Cross Benefits from Cyber-Physical Systems and Intelligent Products for Future Smart Industries

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***Abstract*—The manufacturing industry is facing a technology paradigm change, as also captured in the Industrie 4.0 vision as the fourth industrial revolution. Future smart industries will require to optimize not only their own manufacturing processes but also the use of products and manufacturing resources, their maintenance and their recycling. In this context the strengths and weaknesses of two key concepts, namely Cyber-Physical Systems (CPS) and Intelligent Product (IP) are discussed, and it is suggested that an integration of these two approaches to meet the introduced emergent requirements is beneficial. The integration of CPS and IP is shown via two real-world industrial cases, covering different phases of the product life-cycle, namely the production, use and maintenance phases.**

I. INTRODUCTION

Business continuity and agility form the core modus operandi of modern global enterprises [1]. As business competition increases, significant efforts are directed to operational improvement, which introduces new demanding requirements across the enterprise. In this context, manufacturers are under great pressure to comply with rapid market changes and the diversification of the product life cycle [2]. As a result, changes on the factory floor are becoming increasingly frequent, and traditional methods for production planning and control need to be adjusted to fulfill the new requirements, e.g., minimize cost, optimize production planning and enhance life-cycle management.

In the last years, the visions of “Smart Factory”, “Industrie 4.0”, “Factory of the Future”, etc., make it clear that there is a need to design manufacturing processes that are more reactive, agile and efficient. These visions have in their core key monitoring and control aspects based on decentralized systems, such as Cyber-Physical Systems (CPS), Multi-Agent Systems (MAS) and holonic architectures. Targeted efforts for specific industry needs, especially towards cloud-based Industrial CPS [3] and industrial agents [4], are seen as promising technologies. In particular CPS, especially when coupled with smart agents [5] have the capability of empowering industrial systems towards achieving the long-pursued vision of collaborative manufacturing [6].

Additionally, customer and societal needs, along with the relevant stakes for sustainability, require optimization of products i.e. their use, maintenance and recycling phases, while their complexity and the diversity of parts on which they are made of also increases. In such a context, manufacturing, among the others, is gaining importance. Innovative approaches based on the Product Life-cycle Management (PLM), suggest new concepts such as Intelligent Products (IP), and Product-Service Systems (PSS) [7], and analyze the global footprint of products thoroughly their life-cycle, from design to recycling, including the production phase, and considering manufacturing resources as a product like-the-others for which the life-cycle can be assessed [8].

As a consequence, future smart industries will require to optimize not only their manufacturing processes [9] but also the use of products and manufacturing resources, their maintenance and their recycling. The former view can be regarded as vertical, inside one phase of products life-cycle (their production), while the latter view can be regarded as horizontal paying attention to the different phases of the systems life-cycle. In this context, strengths and weaknesses of two innovative concepts, namely CPS and IP are discussed and their proposed integration is illustrated by two real industrial examples, namely a train manufacturer (Bombardier) and a washing machines producer (Whirlpool), covering different phases of the product life-cycle.

The paper is organized as follows: section II and section III overviews, respectively, the CPS and IP concepts and identifies their strengths and limitations. section IV analyses the potential benefits of combining these two approaches, especially addressing the product life-cycle of complex systems, and section V describes two examples of combining CPS and IP covering the different phases of the product life-cycle for each of the introduced industrial contexts. Finally, section VI rounds up the paper with the conclusions.

II. CYBER-PHYSICAL SYSTEMS

A. Concept

CPS refers the integration of computational applications with physical devices, being designed as a network of interacting cyber and physical elements [3], [5], [10]. CPS consider the computational decisional components that use the shared

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knowledge and information from physical processes to provide intelligence, responsiveness and adaptation [5]. They differ from embedded systems where the focus is on computational elements hosted in stand-alone devices, as CPS are mostly designed to be a larger network of interacting computational and physical elements.

The realization of CPS may involve the use of several emerging technologies, such as MAS (to provide intelligence and adaptation over decentralized modular systems), Service-oriented Architectures (SOA) (to provide interoperability in distributed, heterogeneous systems), cloud computing (to enable the massive data storage and high performance data analytics), Big Data (to enable the implementation of techniques to understand and extract knowledge from the large volume and variety of collected data), Machine-to-Machine (M2M) (to enable the interconnection among devices) and augmented reality (to support the integration of the human in the loop). The design, development and use of innovative aggregation mechanisms that allow this highly complex and cooperative systems to operate in a efficient manner is also imperative.

