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SelSus

Health Monitoring and Life-Long Capability Management for SELf-SUStaining Manufacturing Systems

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1 Summary

The vision of SELSUS is to enable the European industry towards smart manufacturing systems in conventional production. The project aims at creating innovative solutions in order to improve the competitiveness for this industry sector. This goal will be reached by a new concept for fast and optimized ramp-up and operation of production lines with heterogeneous devices. By this, significant reduction of time and efforts during the setup and re-configuration of production will be reached. At the same time, production costs will be reduced by increasing the efficiency of manufacturing.

This document describes the implementation and use of the Sensor Cloud concept developed in the SelSus project. The main motivation for this work is the easy integration, processing and visualization of sensor information in the industrial field, and the impact of such approaches entering in the manufacturing world. Therefore, the main functionalities will be depicted, detailed and discussed regarding the increasing relevance of such technology, and the advantages they bring to the nowadays manufacturing environment. Functionalities such as easy integration of sensors into a WSN regardless of their manufacturer, processing methods to pre-process data to be used for further decision making and how to integrate new methods for statistical analysis are the main core of the present document.

2 SelSus

2.1 Technological Approach

The SelSus vision is to develop a new synergetic diagnostic and prognosis environment which is fully aware of the condition and history of all the machine components within a system or factory and is in constant knowledge enriched dialogue with their human personnel. Therefore, the objective of the project is to create a new paradigm for highly effective, self-healing production resources and systems to maximize their performance over longer life times through highly targeted and timely repair, renovation and upgrading. These next generation of machines, fixtures and tools will embed extended sensory capabilities and smart materials combined with advanced ICT for self-diagnosis enabling them to become self-aware and supporting self-healing production systems.

One key area explored in the SelSus project is related with Wireless Sensor Networks (WSN) and Cloud Systems in Industry that ranges from sensor integration, sensor data visualization, statistical processing and access, where sensors, external to the process, used for machine monitoring were introduced at the shop-floor level. The suitability of WSN in industry has been successfully applied during the past few years in several test and real case scenarios. Sensor information is considered one key element for machine behaviour modelling and process optimization, due to the possibility of gathering not only data from machine parametrization (variables that control the process) but also from the observable impact of this parametrization in the final quality of the product. Moreover, knowing this type of information, despite allowing an immediate monitoring of the process conditions, it can be used in a myriad of applications. From predictive maintenance where a failure of a certain machine can be predicted within an interval of confidence, to the optimization of a certain process to minimize the cost not jeopardizing the product quality, and even knowing if a process is drifting from what was defined in the design phase.

Recently, technologies that leverage the presented advanced manufacturing environments are hot topic among academy, private sectors and government. The remaining part of this section urges the increasingly importance to develop systems and components that are embeddable and interact with advanced production environments. Such is the case of Industrial Sensor Cloud (ISC) and Industrial Cyber Physical Systems (Industrial CPS). The proposed Cloud solution must be designed with this necessity in mind, a few important benefits of such approach are pointed next: 1) Physical hardware and software used in the factory can be intelligently perceived, and therefore, the information collected can be intelligently processed and used in the whole life-cycle of production; 2) Cloud Computing applications can work over large quantities of data enabling production-related & product-related services and even more advanced business models; 3) Smart logistics of both machine and human labour as well the energy spent. Recent Cloud Manufacturing Service frameworks are based mostly in the adoption of Internet of Things (IoT) and Wireless Sensor Networks (WSNs) technologies, where industrial clouds are heavily sensor based. The CPS role is to realize intelligent monitoring and intelligent control, combining embedded systems, networks, sensors and actuators. ISC supports Industrial CPS by providing computational power, integration in value and market chains, internal coordination and control, and external access through secure mechanisms. The development of industrial environments that combine both technologies is so attractive that many countries had made Industrial CPS and ISC national development strategies. It is also an opportunity to the proposed Sensor Cloud solution, since the development of such solutions will determine the realization of advanced manufacturing environments

2.2 SelSus Cloud

In order to achieve all the project goals, the important concept of *Cloud Computing* for data acquisition, storage, processing, visualization and access purposes was peremptory to be explored. Thus, the overall architecture that supports all the required functionalities and components of SelSus was based, already on its early stages, on a Cloud-based solution. The main intention of exploring such a concept is related with the necessity for easy collection of data from multiple components, quick visualization of manufacturing process dynamics, statistical processing for monitoring purposes and information exchange to other external applications. These multiple communication points (shop-floor components) that generate high volumes of data need to be able synchronize its raw or pre-processed data in a standardized way for quick detection of its ongoing operations. Thus, to support these requirements the concept of SelSus Component (*SelComp*) was created. The SelComp is a virtual representation of the physical equipment operating at the shop-floor level. This concept is applicable to both machine and Wireless Sensor Networks, and is a virtual representation of these shop-floor components. This means that we can have a SelComp representing a Machine and another SelComp of a WSN, both sending data to the Cloud system and uniquely identified. This way, is possible to visualize and analyse independently the information from each component, notwithstanding a collective analysis using all a group of SelComps to calculate the main manufacturing Key Performance Indicators.

