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PLM-MES integration: a case-study in automotive manufacturing

Gianluca D'Antonio¹, Joel Sauza Bedolla¹, Gianfranco Genta¹, Suela Ruffa¹, Giulio Barbato¹, Paolo Chiabert¹, Giorgio Pasquettaz²,

¹Politecnico di Torino, corso Duca degli Abruzzi 24, 10129, Torino, Italy
{gianluca.dantonio, joel.sauza, gianfranco.genta, suela.ruffa, giulio.barbato, paolo.chiabert}@polito.it

²Centro Ricerche Fiat, Vehicle Division, Advanced Manufacturing and Materials
Strada Torino 50, 10043, Orbassano (TO), Italy
giorgio.pasquettaz@crf.it

Abstract. Nowadays, the development of high-quality, highly-innovative products is mandatory to satisfy the market requests. To support this process, the deployment of IT tools, such as Product Lifecycle Management (PLM) and Manufacturing Execution Systems (MES), is necessary. However, the efficacy of such instruments can be increased if they are able to exchange information with each other. Such integration provides the designers with a feedback from the shop-floor: this allows to improve the quality of the product and the performance of the process, as well as to quickly react to solve possible issues. To emphasize the benefits of PLM-MES integration, a case-study in the field of automotive components manufacturing is provided: the MES is equipped with a real-time algorithm to control possible drifts of a monitoring system for a laser welding process. In case of process instabilities, the design department is immediately informed to evaluate possible solutions, and the critical event is tracked into the PLM.

Keywords: Product Lifecycle Management (PLM), Manufacturing Execution Systems (MES), Monitoring systems, Integrated product development.

1 Introduction

In the last years of the 20th century, many companies attempted to deal with global competition focusing on the reduction of the finished product cost. Thus, numerous facilities have been offshored in countries characterized by a low labor cost. However, today customers require high quality, customizable products; thus, an effective cost management is not sufficient to comply with market requests. Hence, several manufacturing companies are shifting the focus of their business models from the production cost to the quality and the innovation content of their products. This process is supported by the deployment of IT tools which allow higher process performance and greater automation levels; they make feasible higher product quality

and customization, as well as extended cooperation among companies and suppliers across the value chain.

Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) are among the mostly deployed IT systems in modern manufacturing companies [1].

PLM is a strategic business approach that integrates all the information related to the company products and activities throughout all the product lifecycle; it supports the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from conception to end of life, and allows information and knowledge sharing within and between organizations [2, 3]. The aim of PLM is to ensure the fast, easy and trouble free finding, refining, distribution and reutilization of the data required for daily operations [4].

ERP systems are software programs used by the company management to integrate and coordinate information in every area of the business. ERP provides an enterprise database in which all actions concerning finance, sales, marketing, purchasing and human resources are traced [5].

A MES is a layer of communication that enables data exchange between the organizational level, usually supported by an ERP, and the shop-floor control systems, in which several, different, very customized software applications are employed [6]. The aim of a MES is twofold. First, the system has to evaluate the optimal sequence planning taking into account the basic features of the process, such as processing and setup times, and workstations capacity, considering the requirements and the necessities given by the organizational level of the company. The system also has to manage and allocate resources such as the staff and the material necessary for the manufacturing process.

The second aim of a MES is the management of the bottom-up data flow: information collected by monitoring systems at the shop-floor level can be used to assess product quality and process performance. The MES analyzes such data; the results are provided to the organizational level and used for process controlling tasks. The functionalities of a MES have been grouped in 11 categories by MESA International [7] (see Fig. 1); furthermore, the tasks for each enterprise layer and, in turn, for each kind of information system are listed in the ISA95 – IEC62264 standard [8]. This standard also provides definitions for the data structures to be exchanged among information systems aiming to enhance their integration; however, it mainly focuses on ERP-MES-Shop floor integration.

