Smart Factory Systems - Fostering Cloud-based Manufacturing based on Self-Monitoring Cyber-Physical Systems

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***Abstract*—This paper describes the concept and realization of an architecture using cloud-based smart components to achieve a more responsive production system that provides a modular and re-configurable production framework. For each important part of the plant and the manufactured product, digital virtual copies are created and stored in active digital object memories, a unified structured format for data access and further processing. Cyber-Physical Systems act as intelligent nodes within the cloud-based network and guarantee the function of technical communication and data exchange. Moreover, these systems continuously perform and execute almost autonomous simple state and feature checks, up to a certain level of complexity. In various points of the production process these simple checks can ensure or even optimize the quality of the product. An assistance system makes use of these technical solutions and manages and monitors the distributed components and their responsibilities for quality assurance during the whole production process. In compliance with prescribed quality characteristics and the situational context necessary processing steps are defined or rearranged.**

Keywords–active digital object memory; cyber-physical systems; cyber-physical production system.

I. INTRODUCTION

The present approach of intelligent manufacturing, called cyber-physical Production Assistance System (cPAS), shows the realization and implementation of a concept of networked autonomous devices, sensors and machines that monitor themselves and perform condition-based, decentralized small tasks for continuous monitoring and self-diagnosis by simple state checks. The crosslinking is carried out by upstream Cyber-Physical Systems (CPS) and the data storage and the extended decentralized monitoring is realized by Active Digital Object Memories (ADOMe) [1].

The industry is facing a change and needs improved production system efficiency and robustness through more flexible, automated production, because it will no longer be sufficient to produce good products in high quality. The current order of the market is shifting more and more towards the idea of contemporary customer-specific individual production, combined with the shortest possible cycles for development and processing, different product variants need to be made in almost no time [2]. However, this flexible approach also requires that future factories must be easily adapted and converted to the order situation, but this is time-consuming and costly. To make such a complex task more manageable, parts of the plant, e.g., sensors, machinery and products need to be developed that will make a flexible and modular engineering possible. Through the application of innovative self-monitoring techniques for manufactured products and field devices the efficiency in production will be increased [3]. Nowadays, as a general trend, the focus shifts from pure engineering, which is based on mechanical processes, to software-controlled processes that offer potential for further optimization [4].

The evolution of the Internet to the Internet of Things (IoT) corresponds to the fusion of the real and the virtual world. When considering this trend, CPS play a main role by coupling the different scientific worlds - mechanical engineering, electrical engineering and computer science. This trend reveals the German industry that it stands on the threshold of the fourth industrial revolution (*Industrie 4.0*) [3]. Future production processes are characterized by specific requirements to the individual manufacturing of products. This opens up new requirements for highly flexible production systems, and increasing efficiency in industrial production processes will become a significant competitive factor. CPS form a solid basis for *Industrie 4.0* [5], and this approach shows the integration of these systems in a real production environment. The vision of *Industrie 4.0* describes the digital transformation of industry and the networking of production and products. With the development of *Industrie 4.0*, machinery, equipment and sensors are communicating with each other and exchange data. This leads to a combination of the physical and the virtual world [2], [3].

The development of component-based machine-to-machine (M2M) communication technologies enable field devices to exchange information with each other in an autonomous way without human intervention. The concept of IoT extends this M2M concept by the possibility to communicate and interact with physical objects, which are represented by CPS. These CPS provide the necessary computing power, storage, sensors and ubiquitous access to the functionality of the instrumented machines and field devices [6], [7]. In this approach, all major field devices are equipped with CPS and installed in spatially separated production lines. The idea goes here towards the concept of “retrofitting” [8]. Retrofitting means the advanced equipment of existing facilities through additional hardware: function-enhancing modules for communication and distributed processing. With this instrumentation, it is possible that individual field devices and the manufactured products communicate with each other, until the industrial plant meets the standards and directives of future factories and principles of *Industrie 4.0* [9].

In Section II, this paper gives an overview of used technologies and introduces the terms field devices, IoT, CPS, automation pyramid, active digital object memories, smart factories and smart products. It closes with a with a brief summary that addresses the importance of networking in the industry and manufacturing domain. Section III describes the concept of cloud-based manufacturing, the modeling, and distributed decentralized CPS and corresponding locally and globally stored data structures. Section IV describes the scenario and application domain and shows how the approach and the developed framework can be used in this industrial environment. In the following Section V, the technical realization of an infrastructure for distributed CPS-based product memories and the upstream assistance system of the CPPS is shown. Section VI gives a conclusion and an outlook on future work.

II. Background

A. Field Devices

Field devices are electronic devices that are located at the field level, the lowest level in the hierarchical level model for automation. They are associated with sensors that, on one hand, detect the data of the measuring points and on the other pass the control data to the actuators. At certain time intervals, field devices continuously supply measured data for process control and receive control data for the actuators.

B. Internet of Things

The inexorable growth and innovation diversity of information and communication technologies leads to a fundamental change in daily life. Computers are becoming smaller and can be used almost anywhere. They are built almost inside of all of our technical equipment, e.g., smart watches that track bio-physical data. These devices provide a wide range of technical capabilities that can be used quite comfortable and allow individual components to communicate and cooperate by constantly exchanging sensor information. Following this future trend it can be expected that all utensils of our daily life are turning into smart nodes within a global communication network: this is called the IoT [10], a trend that will also find its way into domains such as consumer electronics and also industrial production.

The term *Internet of Things* was coined and popularized by the work of the Auto-ID Center at the Massachusetts Institute of Technology (MIT), which in 1999 started to design and propagate a cross-company RFID infrastructure. In 2002, its co-founder and former head Kevin Ashton was quoted in Forbes Magazine as saying, “We need an internet for things, a standardized way for computers to understand the real world” [11]. This article was entitled “The internet of things”, and was the first documented use of the term in a literal sense [12].

