema in Action: Improving the Maintenance Process

Project Teorema is already in production with 1268 remotely controlled machines, installed in several European countries. The functions provided by Teorema, as well as the technologies adopted for their implementation, are proving robust and effective. Teorema-controlled machines have already proved the importance of keeping the machines under real-time control, promptly identifying faults and, in some cases, even identifying worn down components and machines that are likely to break in the near future.

The Teorema diagnostics functions enable Carpigiani technicians to perform many assistance operations remotely. In case an on-site intervention is necessary, technicians can leverage on Teorema provided information to identify and carry with them the required spare parts, thus reducing the need for further on-site operations. In addition, real-time access to diagnostics information allows to make sure that ice cream machines do not experience costly downtimes due to improper or untimely management by operating personnel, e.g., unjustified delays in the load of ingredients or in the cleaning of the machine. For instance, in a recent maintenance intervention a Carpigiani technician received an alarm from a Teorema-enabled machine and managed to trace the source of a problem to an obstruction in the ventilation grid – a misuse that can lead to serious damage to the machine. The technician immediately contacted the customer, who confirmed that there was a folded cardboard box leaning on the back of the machine and removed it, thereby fixing the problem.

Finally, the Teorema prognostics functions enable to identify which components are likely to break in underperforming machines. For instance, in one machine Teorema detected the upcoming failure of the beater blades component by identifying a negative trend in the ratio between the number of served ice cream cones and the number of working hours for the refrigeration engine. Teorema prognostics information has enabled Carpigiani to shift to a proactive "predict and prevent" maintenance strategy, with significant reductions of machine downtimes. The remote detection of the type of assistance intervention required for failed components allows to optimize on-site assistance interventions, that now are better planned and scheduled.

In addition, Teorema has enabled a more effective use of work time from expert technicians, a critically scarce resource, who now can be much more productive as they do not have to spend most of their time travelling to gain on-site access to the ice cream machines. The ubiquitous Web-based access to all maintenance data also facilitates the cooperation of technical support personnel operating on-field with the experts of the Carpigiani management division working at the Carpigiani HQ.

Overall, the adoption of Teorema has lead to very significant savings. In the last month, around 20% of the assistance interventions for Teorema-controlled machines have been performed remotely. This has brought to a reduction in maintenance costs of almost 25%, and we estimate that in the long run reductions could stabilize around 40%.

Finally, from the Carpigiani's customers perspective, the promptness improvement in maintenance intervention enabled by Teorema translated into much smaller machine downtimes, and therefore significantly decreased loss revenues due to faults.

4. Customer Access to Production Data

Teorema enables Carpigiani to provide an improved and innovative service to its customers. On the one hand, Teorema drastically increase the maintenance intervention responsiveness and significantly reduces after-sales assistance costs, by exploiting its remote monitoring and control and diagnostics/prognostics functions. On the other hand, Teorema allows Carpigiani to provide direct access to both production and maintenance data to its customers.

Providing customers with real-time access to production data, such as machines productivity metrics,

working parameters, reliability indicators, and geographic location, represents a significant innovation in the ice cream machines market. In fact, the availability of real-time temperature data during the refrigeration process is a very important feedback that significantly facilitates the development and preparation of peculiar ice cream recipes. This feature has been much appreciated by customers, which in some cases have asked Carpigiani to tune their ice cream machines working parameters to ease the production of their signature recipes. In addition, customers can now leverage on Teorema-provided temperature data related to pasteurization and refrigeration processes to demonstrate their compliance to food safety rules to the control and certification authorities in their country.

Finally, customers take advantage of Teorema to access information about the machines' assistance history, including up-to-date reports on the status of ongoing maintenance interventions. This feature grants customers a transparent view of the Carpigiani after-sales service operations, allowing to evaluate its efficiency and its conformance to the subscribed service level agreements.

The provisioning of e-maintenance data to customers opens up the way to new business models. Customers do not simply purchase a manufacturing product, but subscribe to a comprehensive service that monitors machines for both management and production. The servitisation of business models has proved to be a very effective way to align a company's offer to its customers' needs [9]. In this context, Teorema represents a major step for Carpigiani, traditionally a product-based company, towards a more service-oriented offer.

5. Implementation Insights

The development of the Teorema platform is exclusively based on Open Source Web-based technologies, as they allow Carpigiani to protect its investments by not restricting the software platform to a single proprietary vendor. In particular, the technologies we have adopted are highly innovative, albeit already mature for the industrial use and very well supported.

The core part of Teorema is a Ruby on Rails application. Ruby on Rails is a framework for the development of Web 2.0 applications based on the Ruby programming language and purposely designed to enable agile programming practices. The Ruby on Rails characteristics allow the rapid development of new features, minimizing their time-to-deployment [10]. This makes Ruby on Rails a perfectly suited framework for a dynamic and rapidly-evolving platform such as Teorema.

Carpigiani machines leverage on Internet-based communications and can exploit a wide range of network connectivity media, e.g., 802.11, GPRS, and Ethernet, according to the specific deployment conditions. In addition, open standards and the widespread availability of COTS hardware and software components significantly help to reduce costs.

6. Conclusions

The deployment of Teorema has allowed Carpigiani to achieve considerable savings through the reduction of on-site maintenance interventions and the restructuring of the maintenance process. In addition, Teorema has significantly improved the quality of after-sales assistance service provided to customers. We have received a very positive feedback from Carpigiani's customers with regards to the capability to access their after-sales maintenance data in real time. We have been reported that in some cases Teorema has been a key factor in the customer decision to purchase Carpigiani's machines. The results achieved so far identify Teorema as a strategic asset for Carpigiani to win over competition in an increasingly difficult global market.

Future developments of the Teorema platform will also consider the automated construction of knowledge from customer reports and telemetry data, by exploiting data mining techniques. The transition to the new hardware will also allow to implement more sophisticated diagnostics functions directly on the ice cream machines.

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