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A Novel Architecture for Cyber-Physical Production Systems in Industry 4.0

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***Abstract*— The Hyperconnected Architecture for High Cognitive Production Plants (HyperCOG) project aims at the process industry's complete digital transformation through an advanced Industrial Cyber-Physical Infrastructure. It is based on advanced technologies that allow a hyperconnected network of digital nodes to be created improving the classic automation hierarchy of communication layers. The nodes will collect data streams in real-time, offering cognitive sensing and information along with high performance computing capabilities making the process industry businesses solid in different scenarios. The system is validated in three fields of the process industry: steel, cement and chemical where optimization in the use of energy and raw materials is obtained, among other benefits.**

I. INTRODUCTION

Currently manufacturing companies are facing increasingly competitive and dynamic markets, which trend point towards a great variety of products and services, 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 speed to reach the market and strong pressure for price margins. This implies, the need to build highly flexible manufacturing environments, capable of continuously adapting themselves to variable conditions through advanced technologies and decision-making processes that take advantage of massive data in real-time.

In this environment, cognitive manufacturing refers to a new manufacturing paradigm with fully connected machines, monitored by sensors, and controlled by advanced computational intelligence to fine-tune product quality, optimize performance and sustainability while reducing costs. In this context, production will increasingly rely on digital innovations like data acquisition, 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 material consumptions & energy) and safer processes with lower environmental impact. Nevertheless, such cognitive features have not been realized yet in the process industry.

In Industry 4.0 or smart manufacturing, Cyber-Physical Systems (CPS), are considered the main pillar [1]. The CPSs are the technologies that integrate computational and physical (devices, material, products, machinery and facilities) capabilities. CPSs systems are recognized 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 manufacturing industry is in in their relative infancy, since current research is mainly focused on CPS concept, technologies and architecture [3].

This work suggests an innovative CPS to support industrial production needs in the nowadays technological context of Industry 4.0. The system, developed within the European Hyperconnected Architecture for High Cognitive Production Plants (HyperCOG) project, is based on advanced technologies that enable the development of a hyperconnected network of digital nodes. The nodes can acquire 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. Section IV shows an implementation of the proposed CPS architecture carried out in Lortek research facilities.

A. Cyber-Physical Systems

In 2006, the term Cyber-Physical Systems was introduced to refer to "the integration of physical systems and processes with networked computing". The goal of CPS is to add new capabilities to physical systems by using computation and communication deeply embedded and interacting with physical processes [4]. CPS describes 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 Industry 4.0 and Smart manufacturing, CPS are key in process control and productivity optimization of manufacture of goods or services. The importance of the development of CPS relies in 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 companies business models making them to shift from selling products to the provision of integrated solutions [5].

Nevertheless, research is still at the initial stages [6]. 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: architecture, design and

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integration of systems and components, connectivity and interoperability, safety, security and reliability, computing and storage, electronics process technology, equipment, materials and manufacturing [4].

B. CPS based smart manufacturing

Nowadays, industrial networks are implemented following a centralized and hierarchical control architecture, with different layers at device, control and management level. This conventional structure does not normally allow a direct communication between and amongst the separate layers, and hinders an agile and flexible response to changing conditions. Nevertheless, 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 context, several standardization bodies, industrial consortia and research groups actively work in the field of system architectures for Industry 4.0 to provide possible solutions for overcoming the layered structure to make system interaction more flexible and dynamic [7]:

- In Germany, the Deutsches Institut für Normung (DIN) and other organizations, published the "Reference Architecture Model for Industry 4.0 (RAMI 4.0)" [8].
- In United States, the National Institute of Standards and Technology (NIST) has published a Standards Landscape for Smart Manufacturing Systems [9].
- IMSA, Standardization Administration of China (SAC) published the National Smart Manufacturing Standards Architecture Construction Guidance [10].

The aim 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 development towards CPS has led to new possibilities that enable improved integration of distributed heterogeneous devices and systems, ranging from the physical device 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 system will be robust to face any variable and uncertain scenario. The solution will be developed to allow for real-time monitoring, the analysis of a high volume of data, multilateral communication and interconnectivity between people and CPS.