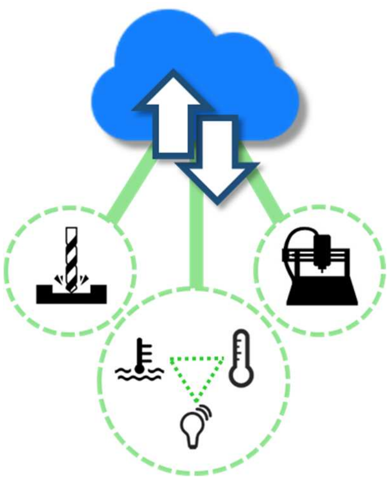

Figure 1 - SelSus Cloud Concept

Based on this, the idea is to have as many SelComps as required for the Manufacturing Process virtualization, sending all the generated data to the SelSus Cloud. In Sum, the SelComps can be seen as nodes providing information in a SelSus network, and the Cloud acts as a receiver of all that information for further analysis and visualization (
Figure 1). This is a simple approach with a simple architecture representation and flexible enough to be extended to support new components and other functionalities.

SelComp **Concept**

The SelComp concept was primarily developed to create a representation of the operational shop-floor equipment as a way to easily acquire the generated data and synchronize it with a Cloud system. For that purpose, a base technology for device discovery and data exchange was explored, with support for both Java and C# programming languages. After a thorough analysis, these requirements were fulfilled by using the Universal Plug'n'Play (UPnP) architecture. It's flexible implementation of publish-subscribe pattern by using both UPnP Control Point (receiver) and UPnP Device (sender) allowed for the quick implementation of the base template of the SelComp. The development of this template was supported by a set of tools available to implement the wrapping technology for all the equipment. Furthermore, the SelComp template is easily adaptable according to the specificities and necessities of each partner present in the project consortium. Since different partners operate in different markets, this requirement was contemplated beforehand.

Based on the fact that the main objective of the SelSus project is to explore concepts like Condition-based Monitoring and Machine Diagnostics, two major types of shop-floor equipment are considered: 1) Machines / Controllers (*Machine SelComp*) and 2) Wireless Sensor Networks (*Sensor SelComp*). This distinction between machine and sensors is nowadays critical in industry, based on the fact that there are operating machines that are not prepared to collect data from its own process, which impairs the use of complex methods to, e.g. infer any deviation from the normal process behaviour. Therefore, the use of additional sensors that 1) do not influence the process itself, 2) are quick to deploy and reconfigurable when process requirements change and 3) are fully integrated with a data visualization / analysis platform was the key point explored in the Sensor Cloud technology developed in SelSus project.

Based on this, the next sections will explain the main innovative features that compose this Sensor Cloud technology, starting with the main building blocks of the Sensor SelComp such as:

1) **Dynamic Modular Software Reconfiguration** that allows to change the data treatment on-the-fly even before data is synchronized with the Sensor Cloud;
2) **Flexible Sensor Integration** solution that allows to graphically develop an interpreter of raw byte data packet at the gateway level for automatic data acquisition; and;
3) **Statistical Analysis** section to detail some of the potentialities of using certain methods and algorithms to analyse Machine and Sensor data, available at the Sensor Cloud level, and can be used in the reconfiguration process of the Sensor SelComp.

3 Sensor SelComp

The SelSus Component concept (SelComp) envisages to create an innovative smart component, with enhanced reconfiguration, sensing, decision making and collaborative capabilities.

These smart components are capable of providing a quick response in real-time scenarios and to collaborate in synergy with other entities while present in complex industrial scenarios; such as Industrial Cyber Physical Systems (Industrial CPS). By combining the capabilities of reconfigurable software, machine to machine communication and sensing, this solution is capable of delivering specific and specialized computational analysis with a great degree of flexibility. A tentative of definition, led by the smart components community is:

"Smart Components in manufacturing are components which incorporate functions of self-description, communication, sensing and control in order to collaborate with other smart components, analyse a situation, make decisions based on the available data and modify their behaviour through feedback".

