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Hyperconnected Architecture for High Cognitive Production Plants

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Abstract

The HyperCOG project addresses the full digital transformation of process industry through an innovative Industrial Cyber-Physical System and Data Analytics. It is based on advanced technologies that enable the development of a hyperconnected network of digital nodes. The nodes can catch outstanding streams of data in real-time, which together with the high computing capabilities, provide sensing, knowledge and cognitive reasoning, making companies robust in the face of variant scenarios. The breaking-edge system proposed in this work is validated on productivity, environmental and replicability aspects on three use cases of three different sectors: steel, cement and chemical.

Keywords: Cyber-Physical System, Industry 4.0, Data Analytics, Smart manufacturing ;

1. Introduction

Manufacturing companies are facing increasingly competitive and dynamic markets, which trend towards a great variety of products, a high degree of product customization and configurability, and greater regulatory requirements in terms of quality, processes and environmental impact, all in a context of strong pressure for price margins and speed to reach the market. This implies the need to build highly flexible manufacturing environments, capable of continuously adapting themselves to changing conditions by means of advanced technologies and decision-making processes that take advantage of massive data in real-time.

Cognitive manufacturing refers to a new manufacturing paradigm where machines are fully connected, monitored by sensors, and controlled by advanced computational intelligence to fine-tune product quality, optimize performance and sustainability while reducing costs. In this regard, production will increasingly rely on digital innovations like data capture, planning and control, modelling and simulation, optimization and big data analysis. Enterprises shall be able to convert data into knowledge in real time, supporting more efficient (lower energy & material consumptions) and safer processes with lower environmental impact. However, such cognitive features have not been realized yet in process industry.

Cyber-Physical Systems (CPS) are considered to be the main pillar of Industry 4.0 or smart manufacturing [1]. The CPS are the technologies that integrate computational and physical (devices, material, products, machinery and facilities) capabilities. These systems are perceived among the scientific community as the enabler of a fundamental change on existing industrial operations towards the next generation smart systems [2]. Unfortunately their implementation on the manufacturing industry is in their relative infancy, since current research is mainly focused on CPS the concept, architecture and technologies [3].

This paper proposes an innovative CPS to cover industrial production needs in the current technological context of Industry 4.0. The system, developed within the European HyperCOG project, is based on advanced technologies that enable the development of a hyperconnected network of digital nodes. The nodes can catch outstanding streams of data in real-time, which together with the high computing capabilities, provide sensing, knowledge and cognitive reasoning, making companies robust in the face of variant scenarios. In the last section of the paper, an implementation of the proposed architecture in Lortek research facilities is shown.

1.1. Cyber-Physical Systems

Cyber-Physical Systems term was introduced in 2006 to refer to ”the integration of physical systems and processes with networked computing”. The aim of CPS is to add new capabilities to physical systems by using computation and communication deeply embedded and interacting with physical processes [4]. CPS represent a network of interacting elements with physical input and output instead of as standalone devices [5]. Since 2006, the U.S. government and the United States Smart Manufacturing Leadership Coalition (SMLC) have introduced CPS in their development strategies, the National Science Foundation (NSF) have awarded large amount of funds to research on CPS and the German “Industrie 4.0” paradigm aims at incorporating CPS into manufacturing [6].

In particular, in Industry 4.0 and Smart manufacturing, CPS are key in process control and productivity optimization of manufacture of goods or delivery services. The importance of the development of CPS relies on the fact that it will foster the creation of data- and service-related business models [4]. This is forcing changes not only on the technological side, but also on the company’s business models, making them shift from selling products to the provision of integrated solutions [5].

However, research is still at the initial stages [7]. It is considered that existing methodologies do not scale to the next generation CPS. At this respect, the Electronic Components and Systems for European Leadership (ECSEL) indicates in its roadmap that future CPS will require advances in: 1) architecture, design and integration of systems and components, 2) connectivity and interoperability, 3) safety, security and reliability, 4) computing and storage, and 5) electronics process technology, equipment, materials and manufacturing [4].