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

In the future, ideally, the CPS will be the automation system of the process industries. However this transition from hierarchical structures to CPS architectures should be accomplished step by step, as shown in Fig. 1 with both

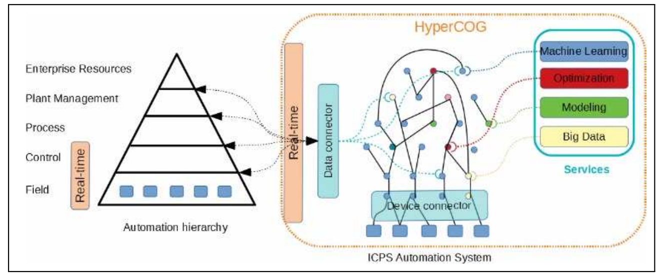

Fig. 1. Technical concept of the Hyperconnected Architecture for High Cognitive Production Plants (HyperCOG) project.

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.

II. GAPs OF CYBER-PHYSICAL SYSTEMS IN INDUSTRY

To determine the main gaps in CPS, in the Road2CPS project [11], a systematic review of 54 previous EU projects was carried out. From the 75 gathered gaps, some of them were of special relevance for Industry: Connectivity, social acceptance and security related gaps.

As for 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, industry should focus in cybersecurity for CPS.

Hence, 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: cement, steel and chemical. Although for the moment the architecture is being implemented in the steel use case, this development is focused on providing support to the rest of the use cases. Therefore, the following is a brief description of the gaps presented by the different use cases, to which the proposed architecture will provide a solution.

A. Cement use case

The first use case involves a white Portland cement production line. This process begins with the grinding of clay, sand and raw meal components. After grinding, components are stored in a silo and from there enter to a rotatory kiln, where the clinkerization process is performed. Finally, the clinker is mixed with several materials and water to obtain white cement.

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

B. Steel use case

The second use case corresponds to a steel producer, which obtains steel semiproducts from raw materials (scrap and ferroalloys). The semi-products are billets or blocks (long square section bars of various sizes) that feed five rolling mills in other facilities.

The process of this use case consists 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.The process of this use case consists 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 fed into the ladle and the second metallurgical sub-process begins where the composition of the melted scrap is adjusted to achieve the desired steel grade. At the end, the liquid steel is solidified in a casting machine, obtaining the semiproducts.

Heat is the basic production unit, which is grouped in sequences with the same characteristics. Changes in the sequence to obtain different qualities of steel grades to the start-up of the machine and, therefore, to non-production and its consequent periods of non-production. Therefore, the grouping of the heats in sequences and the order of the heats within the sequence, as well as other process variables, are a key issue. However, the optimization of heat scheduling is carried out by humans due to the required knowledge, supported by various simulation models. However, often the heat scheduling must be modified, without the help of simulation tools, due to difficult failures. simulation tools, due to errors that are difficult to predict. Consequently, the objective of this use case is to optimize thermal scheduling and assist operators in decision making, in order to solve online production planning problems.

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

III. PROPOSED ARCHITECTURE

The architecture proposed in the HyperCOG project is a step forward that breaks with the traditional information systems architectures for industrial process environments. With this approach, the networked ICPS replaces the traditional hierarchical information system. In this context, the proposed architecture is designed as a set of nodes running on various devices and communicating with each other without the need for hierarchical layers or specific channels. Thus, this novel architecture is characterized for being a modular and decentralized approach which allows a flexible and robust solution. Therefore, these aspects make the proposed architecture capable of monitoring in real-time, analyzing large amounts of data, multi-lateral communication and interconnectedness between CPSs and people.

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.

In this innovative architecture, there are no layers in the network, so all entities, whatever their function in the network, can be considered as a node, which can share information with any other node in the CPS. Therefore, as shown in Fig. 2, the resulting communication path is a fully connected network topology in which a large variety of nodes operating on various devices, whether they are on the same host or on another host, create direct information pathways between each other. The software and tools to be implemented are the main challenges faced by the HyperCOG project to evolve from the classic hierarchy of industrial communication layers to the proposed solution.

