Reliable Self-Learning Production Systems Based on Context Aware Services

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Abstract—The paper presents the key results of the EU-project Self-Learning. The strategic objective of Self-Learning is to strengthen EU leadership in production technologies in the global marketplace by developing innovative self-learning solutions to enable tight integration of control & so called secondary processes (e.g. maintenance, energy efficiency) of production systems. The project developed highly reliable and secure service-based self-learning solutions aiming at that integration. Approaches based on SOA principles, using distributed networked embedded services in device space, are the most appropriate for implementation of such self-learning solutions. Context awareness, providing information about the processes & equipment and circumstances under which the services operate and allowing them to react accordingly, is a promising holistic approach to assure needed self-learning adaptation to changes in processes and equipment states. The key components of a self-learning solution include a Context Extractor module to allow for dynamic context extraction, processing and storage, an Adapter module to allow for a holistic process control of considered systems and a self-learning module to allow for self-learning. Three industrial application scenarios drive the project.

Keywords: Self-Adaptive, Context Awareness, Ontology, SOA, self-learning, Context Extraction

I. INTRODUCTION

The strategic objective of the EU-project Self-Learning is to strengthen EU leadership in production technologies in the global marketplace by developing innovative self-learning solutions to enable a tight integration of control & secondary processes of production systems and by this improve operation of such systems under changing conditions. In more detail, the objective is to develop highly reliable and secure service-based self-learning production systems aiming at merging the world of secondary processes (e.g. maintenance, energy efficiency) with the world of control, i.e. aiming at holistic process control. Secondary (support) Processes are business processes that produce products or support primary processes that are invisible to the external customer but essential to the effective management of the business [1]. The key assumption of the project is that a context awareness approach will allow for the adaptation and integration of control and secondary processes of production systems. As described in [2], the challenge is to define an adapter able to handle a wide scope of ‘disturbances’/changes coming from either enterprise level, or process and equipment parameters changes, requiring harmonized adaptations of both control and “secondary” activities. The proposed approach is to identify (on-line) current dynamically changing context in which the production system operates and to ‘use’ this identified context to adapt both control and secondary processes. Therefore, the proposed approach includes a self-learning context extractor (as a generalized ‘observer’ providing current context) and an adapter (as ‘active’ part).

The project is driven by three industrial application scenarios, addressing different aspects of holistic control of complex automation systems / manufacturing lines, in order to assure industrial relevance for the development of self-learning production systems.

The project addresses the key S/T problems is to allow for self-adaptation of production systems, integrating control & maintenance of production plants.

- self-adaptation ability of production systems, based on self-learning algorithms, in response to changes of context for both control and maintenance activities,
- organizational problems related to holistic process control activities,
- context awareness as a prerequisite for such dynamic self-adaptation
- SOA infrastructure including a security & trust framework for embedded services in manufacturing industry.

The targeted self-learning solutions are likely to have a high impact on manufacturing industries in terms of reduction of time and efforts needed for development/installation of control systems of production systems. Furthermore, these solutions aim at reduction of down times during product exchange and conflict situations, reduction of maintenance time and increase of Overall Equipment Effectiveness (OEE).

II. SURVEY OF THE STATE OF THE ART

The modern production systems exist in uncertainty-change is expected, but the future is unknown [3]. The desire for ‘robustness’ stems from the fact that change is inevitable, both

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in reality and perception [4]. Different approaches were developed both in industrial practice and theory to cope with such inevitable changes. Evolvable Production Systems are complex and lively composed of intelligent modules that interact, through bio-inspired mechanisms, to assure high system availability and seamless reconfigurations [5]. Contrary to the changeable system approach, aiming to design the systems robust to various unknown changes [3], self-learning production systems aim to learn in real time how to adapt to changes. The research has demonstrated that the application of machine learning techniques, dynamic self-adaptation and operator’s feedback in the loop promises to increase the intelligence of the overall system in such a manner that its ability to deliver value under changeable conditions is improved [6], [7] and [8]. In production systems in particular, these methods have been proven to be especially useful for monitoring/diagnosis [9], [10], [11] and control [12]. However, the applications of self-adaptation of production systems and learning in industrial practice are still in initial phase [2].

The approach presented in this paper to assure robustness and effectiveness of the production systems by integrating control & secondary processes, is based on self-learning context awareness, where the system is learning, from adaptation and operator’s action, both to identify changed context under which the production is carried out and to adapt to these contextual changes at run time.

