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Intelligent products: The grace experience

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ABSTRACT

Product intelligence is a new industrial manufacturing control paradigm aligned with the context of cyber-physical systems and addressing the current requirements of flexibility, reconfigurability and responsiveness. This paradigm introduces benefits in terms of improvement of the entire product's life-cycle, and particularly the product quality and customization, aiming the customer satisfaction. This paper presents an implementation of a system of intelligent products, developed under the scope of the GRACE project, where an agent-based solution was deployed in a factory plant producing laundry washing machines. The achieved results show an increase of the production and energy efficiency, an increase of the product quality and customization, as well as a reduction of the scrap costs.

1. Introduction

Traditionally, manufacturing domain operates in a conservative market place, with plants running for more than 10 years, unanticipated downtime provoking significant losses and using Enterprise Resource Planning (ERP) systems focused on mass production. However, worldwide markets are imposing strong requirements in terms of cost, quality, customization and responsiveness (ElMaraghy, 2006). These requirements create new needs related to the introduction of new manufacturing paradigms and methods, and especially decentralized approaches, being manufacturing companies forced to adopt more modular, flexible, adaptive and reconfigurable systems aiming to remain competitive in this severe context. Particularly, manufacturing systems should cope with the high degree of complexity required to implement agility, flexibility and reactivity in customized manufacturing (Morel, Valckenaers, Faure, Pereira, & Diedrich, 2007).

The factory of the future can be seen as a large and complex system of systems, where collaboration takes place to reach global goals, complemented with other key issues like intelligence, responsiveness and adaptation. The achievement of the factory of the future raises several challenges, namely interoperability, plug and play, self-adaptation, reliability, energy awareness, cross layer integration, event propagation and management. The achievement of these advanced functionalities requires the use of new paradigms, such as Cyber-Physical Systems (CPS) (Rajkumar, Lee, Sha, & Sankovic, 2010; Colombo et al., 2014). In opposite to the concept of Internet of Things (Gershenfeld, Krikorian, & Cohen, 2004), where the focus is more in the interconnection of cooperative objects, the CPS concept also considers the computational decision-making components to provide intelligence, responsiveness and adaptation. In fact, CPS combines mechatronics and Information Technology (IT) to control physical processes and systems, designed as a network of interacting software and hardware components, devices and systems, each one with a higher level of autonomous decision making. CPS focus intelligent, dynamic and self-* large-scale systems, such as manufacturing and processes plants, electrical power grids and pipelines, logistics and transportation.

Industrie 4.0 is a German initiative constituting a concretization of CPS to promote the computerization of traditional industries aiming to achieve intelligent factories characterized by adaptability, efficiency, reliability, safety, and usability, and supporting the integration of the supply chain (Böhler, 2012). This vision, seen as the 4th industrial revolution, considers distributed intelligence and self-* methods, e.g., adaptation, configuration and diagnosis. In the United States, a similar concept is the Industrial Internet that aims the integration of complex physical machinery with networked sensors and software. The Industrial Internet Consortium comprise General Electric, AT&T, Cisco Systems, Intel, IBM and United States government and has a broader scope than

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industrial production, namely covering also smart electrical grids, smart transportation and smart healthcare.

The concept of intelligent product (Meyer, Främling, & Holmströmc, 2009; McFarlane, Giannikas, Wong, & Harrison, 2013) is a new industrial manufacturing control paradigm, aligned with CPS. Intelligent products carry the knowledge about their characteristics, wirelessly connected to share, in real-time, information about their state or environment, or to communicate with other cooperative objects of the Internet of Things (IoT). Intelligent products collect and store data to support the implementation of monitoring, traceability and decision-making functions.

The use of intelligent products can bring important benefits in the Industrie 4.0 and Industrial Internet contexts, namely:

- Establishment of a product-driven production approach (i.e. the product takes the initiative during the plan execution (Wang, Huang, & Dismukes, 2004)).
- Improvement of the entire life-cycle of the product, comprising the design, production, distribution, operation and end of life (Parlikad & McFarlane, 2007) phases.
- Improvement of the product quality and performance through the application of self-⁎ methods, such as self-learning, self-diagnosis, self-adaptation and self-optimization.
- Improvement of the next generation of the product.