To accomplish the requirements of the hyperconnected network in the HyperCOG project a middleware is used. Which is a software layer that offers services to applications outside of what's offered by the operating system and is used to abstract the communications in a distributed system, as a CPS, composed of several connected devices. The middleware used takes advantage of Data Distribution Service (DDS) [12], that is a well known and tested standard that aims to enable dependable, high-performance, interoperable, real-time, scalable data exchanges using a publisher/subscriber pattern. The DDS protocol is based on a communication paradigm very appropriate for the concept of the HyperCOG project where the communication must be

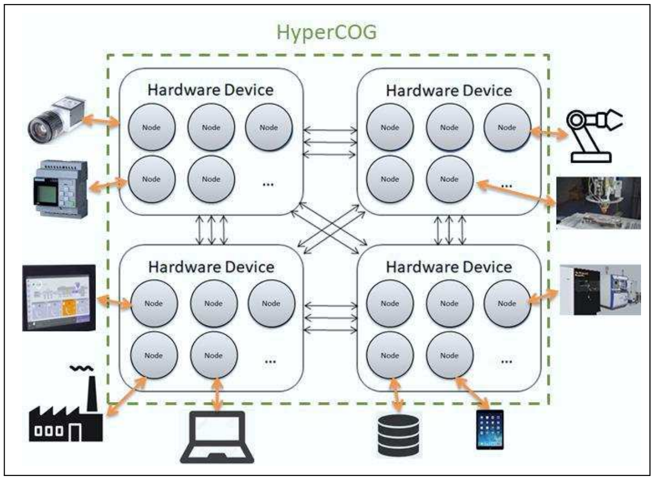

Fig. 2. Illustration of network topology of nodes.

pervasive. The DDS layer handles complex aspects of node discovery, queue management, forwarding, quality of service or security, among others. DDS is an open standard by the Object Management Group (OMG) consortium that manages the Unified Modeling Language (UML) [13]. In this context, there are several middlewares that support DDS Application programming Interface (API) as FASTDDS, an open source implementation by eProsima [14].

DDS protocol handles the communication between HyperCOG nodes. Nevertheless, the necessary protocols and methods, such as OPC-UA, Ethernet/IP, ProfiNet or EtherCAT, will be used to implement the requirements for communication with the external environment and its devices in the industrial environment.

The proposed architecture is adaptable to different use cases selecting the devices, nodes, algorithms and the input and output communications paths with the plant. Different types of tasks have been identified that the ICPS systems will have to handle. In order to achieve the different functions, several types of nodes have been defined. Each instance of running node of HyperCOG will belong to one of the following node types:

- Launcher node gets information from a repository and starts other nodes in the device where it is running.
- Repository node provides information available on a database to other nodes in the net concerning the configuration of the devices and nodes, and the topology of the network.
- Supervisor node checks the status of the system discovering nodes, asking the status and connections of them and registering warning and errors and other information in a database.
- Acquisition nodes acquire real-time data from the physical world through sensors deployed in the field and connected to a PLC or other device.
- Collector node collects historic data from a source that can be a database, a file or other file that contains information about the process.
- Actuator node acts on the physical world by sending real-time commands to a PLC or other device in the system.
- Recorder node records data in a database or sends it to a queue.
- Executor nodes are capable of executing different types of optimization algorithms, machine learning or artificial learning (AI) models, among others. Acquisition and collector nodes fed the algorithms running on executor nodes, using the results of the algorithms as inputs to the actuator nodes.
- HMI nodes are used for human interaction. HMI nodes supply valuable process information to support operators and obtain data and commands from them.
- Cybersecurity node checks cybersecurity aspects of the nodes and the network.