While the concept of context awareness is widely applied in modern ICT solutions its application in self-learning production systems is not well investigated. The approach in this paper was to re-use the experience on context awareness from other domains and adapt them to the specifics of self-learning product systems. Following this approach, different methods to context modelling were studied, where ontology based context modelling is mostly investigated. Based on the formal description of context information, context can be processed with contextual reasoning mechanisms. Since contextual information has some inherent features (it can be considered incomplete, temporal, and interrelated) context reasoning can exploit reasoning mechanisms to deduce high level, inferred context from low-level raw contextual information. Furthermore, contextual reasoning can be used to verify and possibly solve inconsistent context knowledge due to imperfect input [13], [14], [15].

As already indicated in [2], of high interest for the work presented in this paper is Service Oriented Architecture (SOA) in manufacturing i.e. the relation between self-learning production systems and SOA [16]. OPC Unified Architecture is the recent OLE (Object Linking and Embedding) for process control (OPC) specification from the OPC Foundation and differs significantly from its predecessors. Scalable SOA holds promise for seamless integration, interoperability and flexibility in manufacturing environment. However, there is a lack of adoption of overall SOA based self-adaptive production systems in discrete manufacturing environment. Application of context awareness for SOA based self-learning production systems has not yet been sufficiently investigated. The approach proposed in this paper applies the ontology-based context modelling, and reuse of experience of other projects [17] for context extraction in highly flexible and dynamic self-learning production systems [18].

III. SCIENTIFIC AND TECHNICAL RESULTS

A. ICT Concept

The Self-Learning ICT environment is presented in Fig. 1. As the figure indicates, the Self-Learning environment consists of conceptually several different layers, mainly focussed around the Core Services. The Self-Learning project addresses a generic solution for context-based self-adaptation of production systems. Project results derive required features and functionality for the overall Self-Learning architecture to meet industry specific needs, driving the applications of common project results to the wider scope of discrete manufacturing industries.

Context awareness allows for dynamic self-adaptations and learning in production systems. The system adapts to run time critical contextual changes and learns from it. Learning is also enhanced by operator’s feedback and experiences.

The architecture is designed following SOA principles as an add-on to the standard control following the conceptual approach as presented in Fig. 1.

The components of the proposed system include:

<table>
<thead>
<tr>
<th>Component / Service</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Context Extractor</td>
<td>Use all monitored “raw data” provided via the data access layer to derive the machine’s current contextual situation. Using the ontology/context model the monitored data is evaluated and the context extracted. Based on the identified context, situations can be compared to previous ones and stored.</td>
</tr>
</tbody>
</table>

Context model / ontology

The context modelling is following the ontology approach. The purpose of the Self-Learning ontology is to define a fundamental data model for context extraction. Basically, the Self-Learning ontology defines two ontologies: Generic Device Context Model and sector-specific context ontology.
## Adapter

Adapter is the set of services responsible for updating system behaviour in response to a change of context in the environment. Informed by the Context Extractor about a variation on the system (change of context) and adapt the system to handle the new reality. The Adapter is guided by a set of rules that describe how to system should behave in each particular context. These rules can be updated through learning based on lifecycle history data, context and user validation.

## Learning Services

Self-Learning (both for Extractor and Adapter) relying on data mining and operator’s feedback to up-date execution of adaptation and context extraction at run time. See following sections for more details on Learning Services.

## Service Infrastructure

Underpinning framework ensuring information is securely gathered from trusted context data sources and that the control updates are securely communicated to control systems with appropriate levels of authentication. The communication authentication components ensure seamless and secure connectivity with existing manufacturing and information systems communication protocols and security mechanisms. The service infrastructure is based on the Security Framework concept which assures safe Information Flow, Data Isolation, Damage Limitation. The Secure Multi Domain Monitor may have additional use beyond supporting the Self-Learning solution. The portioning approach to secure data monitoring may also be an important concept for achieving greater integration of control systems and enterprise systems for manufacturing organisations.

## Expert Collaboration Platform

The identified solutions are required to be validated by user, where the user can manually/automatically accepts/rejects any new solution. The user validation UI sends the feedback to the adapter and learning module.

## Evaluator

Performance of adaptation and context extraction are measured by the evaluator either manually via operator’s feedback or automatically via mapping against objective functions at run time. Evaluation results are sent to the Learning module.

## Data access layer

These services are responsible for the bidirectional processing of information and perform e.g. preprocessing of monitored raw data acquired via the data access layer, before the context is identified. Main functionality is to transform the raw data in a format, which serves as basis for context identification. The Model Repository contains ontology based plant specific models for equipment, production processes and products. The models are shared by different software components at run time. The Context Repository allows up-date and storage of extracted/processed contextual information for later retrieval. Information flow among the modules is event driven in some cases and time based in other cases.

