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Self-Learning Production Systems: A New Production Paradigm

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Abstract Self-Learning Production System (SLPS) is a fundamental paradigm introduced to ensure industrial systems evolvability along time. Evolvability is considered as the capability of a system to change its behaviour, i.e. its internal status and/or parameters, according to different production contexts. The SLPS approach is intended to confer evolvable capabilities to a manufacturing production system by enhancing its monitoring and control solutions with context-awareness and data mining techniques. The key assumption is that the deep use of context-awareness and data mining techniques to extract, analyse, and process relevant data generated during production activities will ensure system adaptation.
Current work is an effort to systematize the technical and theoretical developments in the context of SLPS in order to provide the baseline upon which SLPS solutions can be built.

1. Introduction

Globalization has changed significantly the way manufacturing companies operate and compete: one of fierce competition, shorter response time-to-market opportunities and competitor's actions, increased product variations and rapid changes in product demand are only some challenges faced by manufacturing companies of today. These challenges are influencing the way production systems are designed and deployed. To capitalize on the key markets opportunities and winning the competition for markets share, the manufacturing companies are engaged in an innovation race to implement exclusive, efficient and sustainable production systems able to produce innovative and appellative customized products as quickly as possible with reduced costs while preserving quality.
Manufacturing can be defined as the application of mechanical, physical, and chemical processes to convert the geometry, properties, and/or appearance of a given starting material to make finished parts or products [1]. The ability to produce this conversion efficiently and effectively determines the success of the company. Therefore, production companies need to optimize their computer controlled process parameters for each different production context. For such optimization task, it is imperative to take into account not only production control and execution processes but also related secondary processes in a fully integrated approach. Secondary processes, such as maintenance activities, energy saving, and lifecycle system optimization, have always been very important for industrial production

systems. Nevertheless they are typically detached from the core monitoring and control system, implying poor machine tools performance, higher lifecycle production costs and increasing environmental impacts during manufacturing production system operation. As stated in [2], an integrated and holistic approach merging the main manufacturing production processes (both primary and secondary processes) in a single general vision will enhance the efficiency and effectiveness of production activities. The main consequence of this trend is that traditional monitoring and control solutions must become more versatile, flexible, robust, customizable, configurable, and self-optimizing by adapting to operational changes in contexts, environments or system characteristics [3].
In the scope of this paper, the SLPS paradigm is presented as a reasonable way to address a fully integrated view of a production system and improve control and monitoring system capabilities in terms of reconfiguration, monitoring of equipment performance degradation, and sustainability. Novel technologies such as context awareness and data mining techniques are considered as the foundation for the new generation of manufacturing production systems that will be capable to self-adapt and learn from continuously changing environment.

2. Agility Requirement for Modern Manufacturing Systems

The social, economic and technological aspects always imposed a set of requirements on manufacturing companies influencing the way their manufacturing processes were organized. From one side, any change in society as well as in markets and economy conditions trigger new and more challenging requirements for manufacturing industry. From the other side, the fulfilment of the new requirements strictly depends on the technology available. As stated in [2], globalization has activated a new industrial revolution enabled and supported by the advent of new technologies. Demands for high quality and highly customized products at low cost, oblige companies to cope with a minimum possible time-to-market in order ensure a clear advantage over major competitors preferably without escalating expenses. As exposed in [4], this is forcing major companies to push their production sites to underdeveloped zones where cheap and untrained manpower is available, and where it is possible to escape from strict labour conditions policies. However, this solution only focuses on retrieving profit by cutting personnel wages and labour conditions – traditional shop floor reality remains barely untouched and do not provide really new solutions to avoid or reduce the production offshoring trend. Nevertheless, modern manufacturing companies are becoming aware of their role and impact on future generations and thus future market evolution, meaning that these are pushing for a paradigm shift from the classical cost-oriented to the High-Adding Value (HAV) [2]. Manufacturing companies are striving to adopt and implement flexible and adaptive approaches, in order to better meet market needs whilst maintaining the low cost base of heavily automated mass production techniques [5]. In this scenario, the key to competitiveness is the reduction of the production costs during production system lifecycle, and most important, the capability to have systems that are able to quickly respond to markets variations and demands for new, innovative and highly customizable products.