Therefore, the use of CPS aims to increase the implementation of large-scale systems, improving the adaptability, autonomy, efficiency, functionality, reliability, safety, and usability of such systems [11]. These systems are being applied to diverse areas such as smart manufacturing, smart cities, smart energy systems and smart buildings.

B. *Strengths*

CPS is a crucial issue in the realization of the so-called fourth industrial revolution, sustained by the German government initiative called Industrie 4.0 [12], that promotes the digitalization of manufacturing and business at large, towards the emergence of smart factories and collaborative interactions. This vision towards the factory of the future is being widely disseminated and adopted over the world, with different local strategies and research programs, namely "Industrial Internet" in US, "Industria Conectada 4.0" in Spain, "Made in Sweden 2030" in Sweden, "Smart Industry" in Netherlands, and "Made in China 2025" in China, only to refer some examples.

The CPS paradigm allows to move from a traditional centralized and monolithic automation pyramid into a more modular, decentralized and self-organized way of operating, exhibiting agility, responsiveness and reconfigurability to condition changes [13]. CPS also support the dynamic system re-sizing and reconfiguration to meet distinct business opportunities. By being naturally "connected", CPS is also empowering the notion of data-centric production systems in the way that tighter information flows are implemented with the potential of a higher production efficiency, e.g., by decreasing the production down-times, increasing product quality, adjusting production planning to real-time business needs [14] etc. This agility enables modern factories to realize the collaborative manufacturing vision [6], and easily adjust their production processes to the overall enterprise needs [9] e.g., high performance, energy efficiency, cost effectiveness, etc.

C. *Limitations*

CPS have drawbacks considering the discussed context as they are mostly designed to perform excellently in specific phases, typically the production phase, and they are thus not sufficiently integrated with preceding and follow-up phases of the product life cycle. For example, when a product leaves the production phase, the link with the CPS used in that phase is forgotten and the product enters into a new era of its own life, living and interacting with other systems, potentially designed as CPS. The same occurs at the end of its life: it will be dismantled and re-manufactured using systems potentially based on other CPS approaches and architectures.

III. INTELLIGENT PRODUCTS

A. *Concept*

The concept of IP has been introduced in the early 2000s, thus before the conceptual development of CPS and Industry 4.0. There is no clear unanimous definition of what is an IP. Meanwhile, in the literature, there are some key definitions that are often used by researchers for this purpose (a flagship literature review in the IP field is proposed in [15]). In [16], an IP is defined as a product able to interact with its environment during the production phase. In [17], an IP is able to manage its information and relevant logistic processes, including routing, through its life-cycle. Close concepts are PEID (Product Embedded Information Device) [18], “active product” [19] or the historical “product holon” proposed by the PROSA holonic reference architecture [20]. Figure 1 provides a classical example of an IP, as defined by [21].

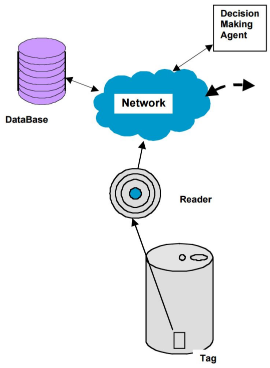

Figure 1. Intelligent Product principles – a classical example [21].

The minimal feature for an IP is its capability to manage its own information, given by sensors, RFID (Radio Frequency Identification) tags and readers and other techniques. A more elaborated definition for an IP, denoted as active IP, is able to memorize information, communicate and trigger events or notify users when a problem is detected (e.g., an IP has fallen or its temperature is too high). The most elaborated definition for an IP refers its capability to execute decisional algorithms, including possible learning mechanisms [22]. RFID and Internet of Things (IoT) are key technological enablers for the implementation of the IP concept. For some aspects, the concept of IP, contributing to the integration of the cyber and physical worlds, is clearly related to the concept of CPS. Meanwhile, some major differences and interesting complementarities arise between the two concepts, as the following parts will highlight.

B. Strengths

IP is the core active element around which manufacturing, logistics and maintenance can be organized. Since an IP is able to participate in the decision-making about its own life, this concept is sometimes presented as the way to close the loop in PLM, that is, the spinal column enabling backward information flows [23], [24] and around which everything can be designed and organized [22] in a product-centric approach. This is possible since the product is the only element that goes through its life-cycle, making it the core element, operating with all the other manufacturing resources (for example using ontologies to ensure interoperability with the different systems met during its life) [25], [26].

It is important to note that, according to the classical approach in PLM, the product is rarely active and intelligent. The main novelty brought by the concept of IP in PLM is that IPs are by essence active, they participate to the decisional processes that concern themselves, whatever the life-cycle phase for which these decisions apply.