C. Industrial Internet

The idea of the Industrial Internet, also known as the Industrial Internet of Things (IIoT), is a network of physical components, systems and applications that contain embedded technology to communicate. The term is coined by the company Frost & Sullivan and refers to the integration or union of physical machines with their networked sensors and actuators with complex software technologies, like Machine Learning, Big Data, IoT, and Machine-to-Machine communication. Machines are talking to machines and analyze and optimize data to perform better. Different components, like sensors or actuators, share intelligence and solve complex problems in combination with a CPS.

For a better coordination, acceleration, and development of Industrial Internet technologies the Industrial Internet Consortium (IIC) was founded by AT&T, Cisco, General Electric, IBM, and Intel, in 2014. This consortium of industry players from multinational corporations attempts to establish a comprehensive application of the identified technologies.

The focus of the IIoT is on improving efficiency, safety, productivity of processes in the field of production. Optimized machine-to-machine communications, efficient parametrization, easier monitoring, and a better planning of capacities leads to a significant cost reduction in production and to a quick return on invest [13].

D. Cyber-Physical Systems

In the fields of agriculture, health, transport, energy supply and industry, we are facing a revolution, a new era, and the IoT will open up new ways and possibilities in the upcoming years. Modern information technologies connect data out of different areas and bring them together. This works, if there is a virtual counterpart for every physical product, that can reproduce, by means of sensors and cameras, the environment and the context to combine simulation models and predictive models.

Therefore, the paradigm of the IoT describes distributed networks, which in turn are composed of networks of smart objects. As a technical term for such smart objects, the term Cyber-Physical System (CPS) was coined [14]. The main feature of a CPS is that the information and communication technologies were developed and finely tuned to create virtual counterparts to physical components. CPS link data of the real world and this increases the effectiveness and does not encapsulate computing power in an embedded system. Over the communication channel available distributed computing power can be used to solve problems within a network.

The IoT and CPS are not fundamentally new concepts. Indeed, Simon [15] already identified the importance and benefits of combining both, physical and virtual domains. His approach was presented many years ago, when not all embedded platforms and manufacturing techniques were developed as today. In fact, the possibility to develop and use a mature platform and techniques are nowadays widely accepted by the industry. Production processes in the context of the initiative “Industrie 4.0” of the federal German government can be fine-grained equipped with sensors and deliver real-time internal and external production parameters in an very high level of detail [3], [16].

These following four features typically characterize CPS [17]:

- A physical part, e.g., sensors and actuators capture physical data directly. This allows a direct influence on physical processes.
- A communication part, e.g., connected to digital networks: wireless, bound, local, global. This allows the use of globally available data and services.
- A computation part, e.g., save and evaluate data and interact on this basis, active or reactive with physical and digital worlds.
- An interaction-layer for HMI, e.g., feature a range of interfaces for multi-modal human-machine interaction.

This provides dedicated facilities for communication and control, like control by speech and gestures.

In this approach, CPS are embedded micro-controllers installed either inside or outside of physical objects, responsible for the connection and communication over a network, e.g., the Internet. The technical aspect of classical embedded systems is extended by the idea of *Real World Awareness* and tight integration in digital networks. In the context of this implementation, CPS act as digital counterpart and couples the real and the virtual worlds [5], [18]. Furthermore, the "Real World Awareness" and dynamic integration of CPS is based on three basic principles: self identification (*Who am I?*), service exploration (*What do I offer?*) and active networking (*Where are my buddies?*).

E. Cyber-Physical Production Systems

The application of CPS in production systems leads to the Cyber Physical Production Systems (CPPS), in which products, machines and other resources are represented by CPS sharing information and services across the entire manufacturing and value network. Future factories use CPPS, semantic machine to machine communication (M2M) and semantic product memories to create smart products [19]. These smart products are the basis for smart services that use them as a physical platform.

Overall, a CPPS, which is based on decentralized production logic and networked principles, offers advantages in terms of transparency, adaptivity, resource efficiency and versatility over traditional production systems. In the context of CPPS, CPS are fundamental units that have almost instant access to relevant information and parametrization of machines, production processes and the product itself. On the automation level of a CPPS all these information out of the CPS-network is needed to run the manufacturing process successfully and to make strategic decisions. For decision making and control of the manufacturing processes, consistent and coherent information of the "real" world is needed [20].

F. Automation Pyramid

Today's conventional automation pyramid consists of three clearly separated levels, see Figure 1. The automation level, where sensors, actuators and in general field devices are located, the Manufacturing Execution System (MES) level, and the Enterprise Resource Planning (ERP) level. In each of these levels, different planning and construction processes take place. A new control paradigm, based on CPS and Service-Oriented Architectures (SOA) that interact in an automation network, and the direct communication and administration of field devices puts a question mark on the strict separation of the automation pyramid. The digital transmission and permeability of the engineering is in the focus of current factories of the future and softenings up the concept of the strict separation in encapsulated automation levels, where a strong vertical and horizontal communication of field devices within automation systems is not considered [3], [21].

