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A telemetry-driven approach to simulate data-intensive manufacturing processes

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Abstract

Telemetry enables the collection of data from remote points to support monitoring, analysis and visualization. It is largely adopted in Formula One car racing, where streams of live data collected from hundreds of sensors installed on car components are transmitted to the pitwall to be used as input of real-time car performance simulations. The aim of this paper is to evaluate the potential of a telemetry-driven approach in a manufacturing environment, where researchers are still looking for efficient methods to perform valuable simulations of the production processes on the basis of real data coming from the factory. The telemetry could contribute to the implementation of a virtual image of the real factory, which in turn could be used to simulate the factory performance, allowing to predict failures or investigate problems, and to reduce costly downtime. This study addresses in particular the efforts to combine and adapt methods and techniques borrowed from the field of Formula One car racing. Moreover, the investigation of the exploitation possibilities of the factory telemetry is paired with the design of a software application supporting this technology, starting from the elicitation and specification of the functional requirements.

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1. Introduction

One of the major issues affecting the current manufacturing companies is the lack of a full bidirectional synchronization between the physical world at the shop-floor and its digital equivalent counterpart (so-called *Factory Image*) [1] [2]. When the latter is constantly connected to the production system, it represents a true reflection of the real factory which can be used to monitor and simulate the factory performance, allowing to adjust and optimize processes, anticipate failures or investigate problems, and thus increasing efficiency by orders of magnitude and reducing costly downtime. The current state of the art shows that some potential solutions are available in literature for transferring the digital rendered designs to the shop floor in order to build the right product [3]. However, to the best of our knowledge, none of the proposed solutions implement the reverse information flow from the real to the virtual world.

In order to close this loop and provide the full range of capabilities that synchronization between the real and digital factory have to offer, a wide variety of different technologies is needed. A key-enabler is the Cyber-Physical System (CPS) technology [4], a network of interacting collaborative elements in constant connection with the surrounding physical world and its on-going processes. The use of these smart devices within the manufacturing execution phase allows to generate a *factory telemetry* under the form of a large amount of intensive and multi-source data, which can then be routed real-time towards various enabled devices connected to the company network. The major obstacle in the implementation of such a telemetry approach is the difficulty of handling an enormous amount of data coming from the real plant to get aggregate values suitable for the analysis [5].

This paper aims at looking for new strategies to capture, compare, and view disparate sets of data coming from various elements of a CPS in order to extract relevant knowledge and

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provide better insights over the status of the resources at the shop floor. In this regard, a new vision for processing the factory telemetry is proposed, by combining and adapting methods and techniques borrowed from the field of Formula One (F1) car racing, where telemetry is largely adopted to collect data from remote points in order to support real-time car performance simulations. The idea behind this study is that the envisioned approach allows to generate an integrated and aggregated view of the factory telemetry that dynamically augments and enhances the data-driven simulation applications supporting the manufacturing execution phase. Finally, the investigation of the exploitation possibilities of the factory telemetry is paired with the design of a software application supporting this technology, starting from the elicitation and specification of the functional requirements.

The remainder of this paper is structured as follows. Section 2 illustrates the analogies in the use of the telemetry between the worlds of racing cars and factories. Section 3 introduces an overview of a software application supporting the factory in industrial scenarios and illustrates major challenges to realize it. Finally, Section 4 draws the conclusions, summarizing the main outcomes.

2. Towards a factory telemetry: similarities with the racing car

Analogies can be a valid way of analyzing the performance of industrial processes in order to understand potential improvements. A significant example is represented by the several parallels between biological and manufacturing systems that have been drawn in literature to solve a series of problems of the modern manufacturing, through the study of the structure, control mechanisms, and functions of the biological systems [6] [7] [8].