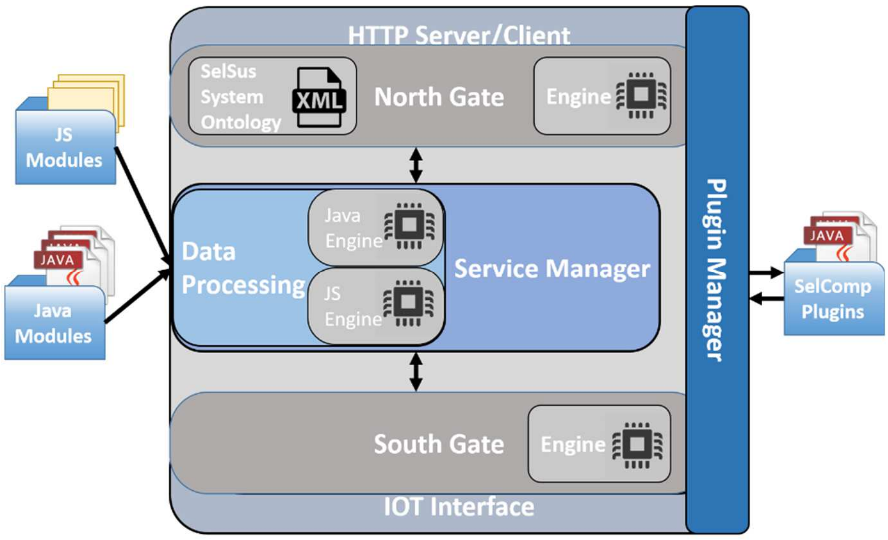

Figure 2 – Sensor SelComp Building Blocks

The proposed solution takes advantage from the Internet of Things (IoT) advent when in regard to the base technologies adopted. The advantages of such solution are countless.

Economically speaking, the hardware solutions adopted are low cost and widely employed in recent smart manufacturing systems. Low cost embedded hardware platforms, such as *RaspberryPi* and *Beaglebone Black,* provide the necessary computational power, sensor interfacing and communication capabilities. The market of low cost sensors has also a wide range of products for the measurement of a large set of physical properties with several degrees of precision.

From a technological and state of the art point of view, by adopting IoT hardware and software solutions, the SelComp solution is taking profit of cutting edge technology and contributing to the creation of standardized technology.

The Sensor SelComp architecture is illustrated in

Figure 2. The component is fully modular and each module can be updated by deploying a new plugin in the system.

Analogous to the plugins, but for different purposes are the *JS (JavaScript) Modules* and *Java Modules*. These are data treatment modules, which perform analysis on data, e.g. Neural Networks or Control Charts. These modules are "*write once, run everywhere".* Once developed, these files can run in any Sensor SelComp. The modules are maintained in the Sensor SelComp file system, and the SelSus Cloud controls what data processing modules are present and running in each Sensor SelComp.

Each block controls a specific functionality and the system is mainly divided in three core functionalities.

North Gate and SelSus Cloud share the same ontology. The *North Gate* is responsible to handle Cloud interactions. The Sensor SelComp exposes through this interface its services to the network and the SelSus Cloud is aware of all the services available. There are four static services which the cloud (or external components) can invoke:

- Internal Structure Reconfiguration;
- Submit Data Processing Modules;
- Submit System Plugins;
- Submit Sensor Parsers.

Let us discuss in more detail the ***Internal Structure Reconfiguration*** since it is the main innovative functionality that drives the Sensor SelComp internal data processing**.** The core of the Sensor SelComp is composed by services. The SelSus Cloud, a Sensor or an External Component is virtualized and treated as a service which provides and/or receives data. The Data Processing modules presented can be instantiated. The instance is transformed into a service, which provides data after being treated.

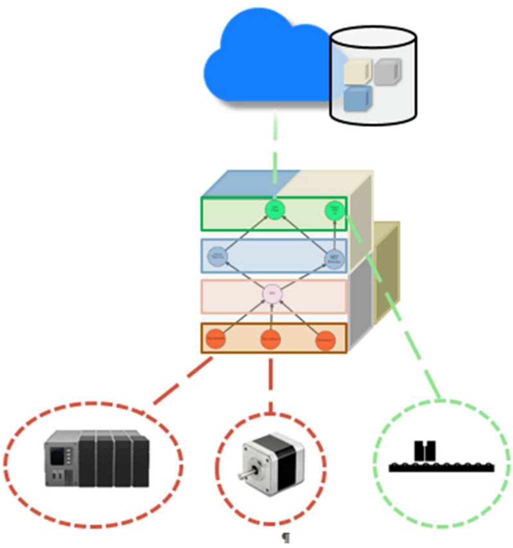

Figure 3 - SelSus Cloud and SelComp Interaction

The whole logic is that every service running in the Sensor SelComp implements the publish-subscribe pattern and can be connected in a directed acyclic graph arrangement fashion, as presented in Figure 3. Data flows from the bottom of the graph, through data processing services and ends up typically in the SelSus Cloud or in other components in the network subscribing the Sensor SelComp services. This design puts a strong emphasis in the *"servicitization"* of processes and physical devices. This virtualization turns the shop-floor in a digital twin of the physical world, which makes this system to be aligned with the recent Industrial CPS and ISC trends.