Agility is a fundamental requirement for modern industrial automation companies to improve sustainability and face challenges triggered by globalization. The concept of agility covers different areas of manufacturing, from management to the shop-floor. An agile manufacturing enterprise should be capable to detect the rapidly changing needs of the marketplace and propagate these needs to the lower levels of the enterprise in order to shift quickly among products and models or between product [6]. Therefore, it is a top down enterprise wide effort that supports time-to-market attributes of competitiveness [7]. Thus, to be agile a manufacturing company needs to integrate product and process design, engineering and manufacturing with marketing and sale in a holistic perspective. In this context, ICT represents the cornerstone for achieving agility. The concept of agility has been widely debated in the literature [8]–[12], and several definitions have been created. Inside this range of definitions, one can identify a common stream where agility is considered as the capability to compete and prosper within a state of dynamic and/or continuous change. This involves two main aspects, as stated in [13], namely:

1. **Responding effectively to changes**;
2. **Exploiting changes by taking advantage of changes** as an opportuny.

Although the notion of agility as a competitive concept has been around for some time, it remains more a concept then a reality. The problem is rooted in the fact that there is a lack of theory and the question of how implement agility in manufacturing company has not been yet properly answered [13]. Furthermore, there is a great confusion about the relation between flexibility and agility [14]. Some researchers consider them synonyms or almost synonyms [8], [15], [16]. Others specify a dependency relation between them. Evgeniou [17], considers flexibility as a necessary condition for adaptation and in turn agility. Dove [18], differentiates flexibility from agility by stating that the former refers to the ability to respond to expected changes while the latter concerns unforeseen changes as well.

In the context of this paper, the term agile is adopted and considered as the ability to sense environmental changes, extract all the necessary information from the "sensed" changes, start a reasoning process to adapt the manufacturing process parameters according to the extracted information and finally learn from human expert input. Therefore, agility is not a simple response and/or reactive process triggered by environmental changes but incorporates, above all, the ability to proactively cause changes in process to better respond to actual contextual conditions implying self-organization and self-learning features.

3. Self-Learning Approach

3.1. Background

Today trend towards services to support the product lifecycle and the need for customized product impose a paradigm change in manufacturing production processes from a very static approach to new one that integrates the concept of evolution and, thus, adaptation over time.
Manufacturing production processes are typically characterized by heavy and bulky equipment meaning that to explore a self-adaptive behaviour the emphasis is given to the software [3]. Therefore, control and monitoring solutions at shop-floor level represent the main degree of freedom to ensure adaptability still guaranteeing reliability and availability of manufacturing production systems. Nevertheless, traditionally manufacturing companies have their own industrial standards for designing and developing control and monitoring solutions (e.g. automotive industry). The presence of such standards, has two fundamental implications as exposed in [19]. From one side, standards contribute to reduce the flexibility of the programmer while discouraging any technique/technology other than the defined in the standard. From the other side, the rigid and strong software structure opens the doors to the development of adds-on solutions capable to work in harmony with the existent control and supervision systems while optimizing their activities.
The SLPS is a new concept in production philosophy where cybernetics principles are applied to manufacturing environment to derive more intelligent systems. It is aimed to provide a generic and easy-to-integrate architecture/solution for improving current control and monitoring solutions by exploiting self-adapting and self-learning capabilities. Therefore, it extends the concept of Self-Adapting production systems. The key assumption is that a deeper use of context awareness and integrated data mining techniques will allow (on-line) identification of current dynamically changing context in which the manufacturing production system operates and adaptation of process parameters according to the detected changes in context (see Figure 1).

3.2. The Self-Learning Approach in Detail

In the same way of traditional feedback loop [20], the self-learning approach relies on four main pillar activities, namely:

1. **Sense:** the current state of the production line is analysed.
2. **Extract:** the current state of the production line is extracted.
3. **Reason:** reasoning mechanisms are applied on the information extracted in order to identify if any change in selected parameters is needed.
4. **Adapt/Learn:** the result of the reason activity is a new parameterization for the system; this parameterization should be sent to the system for

adapting its behaviour. Moreover if the result of the reason activity is not correct then input from the user expert of the production system is considered to allow the SLPS to learn how to act in this specific case.