The idea behind this study is that various analogies can also be observed between the worlds of F1 racing cars and modern factories. In fact, like the F1 cars, a manufacturing environment comprises a set of processes to be monitored in near real-time, huge information flows (and corresponding software applications) from which to take critical decisions in limited time, and a team of people that has the task of developing, maintaining, measuring, and adjusting the system under changing conditions [9]. On the basis of these analogies (Fig. 1), it is interesting to experiment a transfer of methods and tools from one field to the other. In this regard, the focus of this section is on a set of relevant features of the telemetry, a proven technology of F1 in which important measurements are made on board of the cars for data recording and monitoring (Fig. 2). Such features are then analyzed in order to investigate the potential of the factory telemetry in the world of the manufacturing. Moreover, it must be emphasized that F1 represents a relevant reference case, since it is always on the cutting edge of technological development.

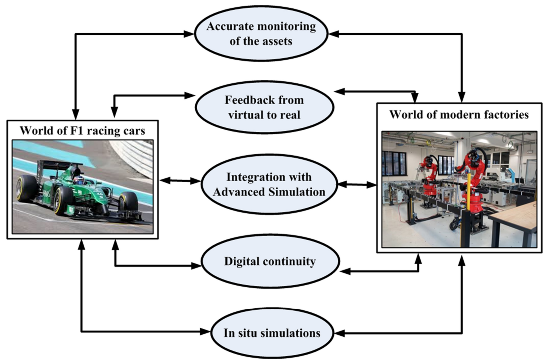

Fig. 1. Similarities between the worlds of F1 racing cars and modern factories

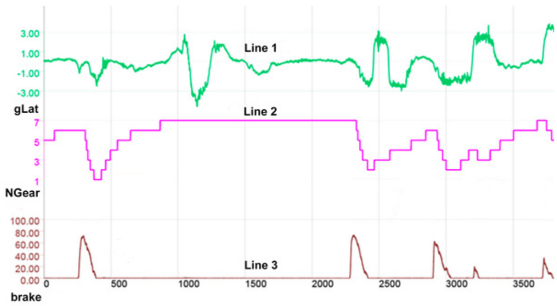

Fig. 2. Telemetry of a F1 car which contains speed, gear and other channels (SOURCE: Caterham F1 Team/Renault Sport F1)

2.1. *Accurate monitoring of the assets for critical decisions making*

Telemetry is a proven technology of F1 through which a deluge of data is transmitted from the car to the pitwall in order to allow a team of engineers to monitor accurately and constantly several parameters about car systems such as suspensions, engine, transmission, and wheels [10]. In this way the engineers can watch over the racing car performance and optimize the vehicle setup, suggesting drivers to change one of these parameters. Moreover, they can use the telemetry to analyze tactics and strategies, investigating on which corners car could go faster.

The accurate monitoring supported by a similar *factory telemetry* would be relevant for any manufacturing company where data provides the basis for critical decisions making. In particular, there are two major areas of associated benefit: the management of the allocated resources, and the continuous improvement between design, development, and manufacture of the products (enabling a kind of loop between the three stages). Along the whole factory life cycle, the sensors connected with the real factory components can provide detailed information about the performance of various processes, ensuring a better visibility and control of the used resources and a more reliable forecasting. Moreover, a proper integration of the data coming from telemetry and from enterprise systems such as MES or ERP could help operations managers to analyze the dynamics of the manufacturing processes and seek to identify potential improvement actions (e.g. reconfigurations of the input parameters, changes in the management of maintenance activities, etc.). In this way it is also possible to identify and address any bottleneck and ensure a smart utilization of expensive machineries which allows to maximize the throughput. Finally, the analysis of the gathered data enables also the check if the product "as built" is compliant with the specifications and requirements of the designers, helping the company to adjust and optimize processes between design and production stages. Specifically by merging the designer specifications about how the product is to be manufactured and the information about how the product is actually being manufactured, it is possible to build an instantaneous perspective on how the manufactured product is meeting its design specification goals.