3.1 Dynamic Modular Software Reconfiguration

The Dynamic Modular Software Reconfiguration is the proposed solution embedded in the Sensor SelComp to be highly reconfigurable and to quickly adapt to industrial demands. Therefore, it must provide consistent mechanisms to configure, deploy and dynamically reconfigure the Sensor SelComp source code responsible for data processing, which traduces in a component-based middleware. It is component-based because each piece of software that can be reconfigured at the Sensor SelComp level is seen as a component that can be easily updated or exchanged.

In software engineering the terms "Modular Software" and "Software Component" are the most approximate topics to what we refer as "Reconfigurable Software". **Component reuse**, **reduction of the production cost**, **reconfiguration in *runtime*, short time to market** and **systematic approach to the system construction** are some of the key benefits of using a component model. Component models can be divided in two categories: 1) as in object-oriented programming, components are objects; 2) components represent units in software architectures. *"A generally accepted view of a software component is that it is a software unit with provided services and required services. ... In current component models where components are objects in the sense of object-oriented programming, the methods of these objects are the provided services".*

In the proposed solution two component model approaches are offered to provide an even better flexibility. At the system level there is the possibility to extend the Sensor SelComp building blocks with plugins. At data processing level, there is the possibility to add new data treatment and processing modules to the Sensor SelComp to use. There are two ways to develop data treatment modules: 1) develop code in *Java* using the defined interfaces; 2) develop code in *C#, Java* or *C++* and use the SelSus Cloud to convert the code in a *JavaScript* module file. In both ways, the SelSus Sensor Cloud uploads the modules to the Sensor SelComp, which maintains the modules in the local file system

Figure 2.

A SelComp internal logic arrangement is represented using a directed acyclic graph (DAG). The graph structure in Figure 4 can be divided in three levels, each with a different label and colour assignment: the Sensor Level includes sensor instances (bottom level), providing data to the gateway; the data treatment level (middle level), includes nodes representing instances of algorithms embedded at the gateway that can treat information in several ways (e.g. aggregate and validate data using techniques such as control charts, perform trend analysis, etc.); the Network Level (top level) includes nodes where the flow resulting from the lower level nodes can be redirected to subscribing hosts in the network (e.g. Sensor Cloud, industrial machines). This internal structure can be dynamically rearranged in runtime using the Sensor Cloud, where new sensors and data modules can be loaded and therefore, the connections between nodes can be reformulated to synchronize and treat data in new ways.

