Intelligent Manufacturing based on Self-Monitoring Cyber-Physical Systems

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Abstract—**This paper describes the approach and implementation of a system that combines real industrial environments with a virtual copy of these components. The coupling elements for communication and data management are cyber-physical systems and active digital object memories. The idea of this approach is to create an assistance system that relies on these virtual digital object memories to ensure quality characteristics and to describe any information in a unified structured format. Up to a certain level of complexity, state changes and feature checks are done decentralized by each object memory, in the way of autonomous control.**

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

I. INTRODUCTION

The current order of the market is shifting more and more towards the idea of an individual production, different product variants need to be made in almost no time. 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. Nowadays, as a general trend, the focus shifts from pure engineering, which is based on mechanical processes, to software-controlled processes [1]. Future-oriented technologies will increase efficiency in production, for instance through the application of self-monitoring for manufactured products and field devices [2].

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, Cyber-Physical Systems (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) [2]. 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 [3], and this approach shows the integration of these systems in a real production environment.

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. 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”. 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.

In Section II, this paper gives an overview of used technologies and introduces the terms field devices, IoT, CPS, active digital object memories, smart factories and smart products. The Section III describes the concept of 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 creation of an infrastructure for distributed CPS-based product memories is shown in detail, and 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 [4], 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” [5]. This article was entitled “The internet of things”, and was the first documented use of the term in a literal sense [6].

C. Cyber-Physical Systems

In the fields of agriculture, health, transport, energy supply and industry, we are facing a revolution, hat 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 Systems (CPS) was coined [7]. 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 [8] 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 [2][9].
These following four features typically characterize CPS [10]:

- 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 [3][11]. 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?*).

D. 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 [12]. 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.

E. Active Digital Object Memories

The development of the IoT makes it possible to assign a digital identity to physical objects [13][14]. 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 [15]. 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 [16]. 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 [17].

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 [18] and *Industrie 4.0* in Germany [2].

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) [19] 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. [20] 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) [21] and implemented an own 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. The present work uses the idea of the Object Memory Modeling (OMM) [21] and implemented an own 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.

F. 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 1 [22].

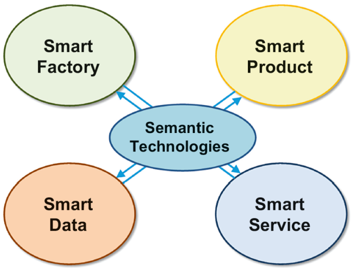

Figure 1: Customization based on semantic technologies [22].

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.

III. CONCEPT OF DISTRIBUTED MANUFACTURING DATA

In our approach, we consider 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.

The idea of this approach is to distinguish between locally and globally accessible data structures, respectively represented by an ADOMe. 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.

IV. SCENARIO

In our scenario, depicted in detail in Figure 2, 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, that 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.

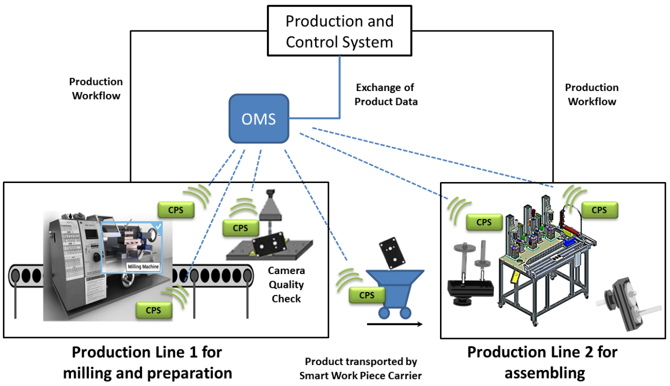

Figure 2: Production scenario.

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, that 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. In this special case, every produced part has its own 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.

In order to deploy and synchronize a global ADOMe, an own 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 3 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.

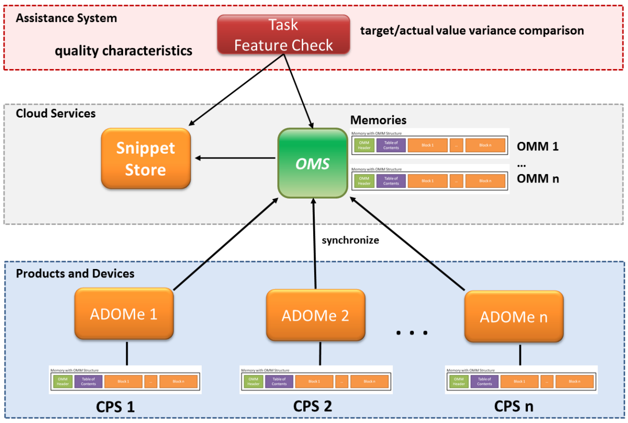

Figure 3: Interaction of the individual components of the framework.

A. Production Assistance System

In an 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 on Figure 4, 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.

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 3. Furthermore, 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.

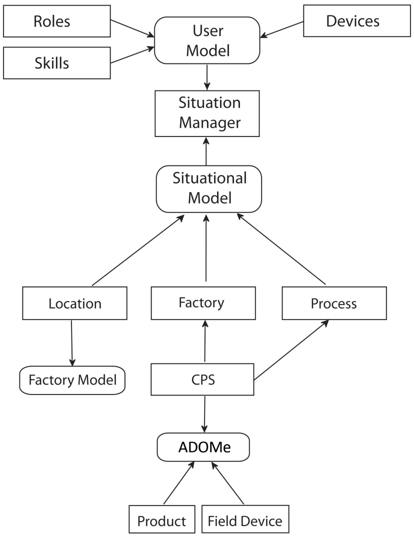

Figure 4: Contextual management based on a situational model.

B. Cloud-based Manufacturing

This approach makes use of the potential of a cloud-based networked solution to improve the production process, information sharing, and quality management. Within the cloud, resources, such as processing power, memory or software, in the form of little scripts, are provided dynamically and appropriately over a network. The Object Memory Server (OMS) is the main infrastructure component that stores ADOMes, according to the model of an application server to serve a large number of users. 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 5 shows the interaction of the CPS’ client layer with the OMS. The OMS uses an own implementation (API) of the Object Memory Model (OMM) 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. 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.

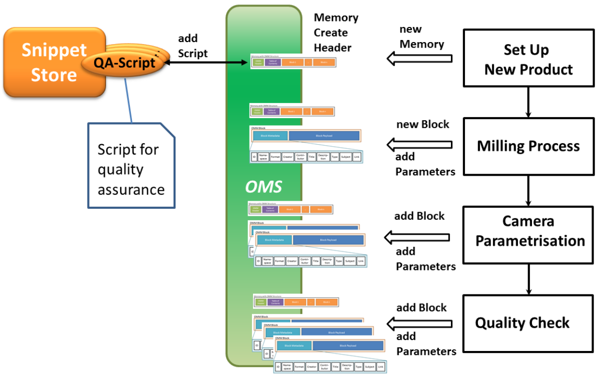

Figure 5: OMS creates ADOMe in production.

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 6. This overview allows the trained experts to draw conclusions about the manufacturing process and possible bottlenecks. 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

Figure 6: Worker performing a maintenance task with a mobile device.

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, hosted on a dedicated Object Memory Server. The described cyber-physical systems 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. 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 cyber-physical systems, it will be possible to implement further product requirements, such as the efficient use of energy and raw materials in production. Furthermore, it will be possible to personalize products and adapt product features in regards to local needs and their individual manufacturing process.

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).

VII. ACKNOWLEDGMENT

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