2.2. Feedback from virtual to real to apply corrective decisions

The F1 two-way telemetry is a bidirectional data flow that allows engineers to make real time adjustments remotely on the car even while the latter is running on the track. In this way it is possible to align the setup of the car with the needs of the driver also taking into account external conditions. From the 2003 season, the two-way telemetry has been banned from the FIA (Fédération Internationale de l'Automobile), with the exception of the system for the activation the DRS (Drag Reduction System), which allows the driver to adjust the rear wing in order to reduce drag and increase top speed. In fact, this system is automatically enabled only in certain circumstances on the basis of the data coming from the cars telemetry [11].

Similarly, within the factory, a two-way telemetry would allow project managers and designers to accurately monitor manufacturing processes progress in real time, enabling them at the same time to detect problems early (e.g. breakdowns) and apply corrective decisions based on the information they receive and analyze. Once these decisions are final, they would be applied to the real factory, thus implementing the closed loop between the virtual and real factory [2].

2.3. Integration with Advanced Simulation and Forecasting

Telemetry not only allows F1 teams to collect and monitor information in real time but also to use them in order to properly simulate the car for maximizing its performance. These simulation models have become so advanced that potential lap time of the car can be calculated, and this time is what the driver is expected to meet. Moreover, between a race and another, the F1 teams compute a series of analysis through which they are able to build predictive models of how the car will perform with different setups, different tracks under changing ambient conditions, on the basis of the collected historical data [12].

If a telemetry-based simulation is used on the factory floor next to the machineries that it models, it could give operators a digital representation that looks and acts exactly like the machine itself. In this way it can offer the capability to execute the operations through a simulation environment where the various product components can be inserted and tested in different configurations across the entire production chain. Under these conditions, operators can optimize and validate new processes into state-of-the-art machine, without taking the latter out of production. In order to realize this approach, the data telemetry should be fully integrated with discrete or continuous simulators, which allow to model the complex dynamics of a manufacturing system. The latter can refer to the processes of a single cell, a production line, an entire factory, or several companies interconnected with the warehouses through a network. Another key success factor of the approach is the capability to initialize the simulation models through a snapshot of the real system [5].

2.4. Digital continuity between telemetry historical data

The simulation-based analysis of the F1 car performance mentioned in the previous subsection can be effectively exploited only if the digital continuity between telemetry historical data is guaranteed. Indeed, it must be ensured that data can be playbacked and passed as input to the simulation tools in order to perform forecasts against which to compare the behavior of actual running real-time systems. Digital continuity is also important from a reliability point of view, since statistics based on historical data make sure that installed components not exceed their recommended lifetime ranges [12]. Finally, digital continuity plays an essential role in case of an accident, since FIA can determine driver errors as a possible cause on the basis of the driver inputs that have been recorded.

Similarly, digital continuity between historical data of factory telemetry allows to create numerous simulated data streams that are semantically interoperable with real operational data. Such data emulation offers a real-world environment to train personnel, where for example control room operators can directly interact with the system and receive real feedback [13]. Specific analytics have to be performed on the gathered information to extract better insight over the progress and status of each single machine. These analytics can provide comparison between machine performance. Moreover, historical information can be measured to predict the future behavior of the allocated machineries.

In order to guarantee the digital continuity between historical data, Terkaj et al. [14] proposed to use an history model of factory objects. In this way, historical data can be collected and stored in a distributed way, while keeping an overall coherence thanks to a common virtual factory model.

2.5. In situ simulations

The seamless integration of simulation tools and the real environment of the factory paves the way to *in situ simulation* approaches, which takes place in the working environment and involving those who work there. The in situ simulation is distinct from *center-based simulation*, which is performed in a context separated from the work environment [14].

A similar philosophy can be found in F1 behind the driving simulator, which is a car cockpit that gives drivers true feel of a real environment and direct feedback on their actions. The driving simulator replicates real race track conditions and is used to test different aspects that affect performance of the car such as wings and brake settings. The high fidelity of the simulator allows the driver to feel the difference that modifications applied to the car setup can produce without the high acceleration of a real test drive. As the new FIA regulations limits the number of test days on the track and also wind tunnel time to reduce costs and level the playing field, the driving simulator plays a key role for drivers training, saving at the same time both time and money while respecting new regulations. Moreover, the driving simulator can be used to test future car designs and train new drivers on different circuits.