Through the vision of networking of Industrie 4.0 this strict separation of the levels and the top-down approach of the information flow is mixed. Intelligent networked devices can operate independently and communicate with each other via

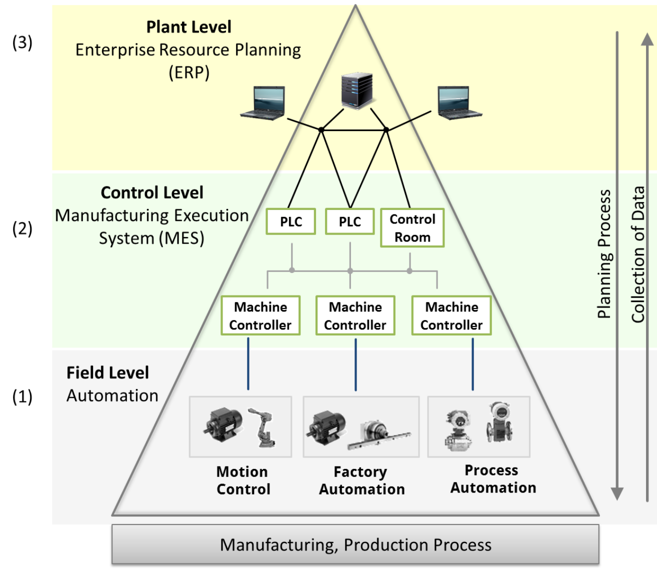

Figure 1: Conventional automation pyramid.

services that in turn can be used flexibly to support value-added processes [22].

G. Active Digital Object Memories

The development of the IoT makes it possible to assign a digital identity to physical objects [23], [24]. Paradigms, such as human-machine interaction and machine-to-machine communications are implemented by the use of clearly identifiable markers, so-called smart labels. However, the identification is not only bound to those labels, it can be also achieved by integrated sensors or by providing identification methods.

These developments pave the way for the concept of Active Digital Object Memories (ADOMe), which extend the usage of smart labels by additional memory and processing capabilities [25]. By the use of the product memory concept all data in the life cycle of a product (manufacturer information, suppliers, dealers and users) can be added, and furthermore, the data exchange can be made over this specific memory model. Also, memory-related operations can be performed by small scripts in a local runtime environment directly on the ADOMe [26]. According to the functionality of these scripts it is possible to closely monitor decentralized production processes and resource consumption, to impove the quality of the products [27].

These innovative technologies and techniques are crucial parts and the further development is highly supported in national research initiatives, such as *Smart Manufacturing Leadership Coalition* in the US [28] and *Industrie 4.0* in Germany [3].

The next step in the development and to establish new technologies is to evaluate, process and merge data from existing enterprise resource planning systems (ERP) [29] and data from different ADOMes. Both sources, considered as a single unit, offer comprehensive access to domain knowledge and contextual information. A more concrete description of the industrial environment and the running manufacturing processes enables a better user assistance to automatically recognize intentions and activities of the worker. Recommendations for improvements of the current activity of the worker can be presented proactively by the system. The approach of Haupert et al. [30] refers to a system for intention recognition and recommendation that shows an example scenario also based on ADOMes.

Furthermore, the concept of digital product memories still has an active part. This activity is realized in the form of small embedded scripts that can be run in a separate runtime environment on the specific CPS. Thus, according to the computing power and storage capacity autonomously simple tasks can be executed independently in a decentralized way. In a certain interval or linked to events, deployed scripts are executed and perform small tasks such as storage cleaning, threshold value monitoring or target/actual-value comparisons.

The present work uses the idea of the Object Memory Modeling (OMM) [31] and implemented an Application Programming Interface (API) on this basis. OMM is an XML-based object memory format, which can be used for modelling events and it also defines patterns, so called block structures, to store information about individual physical objects. Moreover, this format is designed to support the storage of additional information of physical artifacts or objects.

H. Fields of Application - Smart Factories and Smart Products

Powerful computers are becoming smaller, inexpensive and energy efficient and suitable for the integration in devices, the instrumentation of everyday objects and integration in clothes - *smart products*. Tiny CPS-adapted sensors and actuators are able to perceive and respond to their environment and interact with connected services in the network. These sensor networks are an essential piece of the foundation for future factories - *smart factories*. Software-defined platforms, like CPPS, make sensor data available and processable, enriched with intelligence by integrated analysis methods for monitoring and controlling. CPS-enabled factory modules or factory parts and the produced smart products communicate and interact with each other. In this context, ADOMes provide a way to collect and analyze structured data and gives an answer to the question in which format the obtained data sets of all connected CPS could be stored. A smart service uses a smart product of the smart factory, to use smart data as an asset, linked via semantic technologies, see Figure 2 [32].

Smart factories and smart products characterize a generation change to new, highly flexible and adaptive manufacturing technologies for the production.

- More computing power in many small devices - extend functionality of existing industrial plants with several CPS.
- Better networked via Cloud-services.
- Gathering and fusion of information - local and global data processing (sensors, actuators).
- Create object memories, and store product/object-specific data.

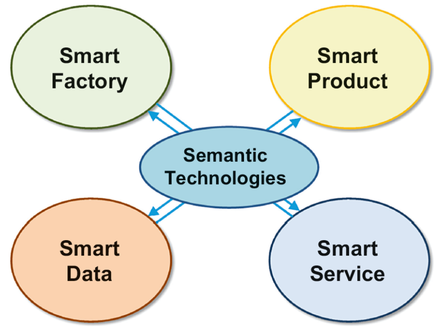

Figure 2: Customization based on semantic technologies [32].

I. Summary

Goal of research in this field is the virtualization of the traditional automation pyramid from sensor control to the ERP level to achieve the synchronization of the digital and the real world, as well as the integration of novel distributed architectures into existing production systems. Mechatronic and logical hierarchies must be decoupled and the turn to service orientation leads to an adjustment of the existing hierarchical layer structure. In our point of view, a production line, of a Smart- or Future Factory, consists of many autonomous CPS-enabled modules, which in turn could be composed of several CPS. Only with the appropriate infrastructure it is possible to create hybrid products, combinations of goods and services.

The IIoT uses the embedded technology of CPS to communicate and share intelligence within a network of physical objects. It connects platforms, applications sensors, and devices and enables improved availability and affordability of sensors, devices, processors and other infrastructure components that facilitate and provide a stable access to real-time information.