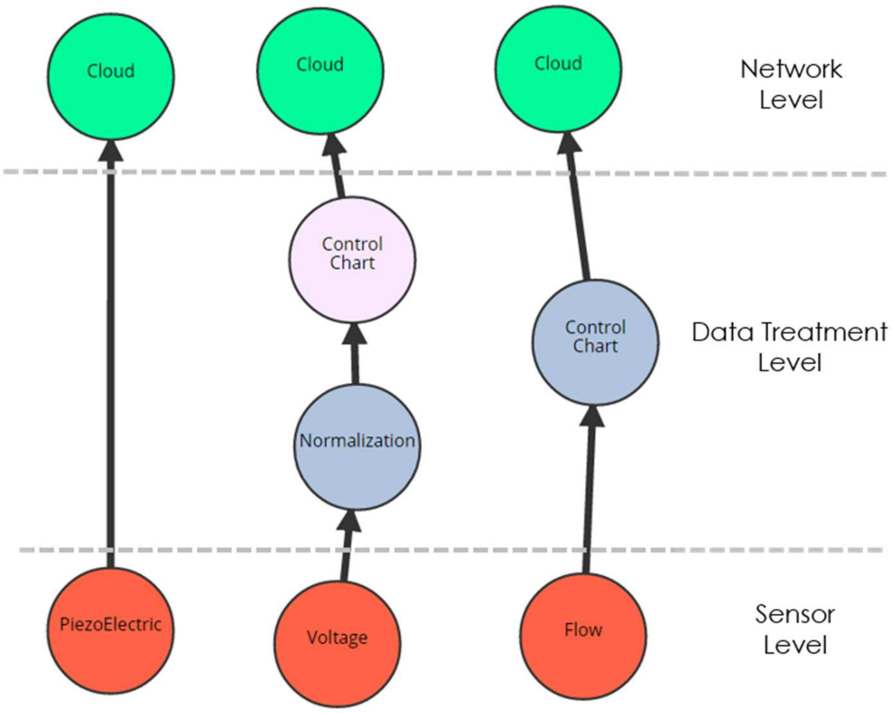

Figure 4 - Sensor SelComp configuration

3.2 Flexible Sensor Integration

The technology developed for flexible and easy Sensor Integration in the SelSus project is a cloud-based user interface solution that enables a person without or with little programming knowledge to specify a new Wireless Sensor Network (WSN) message parser. The typical architecture for a WSN is composed of *sensor nodes* and *gateways*, being the sensor nodes the generators of data, and it needs to reach the gateway where it is then handled by the Sensor SelComp. This means that the technology developed is operating on the South Gate of

Figure 2.

The construction of this WSN message parser is not only suitable for new nodes to be integrated in the network, but also to extend existing ones to support new sensors in the node itself. In order to build the desired parser, there's the major assumption that the message frame content is known. Based on this, we started to define that a certain message frame is composed by a set of items. The item is the atomic element that needs to be found in the messages received in the gateway. This way, an item can be defined as only one byte or set of bytes, depending on the user preferences, that can be in a pre-defined position / location in the message, called *index* (in case of non-variable size messages) or vary according to the encoding of the message (in case of variable size messages). Based on this, the *Flexible Sensor Integration* solution will look for these items on new messages received, by a specific order ruled by the *indexes* defined in the interface, and if all items match the message received, it can be correctly interpreted.

Normally, the first item is a SYNC which is a sequence of chars that uniquely specifies the start of a message. This kind of item is particularly important because it defines when to start interpreting the message, and also is used to know which type of message is, and choose the right parser for decoding.

Therefore, for each item is specified by 1) Name; Type (how should be decoded); 2) Default Value (if it has one, hex-encoded); 3) Start Index; Size (if it isn't variable); 4) Variable Field (true or false depending if the size is or not fixed).
If an item is variable (not fixed size for interpretation), the immediate next item in most cases is a separating char.

Additionally, the user interface is also used to provide additional information like manufacturer, model, serial port configuration (only for protocol that needs one), physical link, protocol name and protocol norm. For ease of sensor integration, the SelSus system already have component meta-information that can filled for further ease of integration in the system.

After creating the parser in the Cloud solution, all the parsers are converted to a XML encoded representation with all data needed to receive and decode one message type. Moreover, at the Cloud level is possible to deploy the parsers to any chosen Sensor SelComp, becoming immediately available to interpret new data from the sensor nodes.
The present solution for sensor integration was validated using IEEE802.15.4 RF Protocol, with 4 motes, 2 different baud rates (115200, 57600), 4 sensors (Battery, ACC, PIR and Temperature). These tests were performed not only in a PC platform, but also in a Raspberry Pi 2 to test the efficiency in lower computational powered devices. Two major tests were made: 1) 4 motes with one sensor each; 2) 4 motes, but 1 mote with 1 sensor, 1 mote with 2 sensors, 1 mote with 3 sensors and finally 1 mote with 4 sensors each).

Some preliminary results are depicted in Figure 5 and Figure 6 where the amount of time required to interpret a single sensor message is presented in milliseconds. The tests were made using a Sampling Rate of 5 seconds (0.2Hz) for a period of 1h. From the figures, we can also see that the performance of the PC is better comparing with the Raspberry Pi 2, as expected. Using the PC platform (Figure 5) the mean value of all decoded messages is 0.056 milliseconds and standard deviation of 0.095 milliseconds. For the Raspberry Pi 2 test, the mean value is 1.27 milliseconds, with a standard deviation of 1.05 milliseconds.