3. Factory Dynamic Simulator: A dedicated software for telemetry analysis

A typical infrastructure supporting the telemetry data flow from the real to the virtual factory should include three main components (Fig. 3). The first is an embedded controller unit enabling sensor data collection and logging and corresponds to the first level of the 5C Architecture for CPS introduced by Lee at al. in [15]. The second component is the communication module, which commutates dynamic data read from real components into a real-time transmission stream. The third component is a software application that receives, interprets, persists, integrates, and analyzes the collected data. This section focuses in particular on the requirements elicitation of the third component. During this activity, a valid starting point can be the evaluation of existing F1 telemetry systems, such as Atlas [16], which is the standard system, or Wintax [17].

The following list highlights the major features that a software application supporting factory telemetry should provide: capability to maintain the links between factory configurations/layouts and telemetry data; simulation of the effects of different input parameter values on a given factory process; and direct comparison of simulated results with real telemetry data or with other simulations.

Data visualization is an essential task of the envisioned software tool. XY Charts, waveform and scattered plotting, statistics and animations permit to show under different views the data telemetry acquired from the sensors which are connected to the real factory. In this way, it is possible to study accurately a particular aspect of the factory. Among the most significant graphical features, the new environment should include functionalities to filter and select a part of the collected data stream in order to provide it as input of a new simulation. Using a multiscale model as reference, the envisioned software application should also comprise capabilities to zoom in and zoom out the selected data in order to drill down into specific data subsets. Moreover, the Graphical User Interface should also provide facilities to change the *factory setup* which comprises the different input parameter values for the proper configuration of the factory processes; the setup can be stored to a database in order to be used as input for a following simulation. Each new created setup should be compliant with the previous already saved setups, allowing in this way to guarantee their Digital Continuity, as discussed in the previous section.

A typical issue of the data coming from sensors is the noise errors. As it is better to have a smooth curve to analyze the factory performance, removing high frequency noise and spike is a necessary feature for the envisioned software application. In this regard it is essential to use various techniques of high frequency noise removal such filtering and smoothing [18]. Also, the end-users should have the possibility to introduce a sensor offset/gain or implement a sensor correction. Combining the digital versions of telemetry signals and a lot of math/logical/filter/statistical functions, also through the integration with external commercial tools such as Excel, Matlab and Simulink, it is possible to create the so-called *virtual channels*, which represent a method to abstract and remap the original telemetry channels (for example to create alarms). A proper API (Application Programming Interface) should guarantee the access to telemetry data, enabling data analysis in external tools (e.g. Matlab). Finally, a *Multicast* transmission of the data over the factory network would allow the software application to receive the telemetry regardless of the PC where the software application runs, as long as it is connected to the network and enabled.

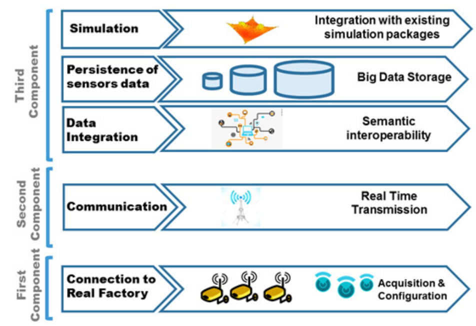

Fig. 3. The components of a typical infrastructure supporting telemetry

4. Conclusions

This paper has highlighted various analogies between the worlds of F1 racing cars and modern factories. On the basis of these analogies, the paper has analyzed the benefits of the technology transfer of the telemetry, proven in F1, to the manufacturing field. In particular, it is shown that the exploitation of the factory telemetry could offer various methods to perform valuable simulations of the production processes, using as input the data coming from the real factory. Moreover, the requirements of a software application supporting the factory telemetry have been elicited. Further developments of this study will address the difficulty in integrating the telemetry with existing simulation packages, the semantic interoperability of the data coming from heterogeneous sensors, and the need for more efficient and scalable databases for Big Data storage [19].

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