## Middleware

Information from ERP level, devices or plant data servers are brought to data access layer directly or via middleware depending on plant specific equipment and communication protocols.

The Self-Learning system has been implemented as a generic system thanks to an SOA approach and to the context model, making it easy to adapt it for different organisations and contexts. For this, different knowledge base could be produced to adapt the system usability in specific context. Specific tools can be connected to the Self-Learning services to respond to the specific organisations’ needs. The Self-Learning solutions can be deployed in different contexts. In the scope of the project, it was deployed to three different solutions.

### B. Self-Learning Services

These services are used during the Adaptation process, during the Proactive behavior and during Context Extraction. When an Adaptation process is triggered, the monitoring data is retrieved and encapsulated into a structure (ReasoningInput) that in turn is sent to the Learning module to be processed. The result is again encapsulated into a structure (ReasoningOutput) – see Fig. 2. The selected algorithm is instantiated, to be used for current Adaptation process, i.e., based on the ReasoningInput structure the Learning module is able to instantiate the necessary number of algorithms to face the current application scenario. The ReasoningInput is generated using the MonitoringData coming from the ContextExtractor and contains a list of contexts representing the actual/current system status allowing the Adapter to know exactly how many algorithms to instantiate.

The two core operations learn and reason, allow the training of the algorithm using a particular model and elaborating a result. The number of necessary models used to train the instantiated learning algorithms depends on the particular business case and in the same business case several models can be used depending on the current application scenario. The number of instantiated algorithms determines the number of necessary models to use. The result of the process depends not only the actual context comprised within the ReasoningInput instance but also on the learned model, since the quality of the learned model is essential for assuring a good algorithm performance. Finally, an update of the existing learning models is performed using the last Adaptation process result. Based on these updated learning models, the context model is updated accordingly. These new models are then available for future learning tasks as well as for context extraction tasks.

The Learning Service has been implemented using RapidMiner\(^1\), which allows the employment of the necessary learning algorithms; however, their input data has to be transformed in a well-defined manner in order to enable the algorithm handling. The following learning algorithms are possible to be executed through the Learning Service: ID3 Learner, Naïve-Bayes Learner, Support Vector Machine, Neural Networks, Rule Induction and Least Mean Square. Furthermore, the Learning Service supports a straightforward integration of

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1. RapidMiner: http://rapid-i.com/
further algorithmic components to be available under the same service interface.

C. Key Results

The project is seeking to maximise the benefits to the European manufacturing industry and is making the core project technologies available as free software to enable broad industry access and exploitation. The following core technologies of the Self-Learning system will be made available as free software.

- Prototype of Self-Learning Adapter
- Prototype of Context Extractor
- Prototype of Service Infrastructure

Parts of the free products resulting from Self-Learning are extensions to existing open source products (e.g. Infrastructure) and as such will be submitted as updates or specific versions to existing open source repositories.

Submission to Standards Body: The following Self-Learning project results will be published and submitted to the appropriate standards bodies as revisions or extensions to industry standards.

- Methodology for Context Modelling and Extraction. This specification describes the methodology to select and customise context modelling, and the Self-Learning context extracting approach by providing a description of the services and algorithms for self-learning context extraction. The overall concept is presented and each of the services are described.
- Specification of Service Infrastructure. The specification addresses the underlying framework to support the deployment of self-learning adapters and context extraction processes. The document describes the design of a decentralised and verifiable security framework that is scalable and able to integrate context data sources and support adaptations of control systems while maintaining the required security protocols and integrity of the various operational domains.

Published specifications: The following Self-Learning project results will be disseminated as published specifications in order that other technology vendors and industrial technology providers are able to create components and platforms that exploit or interoperate with Self-Learning technologies.

- Methodology of Integrated Control & Maintenance
- Methodology for Context Modelling and Extraction
- Specification of Service Infrastructure

Commercial Products: The following project results will be made available as commercial products from three industrial partners within the project that provide production systems to manufacturers in Europe and around the globe.

- Self-Learning system for machine tools
- Self-Learning system for machines/automation systems
- Self-Learning system for FMS Cells

The project has developed and makes available training materials that support industrial use of the Self-Learning core technologies and supports industrial exploitation of the results.