1.2. Smart manufacturing based on CPS

Current industrial networks are implemented following a centralized and hierarchical control architecture, with different layers at device level, control level and management level. This traditional structure does not normally allow a direct communication between and amongst the separate layers, and hinders an agile and flexible response to changing conditions. However, a manufacturing system, especially in the current variant market involves a large decision-making at different levels and has a wide range of operations needed to be optimized.

In this regard, several standardization bodies, industrial consortia and research groups actively work in the field of system architectures for I4.0 to provide possible solutions for overcoming the layered structure with the aim of making system interaction more dynamic and flexible [8]:

- In Germany, the Deutsches Institut für Normung (DIN), along with other organizations, have published the ”Reference Architecture Model for Industry 4.0 (RAMI 4.0)”.
- United States the National Institute of Standards and Technology (NIST) have published a ”Standards Landscape for Smart Manufacturing Systems”.
- IMSA, Standardization Administration of China (SAC) published the ”National Smart Manufacturing Standards Architecture Construction Guidance”.

The purpose of these reference architectures is to provide a road-map for the use of standards in smart factories that can then be applied on a global scale. The next generation of industrial automation systems is being designed to be networked and with a decentralized organization.

The evolution towards CPS has led to new possibilities that enable improved integration of distributed heterogeneous devices and systems, ranging from the physical device or tool control level up to the higher levels of the business process management system. Within the HyperCOG project a hyperconnected CPS platform has been built to provide process industries with the basis for faster and better decision-making. The project’s smart manufacturing system will be robust in the face of any variable and uncertain scenario. The solution will be designed to allow for real-time monitoring, the analysis of a high volume of data, multilateral communication and interconnectivity between CPS and people.

In this regard, the hierarchical structure is replaced by a fully connected network. This approach breaks down the traditional concept of information system for industrial process environments; it replaces the traditional hierarchical information system with a networked industrial cyber- physical system (ICPS).

Ideally the CPS will be the automation system for process industries in the future, however this transition in the manufacturing industry should be accomplished step by step, that is why in Figure 1 are depicted both systems connected by the ”data connector”. Both systems should be coexisting in a symbiotic relationship for a while. HyperCOG will build on the existing robust core functionality with modern digital technologies and thereby provide current vital systems with the functionality and utility required to remain competitive over the longer term

2. Gaps of CPS in Industry

In the Road2CPS project [9] a systematic review of 54 previous European Union projects was performed to determine

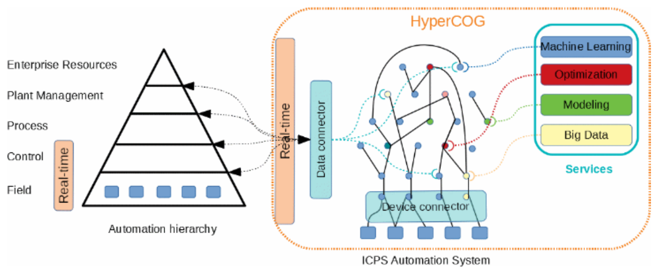

Fig. 1. HyperCOG technical concept.

the main gaps in CPS. From the 75 gathered gaps, some of them were of special relevance for Industry: Connectivity, social acceptance and security related gaps.

Regarding connectivity gaps, one of the main challenges of CPS in industry is to capture all the relevant information of the process from a vast number of data sources. The CPS must manage the interconnection between several data sources such as sensors, cameras, machines or manual data and even data from different departments of the company. This data integration must be achieved without stopping the production or altering the production systems. Another relevant gaps are social acceptance related gaps. These gaps address the issues related with the interaction between the CPS and humans and the incorporation of human knowledge to the CPS. Finally, security related gaps analyze the security needs of Industries from different perspectives. These gaps emphasize the need of ensuring data and process security and the physical safety of the workers. In addition, cybersecurity must be a major concern for CPS in industry.

Therefore, any CPS implemented in the industry should cover these general gaps. In addition, it should cover the specific gaps and requirements of each use case, according to its particularities. Within the HyperCOG project, the proposed architecture will be evaluated in three different use cases of different sectors: steel, cement and chemical.