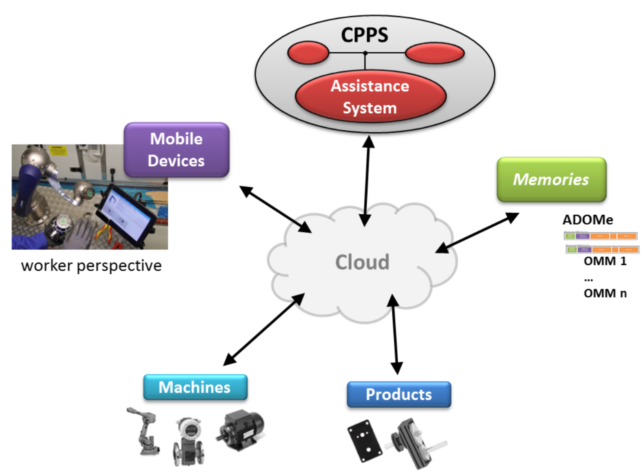

Figure 3: Cloud infrastructure.

Figure 3 shows the cloud that connects and combines infrastructure components, like the assistance system and the ADOMes, the interaction layer via mobile devices (from the perspective of the worker), the manufactured products, and the field device level, e.g., sensors and machines. Based on a systematic monitoring of all components intelligent data analysis (data mining) can help to detect early signs of problems or uncover impending problems on device level. This saves maintenance costs and avoids a system break down.

III. Concept of Distributed Manufacturing Data

This concept is based on the idea of distributed manufacturing data across a network. This distributed functionality forms the basis for the independent configuration of system components and the context-specific consideration by analysis tools. In the implementation, we use the vision of agile automation systems that is based on distributed CPS and SOA. This vision defines a new control paradigm to improve traditional control structures in the domain of industrial automation [21], [33] and puts focus on the four-stage concept of intelligent behavior of production systems [5]:

1) Communication and distributed functionality
   - Factory as a network of mechanical parts
   - Resolution of the communication hierarchy
   - Horizontal and vertical integration
2) Adaptivity and autonomy
   - Independent configuration of the system control at run-time
   - Autonomous control of machining processes by target
3) Context-sensitive cognitive machine systems
   - Dynamic adjustment of production parameters is determined by environmental influences
   - Consideration of knowledge of products and systems to optimize production by target
4) Self-optimizing production systems
   - Independent setting of production targets of the individual process steps for the comprehensive optimization of the value chain

Today's efforts tackle the challenges, described at the first stage *communication and distributed functionality*, with focus on the horizontal and vertical integration and the communication without hierarchical restrictions. This work exactly aims on this aspect and considers a production line of a smart factory as a sum of several autonomous CPS. In addition to these aforementioned smart products, there are also intelligent CPS-enabled ADOMes that structure the accruing data of field devices and produced objects and make them accessible. Accordingly, each of these systems is able to act self-regulating and self-monitoring as autonomous factory component, consequently they are able to communicate with each other.

To get a higher impact and more context-sensitive adaption of the production system, the heterogeneous environment of a production line must be virtually mapped and formalized. In this concept we use the ADOMe-approach in combination with suitable models that describe resources and the situational context. These models minimize the dependencies between technologies providing flexibility and individual adaptability. The creation, maintenance, evaluation and handling of the models require a series of processing steps that have been merged into one production system to achieve a combination of decentralized control, data storage, and access.

A. Cloud-based Manufacturing

This approach makes use of the potential of a cloud-based networked service platform to improve the manufacturing process, information sharing, and quality management. The advantages of the IoT and information technology, that everything is linked via network, promote the combination and conversion of manufacturing and service, to integrate new resources or orchestrate existing resources in the manufacturing process in a new manner [34], [35]. Figure 4 shows the focus on SOA and services, which means that the existing hierarchical level structure needs to be adjusted. Tasks and functions of individual systems will be divided and provided by services. Functionalities of the MES level are split up and different parts are assigned to the CPPS and the field device level. Basic services describe field device functionality and each device also addresses dedicated requirements and complex dependencies. In addition, the services provide convenient access to their knowledge sources and the parametrization of dedicated field devices and sensors. Thus, it is possible to adjust a device for the purposes of configuration or optimization within the cloud.

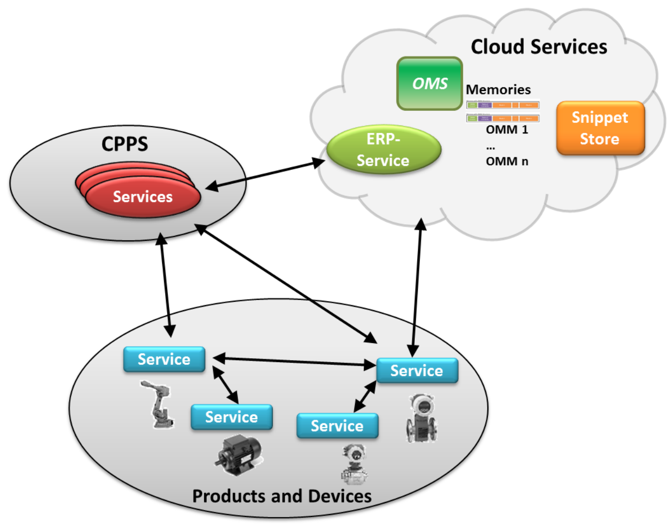

Figure 4: Cloud-based automation network.

Within the cloud network different resources, such as processing power, memory or software, in the form of little scripts, are provided dynamically and appropriately. In this approach, small decentralized scripts perform simple comparison tasks, like state monitoring and value checks, and the result is reported to an upstream assistance system. In same cases a reaction, like a rework task for drilling a whole again with another drill, can be immediately triggered in the process.

The Object Memory Server (OMS), described in detail in Section V-B, is a decisive infrastructure component that stores ADOMes, according to the model of an application server to serve a large number of users.