IV. Application

The proposed concept has been developed and applied in three different scenarios. The three application scenarios belong to different industrial sectors (although all three address discrete manufacturing and machine vendors’ views). Their main characteristics are presented in the following.

<table>
<thead>
<tr>
<th>BC</th>
<th>Main Business</th>
<th>Application Scenario</th>
<th>Objectives/Technical issues addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>control, automation and drive systems</td>
<td>Control systems of machine tools</td>
<td>Improve current service platform by integration of control and secondary processes (e.g., power saving, maintenance), specifically by improved transparency of complex machines, improvement of tools and methods for the analytical optimisation of secondary processes (e.g. maintenance plan / scheduler, NC-program with “Power save commands”), self-learning idle-time recognition of machine tools</td>
</tr>
<tr>
<td>BC2</td>
<td>machines and automation systems for shoe industry</td>
<td>Control systems of machines/automation systems under development</td>
<td>Enhance machines with self-learning features by allowing machines to inspect statistically the condition of products and equipment, report and analyse proactively the gathered statistic values, enabling the machines to decide and adapt the parameters and keep them always inside the “optimized” working range. 3 challenging scenarios defined aiming to identify the unique self-learning solution</td>
</tr>
<tr>
<td>BC3</td>
<td>highly customised FMS systems</td>
<td>FMS experimental cell</td>
<td>Optimisation of usage of FMS by maximum utilization rate of production machines, minimization of the lead time of production orders. Optimisation of reactive scheduling model for self-learning scheduling and dispatching in FMS</td>
</tr>
</tbody>
</table>

Throughout these three distinct Business Cases, several users were involved in the assessment of the Self-Learning Prototype. Each Business Case covered specific test cases correlated with the companies use cases.

The results of testing from all Business Cases and assessments have been collected. These issues and possible refinements served as an additional foundation how to extend, fulfil and conclude the Self-Learning solution for the proto-type.

The users, which were using, testing and assessing the Self-Learning solution within the three business cases, were overall satisfied with the functionality provided by the solution. Overall, several conclusions can be made based on the test and assessment concerning the acceptance and usability of the Self-Learning solution within the three business cases.

- The Self-Learning prototype was well accepted by the users / operators
- The users / operators found the system having some intelligence / awareness to understand what the monitored systems and machines were doing
• Configuration of the system and the application scenarios allowed an easy installation and maintenance. It was not necessary to implement bigger changes in the existing IT infrastructure.

• The users / operators highlighted the simplicity of using and integrating the Self-Learning solution into existing system. From their point of view there is no need to drastically change their usual workflow after integrating the Self-Learning solution.

• Administrators and personnel dealing with security and privacy issues were impressed by the security infrastructure and the secure handling and transfer of data between existing solutions and the Self-Learning prototype components.

Nevertheless, there were some new requests for features and enhancements to the prototype, which could be included in another iteration of the software when it comes to commercialization:

• The graphical user interfaces should be more simplified for some application scenarios and business cases to ensure usability for all users.

• The security infrastructure is a very complex and powerful system and could be more lightweight for future applications in terms of configuration and setup.

• The overall performance of extracting and identifying context and in a next step making adaptation proposals could be increased.

A. Benefits

The project benefits are expected at various levels. In the text to follow these potential impacts are briefly analyzed.

1) S&T Impact

The project was exploring one of the most critical problems of self-learning systems: How to assure effective self-adaptations of the production systems in order to achieve holistic process control and assure reliable and secure work of self-learning production systems. The project provides solutions on how to apply self-learning approaches for holistic process control adaptation and integration and on how to extract context from services and processes and reuse it for highly reliable self-learning services to comply with the above-mentioned requirements regarding reliability and security of control & secondary processes integration. Self-Learning shows how a context can be used as a bonding element between control and secondary processes of production systems and different services/networks. Due to the wide impact and applicability in diverse application scenarios, it is envisaged that the research may have an impact on many other S/T areas, while fitting with the challenges as identified within both MANUFACTURE/LEADERSHIP and the Embedded Systems Research Roadmap, and serving as a bridge between ICT and NMP domain.

2) Benefiting communities

The communities most likely to benefit from Self-Learning results are:

- Manufacturers of industrial installations: equipment, automation and electronic devices,
- SMEs and LE users of industrial automation in different sectors (first target is automotive, aerospace and machine industry as direct customers/partners of the three industrial partners,
- ICT community (embedded SW and service providers).

The benefits and impact upon the end-user groups in three BCs are presented in the following table.