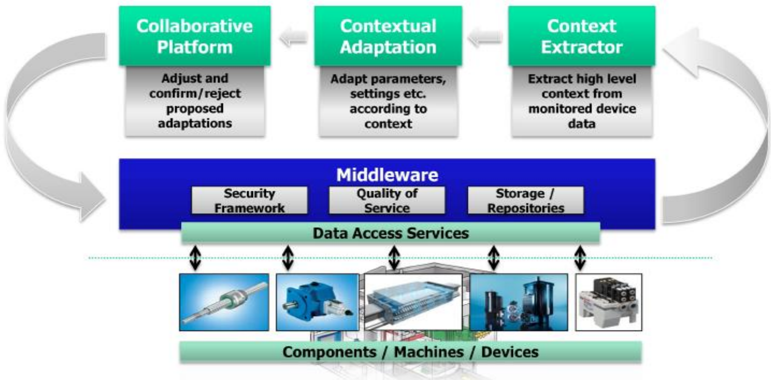

Figure 1 – Self-Learning Production Systems approach overview

Therefore, a SLPS will be able to "sense" the current state of the manufacturing production system in which it is embedded (also called context), "extract" all the necessary context information from the environment, "reason" on it inferring conclusions about the best fit parameterization for the current context and, finally, "adapt" the manufacturing production system according to it or "learn" from human expert decision if some parameters have to be changed. Taking into account these four pillars, the SLPS approach relies on two main generic components: the Extractor and the Adapter. The Extractor is the component that is responsible for identifying any change inside the production environment. The changes in the environment are detected by continuously extracting information from different sources (i.e. external systems, sensors, etc.). Whenever a change is identified then the information about the production line is extracted and sent to the Adapter for further analysis. Therefore in a SLPS, the Extractor acts as an observer of the production process during its operation. On the other hand, the Adapter is responsible for updating the system behavior (locally and/or globally) in response to a change in the environment detected by the Extractor. The system behavior update (i.e. Adaptation) takes into account two main source of information, namely:

1. The **current state of the production system**.
2. The entire **history of the production system** recorded during the SLPS lifecycle. The historical data are constituted by all the changes in the environment detected by the Extractor together with all the adaptations performed by the Adapter.

The SLPS approach is intended to provide evolvable capability to the production system in which it is inserted. To do that, two closed-loops feedback are considered (see Figure 2).

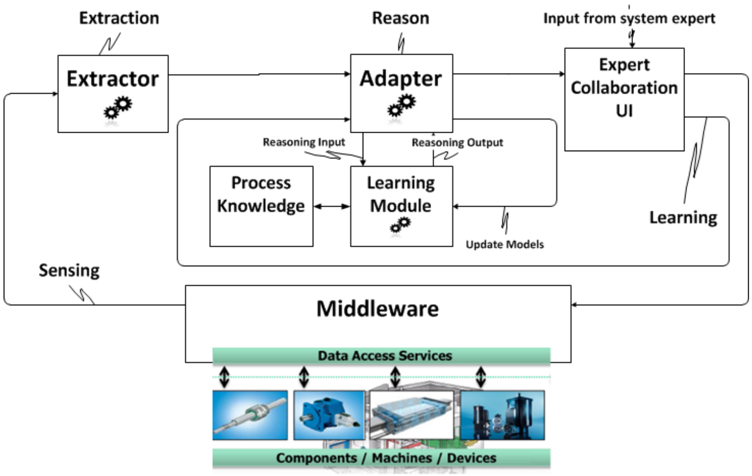

Figure 2 – Self-Learning production Systems elements and control loop

The first one deals with the adaptation of the system behaviour performed by the Adapter whenever it is triggered by the Extractor with relevant information from the environment. The second deals with the learning of new knowledge taking into account the system expert feedback. Therefore, this closed-loop feedback is responsible for enabling the embodiment of the system expert knowledge/expertise inside the system. This knowledge/expertise is translated into rules that are used to make prediction. Moreover, the feedback from the system expert is stored in order to be considered for future adaptations meaning that the past history of the system is always used when adapting the system behaviour. Finally, the second closed-loop feedback can be cut off when the system has the capability to fully reproduce the system expert knowledge.

4. Requirements to realize Self-Learning Production Systems applications

In order to develop SLPS applications, it is necessary to cope with the following list of requirements:

Functionality: the SLPS solution should support the interaction with existing manufacturing process equipment in such a way as to make possible the collection of all the necessary data to frame the actual operational context of manufacturing process. Hence, the collected data should be used to adapt manufacturing process machine parameters. To enhance the adaptation of manufacturing process parameters the solution should be capable to consider both the actual and past operational contexts. The development of explicit representative model of the manufacturing process from empirical apparently unstructured data is peremptory.

Usability: the SLPS solution should be easy to understand with limited training effort and supported by a comprehensive help system for allowing any user (especially those without any computer expertise) to be able to use the system in a

satisfactory manner. All the displayed information should take into account the expertise of the operator and the current application context.
Security: the SLPS solution should limits the access rights to particular functionality while guarantying the privacy of the information and the protection of data during transmission.
Reliability: the SLPS solution should enable continuous operation and, in case of failure, should resume its normal operating cycle.
Efficiency: the SLPS solution should be a totally non-intrusive system, designed to improve legacy monitoring and control solutions without affecting their normal execution and to respond in an appropriate time frame.
Maintainability: the SLPS solution should be designed and implemented following a modular and distributed approach enabling easy extension and minimum impact if changes in one module have to be implemented, as well as distribution of its parts on different machine/environment. Furthermore, failures during system operation should be detected with minimum effort.
Portability: the SLPS solution should be generic enough to be easily portable between different environment while continuing to work as expected and, above all, ensuring minimal reprogramming needs.
The Figure 3 resumes all the generic requirements that the SLPS solution has to attain.