B. Smart CPS-enabled Field Devices and Active Digital Object Memories

In this approach, each field device has an upstream CPS, described as CPS-enabled, but in the future existing micro controllers and CPS merge to a smart system and take over the tasks of networking and automation control. The specific functionality of each the field device is offered by a service description, e.g., Web Service Description Language (WSDL) [36], in a SOA, shown in Figure 5. The networking of the individual devices is carried out in accordance with an IP network.

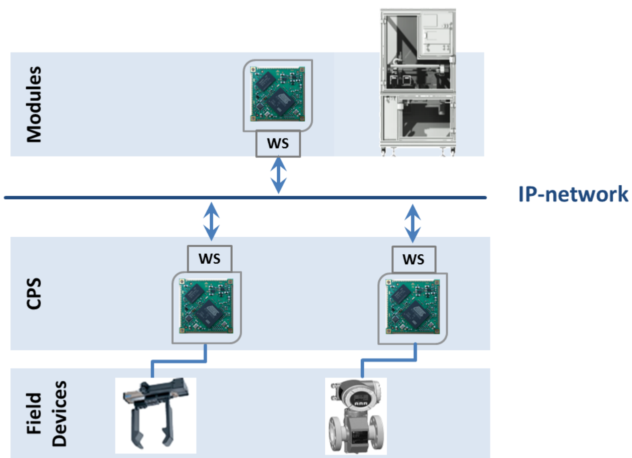

Figure 5: Smart CPS-enabled field devices.

From the user perspective it is absolutely essential to save the production data both locally and globally in a respective ADOMe. This is intended for safety reasons in case of failure or network problems to provide additional security and another possible way to access the production data. Whereby both versions differ from each other, the local memory represents only a subset of the global memory. Because large amounts of data or storage-intensive data types (e.g., CAD drawings, manufacturer documentation and other internal company documents, videos and examples, electrical wiring diagrams, data history) must be stored in the global version of the ADOMe, because the storage capacity of embedded systems is usually tight. Taking into account these memory restrictions, the local version is an adaptation or filtered version of the global ADOMe, only the necessary information, required for operation and production are stored here. But to accomplish this and to create a special limited local version of an ADOMe, there exist synchronization points and communication structures to ensure the correct synchronization when modifying local or global variables or parameters. Nevertheless, the specific parametrization of field devices should be done first on the unit's local ADOMe and shall be directly accessible. For the fine tuning of dedicated field devices, it is to complex and not practicable to access the central CPPS or global ADOMe. This decentralized parametrization can also be advantageous by setting up a new plant whose infrastructure is also still under construction, or when plant parts are reconstructed and quick compatibility checks must be performed using local data access.

Moreover, by the idea that the data is available on the produced object, the ability is given to access these information, just in other factory halls or other companies without access to the central network. Due to the possibility, to keep only certain production data locally in the product's object memory, no sensible production data leaves the factory.

C. Data Modeling and Interpretation

Modeling is an aim to make a feature or part easier to understand, define, monitor, and analyze by referencing on common knowledge. Modelling processes using semantic technologies provide machine- and as well as human-readable descriptions. Such descriptions give more control on the defined processes compared to syntactic technologies in terms of meaningful relations, reusability, and interoperability.

Within complex processes of modern production facilities information from different sources of knowledge are used to monitor and analyze the expiring manufacturing processes. A simplified representation of complex processes and data structures by special classification structures or taxonomies of categories and concepts can contribute added value, because problems, e.g. of field devices or machines, can be detected in an early stage of production. Figure 6 shows needed parts for a uniform description of field device functionality.

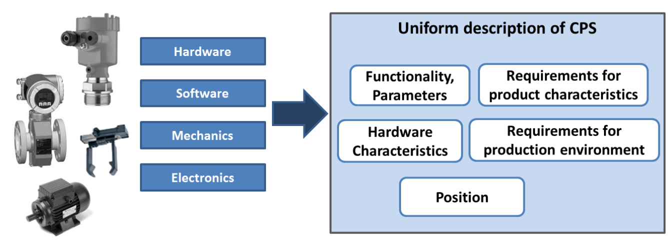

Figure 6: Uniform description of field device functionality.

As a solution of this project, we created semantic models of the different application domains that represents the properties and characteristics of the factory environment, sensors, processes, products and field devices and describes them formally and unambiguously. To bind all of these different application models via one situational base model allows drawing connections, so-called implicit dependencies, e.g., of certain groups of devices or users and processes.

The situational model represents the data structures from all connected application domains, see Figure 7. The user model gives a personalized view on handling user roles and skills. Whereas the device and resource model creates a semantic description for the whole factory view. This includes large amounts of sensor and field device data as well as the functionality parametrization of these different devices. The process and the product model handle large amounts on process or product data. One goal of this approach is to examine technical specifications and dependencies of products and their quality characteristics and create a specific model, in order to make a discovery or usage in the production process possible.

Through the use of such a device model, neighboring CPS-enabled devices can communicate with each other. This allows

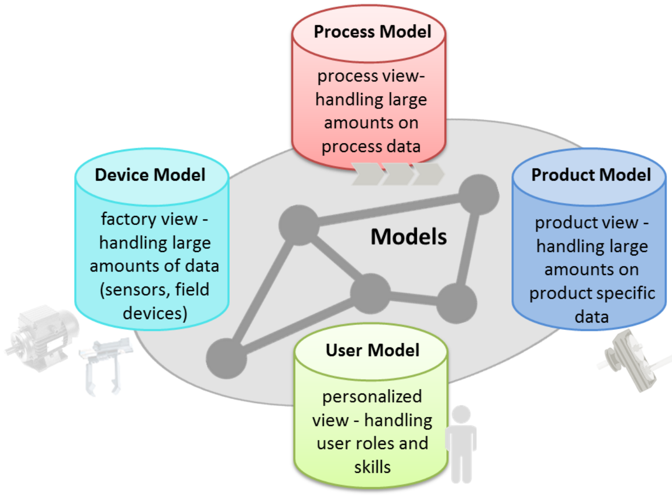

Figure 7: Models of different application domains.

a better coordination of relevant dependencies of field devices with encapsulated functionality, e.g., just to define the transfer points of a workpiece or the conveyor belt height and speed. Furthermore, this model also allows the aggregation of field devices within a production line. Specific manufacturing steps can be carried out in encapsulated manufacturing steps of a CPS-enabled field device, but all processes are effectively planned, managed, and overall controlled by inference mechanisms at CPPS-level.