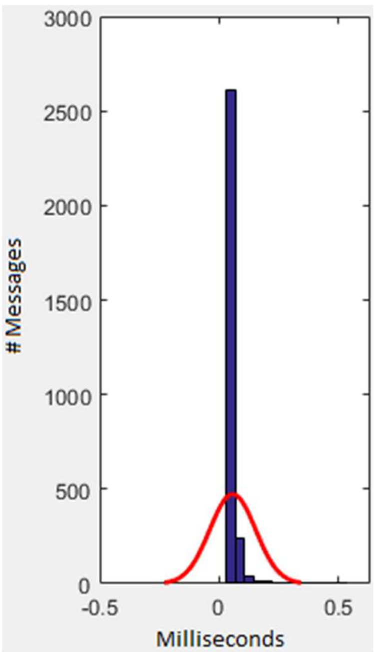

Figure 5 - 4 motes, one sensor per mote, 57600 Baudrate, 1h running, Pc Platform

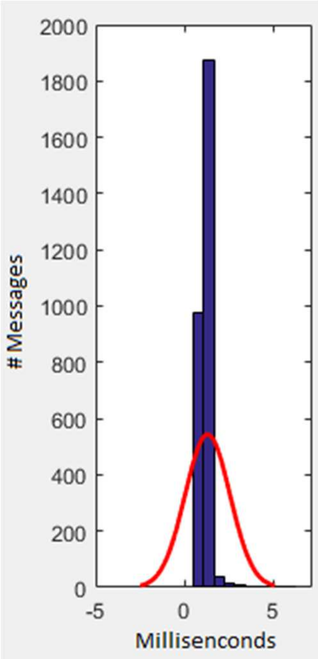

Figure 6 - 4 Motes, one sensor per mote, 57600 Baudrate, 1h Running, Raspberry Pi 2 Platform

3.3 Statistical Analysis

One of the key aspects that is peremptory when assessing the data from sensors installed in a certain shop-floor equipment is the statistical processing. Therefore, one of the main goals in the SelSus project is to develop algorithms and modules for statistical sensor data processing.

Besides validation of sensor readings for the detection of sensor malfunction, algorithms based on statistical analysis have been developed and implemented for data fusion, multi-variable processing, process monitoring and fault detection to process the huge amount of data generated by the sensor network.

One of the main challenges in automated sensor signal processing is the sensor signal validation. Since sensor signals are subjected to drifts and noise, simple fixed limit strategies reveal not to be so effective. A much more sophisticated way is a validation based on Kalman Filter strategies. Consider a sensor delivers temperature data (float precision single value) at certain - not equidistant - time instances. An alarm should be generated when an unusual temperature change occurs. This could be for example caused by a sudden strong friction or a smouldering fire. Additionally, due to day/night and seasonal drifts it is not possible to apply fixed limits for an alarm activation.

The aim of the algorithm is to detect if the measurement series behaves unusually, for example overheating or certain pressure loss while tolerating normal process patterns. Generally speaking, a system state must be observed from noisy measurements and the state movement must be evaluated against a usual drift. The concept of the KALMAN state observer is very suited for this approach because it allows not only the state observation but also the estimation of typical state variance which can be used to detect faulty state or measurement situations. For a proper filter usage, the knowledge of a typical process drift and noise characteristic is required. Base on a series of provided sensor reading, the implemented algorithm is able to estimate these parameters in a reliable manner.

The second implemented statistical approach deals with the analysis of sensor array behaviour. In this situation if there are multiple sensor readings in parallel it would be annoying to setup individual control charts for each individual sensor. Moreover, it would not be possible to detect faults which are due to unusual correlations. Also the natural redundancy of such a sensor array would not be exploitable. So there are many reasons to deal with multivariate methods for assessing sensors array data as a whole. Common methods dealing with this are the Q^2 and T^2 Statistics.

While Q^2 Statistics deals with outliers which are not covered with the multivariate model, T^2 Statistics considers reading which can be explained with the multivariate model, but have unusual features. Both statistical values allow the detection of any unusual environmental behaviour or sensor malfunctions of the data delivered from a sensor array.

A special type of application sensors are used in batch processing supervision. While a batch is processed multiple trace are recorded for different parameter or at multiple places. From a PCA based decomposition a set of characteristic base pattern is extracted from a set of historical recording. Applying these patterns to the traces delivered by the sensors yields to key numbers which characterize the process itself and helps to access and monitor the process quality.

Ultimately, the algorithms have been successfully applied to the HWH and IEF Werner demonstrators. In case of IEF Werner demonstrator, a linear axis which moved up and down was integrated in the system (a SelComp was created to wrap the equipment) and a Statistical Analysis was made from the acquired data. From Figure 7, the statistical numbers T^2, Q^2, maximum model error were calculated and compared against alternating limits (red dots) – always one for up and one for down movement. If any limit is exceeded, the run is considered as faulty (red circle) and it ran for 50 cycles.