<table>
<thead>
<tr>
<th>BC</th>
<th>Innovation/Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>The self-learning system will give substantial support in mastering the optimization of production equipment with respect to such “secondary processes” and will change the capability of automation systems qualitatively because of three main reasons: Self-Learning capabilities will gain access to information about the organisation of production, which is not explicitly available on process level normally. This will reduce communication needs between manufacturing execution- (MES-) and production layer to an acceptable level, thus enabling for complex optimization of automation systems. Secondary process models will be extractable from control and drive states, thus enabling for the application of optimization rules. In fact the control will learn about the machine it’s controlling, resulting in some self-awareness of the machine. The whole concept of integrating models of machine and environment in the control is a paradigm change in automation, fundamentally increasing transparency and flexibility by adding semantics to software-objects directly linked to physical objects.</td>
</tr>
<tr>
<td>BC2</td>
<td>The worker or operator is not forced to bring highest skills to run the equipment and generate a profit for his society but more concentrating on the core processes while the production equipment is self-controlling all relevant parameters to keep the process running and manufacturing the products on the highest quality level. The self-learning modules are integrating more intelligence into the production and generating a higher benefit for the producer while less investment in the human resources are required.</td>
</tr>
<tr>
<td>BC3</td>
<td>Self-Learning technology could be used when: Improving schedule accuracy: Schedule accuracy is dependent on the accuracy of phase times of manufacturing operations; these are normally defined based on empirical data or algorithmic model. Real operation phase time data can be logged in the MES systems. When sufficient quantity of this data has been gathered, a learning algorithm could be used to feedback operation time data back to the fine scheduler. Improving the usability and flexibility of the fine schedule: Created fine schedule is based on rule that defines how candidate jobs of a workstation are prioritized. Backward scheduling rule accomplishes different kind of schedule compared to the one that has been created based on the forward scheduling rule. If the fine schedule, for a reason or another, is not feasible, then users tend to break the schedule by forwarding jobs outside the schedule or jobs that originate from a later time slot. Self-Learning technology could be used to reason whether the fine scheduling primary tenet is intact or not. Self-Learning application could then propose alternative schedules that are based on different schedule generation methods when it observes that the schedule is not advancing as it should.</td>
</tr>
</tbody>
</table>

3) Working conditions and quality of life

The project makes significant contribution to improving working conditions and quality of life. Higher quality of self-learning solutions for integrated control & maintenance will reduce stress on employees of both equipment manufacturers and users. For example, massive introduction of embedded services in manufacturing industry will allow for early provision
of required information in complex networks concerning process execution deviations, breakdown of machinery, change of transport systems or schedule changes, reduce stressing maintenance tasks under high time pressure etc.

V. CONCLUSIONS AND FUTURE WORK

The self-learning context aware production system approach presented in the paper demonstrates advantages over both classical non-adaptive and adaptive control schemes of production systems. It allows for effective integration of control and secondary processes by self-learning adaptation of various process/control parameters. In contrary to changeable production system approach and other novel approaches to cope with uncertainty and various in production system, the approach presented in this paper intends to identify in real time the changes in circumstances under which the production system is running and adapt the system to the identified changes. In classical adaptive system approach the intention is to make system adaptive to changes based on the observation of the performance of the system itself. The context aware production system approach presented in this paper uses all information available about the production system environment/conditions under which the systems is operating (e.g. ambience parameters, external demands etc.) to identify the context changes and then adapt the system. The approach is applied both in context change extraction and adaptation to the identified context.

The advantage of the prosed approach is that it can be easily applied as an add-on to the existing production system control solutions. This means that the proposed approach does not require radical reengineering of the existing (classical) production system control, as is the case in many advanced approach. One of the key reasons why many advanced production system approaches are not applied in industrial practice are too high investment costs and needs to fully replace and re-engineer the solutions. In all three business cases presented above, the new solution was integrated in the existing control systems with minimal changes in the existing classical production systems. This allows for effective application in practice.

The main further research will concentrate on quality and security of SW services which are implementing such self-learning algorithms, especially critical due to high complexity of data acquisition and real-time data analysis algorithms and tools for self-learning production systems. An effective integration of control and secondary processes requires solving both organizational and technical problems. The tight integration of control and secondary processes may lead to critical organizational problems taking into account current ‘separation’ between these activities by many equipment users.

Further research will focus on advanced algorithms for self-learning based on extracted context to (semi-)automatically update the context model. In addition the context model itself will be addressed by further research to allow better utilization of the presented model for other companies as well as for other application domains (for example PDM/PLM, PES/).

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