Actually, few tools to extract information from shop-floor data for online process control have been developed. Existing software mainly focus on product quality and process performance monitoring, using techniques such as control charts. However, there exists a huge variety of sensors that allows to measure several heterogeneous quantities; recently, monitoring and control systems assumed a relevant role in the improvement of manufacturing processes thanks to the development of low-cost, small, easily available sensors. In order to make intelligent a monitoring and control system, these measuring devices should be supported by mathematical techniques able to real-time integrate and analyze data collected from the sensors, to provide a complete picture of the current state of the process and make available useful indications to improve the process itself. Examples of real-time monitoring systems integrated in MES are given in [9-11].

| | |
|--------------------------------|-------------------------------|
| Operations/Detailed sequencing | |
| Dispatching Production Units | Quality Management |
| Labour Management | Product Tracking & Genealogy |
| Resource Allocation & Status | Data Collection & Acquisition |
| Document Control | Performance Analysis |
| Process Management | |
| Maintenance management | |

Fig. 1. MES functionalities defined in [7].

This paper looks forward to extend the state of the art by presenting an original integration between a PLM system and a MES that deploys a monitoring and control system to acquire and analyze shop floor data. In section 2 the case study is introduced. It is the analysis performed on a laser welding process used in the assembly of automotive components. Then a mathematical technique is introduced. It allows to analyze shop-floor data and correct possible drifts in real-time; this technique is profitably integrated into a MES. In section 5 the PLM-MES integration is treated, and finally some conclusive remarks are presented.

2 Manufacturing process description

In order to investigate the integration between PLM and MES, a case-study in the field of automotive manufacturing is presented. The process at stake consists in a laser welding operation: it is a process that obtains fusion by directing a highly concentrated beam of coherent light on a very small spot. It allows to obtain high-speed, non-contact and precise features with low heat effects.

In this study, we consider laser welding of synchronizer wheels and gears. The joining of control gear and clutch body using the laser welding method looks for a more compact and more efficient gearbox. The machine equipped with a CO₂ laser is used to achieve deep welding penetration on different kinds of 40NiCr steel parts. The speed and the power of the machine are adjusted according to the parts to be welded; in our tests, the laser power is 4 kW, and the speed is 3 m/min. The focal length is 200 mm. On average, the actual welding process produces 0.4% defective parts, mainly because of excessive porosity on the material or lack of depth of the welding.

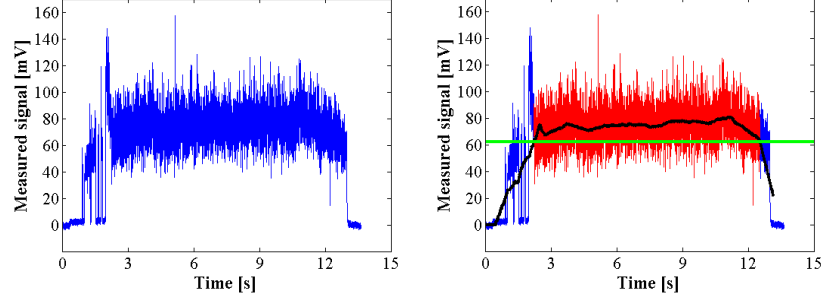


Fig. 2. Example of a signal acquired during the welding operation (left) and result of the filtration through the moving average technique.

An online monitoring system has been integrated into the welding machine to assess the quality of the process. It consists in a Hamamatsu photodiode that converts light variations into current. The sensitivity of the sensor is 270-980 nm; a narrow band-pass filter, centered at 900 nm is applied.

3 The real-time data processing technique

In Fig. 2 (left) an example of a signal representing a welding operation is plotted. A quick visual inspection allows to partition the signal in 5 parts: (1) an initial part in which the monitored quantity is approximately zero: such data are recorded before starting the welding operation; (2) an increasing transient; (3) a steady state phase; (4) a decreasing transient; (5) a final part consisting in data acquired after the welding operation is finished.

The initial and final parts of the signal do not concern the welding operation, as well as the two transients are not representative for the condition of this task. Thus, an initial operation is performed to extract the data corresponding to the steady state phase from the original signal. The welding machine is deployed with different combinations of parameters and to process several kinds of parts; thus, the definition of a unique, general threshold value is not feasible. Therefore, to provide generality to our methodology, a simple moving average approach is used, averaging over 1000 samples: this method allows to neglect sharp fluctuations and to focus on longer-term trends. Through this analysis, we extract the part of the signal in which the moving average value is greater than the overall signal average, and discard the remaining parts. An example of application of this signal filtering technique is shown in Fig. 2 (right).