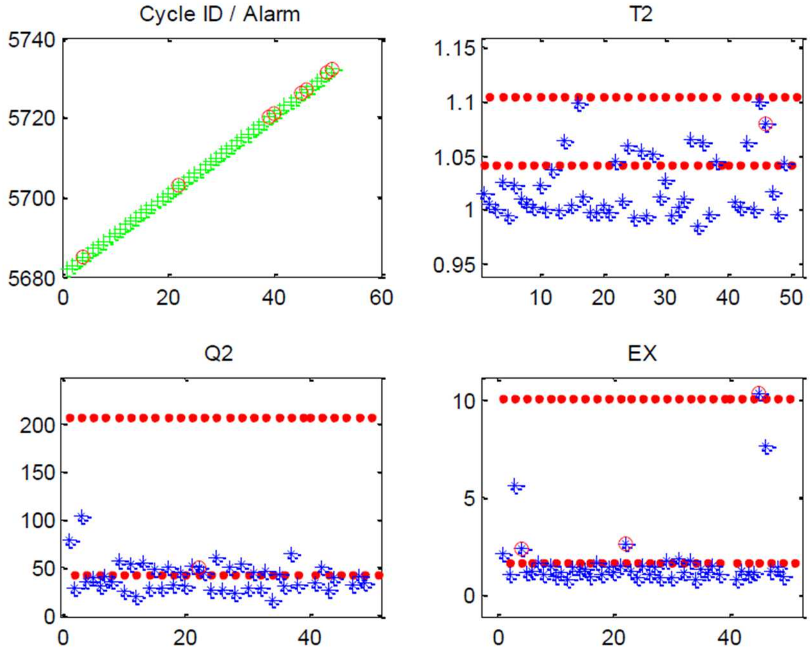

Figure 7 - Statistical evaluation of traces to detect faulty movements – IEF Werner Demonstrator

In the Harms & Wende demonstrator, a welding machine was integrated and the voltage and current curves were obtained. From this curves, a PCA decomposition was made to obtain the most significant components, and by using the singular values a Statistical Analysis was made using again T^2, Q^2 and maximum model error. Figure 8 shows that this analysis is a really good way for monitoring derivations of shapes from process batches captured from the welding machine. For this demonstrator, 250 welds were made to test the solution.

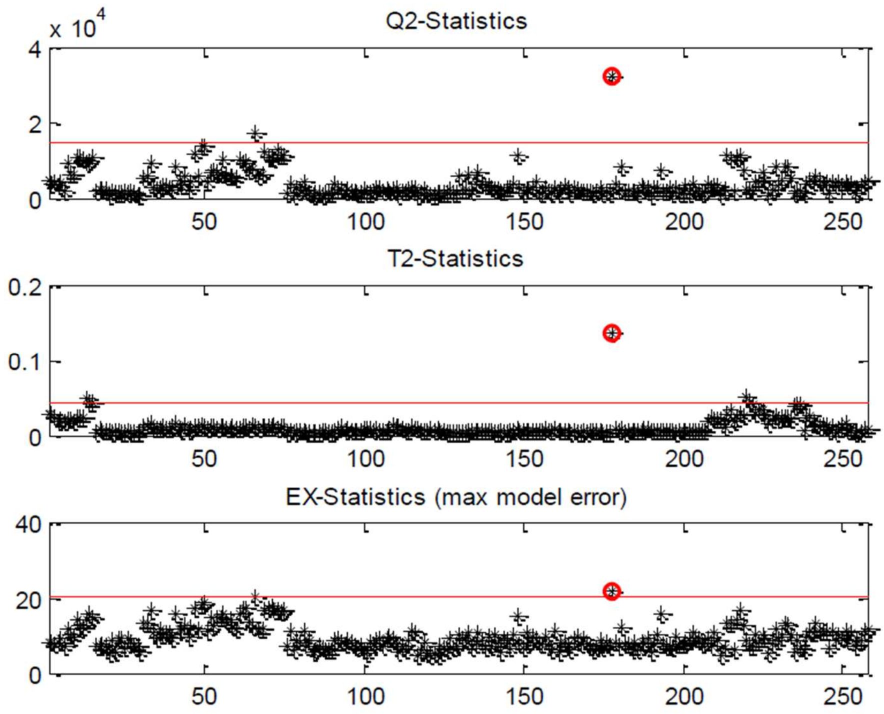

Figure 8 - Statistical evaluation of welding traces to detect unusual shapes – Harms & Wende Demonstrator

4 Impact

4.1 Sensor SelComps in Industry

The impact of the most advanced and robust technological developments in software, hardware, data treatment and others can have a huge impact on how the shop-floor is perceived, analysed, interpreted and operated. With the use of sensory solutions, the factory blueprint can be obtained by simply adding new equipment to measure the main processes, and therefore its dynamics can be quantified. With this quantification, is possible to analyse the key points of optimization and improve the systems performance and reliability. For that purpose, data from various shop-floor equipment needs to be integrated in a manufacturing system, such as MES or ERP for data acquisition, and collectively stored for further analysis.

