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RESEARCH ARTICLE

Hyperconnectivity Proposal for Smart Manufacturing

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ABSTRACT Smart Manufacturing is characterized by the digitization and massive communication of Cyber-Physical Systems under the Industrial Internet of Things paradigm. However, the heterogeneity of communication protocols hinders connectivity among assets due to lack of interoperability. Moreover, the decomposition of the classical production hierarchy towards decentralized self-organization makes the implementation of interoperability in industrial environments key to help decision-making. In this sense, the interoperability of heterogeneous assets (e.g., external, internal, and human) has been defined as hyperconnectivity and supposes a technological challenge in the scientific literature. To prove this novel hyperconnectivity definition, the authors propose and develop a novel hyperconnected demonstrator where all types of assets are interconnected in a case study consisting of the automation of an inspection process. For this purpose, an industrial internet platform has been used for connecting industrial equipment creating a collaborative environment through the use of interoperability. In this regard, it has been possible to communicate assets among the cloud, humans, and CPS with a processing time of less than 10 ms, which demonstrates that the technological challenge of implementing the hyperconnectivity concept of this paper has been successfully addressed.

INDEX TERMS Hyperconnectivity, industrial communications, interoperability, smart manufacturing.

I. INTRODUCTION

The manufacturing industry is part of an economic sector in which goods are produced to improve the quality of life. These products are fabricated through the transformation of materials and the use of human and technological resources. Both human and technological assets can be integrated in a connected environment in order to fruitfully collaborate. In this manner, they can adapt to internal and external constraints to achieve competitive production. In this context, manufacturing has evolved towards a more digitized environment [1] where communications and computing platforms are essential to achieve an intelligent and connected production called, Smart Manufacturing (SM) [2].

The combination of all these elements creates a value chain capable of generating added value to the production processes [3]. However, intelligent systems need data from the physical environment in order to make decisions. For this purpose, data must be transferred to the virtual world.

However, within the real world, humans and machines perceive the reality of the production process in a different manner but their information must be retransmitted in a digitized form to facilitate the exchange of information. In this sense, machines or Cyber-Physical Systems (CPS) employ sensors while humans need interfaces (e.g., haptic, audio, visual) for the exchange of information from the physical to the virtual world.

This exchange of information among assets is done by means of communication protocols [4], which structure the information for its transmission by physical means. Nevertheless, given the great technological heterogeneity of CPSs, several communication protocols adapted to the needs of CPSs have been developed [5]. The resulting heterogeneity of communication protocols represents a barrier to produce a

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direct communication among assets that facilitates the intelligent and connected production of the SM [6].

Furthermore, due to the large number of CPSs used in industry due to their digitization, new wireless communication strategies are required to achieve the high reliability and real-time performance characteristic of industrial environments. In this sense, Lee and Yang [7] have successfully evaluated Multiple-input Multiple-output (MIMO) technology in the Industrial Internet of Things (IIoT) paradigm where it achieves key energetic and spectral efficiency for industrial wireless networks.

Moreover, the IIoT paradigm based on ethernet networks allows the offshoring of assets outside the manufacturing process, facilitating outsourcing services that can obtain data from third-party services [8]. However, connectivity with the outside as well as with internal elements involves a series of risks to the integrity of information, making cybersecurity a critical aspect to ensure the protected operation of the production processes [9].

The different external services range from business management to production planning. These external assets are capable of analyzing large volumes of data due to their computational capacity enabling the execution of algorithms for resource optimization [10], [11]. Furthermore, in this external environment, simulations can be performed on the prediction of CPSs behavior by virtually modeling the production environment [12]. In this way, for instance, decision-making through Digital Twins (DTs) [13] can transfer orders to the physical world, reducing costs and generating added value.

But, in order to increase productivity, this decision-making can be integrated into the production process in an automated way [14]. Nevertheless, the technological heterogeneity of the CPSs [15] and, therefore, of industrial communication protocols [16], prevents directly achieving the collaborative and connected environment on which the SM can take advantage of external services.