2.1. Steel use case

The first use case consists of a steel producer, which obtains steel semi products from raw materials (scrap and ferroalloys). The semi products are either billets or blooms (long square section bars of several sizes) which feed 5 rolling mills in other installations.

The process of this use case is composed of a first stage in which the scrap is melted in the Electric Arc Furnace (EAF) by means of the energy supplied by the arc through the electrodes and the addition of oxygen. When the scrap is melted, it is tapped to the ladle and the second metallurgy subprocess starts, where the composition of the melted scrap is adjusted to reach the desired steel grade. Finally, the liquid steel is solidified in a casting machine, obtaining the semi products.

The basic production unit, named ”heat”, are grouped in sequences, with the same characteristics. Changes on the sequence to obtain different steel grades lead, to machine start-up and consequently non-productive periods. Therefore, the grouping of the heats into sequences and the order of the heats within the sequence, as well as other process variables, are a key issue. However, the heat scheduling optimization is performed by humans due to the required knowledge, with the support of several simulation models. However, frequently the heat scheduling must be modified, without the help of simulation tools, due to failures hard to predict. Consequently, the goal for this use case is the optimization of heat scheduling and to aid operators during decision making, with the aim to solve online production planning problems.

2.2. Cement use case

The second use case consists of a white Portland cement production line. The production process begins with the grinding of clay, sand and raw meal components. After grinding, components are stored in a silo. From the silo the components enter a rotary kiln, where the clinkerization process is performed. Finally, the clinker is mixed with several materials and water to obtain white cement, which is stored in a silo.

In order to optimize the process parameters with the information of the monitored and recorded data, the white Portland cement manufacturing process will be digitized. Where the data of the process is acquired by several sensors such as temperature, pressure or humidity among others and managed by PLCs and SCADAs. The main gap of this use case is to use the monitored and recorded data, in a digital environment, to optimize the white cement manufacturing process.

2.3. Chemical use case

Finally, the chemical use case produces rare earth oxides and carbonates for automotive industry, polishing and medical applications. The aim of this process is to separate rare earths nitrates from rare earths carbonates using solvents, which is the circulation counter currently in the process. Once a rare earth concentration is reached, a separation and purification process is done to extract the rare earths.

The control of the process is performed by sensor measurements (pH and rare earths concentration) at several points along the process. Data is acquired and shown using SCADAs. Response to failures or anomalies in the process is based on operators' experience. Within the HyperCOG project, the rare-earths liquid-liquid extraction process will be digitized. The main gap for this use case is to integrate advanced analytic tools in the hyperconnected network to reduce energy consumption and increase productivity.

3. Architecture

The proposed architecture within the HyperCOG project is an evolution over the classical information systems architectures for industrial process environments. In this context, the traditional hierarchical information system is replaced by a networked ICPS. The proposed architecture is designed as a set of nodes running on various devices and communicating with each other without hierarchical layers or the need for specific channels. The innovative architecture is characterized for being a modular and decentralized approach which allows a robust and flexible solution. Therefore, the proposed CPS enables real-time monitoring, analysis of large amounts of data and multi-lateral communication.

Given the hyper connecting capabilities of HyperCOG, the algorithm running on a node can get information from the rest of the network. The means of the CPS is to evolve from the current industrial networks implemented following a centralized and hierarchical architecture with different layers at device level, control level and management level, to a de-centrally organized system. This decentralization will give the flexibility needed to take advantage of all the current technologies to allow real-time monitoring, high data volume analysis, multilateral communication and interconnectedness between CPS and people.

In this novel architecture there are no layers in the network, so all entities regardless of their role in the system can be seen as a node, which can communicate with any other node in the CPS. Hence, the communication pattern that results is a fully connected network topology as shown in Figure 2, where a plethora of nodes running on several devices establish direct information paths with each other whether they are in the same host or in another.