Based on this, we could notice the increasing publications and citation of scientific papers in conferences and journals relating sensory solutions, mainly Wireless Sensor Networks (WSN), with Cloud-based solutions. This is demonstrated by Figure 9 and

Figure 10 that present the number of citations and published papers, both per year. The Figures show a clear tendency towards the exploration of Sensor Cloud concept, which aims to develop a platform for sensor integration, data storage and data analysis. The idea is to have a distributed system with a well-defined API to establish a standardized communication with heterogeneous Wireless Sensor Networks, allow the easy access to this data for integration with other external systems, and a set of graphical user tools to increase the easiness and flexibility when dealing with such kind of systems.

It's based on this kind of concept and all the major industry difficulties that the developments of SelSus project related with sensors was made. This means that the solutions presented such as *Statistical Analysis*, *Dynamic Modular Software Reconfiguration* and *Flexible Sensor Integration* have a direct impact in the manufacturing processes. These technologies and new concepts are the starting point towards a more connected factory, easier to perceive, easier to handle in case of sudden deviations, and ultimately easier to act when a decision needs to be made.

Nowadays, the paradigm of sensing the factory dynamics can be rewritten towards smart industrial sensors. This means that using the concepts of on-the-fly reconfiguration using statistical analysis, sensors could provide more than raw information, more than a set of data acquired in a high frequency rate that need to be post-processed. They could provide metrics, machine states, process drifts and so forth, used for decision making and even directly feed a machine for online calibration an optimization. The benefits are not only in the efficiency of machines, but also how efficiently the system users operate equipment. Based on the fact that these solutions do not imply a direct coding to perform the desired changes in the system, but instead a graph-like interface to design the workflow of data treatment, opens the doors for many people to work in such industrial environments, with the same outcome as a programmer, but with less effort. This represents a new approach to what the usual systems in industry can provide in terms of flexibility and ease of use.

Additionally, also the concept of Plug'n'Produce is complemented with the solutions proposed. One aspect already explored, is the device discovery and data exchange using the publish-subscribe pattern that is nowadays well-implemented by technologies like UPnP, OPC-UA, DDS and others, so now the effort is focused on how to extract the information from the shop-floor components for further broadcast. This issue is tackle by the *Flexible Sensor Integration* and it can avoid the technicians to code a parser in some programming language to design it graphically. With the use of the *DMsR*, the parsers can be deployed in run-time in the SelComps at the shop-floor level, without the need to turn it down, deploy the parser and turn in up again passing through all the process of device discovery. Once again, the participation of the user in the most important phases of building and maintaining a process line is the key element that drive the presented work.

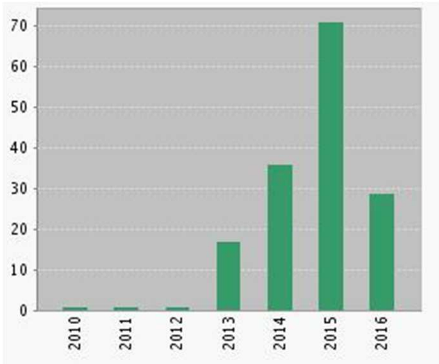

Figure 9 - Paper Citations in each Year

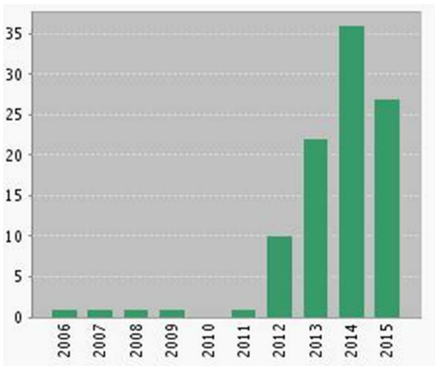

Figure 10 - Published papers in Each Year

5 Appendix A

Set of keywords used for the search in Web of Science platform:

- *Sensor-cloud;*
- *Sensor cloud computing;*
- *Sensor cloud-based;*
- *Sensor cloud industry;*
- *Sensor cloud manufacturing;*
- *Sensor Cloud Application;*
- *Sensor Cloud Storage;*
- *Sensor cloud industrial;*
- *Sensor Cloud Infrastructure;*
- *Sensor Cloud-Oriented;*
- *Sensor Cloud Platform;*
- *Sensor Cloud Servers;*
- *Sensor Cloudware*.