In this sense, numerous architectures have been proposed at a theoretical level such as the Reference Architectural Model Industrie (RAMI) [17], or the Industrial Internet Reference Architecture (IIRA) [18] where integration among different assets of the value chain is established from various points of view (e.g., business, technological organization, product life cycle) [19]. Implementing these architectures requires the integration among all the elements through the exchange of information in a more direct way enabling the aimed collaborative environment of the SM [20].

This transformation towards architectures based on self-organization is possible due to the incorporation of CPSs intelligence, generating more decentralized manufacturing systems which favours digitization and communications [21]. In addition, the intelligent decision-making of DTs or cloud-based optimization algorithms implies modifying the classical organizational hierarchies due to their required computational capability [22]. But, the final achievement of this paradigm requires interoperability among all assets [23], which is a technical barrier for the implementation of this organizational conception.

Therefore, there is an existing technical challenge where heterogeneous assets and technologies should converge through interoperability to achieve an efficient production environment [24]. For this purpose, the authors establish a new term, hyperconnectivity. Then, the technical requirements to achieve an industrial hyperconnected environment as well as the milestones that opens through its implementation, are described along the manuscript.

Furthermore, as a demonstrator of the benefits of hyperconnectivity, the authors have integrated for the first time in the literature all types of assets: external (e.g., DTs, information providers), internal (e.g., Programmable Logic Controller (PLC), collaborative robots (Cobots) [25], Automated Guided Vehicles (AGVs) [26]) and also the human-interaction with this digitized environment (e.g., Human Machine Interface (HMI) and Augmented Reality (AR) [27]) in a real automated inspection process.

The communications of the demonstrator have been implemented through the creation of an industrial internet platform, allowing the connectivity of the most used industrial communication protocols. In addition, to achieve interoperability, a gateway has been implemented for interpreting the data generated from the different communication protocols.

In this context, through the devised demonstrator, the authors present a novel case study containing all the necessary elements for the achievement of the proposed digitized inspection goals, thus proving the need for hyperconnectivity in typical industrial processes. In addition, a series of metrics have been obtained demonstrating the technical and technological feasibility of the theoretical architecture exposed representing a novelty in the scientific literature.

Therefore, the main contributions of this paper can be summarized as follows:

- Definition of a new concept for communicative integration among systems, assets and humans: hyperconnectivity.
- Implementation of an industrial demonstrator where hyperconnectivity is achieved through an application case.
- Performance analysis of the hyperconnectivity demonstrator for different industrial protocols.

The remainder of this paper is organized as follows: Section II provides an analysis of related works. Then, in Section III, the term hyperconnectivity in the field of SM is defined establishing some criteria as well as the new milestones that launches in the SM field. Subsequently, in Section IV, we describe the application framework for hyperconnectivity. Section V defines the case study for the demonstration of industrial asset interoperability. Finally, Section VI shows the results of the demonstrator and Section VII presents the conclusions drawn from the proposal of this work.

II. RELATED WORKS

Reference organizational architectures for Industry 4.0 and SM (e.g. RAMI 4.0, IIRA) are based on the integration of assets along the value chain, including diverse aspects such as economics, logistics or production [19]. These Service-Oriented Architectures (SOA) decompose complex processes into simpler physical and virtual applications (e.g., cyber-security, optimization, or production control) [28]. The architectures integrate multiple applications to be more flexible and less hierarchical allowing a more efficient production environment [29]. To achieve the integration of applications or assets in the entire value chain, high connectivity is required since data or decision-making from one application can be needed in other different applications. For this reason, a wireless network capable of simultaneously connecting a large number of assets is necessary.

In this respect, Lee and Yang [30] have demonstrated both in simulations and at the theoretical level the possibility of connecting 8000 devices under the IIoT paradigm. Therefore, it is technically feasible to communicate a huge amount of assets in an industrial environment with moderate speed and low power.

However, the diversity of communication protocols used by devices at the application layer is a barrier to achieving effective communication [31].

Furthermore, this problem has arisen in projects such as at the University of Southern Denmark [32], where they state that the implementation of the integration of industrial elements with different industrial protocols has supposed a technological challenge. Therefore, the heterogeneity of the protocols used, as well as the diversity of applications to be integrated, is a challenge for both companies and the scientific community according to Zeid et al [33].