Moreover, the intelligence of an IP is not unique and static. It can evolve and may concern different functions, depending on the phase in which the IP evolves [27]. For example, during the production phase, its intelligent may be designed to help to dynamically define the allocation of resources according to their availability (and this is a typical bridge with CPS). But during the use phase, the former intelligence is no more needed and can be removed. Instead, a required intelligence could rather now concern the ability to monitor and to diagnosis itself. Finally, in the recycling phase, its intelligence may concern its ability to analyze its own life history during its use phase, including all the realized maintenance operations, to determine which part of itself can be re-manufactured, which one can be used as a spare part and which one must be recycled.

C. Limitations

The IP concept, taken alone, suffers from several lacks when facing the context explained in the introduction part. Firstly, the examples and case studies often concern to "small" low-value products (e.g., can) with a specific focus on their use phases, for which a RFID tag is assigned while the "intelligent" part is remotely handled, possibly centralized by using cloud technologies. More complex products, potentially composed themselves of sub-products or major mechatronic components, considering in addition their other phases, such as design, production and recycling phases have seldom been studied from an IP point of view. Secondly, IP principles do not assume that "every other items are intelligent", while the concept of CPS fosters this. Having the IP as the core element is an interesting view, but contributions in the field do not consider other possibilities such as those offered by CPS where each system is potentially an interacting complex system of systems, recursively composed of production resources, tools, products, human operators, etc.

IV. CROSS BENEFITS FROM CPS AND IP

It is clear that CPS and IP are complementary approaches:

- The CPS approach provides powerful concepts to design innovative networked systems dealing with complex, system of system products. CPS architectures focuses on a single phase of the product life-cycle (e.g., production, use or maintenance), which can be associated to a kind of vertical view, inside a life-cycle phase.
- The IP approach provides powerful concepts to handle actively the different life-cycle views of products and systems, in a more horizontal way. The dynamic and functional views of the intelligence, varying according to the product life-cycle phases, is a novelty in the context of CPS.

Integrating these two approaches seems to be a promising idea and suggesting such integration composes the core element of this paper. As illustrated in Figure 2, along the product life-cycle, which is for simplification purpose decomposed into three phases (Beginning of Life - BOL, Middle of life - MOL, and End of Life - EOL), different CPS architectures are considered specifically. Typically, the literature focusing on CPS used at the production phase, where the product is virtualized, is abundant. Meanwhile, in fact, the product meets some CPS at one moment, and other CPS at other moments, with no relationships and links between them unless the concept of IP is adopted. This concept, and particularly the capability for an IP to acquire, store and process its own data and also to interact with its environment, constitutes a spinal column that enables to maintain the link between the life-cycle phases (upstream and downstream).

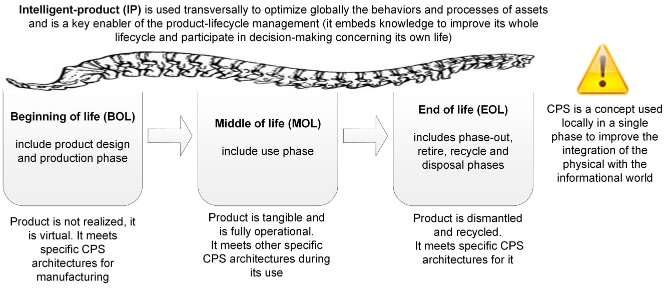

Figure 2. Position of IP in the CPS context along the product life-cycle.

Since the CPS concept opens the door for the consideration of smart products that are uniquely identifiable, located and able to take autonomous actions in accordance of their internal state and knowledge, the linkage of CPS and IP represents a cross benefit to establish the factory of the future. An important issue for this integrative approach to work properly, is the need to "empower" the IP with the collection and decisional mechanisms not only for the production phase but also for the use phase where this data is crucial for the full integration of the PLM cycles.

There is a need to create entry/exit points from and within the IP into the diverse interacted CPSs. Therefore, one of the major concerns regarding this integration would be the definition and adoption of a common language which enables the information exchange among the different product life-cycles. At this point, the consideration of proper and standard data models and ontologies assumes a critical role.