After this pre-processing operation, a feature extraction operation is performed: the mean of the filtered laser welding signal is evaluated. For each acquired signal, data preprocessing and feature extraction are repeated, and the average values are stored. In Fig. 3 four time trends of the extracted averages are shown: they concern monitoring activities performed on different days. This signal selection is representative of the most of the possible manufacturing conditions. The data, acquired in four different days, exhibit different magnitudes, as well as different variability. The plots show that data are clustered because of some production breaks, mainly due to geometry changes or manpower breaks. Discontinuities between the average values across two different production lots occur: after an interruption in the welding operation, the magnitude of signal averages is frequently greater than before the break. Furthermore, the average values of the signal acquired by the photodiode exhibit different trends in different days, that can be decreasing or increasing with different magnitude. However, such drifts do not result in quality poorness. This phenomenon is highlighted by the least-squares interpolation lines; the mean drift rate d and the corresponding uncertainties U at a 95% confidence level are synthesized in Table 1. The results obtained in different days are not compatible among each other, and it is not possible to find a unique common trend for each day. Thus, to evaluate whether the process is in control or not, the drift must be recovered; if the drift is not recovered, a type I error (false positive) may occur. In the following sections, an adaptive, real-time methodology to evaluate and recover data drift will be introduced, in order to reduce the risk of type I error and ensure high-levels for product quality.

As stated, besides the drift of the mean values, data are also divided into groups as there are some temporal interruptions of the production process. For example, the signal in Fig. 4, corresponding to day 1, consists of three distinct production lots. A linear regression analysis can be made for each lot. However, the slopes are generally different from the one obtained on the complete day model, as shown in Fig. 4.

Nevertheless, even the analysis on single data groups does not lead to useful results since the slopes are very different with each other. These results show that it is not

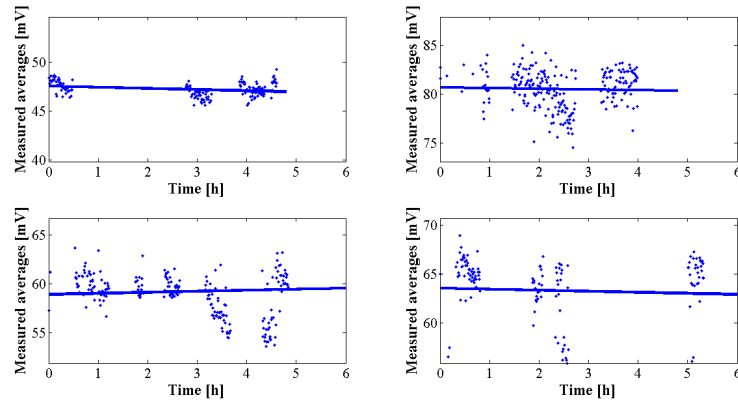


Fig. 3. Time trends concerning the average values of data acquired during days 1, 6, 7 and 10.

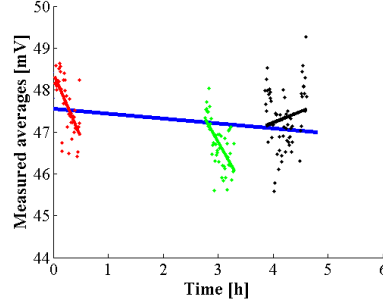


Fig. 4. Time trends for the average values of data acquired in day 1.

Table 1. Slopes and corresponding uncertainties of the least-squares interpolating the average values of the filtered data.

| | d [mV/h] | U [mV/h] |
|--------|------------|------------|
| Day 1 | -2.9 | 1.7 |
| Day 2 | -12.3 | 4.1 |
| Day 3 | 56.5 | 8.9 |
| Day 4 | -3.1 | 2.1 |
| Day 5 | -3.0 | 8.0 |
| Day 6 | -21.6 | 5.7 |
| Day 7 | 2.6 | 3.1 |
| Day 8 | 0.1 | 1.3 |
| Day 9 | -14.8 | 0.8 |
| Day 10 | -2.5 | 8.7 |
| Day 11 | -13.3 | 0.8 |
| Day 12 | -9.5 | 1.1 |

possible to correct the drift over a daily basis, as well as over a single production lot. Thus, a dynamic correction method must be developed.