Moreover, recent studies [34], [35] have shown that the problem of interoperability in the industry has not yet been solved. If these technological barriers are overcome, authors such as Park et al. [36] have established the implications of interoperability for business within the framework of the web3. In addition, Berstein et al. [37] mention the need for interoperability for extended reality (XR) applications in order to integrate human capital into industrial production processes.

In this context, several demonstrators of interoperability between industrial internet protocols have been developed according to Anam Amjad's research [6]. Their literature review revealed that there are no studies in which the global integration of various IIoT protocols such as MQTT, HTTP and PROFINET has been implemented. To solve this challenge, existing studies implement middleware-based architectures to achieve interoperability between two protocols [38], [39], [40].

Wang et al. [41] have implemented a middleware in which data is centrally processed for decision-making by an industrial computer. Hence, there is no information exchange between protocols for asset interoperability. Moreover, this implementation diverges with the decentralization of SM production processes since decision-making is performed on a unique computer.

Another aspect, not often considered in scientific studies, is the interoperability with external services or assets (e.g., electricity market, DTs, optimization algorithms) which need information from the industrial plant in order to automate decision making as stated by Tao et al. [42]. For instance, DTs use modeling and virtualization techniques to predict the behavior of an industrial process [43]. This generated information can be directly transmitted to CPSs to automatically optimize the production processes [44]. However, the diversity of communication protocols used by the assets located in the cloud differs from the protocols used in manufacturing processes preventing communication in a direct way according to the study of Salazar et al. [45]. For this reason, a novel interoperability middleware is proposed in this paper for the integration of cloud services (e.g., DTs) in industrial processes in order to achieve an optimized and collaborative production environment according to the SM paradigm.

Humans are another industrial asset which should be integrated into industrial production processes according to numerous researches [46], [47], [48]. In fact, interactions between humans and machines are also forms of communication according to Gely et al [47]. For this reason, interfaces can be used in order to enable the interaction between humans and digitized assets. For instance, this can be reached through Augmented Reality (AR) configuring AR glasses in order to monitor production processes along the entire value chain. In this context, there are numerous works in the literature such as [49] and [50] where glasses are connected to the cloud allowing the visualization of three-dimensional models (e.g., parts, additional information). However, the communication of these systems with other industrial assets such as DTs or monitoring and control systems in SM has not yet been developed.

Thus, in this paper, the authors aim to integrate all industrial assets (e.g., DTs, humans, CPSs) from a holistic perspective. For this purpose, a novel demonstrator has been developed and implemented in order to analyze and test at a technological level the proposals of the scientific literature. The immersive interaction applications, third-party DTs applications, as well as the CPSs of the production process are integrated within a case study to create a collaborative environment as pointed out by the SM principles.

To achieve this aimed collaborative environment, connectivity among assets is required. Given the collaborative context of the SM a new term, hyperconnectivity is first defined to integrate all the concepts reviewed in this Section. This term encompasses the communications among all industrial assets in the field of SM from a new perspective, as presented in Section III.

III. HYPERCONNECTIVITY

Hyperconnectivity is defined as the ability to securely communicate humans and digital assets (e.g. systems, services and devices) regardless of the protocols or physical media involved. In this manner, hyperconnected systems link all assets, both internal and external, of the processes involved in the supply chain with the objective of generating greater added value and flexibility.

In addition, the employment of hyperconnectivity principles in SM may suppose a series of differentiating characteristics from other fields (e.g., smart cities, health, defense) that we analyze in this Section, proposing a series of potential industrial applications and future milestones that are particularly addressed in the final sections of this paper within a real application scenario.

A. DEFINITION OF HYPERCONNECTIVITY IN THE SM PARADIGM

Although some Industry 4.0 and SM articles mention the term hyperconnectivity [7], [51], [52], [53], the authors propose hereafter a definition of the term hyperconnectivity for the SM paradigm.

Hyperconnectivity can be defined as the massive and universal communication among heterogeneous industrial assets in a digitized context through the use of industrial networks based on Information and Communication Technologies (ICTs). In addition, the term hyperconnectivity may include the representation of data through interfaces and the possibility for humans to interact with the digitized environment of SM [54].