5. Towards a Research Agenda

Nowadays the globalization, the emergent technologies and the requirements for system flexibility, cost reduction, performance improvements, and customized products imposes a paradigm change in manufacturing production processes from a very static approach to new one that integrates the concept of evolution over time. There is an increasing pressure to have more intelligent layers on the top of the current monitoring and control solutions and are capable to work in harmony with them while optimizing their activities. In this scenario, the SLPS approach is intended to have an impact on manufacturing industries and solve open questions concerning:

- R**eduction of time, efforts and errors** during the activity of determining optimal process parameter setting.
- **High degree of flexibility** in the development and installation of production monitoring and supervision systems.
- **Reduction of down times** during product exchange and/or conflicts situations.
- **Increasing of Overall Equipment Effectiveness** (OEE), i.e. plant availability and its productivity over time.

According to these goals it is possible to summarize the research directions that are considered essential to support the SLPS paradigm as follows: Service

Oriented Architecture (SOA), Context Awareness, Data Mining, and Support Decision System/Expert System.

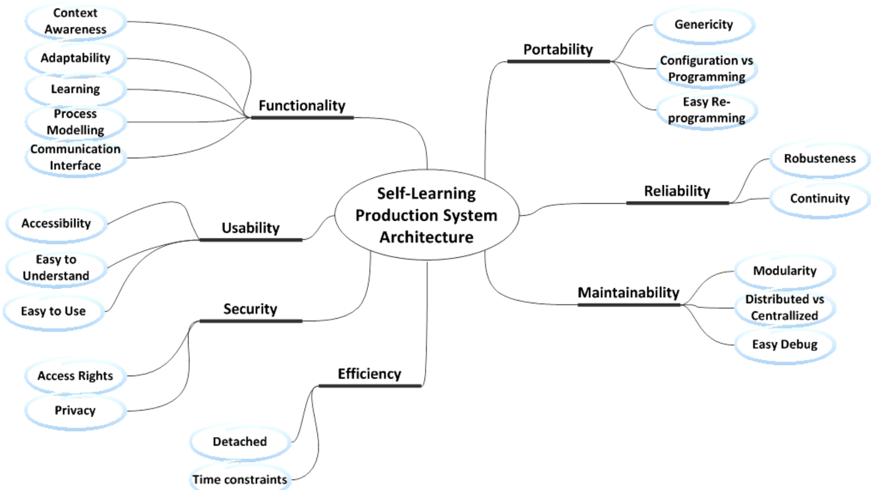

Figure 3 – imposed Requirements for SLPS applications design

5.1. Service Oriented Architecture (SOA)

SOA paradigm has emerged and rapidly grown as a standard solution for publishing and accessing information in an increasingly Internet-ubiquitous world. SOA defines an architectural model aiming to enhance efficiency, interoperability, agility and productivity of an enterprise by positioning services as the building blocks through which solution logic is represented in support of realization of strategic goals [21]. The existence of Web Services technology has enabled and stimulated the implementation and development of SOAs. The application of SOA and Web Services in the context of manufacturing layer is still scarce, since a set of persisting technical challenges exists as pointed in [22]. SOA and Web Service are considered promising techniques for enabling the easy integration of a new system with existing standard-based monitoring and control solutions.

5.2. Context Awareness

Context awareness is widely applied in modern Information and Communication Technology (ICT) solutions for developing pervasive computing applications that are characterized by flexibility, adaptability and capable of acting autonomously [23]. As exposed in [24], a system is context-awareness if it can extract, interpret and use context information to adapt its functionalities and behaviour to the current context. Although, many present-day applications need to be context-aware, the context-dependent behaviour is generally obtained by programming ad hoc solutions, due to the lack of support in modern programming languages as argued in [25].

5.3. Data Mining

The process of extracting/discovering knowledge from large quantities of data is also known as data mining [26], [27]. The discovered knowledge can be used for classification tasks, modeling tasks, and to make prediction about future evolution of the analyzed variables. The application of data mining techniques is quiet old. However, there are areas where these techniques are not exhaustively explored such as manufacturing shop floor monitoring and control. Most of the data mining applications for industry are typically stand-alone, one-of-a-kind and not fully integrated applications inside manufacturing-based enterprise reference architectures. Therefore, the development of a standard methodology for industrial applications of data mining is necessary for allowing reliability and repeatability of data mining processes.