4 The real-time control technique

As shown in the previous section, the measurement of the welding operation is affected by drifts which cannot be predicted: a standard compensation strategy cannot be deployed, and an adaptive correction methodology must be developed.

First, since data are clustered (see Fig. 4) and production breaks lead to discontinuities in the signal magnitude, a methodology to separate different production lots must be identified. Since a single welding takes approximately 15 seconds, we assume that a break occurs when an interruption longer than five minute occurs (i.e. the duration of 20 welding operations).

Then, we apply the technique for drift compensation. It consists in comparing the average value of the signal for the current operation with the median value m of the previous N operations. The deployment of the median value is preferable to the mean value, because it is more stable and less sensitive to irregularities. To remove the drift, m is subtracted from the mean value of the acquired signal, and the obtained value is

compared with the control limits. The aim is to decide whether the welding operation is stable or not. In our tests, N is set to 7.

Fig. 5 shows some results of the developed control technique for three different lots. In each figure, the measured values (centered with respect to the median value) and the corresponding corrected signal are compared. The regression lines show that the drifts are minimized, and the variability of the mean values of the signals is also reduced (Table 2). The blue lines represent the adaptive 99.7% control limits; they are evaluated through an inverse Student distribution, after performing a normality test. In the first lot, approximately at $t=10$ min., one point is slightly up and the following is below the control limit. The third lot also shows that there are two risky points at $t \approx 10$ minutes.

When the production of a new lot is started, the control chart is reset and the new control limits must be evaluated (since the main values and the variability of the measured signals are not constant). Thus, the first few produced parts can be used to train the algorithm. The control limits become tighter as the number of produced parts increases. Therefore, when the control limits are tight enough, the control chart stability of the process can be verified.

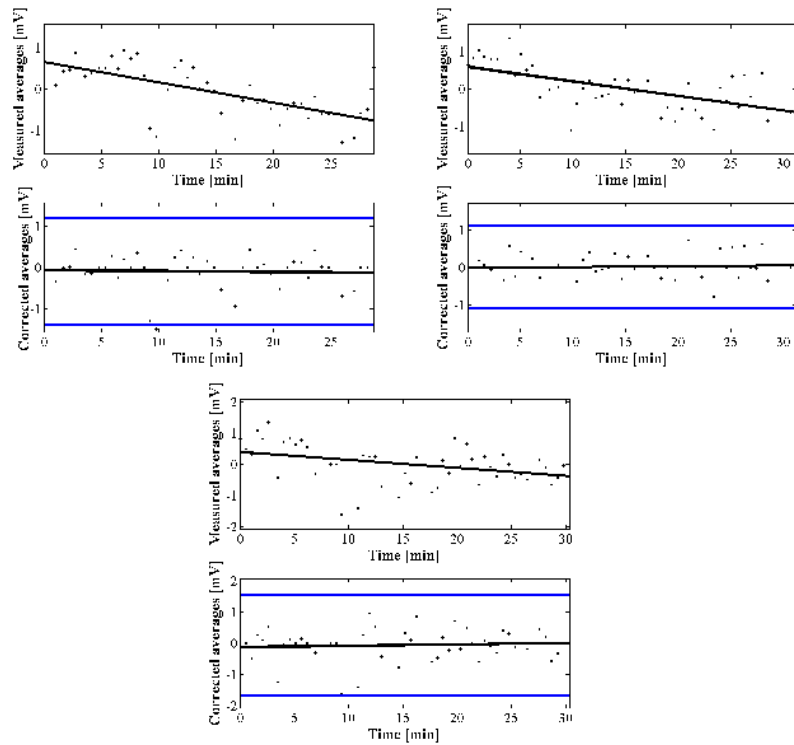


Fig. 5. Data from Fig. 4 before and after drift removal: first lot (top, left), second lot (top, right), third lot (bottom).