The class diagram of Fig. 3 shows all the different node types of HyperCOG, being HCNode the abstract type to which all the nodes of HyperCOG belong to. Each node has the ID attribute that is used to globally identify the instances of any node. Any instance will be of one of the types shown in the diagram.

In order to facilitate the inclusion of dynamic models, machine learning algorithms or AI systems, the system supports the Functional mock-up Interface (FMI) standard [15]. FMI is a standard for the exchange of dynamic models and algorithms developed in different APIs such as MATLAB-Simulink, Python or Modelica, among others.The FMI standard defines an interface to achieve interoperability between algorithms or models, thus enabling interoperability for simulation or model exchange in complex CPS.

In the HyperCOG architecture, the FMI standard is supported by the Executor node, which allows loading several models and feeding them with data from the acquisition and collector nodes. Using the FMI standard, many Executor nodes working together within a network could simulate several dynamic models or digital twins (DT) of the processes and feed them with historical and real-time data. From these models and with the help of AI algorithms and machine learning techniques, the system will be able to give recommendations on the best solution for each use case. It is expected that these systems will allow the application of predictive control methods and support online production

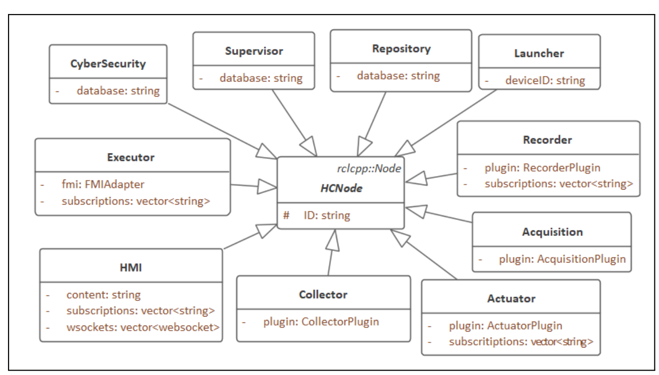

Fig. 3. Class diagram illustrating the different types of nodes.

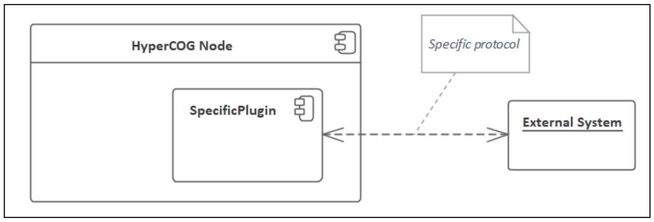

Fig. 4. Illustration of the plugin pattern through a components diagram.

planning, with the purpose of optimizing resources. For example, in the steel use case, heat scheduling, planning and rescheduling during unexpected situations has a strong impact on the optimization of resources. Nodes that interact with the physical world (acquisition nodes and actuators) or with historical databases (collector nodes and loggers) face a complex challenge as the variety of possible sensors, actuators, communication protocols, databases, external I4.0 platforms or SCADAs is large and hard to predict. With the plugin design pattern illustrated in Fig. 4, a single node is created to handle this heterogeneity of devices. This design allows to load specific plugins on demand to handle different requirements depending on the sensor, actuator or protocol used for the devices. This approach allows plugins to be loaded even for requirements not considered during CPS design or even deployment. For example, it is not necessary to know in advance all types of PLCs, sensors or all types of database management systems.

IV. PROOF OF CONCEPT

The final goal of the HyperCOG project is to implement the developed architecture on the three case uses described at section II. 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 thresholds 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.

Fig. 5 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 Fig. 6, 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 (*c1*). 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, recorder node records all the data published by the two acquisition nodes on a csv file.

The results obtained from the implementation of the CPS proof of concept for the demonstrative use case at Lortek are shown in Fig. 7. According to the layout of Fig. 5, 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 (parameters of the welding process). At the beginning of the process, when requested by the executor node, *c1* collector node takes from the thresholds csv file the threshold values (minimum and maximum) for each variable and publishes it in another topic.