In another perspective, and in order to fully potentiate the usage of the IP concepts, there is the need to "re-think" how the several PLM phases are addressed, by introducing higher autonomy and responsibility of IPs, rendering them more "active" during the decisional processes. In the production phase, this would also potentiate the adoption of full concepts from innovative CPS architectures by promoting a closer negotiation/cooperation between the manufacturing assets (ranging from lower to upper levels of the ISA-95 pyramid). During the use phase, the IP can also, knowing its design, production and usage history, suggest predictive maintenance and/or advise maintenance for flaws and solutions, opening also the door for an increase of the process efficiency in the pair {IP, maintenance}. From the IP perspective, this would ease the maintenance process while from the maintenance CPS perspective, a higher efficiency is also foreseen in the sense of a better resource utilization.

The next part details two industrial applications of current and prospective joint integration of CPS and IP, pointing out the will of industrialists to evolve from a single CPS or a single IP paradigm, towards an integrated CPS+IP paradigm, aligned with the context presented in the introduction.

V. ILLUSTRATIVE EXAMPLES

A. Train manufacturer

Trains are complex moving systems that must meet increasing availability constraints expressed by train operators, customers and national agencies. Bombardier was initially interested in the concept of CPS and its potential benefits in the use phase of the life-cycle of a train, especially to increase the quality of the train health status monitoring and diagnosis which is known to be a critical function when aiming at increasing their availability [28]. For that purpose, a CPS approach, named SURFER (a French acronym standing for "intelligent train monitoring") was developed. Because of the complexity of a train, this CPS was based on embedding a recursive holonic monitoring architecture [29]. This CPS has been deployed on several trains that are currently in use. Results are confidential, but thanks to this architecture, some real diagnoses have been successfully led using the knowledge from the SURFER CPS. From this successful full-size experimentation, Bombardier is now paying attention to the concept of IP and its potential benefit to consider the train as an active CPS thoroughly its life-cycle, not only during its use phase (as it was realized during the SURFER project), but also during its design, production and deconstruction.

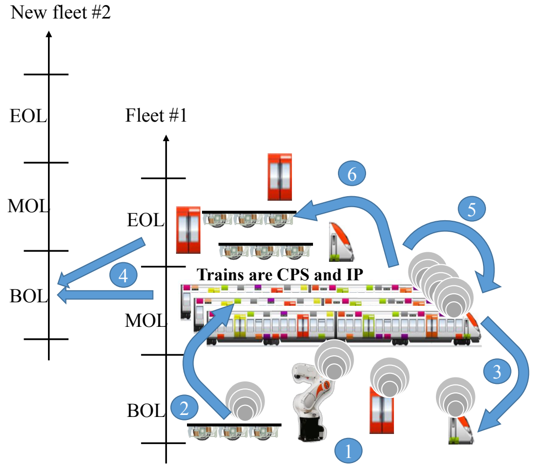

Figure 3. Trains seen as a composition of CPS and IP.

Figure 3 illustrates the expected advantages of such articulation between CPS and IP approaches from Bombardier's point of view. Main features, numbered 1-6 in this figure, are described below:

1) During manufacturing, each major component (subsystem of the train, e.g., doors) and manufacturing resource that process them are active and are IPs. They belong to a CPS and behave in a reactive manner and adapt themselves facing unexpected events during manufacturing and tests. From the IP perspective, production resources are in their use phase and their life-cycle can also then be optimized (e.g., operations and maintenance).
2) Specific manufacturing and design history of each IP component is stored and embedded in the train. Indeed, trains of the same fleet may have differences since the design/production phase of a whole fleet is a very long process (sometimes reaching several years). Technologies and specifications may evolve or can be improved between the release date of the first train and the release date of the last one composing a fleet.
3) As an IP, each train of a fleet capitalized knowledge from its specific use to improve incoming manufacturing operations of future trains to be produced and to specify the retrofit activities aiming to improve IP component functionality.
4) As IP, trains and components capitalize knowledge from their own use phase to improve the design and manufacturing of next train generations.
5) Trains are CPS able to cooperate to optimize the maintenance processes of the fleet to which they belong, negotiating opportunistic, dynamic or stealth maintenance for example with maintenance centers.
6) Components are IP and consequently they capitalized knowledge and history from their use and maintenance. This is exploited to better discriminate the physical parts to be recycled from the ones to be re-manufactured or

the ones re-used as spare parts.

B. *Washing machine production*

In the EU FP7 GRACE (Integration of process and quality control using multi-agent technology) project, the notion of IP was combined with CPS principles to improve the production efficiency and the product quality, considering the use of MAS technology and combining the process and quality control [30]. The demonstrator was a Whirlpool's laundry washing machine production line that is organized as a flow line topology where each product follows a fixed sequence of process steps, which comprise the execution of processing operations (e.g., screwing, welding or assembly) and also inspection operations, scattered in-between the process, responsible for the quality control checks. Finally, at the end of this process, all product instances are submitted to a final set of functional tests allowing to assess the global production quality.