Table 2. Main parameters of the data plotted in Figures 5-7 after drift removal.

| | Lot 1 | Lot 2 | Lot 3 |
|-------------------------------------|--------|--------|--------|
| Mean [mV] | -0.09 | 0.02 | 0.02 |
| Std. deviation [mV] | 0.41 | 0.35 | 0.35 |
| Coverage factor (99.7% conf. level) | 3.18 | 3.17 | 3.16 |
| Sample size | 45 | 48 | 48 |
| p-value | <0.005 | <0.005 | <0.005 |

5 PLM-MES integration

As stated in the previous sections, PLM contains all the knowledge concerning the design of both the product and the related manufacturing process. On the other side, a MES interacting with a monitoring and control system is able to acquire shop-floor data and real-time evaluate whether issues that can affect product quality or process performance are arising. The lack of such system emphasizes the risk of producing defective parts: once a product starts to be manufactured there is not a feedback of what is really occurring in the shop floor. Thus, the first advantage expected by the deployment of the monitoring and control system is product quality improvement: sensors allow to detect, measure and monitor variables, events and situations that affect process performance or product quality.

The integration between PLM and MES ensures product quality over long time periods. The integration among these two systems allows to create a feedback information mechanism that can enhance the performance of the production process and the quality of the manufactured parts. The MES is able to detect systematic trends, criticalities, deviations, and to evaluate the variability of the process. In case a shop-floor issue arises, the cooperation between the two systems allows to quicker take decisions, leading to better and faster reactions to possible problems. For example, some components of the product or some steps of the manufacturing process, even upstream the critical task, can be redesigned; such changes must be stored into the PLM, in order to make them available for future production. Furthermore, the integration among different information systems can be extended across several companies, for example among a company and its suppliers: this cooperation allows a more effective data exchange, leading to enhanced company agility and improved quality of transmitted information.

The real-time control technique introduced in section 4 is integrated into a MES and is able to exchange information with the company PLM system: it transmits information concerning the adaptive control charts. In case of process instabilities, an alert message is generated and the design department has to identify the reason for which the issue arose. A history of issues and critical events is stored, in order to provide useful data for process revisions.

PLM-MES integration is also beneficial when a new product or process is released: the information exchange between the two systems allows to adapt and tune the

manufacturing process in a shorter time and with improved performance. The monitoring system allows to detect differences between the real products and the expected output, as well as to evaluate the performance of the process. Data collected during the ramp-up phase contain a huge quantity of information that can be used to optimize process and product design, resulting in increased competitiveness of the company: production cost and cycle time are reduced, while the productivity and the capacity to manufacture high-quality innovative products is increased. This improved reactivity that allows to better deal with market changes.

The information systems integration is also helpful to improve process sustainability. The monitoring system allows to predict the quality of the produced parts: thus useless operations can be avoided (for example, further operations performed on a product that already exhibits criticalities) and reworking actions can be very focused. This allows to reduce energy consumption and the environmental impact of the process: material waste, water consumption, emission of pollutants are reduced.

Finally, PLM-MES integration enables to create a repository system in which all the knowledge acquired during past operations is stored. This knowledge can be used whenever useful: it can be integrated into an automatic decision system able to undertake the best possible action, as well as used to suggest different possible scenarios to an operator, and support him in making aware decisions.

6 Conclusions

In this paper, a technique that allows the real-time adaptation of a control chart for the laser welding process in the field of automotive components assembly is presented. A photodiode is deployed to monitor the process; however, the collected data exhibit drifts even when the process is in control and the quality of the welded parts is acceptable. Thus, a mathematical methodology has been developed to online remove the drift and real-time evaluate whether the process is in control or not. The methodology is very simple and has a very low computational cost; hence, it can be profitably integrated into a microcontroller installed onto the welding machine.

The integration of this monitoring and control system into a MES is an essential task: the aim of such system is to collect information at the shop-floor level and analyze it to assess product quality and process performance. The first advantage expected by such integration is product quality improvement: the photodiode allows to detect events and situations that affect process performance and stability, as well as product quality. Since the continuous quality control permits to decrease the quantity of defective products, wastes and scraps and, in turn, to reduce production costs can also be reduced.

The integration between MES and PLM is also important: a continuous information exchange between these two systems allows to make quicker and more aware decisions. In the case study presented in this paper, PLM-MES integration ensures that the new welded parts meet design goals while ensuring high quality. This is achieved by incorporating the algorithm introduced in Section 4 into the MES. The developed control technique automates process stability and eliminates the drift of the

process. Furthermore, the developed technique enables real-time detection of issues: thus, the process can be immediately stopped or fixed in case of problems. Several correction strategies can be stored into the MES to deal with the different possible issues that can arise during the production, or alerts can be sent to the design department.

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