To accomplish the requirements of the hyperconnected network in the HyperCOG project, where a high number of devices are interconnected in a distributed system, a middleware is used to abstract the communications. The middleware relies on Data Distribution Service (DDS) [10]. middleware architecture based on publisher/subscriber pattern. DDS is a well known and realiable standard that aims to enable dependable, high-performance, interoperable, real-time and scalable data exchanges. The DDS layer handles complex aspects of node discovery, queue management, forwarding, quality of service or security among others, covering the requirements of the HyperCOG communication paradigm (Figure 3)), where the communication must be pervasive. DDS is an open standard by the Object management Group (OMG) consortium that manages the Unified Modeling Language (UML)[11]. There are several middleware implementations that support DDS Application programming Interface (API), some of them open source, as FASTDDS, developed by eProsima [12].

DDS protocol handles the communication between HyperCOG nodes. However, to carry out the communication requirements with the external environment and its devices in the industrial field, additional protocols and methods like OPC-UA, Ethernet/IP, ProfiNet or EtherCAT have been implemented. The proposed architecture is adaptable to different use cases selecting the proper devices, nodes, algorithms and input and output communications paths for each use case. In order to achieve the different task that the ICPS systems will have to handle, several types of nodes have been defined, such as:

- *Launcher* nodes to get information from a repository and launch other nodes in the device where it is running.
- *Repository* nodes to provide to the rest of the nodes with information concerning the configuration of the devices and nodes, and the topology of the network.
- *Supervisor* nodes to check the status of the system. Supervisor node discovers new nodes, verifies the status of all the nodes and their connections and registers warnings and errors in a database.
- *Acquisition* nodes are on charge of acquiring real time data from the physical world through sensors deployed on the field and connected to a PLC or another device.
- *Collector* nodes collect historic data from databases to fed the implemented algorithms.
- *Actuator* node act on the physical word by sending real time orders to a PLC or other device of the system.
- *Recorder* node records data in a database or sends it to a queue.
- *Executor* node is able to run several types of optimization algorithms, machine learning models or artificial intelligence (AI) systems. The algorithms running on executor nodes are fed by data obtained by acquisition and collector nodes and algorithms output could be used as input of actuator nodes.
- *Human Machine Interface (HMI)* nodes are used for the interaction with humans. HMI nodes report valuable information of the processes to support operators and obtain data and orders from them.
- *Cybersecurity* nodes to check cybersecurity aspects of the nodes and the entire network.

The class diagram of Figure 4 shows all the node types developed within the HyperCOG architecture, being HCNode the abstract node type to which all HyperCOG nodes belong.

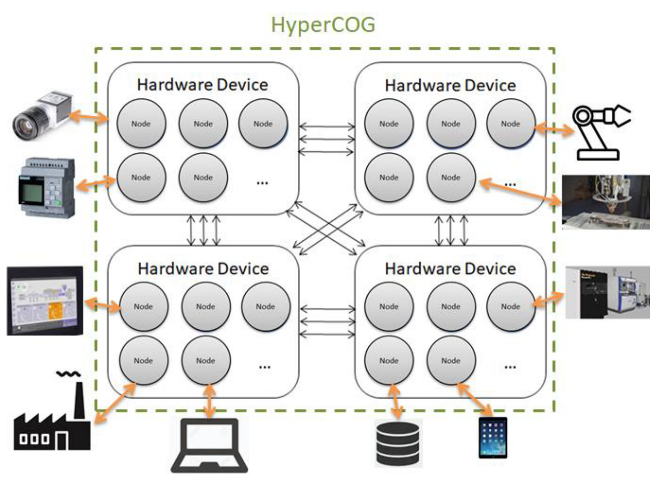

Fig. 2. Illustration of network topology of nodes.

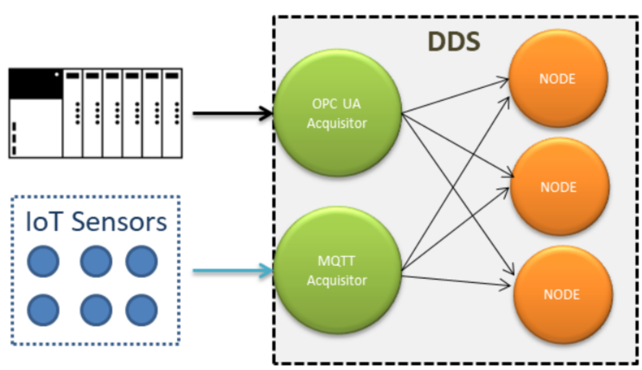

Fig. 3. DDS communication between nodes.