This industrial environment was mapped into a CPS using a MAS infra-structure to implement feedback control loops to support the on-the-fly adaptation of process and product parameters, contributing to improve the product quality and production efficiency. Examples of such procedures are the dynamic and on-line adjustment of the process parameters (including the customization of inspection tests), the earlier detection of quality problems, and the customization of the final washing machine.

The agent-based model is composed by four types of agents, namely the Product Type Agent (PTA), the Product Agent (PA), the Resource Agent (RA) and the Independent Meta Agent (IMA). Briefly, the PTA represents the catalog of products that the company is able to produce, the RA represents the resources disposed along the production line, while the IMA introduces a kind of high-level optimization features by gathering the system information and running data analysis algorithms that correlates this data.

The IP is embodied in the PA that is part of the CPS and represents each product instantiation being produced in the production line. The PA possesses the knowledge to produce itself and is responsible for the monitoring and execution of several functions during its production life-cycle, namely [31]:

- Management of the production process by interacting with RAs to coordinate their actions according to the production dependencies and the production plan.
- Data collection along the production line about the production execution aiming to support the monitoring, traceability and data analysis.
- Re-routing of pallets and particularly adaptation of the control structure to face the current situation of the production process.
- Optimization/adaptation of the processing and inspection operations by correlating the collected processing and inspection data.
- Customization of the product by considering the adjustment of the parameters used by the on-board controller that regulates the product operation during the use phase.

The intelligence of the IP, brought by the PA, is provided remotely in a cloud environment where the PAs that compose the MAS infra-structure are running. Individual PAs gather the information from their counterpart physical products through the use of RFID tags (to collect information from internal sensors), and data related to the process and quality control through the interaction with RAs representing the processing and inspection stations, as illustrated in Figure 4.

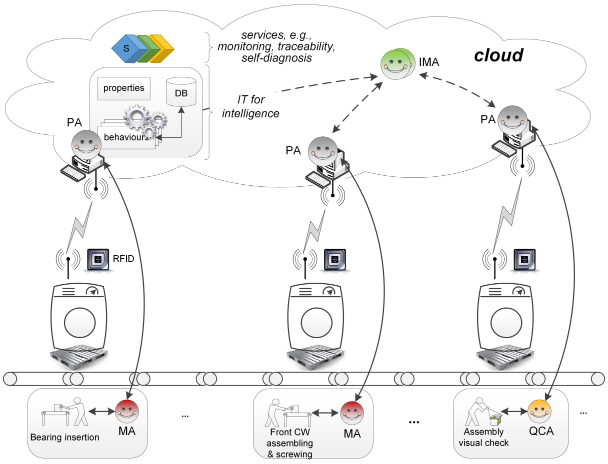

Figure 4. Intelligent product concept applied in the washing machines production line (production phase).

According to the framework defined by [15], the IP concept used in the GRACE project can be classified through the tuple {aggregation of intelligence, level of intelligence, location of intelligence} being positioned as {product itself, intelligent, remote}.

The use of IPs within the GRACE project allowed the achievement of several benefits, namely [30]

- Increase of the production efficiency and reduction of scraps due to an early detection of defected washing machines.
- Increase of the product quality and reduction of the inspection time by adapting the inspection tests and particularly the functional tests, through the adjustment of the sequence of tests for a specific product and by alerting operators to specific details, according to the data historic related to the product process execution and quality control.
- Increase of the product quality and customization by parameterizing the on-board controller based on the production history, making every product unique.

VI. CONCLUSIONS

Both CPS and IP have strengths and weaknesses, as it has been demonstrated so far. However, their integration is beneficial for several industrial scenarios. This integrated approach has been illustrated through two real-world industrial examples, covering different phases of the product life-cycle, namely the production and the use phases.

Business and societal needs, can benefit from the CPS and IP integration. However, their extended impact on the industry needs to be considered including the need to adapt existing IT systems to cope with emerging, unpredictable behaviors from interactions between cyber-physical components (being IP or not). Industrial engineers today design systems mostly top-down in fully-controlled environments and hence may be reluctant to adopt bottom-up emergent behaviors that result from the integration of CPS or IP systems. However, a mix of the two can provide significant benefits, but also raise new challenges as unexpected behaviors from classically designed complex systems caused by internal (not envisaged, because of the combinatorial explosion) or external (environmental) events are often related.

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