Involving semantic technologies in the industrial domain of manufacturing requires a comprehensive analysis of existing approaches, standards and guidelines. The examination, analysis and evaluation of existing research approaches and standards, currently used in the field of automation and process industry, leads to the conclusion that there exists no model for the description of field devices which could be taken without any change or adaptation. To find or develop an existing approach, an analysis and assessment has been carried out, describing how semantic technologies in exactly this areas are used. Private domain models, e.g., to describe field devices of specific plant parts in detail with information classes and concepts have been build on this consideration. Furthermore, this model formally represents encapsulated specific control knowledge and concrete parametrization of field devices in machine-readable structures. This is also important for further processing of the data in order to use background, environmental or implicit knowledge by inference mechanisms.

IV. Scenario

In our scenario, depicted in detail in Figure 8, we take the specific case of the production of a gearbox that should be improved or modified during the manufacturing stage. The focus is on the milling of the base plate and the subsequent process of assembling the individual parts. First, the bottom plate is milled and verified by camera, before in a second production step, the product is assembled. These processes take place in different production lines, which are coupled via a workpiece carrier (WPC). The WPC accompanies the product through the milling, assembling and processing cycle and carries the product physically. The WPC is also equipped with a CPS-enabled ADOMe, which couples the physical product part with its virtual counterpart, which represents all product-specific data. Within this interconnected infrastructure, the WPC has access to all information of the product, to provide relevant and necessary data at the respective part of the industrial plant. The WPC communicates with the ADOMe of the respective object, to provide information for the next production step. Thus, produced objects can be registered early in the process flow.

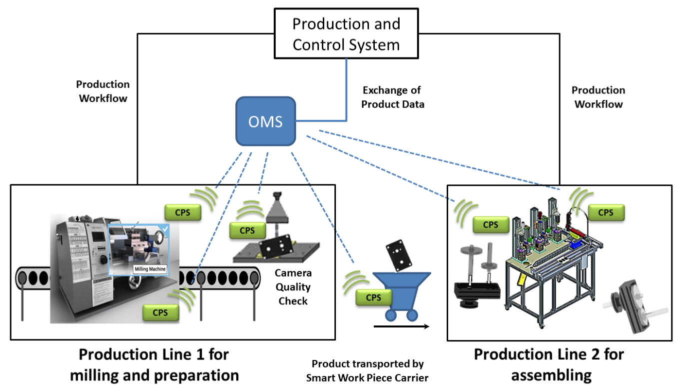

Figure 8: Production scenario.

Beside the idea to structure information in a unified structured format, another goal of this approach is the decentralized autonomous processing of information and immediate derivation of a solution on a CPS-enabled ADOMe. After milling a small script, which has already be embedded to the local ADOMe of the product, checks in a comparison task, whether the actual values match to the specified target values, which are also stored in the same ADOMe. This review will determine, whether the product is fine and meets the quality requirements for the production order, if rework is necessary or it is a faulty product. If reworking is required for that workpiece, a note is stored in the product's memory and the product can be supplied to the production cycle again, when a correctable deviation can be solved directly in the production line. The delayed delivery of produced products, because of reworking, can bring the production process to a standstill. Such bottlenecks can be identified and communicated early enough, so that the overall system is able to reschedule the production workflow.

The smart product knows the sequence and which operations a machine did during the production cycle. Each action is stored by timestamp in an ADOMe. In this assembling scenario of a gearbox, many parts exist that look very similar and have to be prepared and assembled in a certain order. In many cases, it is difficult or not possible to distinguish the material characteristics and the suitability of the gear parts with the naked eye, or depending on the order specification materials of different quality, e.g., stainless steel, titanium or steel, are used and incorporated in the gearbox. In this special case, every produced part has its ADOMe that allows access to the data, which are needed for the next processing or assembling step and for reasons of quality assurance. Furthermore, every single processing step is registered and must be compared with the desired processing steps, defined in the detailed construction phase of the product. Furthermore, also the quality of products varies depending on the customer different dimensions of the gaps are tolerated.

In order to deploy and synchronize a global ADOMe, an server platform was created, the Object Memory Server (OMS), which provides service functionality in the cloud or the local network. This component is described in detail in Section V-B, cloud-based manufacturing.

V. Technical Components of the Framework

The approach can be subdivided into three processing areas that need to interact with each other. Figure 9 shows the actual products and field device level, represented by each CPS and the associated ADOMe, furthermore, the supply level, where services, snippets and ADOMes are hosted as cloud-based networked solutions, and the assistance level for decision support and knowledge acquisition of the *CPPS*. Decision making is based on the dedicated processing steps and the context-adaptive provision of information of field devices and manufactured products stored in their ADOMes. Each product or field device has both a local and a global ADOMe. The local ADOMe is stored directly on the CPS with limited memory, and the global ADOMe, for storage-intensive data types, is stored by a central server, the OMS.