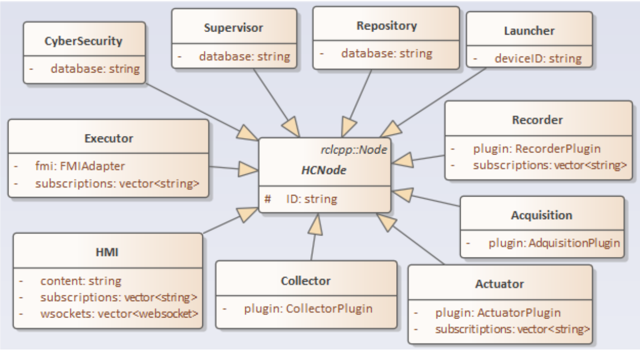

Fig. 4. Class diagram illustrating the different types of nodes.

Each node has the ID attribute used to globally identify the instances of any node. Thus, any node instance will be of one of the types shown in the diagram. In order to facilitate the integration of dynamic models, optimization algorithms or AI systems the Functional mock-up Interface (FMI) [13] standard is supported in the system. FMI is a standard for exchanging dynamic models and algorithms developed in different APIs such as MATLAB-Simulink, Python or Modelica among others. FMI defines an interface to gain interoperability between algorithms or models and enables interoperability for simulation or model exchange in complex CPS. The FMI standard is supported by the Executor node of the HyperCOG architecture, which enables to load several models and fed them with acquisition and collector nodes data. With the use of the FMI standard, several Executor nodes running together within a network would be able to simulate several dynamic models or digital twins (DT) of the processes[14] and fed them with historic and real time data. Based on these models and with the help of AI algorithms and machine learning techniques the system will give recommendations for the best solution with respect to company goals. These systems are expected to allow the application of predictive control methods and to give support for online production planning in order to optimize resources. For instance, in the steel use case, heat scheduling planning and rescheduling under unexpected situations has a major impact on resources optimization.

When deployed on each use case, nodes that interact with the physical world (acquisition and actuator nodes) or with historical data databases (collector and recorder nodes) face a complex challenge since the variety of possible sensors, actuators, communication protocols, databases, external I4.0 platforms or SCADAs is endless. In order to create a unique node type and to handle this devices heterogeneity a plugin design pattern is used, as illustrated in Figure 5.

The plugin design pattern is a key feature of the HyperCOG architecture design, that allows an application to load plugins on demand in order to handle different requirements in function of the sensor, actuator or protocol used for a certain application. This approach enables to load plugins even for requirements not considered during the conception or even the deployment of the CPS. For example, there is no need to know in advance all the PLC types, sensors or all the database management system types.

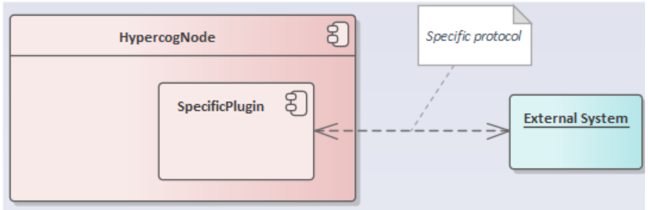

Fig. 5. Illustration of the plugin pattern through a components diagram.

4. Proof of concept

The final goal of the HyperCOG project is to implement the developed architecture on the three case uses described at section 2. However, as a proof of concept, the architecture has been implemented at Lortek research facilities to evaluate the performance of the architecture. For that, a demonstrative use case has been proposed. The proof of concept consists of two robotic cells for different welding processes from which data from several sensors are obtained. The goal of the CPS to be implemented is to acquire a few signals from each cell and to check if the acquired data is within an admissible threshold of the welding process, previously defined in a database. In addition, to enable an online supervision of the process, the CPS should plot in an HMI the signals acquired from the robotic cells. Finally, all the data must be recorded on a CSV file for later analysis.