The executor node, *exe1*, is subscribed to the three topics (*s1*, *s2* and *c1*) and from this data determines if the values of the sensors of the welding process are within the admissible thresholds. The executor node publishes all the data on single topic. In addition this node could publish alarms on another specific topic if any sensor value gets out of the threshold. 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 a supervision of the process. The recorder node, on the other hand, records all the data published by the executor node on a csv file.

V. CONCLUSION

This work introduces the first results of the development of the HyperCOG project for the full digital transformation of the process industry. The approach developed within this project consists in the use of ICPS and Data Analytics following a node-based architecture. A proof of concept of the proposed architecture has been developed at Lortek facilities as first deployment of the system, where some of the gaps of the current digital systems has been addressed as communication and security issues.

Subsequently, new specific nodes will be implemented

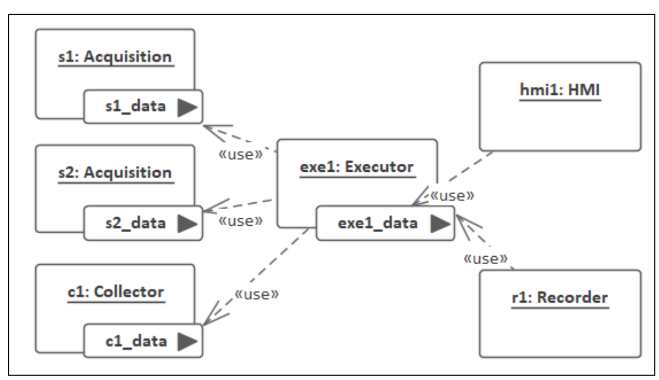

Fig. 5. Proof of concept CPS nodes diagram.

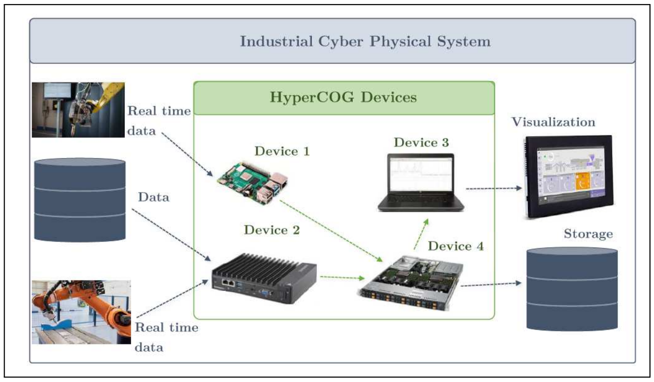

Fig. 6. Implementation of the ICPS proof of concept at Lortek.

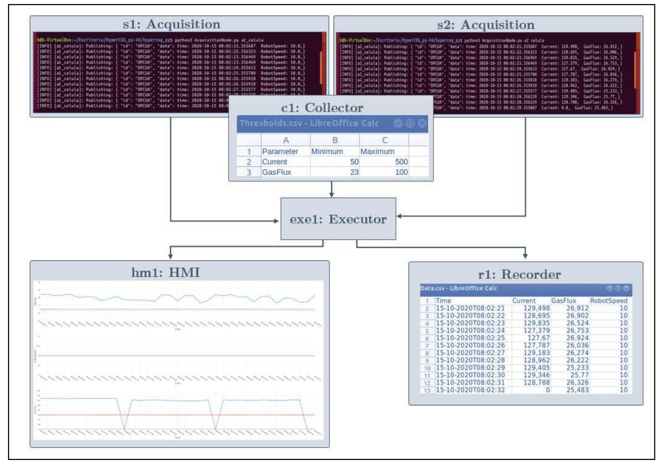

Fig. 7. Proof of concept evaluation at Lortek research facilities.

for each of the analyzed use cases and the necessary AI models will be developed to achieve the optimization of the processes. Firstly, the architecture will be deployed in the steel use case, adding new sensorics, thermographic sensors or cameras, among others. Once the architecture is deployed in the steel use case, the following use cases will follow, thus demonstrating the transversality of the approach used in the project for the digital transformation of the process industry.

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