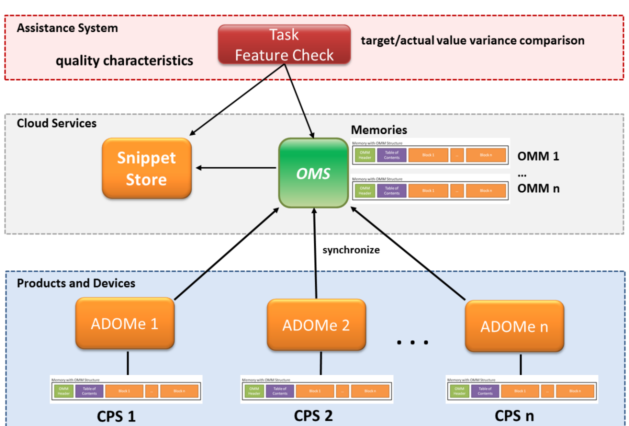

Figure 9: Interaction of the individual components of the framework.

A. Production Assistance System

In a CPPS with many decentralized CPS-enabled modules, condition reports to the overall system are very important. The adopted assistance system for CPPS acts as logical parent unit and is based on managed information out of individual product ADOMes. As presented in Figure 10, the contextual evaluation and context-specific management of processes and procedures is based on facts about the manufactured products (ADOMe), the factory parts (factory model) and the current situation, influenced by the manufacturing process and the skills and role of the user (user model, situational model). The assistance system monitors and supervises the course of production based on process data of the production cycle, and it also monitors and supports the decisions taken by the decentralized scripts. If an intervention in the workflow of the current manufacturing process is needed, based on all converging information here, it generates precise instructions for handling and rescheduling of the production order, or triggers actions, such as maintenance, alteration, or replacement of system components. These reactions of the system are defined in context-dependent rules based on described models, which represents the domain knowledge and the special vocabulary and terminology. The system decides, whether the manufactured parts are ready for further processing, if they must be revised or if it is rejected goods. These actions are transferred to and processed by the module for output presentation and communicated to the registered clients and subsequent actors. [30]

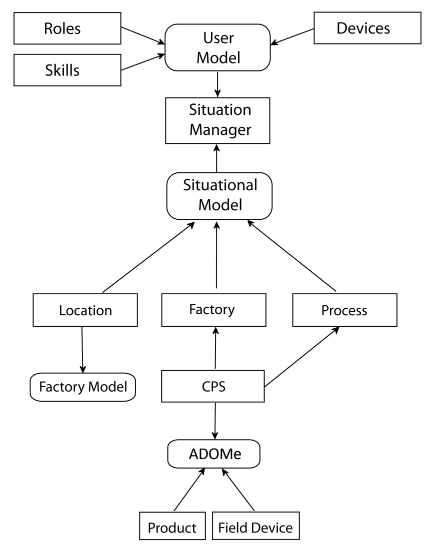

Figure 10: Contextual management based on a situational model.

However, the focus of this approach is not on the consideration and evaluation of complex relationships, for which this assistance system has been designed, but first on simple evaluation purposes, such as self-monitoring and the self-check of quality parameters of a manufactured object or a single field device within its ADOMe and its aligned embedded system. Each distributed ADOMe performs its individual quality checks and returns the data to the assistance system. For example, when a field device is re-parametrized, recommendations are formulated that rely upon the data stored in the history of the memories of this device.

Within the system infrastructure, the tiny scripts, we named them snippets, will be hosted in a central cloud-based *Snippet Store*, see Figure 9. Moreover, based on the task description of the assistance system, e.g., “quality control by target value comparison”, concrete recommendations for scripts are given which adequately provide the required skills. An appropriate matching script is installed in the local ADOMe, when it is compatible with the existing combination of hardware and software of the CPS. The assistance system administrates the runtime of the local ADOMe and sets the execution interval of the script. This scheduling job of the script runs the small tasks, like memory operations or maintenance procedures, based on necessary boundary parameters made dynamically available on the product memory. Moreover, the assistance system must react according to the notification or event mechanism and create a listener functionality for this device configuration. This means that the overall CPPS must check within a time interval, whether the message or event status of an ADOMe has changed. In accordance to these message or event types a recommendation is triggered of the CPPS, which may affect the current production process.

The component is used for decision support and the derivation of recommendations. The structure and the data flow of the assistance system with its input and output channels is shown in Figure 11. Several information sources, like products and machine parts, and also the decentralized working small scripts report data in certain time intervals. All these information are classified and evaluated by the assistance system using the situational model and the models of the different application domains. To evaluate the inputs, a rule system is used that operates on a set of predefined rules, adapted to the present compilation of the plant. The results of the evaluation process are delivered to the presentation manager, which prepares them for the respective user and his device.

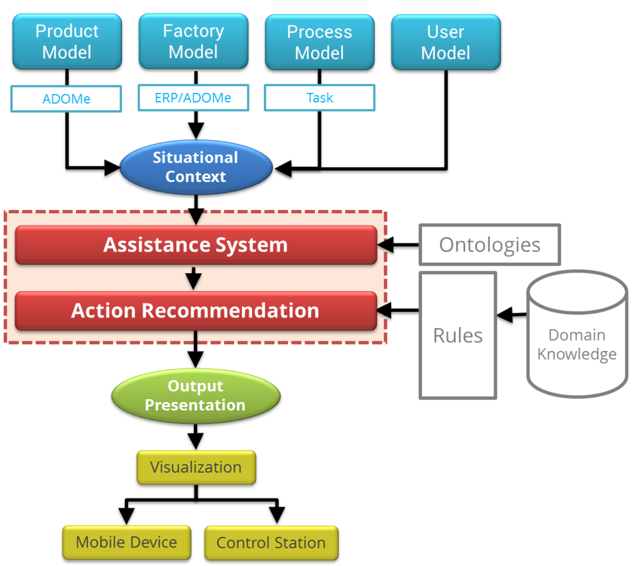

Figure 11: Assistance system and data flow.