Multi-agent systems constitute a software engineering paradigm, derived from distributed artificial intelligence, which is based on a set of distributed, autonomous and cooperative entities, known as agents (Ferber, 1999; Wooldridge, 2002; Leitão, Mařík, & Vrba, 2013). Each agent possesses its own knowledge and skills, being the intelligent global system behaviour emerged from the interaction among the distributed agents. Following the principle of "divide to conquer", multi-agent systems replace the centralized control by a decentralized functioning, allowing reaching a high degree of flexibility, robustness and responsiveness, which are not provided by centralized solutions. Multi-agent systems approach is being applied in several domains, namely electronic commerce, manufacturing and logistics (see e.g., Leitão (2009) for a deeper analysis), and constitutes a suitable technology to implement the intelligent product paradigm.

The objective of this paper is to explore the industrial control paradigm of product intelligence by describing a practical implementation in the manufacturing domain based on the experience gathered during the execution of the GRACE (Integration of process and quality control using multi-agent technology) project (http://grace-project.org/). During this project, a product-driven agent-based solution was installed in a factory plant producing laundry washing machines aiming the integration of process and quality control. The intelligence embedded in distributed and cooperative agents, and particularly in the products, allowed to self-adapt and self-optimize the production and product parameters, improving the production and energy efficiency and the product quality, as well as reducing the costs of scraps.

The paper is organized as follows: Section 2 overviews the concepts and deployment challenges regarding the product intelligence concept and Section 3 overviews the main principles of the GRACE multi-agent system to integrate the process and quality control. Section 4 introduces the concept of intelligent product deployed in an industrial factory plant according to the perspective of the GRACE project, namely describing the embedded intelligence for the on-line decision-making during the production phase and analysing the achieved results. Section 5 presents the intelligence mechanisms for the operation phase to be embedded in the agents hosted in each individual washing machine. Finally, Section 6 rounds up the paper with the conclusions.

2. Intelligent products: concepts and deployment challenges

The concept of intelligent products is being studied by the research community in intelligent manufacturing field (a state of the art in the field can be found in (Meyer et al., 2009; McFarlane et al., 2013)).

2.1. Concepts and theory

The definition of intelligent product is not unique. A possible definition is provided by Meyer et al. (2009) that defines intelligent product as a "*physical order or product instance that is linked to information and rules governing the way it is intended to be made, stored and transported that enables the product to support or influence these operations*". This definition highlights the processes regarding to manufacturing and distribution phases, but should be extended by considering also the operation phase of the product, i.e. when the product is performing the functions for what was created and produced, supporting the closed-loop Product Lifecycle Management (PLM) systems, as described in Kiritsis (2011).

According to Wong, McFarlane, Alunad Zaharudin, and Agarwal (2002), an intelligent product possesses the following five characteristics (or partially):

a) The product possesses a unique identification.
b) The product is capable of communicating with its environment.
c) The product can store data about itself.
d) The product deploys a language to share its features, requirements and plans.
e) The product is capable of participating in relevant decision-makings to its own destiny.

Therefore, an intelligent product comprises IT in the form of software, microprocessors and sensors, and is able to collect and process information and generate knowledge, and even provide reasoning capabilities, as illustrated in Fig. 1. The traceability and identification of products are generally processed by using biometric information or instrumenting the product with related technologies such as barcode or RFID (Radio Frequency Identifier). Each intelligent product provides a set of product related services, e.g., monitoring, data analytics, self-diagnosis and self-maintenance.

Meyer et al. (2009) introduced a three dimensional framework to analyse the intelligence product concept, based on the levels of intelligence, location of the intelligence and aggregation level of intelligence. In terms of levels of intelligence, different levels can be defined, namely:

- Passive: i.e. cooperative objects can only collect and store information.
- Active: i.e. cooperative objects can collect, store, process information (even generating new knowledge), and retrieve information.
- Intelligent: i.e. cooperative objects can reason over collected and stored data and participate in decision-making processes.

The second dimension is related to the location of the intelligence, which can be completely outside the physical product, e.g., running in a remote PC, or located at the physical product itself (in this case, the computational and storing capabilities are required and network connectivity is necessary to interact with other entities). The two possibilities to locate the intelligence are illustrated in Fig. 1. The third dimension is related to the kind of aggregation of the product intelligence, ranging from intelligence only about the product itself or also aware of the components that it is made of (Meyer et al., 2009).