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Semantic data management for the development and continuous reconfiguration of smart products and systems

Michael Abramovici (2)*, Jens Christian Göbel, Hoang Bao Dang

Information Technology in Mechanical Engineering (ITM), Ruhr University of Bochum, Germany

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ABSTRACT

The paper describes an approach to a new generation of data management for an interdisciplinary, globally distributed development and continuous reconfiguration of smart products. The proposed solution is flexible, dynamic, has a high semantic content and considers both virtual product models as well as feedback data from the physical product along its whole lifecycle (digital product twin). The implementation of the proposed approach has furthermore been introduced by means of prototyping a SDM integration platform.

1. Introduction

The rapid development of microchip, sensor and IT technologies has strongly changed the way to build and use physical products. The new product generation is called “Smart Product”. **Smart products** (**SP**), synonym for smart systems, “are cyber-physical products/systems (CPS) which additionally use and integrate internet-based services in order to perform a required functionality. CPS are defined as intelligent mechatronic products/systems capable of communicating and interacting with other CPS by using different communication channels, i.e. the internet or wireless LAN” [1]. This means that smart products not only consist of mechatronic components but also of IT driven components (e.g. internet-based services). One example of a SP is a self-driving ambulance car. These “intelligent” cars can recognize changes in the environment and drive the patients safely to the nearest hospital available without human drivers. Such cars can be built based on different well-known components like mechanical housing, IT hardware, sensors, communication units and internet-based services (in this case apps to check and find the nearest available hospital and the navigation app).

In order to develop and reconfigure innovative SPs, different competences from different companies are needed, who are specialists in their respective domain of technology. It means the development of SPs presupposes various know-hows about different technologies, which the manufacturer alone does not have.

1.1. Relevant information for the development and continuous reconfiguration of smart products

For the development and continuous reconfiguration of SPs, three types of information are needed (**component information**, **architectural information and SP usage information**) (based on [2]). The **architectural information** is the information about the way how different components of SPs are integrated into a coherent whole and how they influence each other. Examples of architectural information are version-oriented product structures and time-oriented instance structures. In comparison, the **component information** is the information about the core design concepts of each component of the SP, including the functions which each component performs. The **SP usage information** is generated during the use of SPs (e.g. use incidents, operation parameters or resource consumption) and from the interactions between SPs and their environment. The three types of information build the fundament to realize the above-mentioned changes.

The greatest challenges in the management of SP-related information lie in the collection and integration of this information as well as in the organization of information flows within a cross-enterprise network. The information (with different structures) specifically needs to be captured in form of knowledge by putting the data in a specific context, with attached rules, processes, and instructions. This “knowledge” derived from different heterogeneous sources (from different partners) has to be integrated in meaningful ways.

1.2. Scope and focus

In this paper, we focus on problems regarding the handling of these three types of information (component information, architectural information and SP usage of information) within a high dynamic cross-enterprise network. Thus, not only information about virtual SP-components will be considered, but also information about the concrete individuals. Furthermore, a semantic data management concept will be presented, which grew out of research in the automotive and machine-tool industries. The concept helps to explain how the development

* Corresponding author.
E-mail address: michael.abramovici@rub.de (M. Abramovici).

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and continuous reconfiguration of SPs can have great competitive consequences.

2. State of the art

One well-established approach to enable storing, managing and re-using product information is the Product Lifecycle Management (PLM) approach. The PLM approach "is a strategic business approach that supports all the phases of product lifecycle, from concept to disposal, providing a unique and timed product data source. Integrating people, processes, and technologies and assuring information consistency, traceability, and long-term archiving, PLM enables organizations to collaborate within and across the extended enterprise [3]." PLM also provides IT-solutions (e.g. PLM system) to facilitate communication and collaboration across functional, organizational and geographic boundaries with an emphasis on SP engineering processes.

The most recent research activities in the area of PLM have a focus on different engineering methods which support the development of mechatronic products throughout the entire product lifecycle. A few of these activities focus on concrete product instances in phases of usage. For example, in context of feedback management, Abramovici and Lindner developed a solution using Bayesian networks in order to improve the next product generation based on information from use phase [4]. Kubler et al. presented an approach for the management of product instance data by using RFID[1] technology [5]. In some of the research activities, cross-disciplinary engineering aspects for instance the PDLM (Produkt-Dienstleistung-Lebenszyklus Management) approach developed by Zinke et al. [6] has also been considered. Table 1 presents an overview over the most relevant research activities and their focuses.