Figure 6 shows the implemented layout for the proof of concept, which consists of six different nodes. Two acquisition nodes (*s1* and *s2*), a collector node (*c1*), an executor node (*exe1*), a HMI node (*hmi1*) and a recorder node (*r1*). As shown in Figure 7, The two acquisition nodes acquire real time data from two robotic cells for welding processes at Lortek. Acquisition nodes obtain data from the robotic cells through OPC-UA communications protocol and publish the data in two different topics (*s1* and *s2*). Collector node, for the proof of concept, reads from a CSV file the threshold values for the selected signals and publishes them on a new topic

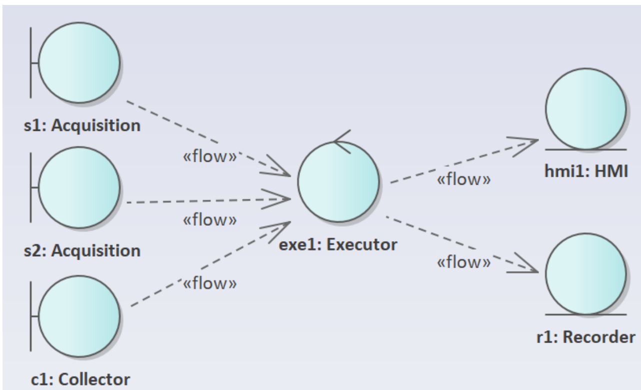

Fig. 6. Proof of concept CPS nodes diagram.

(*c1*). On the other hand, executor node subscribes to the three previous topics (*s1*, *s2* and *c1*) and from there determines if robotic cells signals are within an admissible thresholds of the welding process values. HMI node plots the cells signals and the thresholds to enable an online supervision of the process parameters. Finally, the recorder node records all the data published by the two acquisition nodes on a CSV file.

According to the layout of Figure 6, real time data streams of the robotic cells generated by *s1* and *s2* acquisition nodes can be seen. Each time any sensor of the robotic cells updates its value, a new message is published on the corresponding topic (*s1* and *s2*). Where, *s1* acquisition node publishes time and robot speed and *s2* node publishes time, current and gas flux. All of them, parameters of the welding process. At the beginning of the process, when requested by the executor node, *c1* collector node takes from a CSV file parameters needed to implement a digital twin of the welding process.

The executor node, *exe1*, implements the digital twin using an AI model. It is subscribed to the three topics (*s1*, *s2* and *c1*) and from this data updates the state of the DT. The executor node publishes all the variables that represents the state of the DT on a single topic. The data published by the executor are acquired by the HMI and recorder nodes. The HMI node plots the signals obtained from the executor node, to facilitate supervision of the process. The recorder node, on the other hand, records all the data published by the executor node on a database.

5. Conclusion

This paper has presented the approach to follow in the development of the HyperCOG project for the full digital transformation of the process industry. The approach consists of the use of ICPS and Data Analysis using a node-based architecture. The use cases to be addressed in the project have been introduced and the first deployment of the system has been detailed as a proof of concept at the Lortek facilities.

The next step in the project will be the deployment of the HyperCOG solution in real use cases, steel, cement and chemical case. New sensors will be integrated and the AI models to comply with the optimization of the processes.

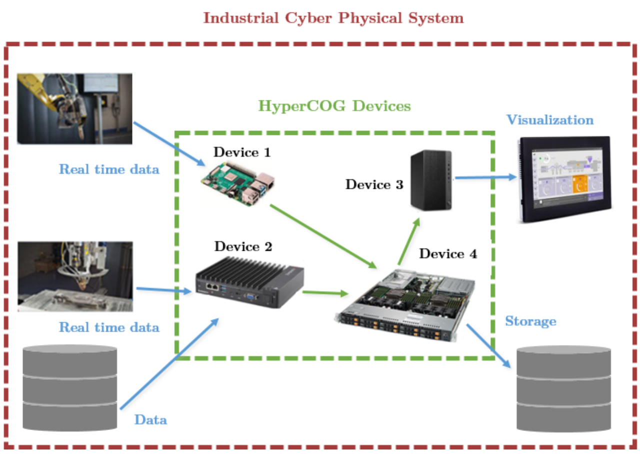

Fig. 7. Implementation of the ICPS proof of concept at Lortek.

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