5.4. Support Decision System/Expert System

Expert Systems (ESs) are a branch of applied Artificial Intelligence (AI). As focused in [28], the basic idea behind the ES approach is to gather the vast body of task specific knowledge of a human expert and transfer it from a human to a computer system. The ES theory represents a fundamental background and starting point for the development of the Self-Learning solutions since some basic concepts are shared such as support to human expert decision making process as well as evolution along time thanks to new knowledge introduced into the system by expert user.

5.5. Self-Learning Production System: a point of confluence

Mass customization has led researches and practitioners to design and implement distinct approaches for manufacturing processes. Some of them are focused on improving responsiveness, reconfigurability and lead time; while others are focused on improving the final product quality, optimizing the production activities, and integrating secondary processes in the main control. The SLPS paradigm falls in this second category. It is intended to deliver additional productivity gains to a manufacturing process by extending the reach of the automation system beyond the world of process control without affecting traditional control approaches. The SLPS concept proposes the application of data mining and context awareness techniques to allow computer based control systems to change their own behavior based on the lifecycle information or, more broadly, on the knowledge and patterns extracted from all the available data. To enable system awareness, ontologies are used as a means to build reliable and easy-to-share description of the particular manufacturing environment. This generic description is the foundation for the adaptation of process parameters. With the domain knowledge settled the next step is using the environment information for adapting system behaviour. Under the framework of SLPS, integrated data mining techniques, relying on supervised machine learning techniques, are used to extract knowledge (i.e. infer conclusion about the state of the manufacturing production system) from the process data encapsulated into the ontological description. The result of the data mining process is then presented to a system expert that is responsible for its evaluation. The result of the evaluation process is used to learn with system expert decisions. Preliminary implementations of the SLPS approach can be found in [29]–[31], where the SLPS principles were applied in three distinct manufacturing production environments. In these proofs of concept ontologies are used to describe the environment and supervised machine learning techniques are used as the foundation for system adaptation. Further, since the SLPS aims to provide an additional software layer to enhance the capabilities of already existent knowledge based systems and automation solution for manufacturing production systems then the adoption of SOA as communication infrastructure can ensure interoperability between the new layer and the legacy ones while improving the entire enterprise visibility. Finally, the Table 1 presents the result of a SWOT analysis performed with the purpose to identify internal and external factors related within the main research directions that are relevant for the SLPS paradigm.

SLPS enabling technologies	Strengths	Weakness	Opportunities	Threats
SOA	• Vertical/Horizontal IT Integration • Loosely coupled systems • Maturity	• Performances • Security issues • Lack of standardization	• Need for Reconfiguration and Self-Optimization • R&D programs addressing SOA	• Adoption in a real industrial environment • New "way of thinking"
Context-Awareness	• Formal description of a domain • Abstraction	• Complexity • Specific vs Generic • Lack of standardization • Maintainability	• Need for Reconfiguration and Self-Optimization • R&D programs addressing SOA	• Adoption in a real industrial environment • Domain Modelling
Data Mining	• Knowledge extraction from apparently unstructured data • Algorithms • Predict future	• Lack of standardization • Time consuming • Dependency on the quality of data and context of application	• Huge amount of data acquired during production activities and not used at all	• Optimized for data post processing • Quality of the Model • Selected Machine Learning Algorithm
Support Decision Systems	• Efficiency and Effectiveness of decision making process • Common problem understanding	• Not designed to filter bad decision • Benefits depend on the "right" or "wrong" queries	• High production system complexity • Need for responsiveness	• Information overload • Possible skill reduction in staff • Software vs human decision

Table 1 - SWOT analysis of SLPS supporting concepts

6. Conclusions

The paper is an effort to systematize the research development in the context of SLPS in order to underline the challenges and benefits of the application of such paradigm. In particular, challenges are both technical and theoretical. The main technical challenges are the ontological description of the environment, the efficient and effective online knowledge extraction from data, the data filtering when different system experts are using the system, and the communication constraints. The main theoretical challenges can be resumed in the exploitation of new concepts and techniques (e.g. bio-inspired concepts) to enable system learning and adaptation. Therefore current paper is not a point of arrival but on the contrary it should be considered as the baseline for new research and development to the paradigm reach the maturation for consistent implementation advancing further than the prototype phase.

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