In summary, none of them considers the interactions between products and IT services or the relationship between smart products (real objects) and their digital product twins (virtual objects). Last but not least, most state-of-the-art methods lack of support for the development and reconfiguration processes of SPs.

Table 1
Relevant PLM approaches and their focuses.

	Focus		
	Considered object	Considered life cycle phase	Considered information
Closed-loop PLM [5]	Material objects (smart products for business-to-customer market)	Operation phase	Instance use and component information
PDLM [6]	Material and immaterial objects (products; product related services)	Entire product and service lifecycles	Not specified
ONTO-PDM [7]	Material objects	Development phase	Component information
Museological PLM [8]	Immaterial objects (cultural heritage)	–	Historical information
OBISO [9]	Material objects	Development phase	Component information

3. Approach of semantic data management

The proposed **semantic data management** (SDM) (see Fig. 1), which emanates from the PLM approach, shows the ways in which all three relevant information types are managed within an enterprise-wide and cross-enterprise network. In regard to SDM development, the management of IT services and the aspects of interplay between IT services and mechatronic components have also been taken into account. Moreover, the proposed approach enables sharing of knowledge within multidisciplinary cross-enterprise cooperation networks.

[1] RFID: **radio-frequency identification** has been used in order to automatically identify and track tags attached to objects.

3.1. Method-specific changes within the SDM approach

In this section, a paradigm shift from PLM to SDM, supporting the development and reconfiguration of SPs, will be described. The focus lies on the changes of different engineering methods along the lifecycle of SPs. Fig. 1 describes the proposed approach and its main engineering methods. Compared to the PLM approach, the SDM approach covers both virtual and real lifecycles of products and the related information flow throughout the lifecycles.

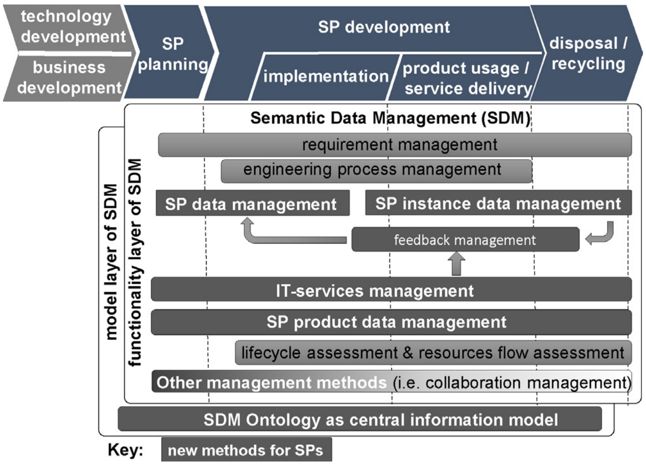

Fig. 1. Approach of semantic data management (SDM).

In the context of SPs, the manufacturer has the opportunity to monitor the use of SPs and to collect different data during the operational phase (e.g. product use information, usage conditions). The **SP instance data management** method provides an effective tool to manage all the information related to SP individuals (incl. **SP usage information**). As a core component of the SP instance data management method, a time-oriented instance structure is used to assembly the data related to the SP individuals. Moreover, this structure records all the changes of real SP components. The SP instance data management provides answers to a variety of questions, such as: (1) How do the (/best) working parameters of different components look like? (in which usage situation?); (2) Which component individuals have been used in which time frame? (3) Which kinds of services have been delivered on which component individuals? (4) Which kinds of failure of which component individuals in which usage situations occurred? (5) When has which component been exchanged or implemented?

Such information can be evaluated by **feedback management methods** and then be used by designers and developers or IT services for the optimization and improvement of products. Depending on each specific goal, divergent Big Data analysis methods can be used. For example, Bayesian networks can be applied to simulate the system behaviour for various possible usage situations based on historical working parameters of SPs [4]. While the SP instance data management and feedback management focus on SP individuals, the virtual SPs (SP models) take the centre stage of the **SP data management**. Similar to product data management in the PLM approach, the **component information** about virtual SPs is the main focus of SP data management. For example, the component information describes how different components of SPs can be realized and which functions they must carry out. In the context of SP design, the functions of SPs can also be realized by using IT services or by combining the IT services and goods. Furthermore, the environment (other products SP is communicating with) also needs to be considered when designing SPs. All these aspects help to better manage the complexity of the development and reconfiguration of SPs.

The next method-specific extension of the SDM approach is the inclusion of different IT services, which make SPs smarter and more agile. IT services analyze usage information of SPs, for example, in order to help SPs or technicians to make the correct