B. Object Memory Server

OMM-based object memories can be created and stored as XML-file or binary block, but this is no longer practical for a large number of memories. For this reason, the OMS has been implemented, which can be embedded as a service in the cloud infrastructure and manages all ADOMes. Figure 12 shows the architecture and dedicated modules of the OMS that can be orchestrated on demand, depending on the intended application scenario. This server component allows the deployment and undeployment of ADOMes at runtime and uses for protection of the stored contents a role based authentication module for restricted access. Currently, three different modes are supported for data access: passwords, certificates and electronic ID cards [37].

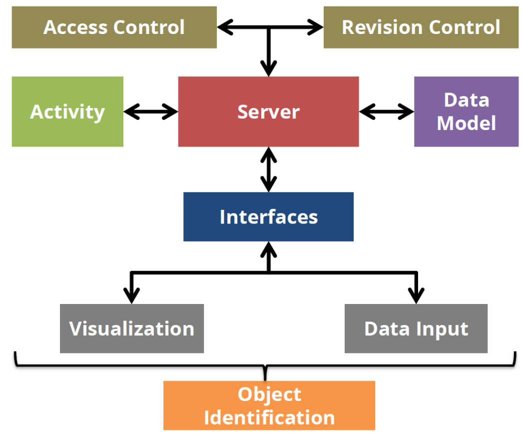

Figure 12: Server-based OMM Architecture [37].

Via a RESTful Web service interface the OMS permits access to process data of each manufacturer and provides the functions to create, store, replace, and modify the data structures in a uniform and consistent manner. Figure 13 shows the interaction of the CPS' client layer with the OMS. The OMS uses an generic software library to handle XML-based OMM representations to structure and represent the delivered data in an appropriate format. This entails the creation of OMS-records, all communicated data are checked and traceably documented at the time the information was accepted and inserted in the CPS' ADOMe [25]. But upon closer examination of the data structures from different manufacturers, it becomes evident that no approach is suitable for all requirements, hence the OMS will always be characterized by a certain heterogeneity.

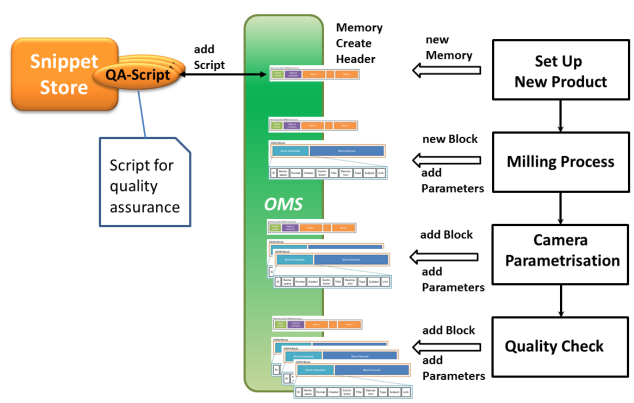

Figure 13: OMS creates ADOMe in production.

C. Interaction and Output Presentation

A smart factory can never operate without human employees, so one key issue is the human to machine interaction. In a production process, a lot of information passes from monitoring and control, but the problem usually lies in the overview and the appropriate visualization. When people work together with self-learning and self-adapting systems like CPS-based systems, they need to understand each other and which processes are internally occurring. Therefore, the user interface for technical experts or operators is dynamically adapted by a personal assistance system and its module for situational management. This system creates specific UI-layouts or templates for the presentation of contents for diverse mobile devices of the workers (notebooks, smartphones, tablets, smart watches). Currently available monitoring data are presented in adaptable views in form of a curve visualization as depicted in Figure 14. This overview allows the trained experts to draw conclusions about the manufacturing process and possible bottlenecks.

Figure 14: Worker performing a maintenance task with a mobile device.

First, the situational management component selects the appropriate visualization for a registered device. This selection is based on the situational model, that provides all gathered information about the present situational factors (e.g., user model, parametric influences of the location, factory and production process). According to specific predefined inference rules, which are applied to this model, a visualization pattern is determined and prepared for different devices. In this consideration, the special privileges and responsibilities play a major role for an adaptive intelligent visualization, because a technician requires a different view in error or maintenance purposes, as a machine operator who inspects the up and running plant.

VI. Conclusion and Outlook

This article described the conceptualization and implementation of a cyber-physical industrial environment and the use of virtual counterparts of real physical objects, whose data is stored in active digital object memories (ADOMe), hosted on a dedicated Object Memory Server. The described Cyber-Physical Systems (CPS) enable these memories to communicate over the network and to fulfill small tasks in a decentralized autonomous way, which contribute to the production cycle, like storage cleaning, threshold value monitoring or target/actual-value comparisons. The expertise of a fully fitted and configured production line is now available and formalized in the dedicated ADOMes of each plant part. Based on this data an assistance system can easily assist in the configuration or reconfiguration of new devices, machine parts, and CPS. Furthermore, the permanent monitoring of the data generates a large amount of data that can be used to improve the early detection of errors and feedback loops, as well as for functional testing. This could even reach a stage, referred to the case of maintenance, in which production systems autonomously order spare parts long before a component fails. With these interconnected CPS, it will be possible to implement further product requirements, such as the efficient use of energy and raw materials in production. Moreover, it will be possible to personalize products and adapt product features in regards to local needs and their individual manufacturing process. According to the product lifecycle management (PLM) and the deposited history in the active digital object memories, it is easily possible to draw conclusions from the product to the plant parts, which has manufactured the product. This could be advantageous in cases of warranty claims.

A smart factory can never operate without human employees, so one key issue is the visualization of the stored contents of a dedicated ADOMe. Future work will cover this topic and will further develop strategies that will help to identify and visualize important key values and how these should be presented to the worker (e.g., via tablets or smart watches).

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