Thus, in the SM context, hyperconnectivity involves communication among all assets of the value chain (e.g., CPSs, Software platforms, and human operators) in order to automatically coordinate them to improve the global efficiency of the industrial plant. In addition, connectivity with third-party services, which import data from the industrial plant and export solutions by processing data and information, is also considered hyperconnectivity. An example of an external service are the DTs which allow the optimization of decision-making. However, external assets require connectivity with other assets to directly influence on the production processes (e.g. CPS involved in the production process, other cloud-based optimization algorithms, or direct connections between cloud and humans). This connectivity can be hampered by differences in data structures for information exchange.

For instance, an autonomous industrial mobile robot needs to know its position to be able to perform navigation tasks, but it may also find useful to know the location and state of other assets to be able to perform its route planning. In turn, a collaborative robot, (i.e., Cobot) may need this information to perform precision tasks with the mobile robot or a DT may use the information to simulate upcoming CPSs actions. In addition, given the diversity of manufacturers and communication protocols within industry, there may be a communication incompatibility among end devices. This fact causes that sometimes two sensors are used to measure the same variable because each device can only be connected to one type of asset. Therefore, with the implementation of hyperconnectivity, the number of devices can be reduced and consequently costs can be lowered.

Thus, hyperconnectivity brings interoperability to hardware, creating new architectures oriented to optimize processes in an automated way [28]. For this reason, technological criteria must be unified to distinguish hyperconnectivity from other terms such as IIoT.

B. HYPERCONNECTIVITY REQUIREMENTS

This section proposes generic requirements for establishing a hyperconnected environment. The criteria are conceptually described in order to be applicable according to the needs of each production process.

- Interoperability among devices is the main feature of hyperconnectivity, but the variety of existing protocols makes direct interconnection difficult. For this reason, protocol compatibility among all devices is a challenge in various domains of knowledge, particularly in the SM. Furthermore, to achieve hyperconnectivity it is necessary to have connectivity not only with manufacturing process equipment but also with the rest of the digital assets (e.g., DTs, XR, or humans) which are value-added generators.
- Cybersecurity is dedicated to preserving the integrity of the network among services by preventing access by unauthorized third parties. Because the connection among services can be delocalized and takes place over Wide Area Networks (WANs), packet protection techniques such as traffic tunneling are required to create Virtual Private Networks (VPNs). In this way, client-to-client or client-to-site messages are encrypted to prevent information extraction.
- The development of advanced interfaces between the virtual world and the human is another cornerstone of hyperconnectivity. The visualization of information in an immersive environment facilitates the interpretation of data since the environment is more realistic. In this regard, new technologies that are emerging such as AR and Virtual Reality (VR) can be integrative technologies to achieve a hyperconnected ecosystem. In addition, the definition of forms of communications for humans to interact with the digitized hyperconnected environment is critical to fully integrate humans in this new collaborative environment proposed.

C. MILESTONES

According to the proposed definition, hyperconnectivity has applications in different fields of knowledge, especially in engineering, due to the convergence between connectivity and data processing, generating the automation of digital environments. In industry, the communication of production process equipment with offshore servers enables remote control, management, and supervision, which is an advantage for organizations with multiple factories. In this sense, complex supply chains can benefit from hyperconnectivity, since the information from one activity or product can be useful to automatically organize the production of another factory.

Furthermore, hyperconnectivity can facilitate customized production through the traceability of intermediate products using Radio Frequency Identification (RFID) technologies, achieving optimized and collaborative production along the supply chain [55].

To achieve these milestones, given the wide amplitude of our hyperconnectivity proposal, we establish and discuss a general framework for the application of hyperconnectivity in Section IV.

IV. HYPERCONNECTIVITY FRAMEWORK

Hyperconnectivity can be adapted to various industries (e.g., pharmaceutical, metallurgical, assembly) by meeting their specific needs (e.g., regulatory, cybersecurity). Furthermore, given the diversity of applications and contexts, as well as the variety of characteristics (e.g., data types, topologies, architectures) a theoretical framework for the implementation of hyperconnectivity is proposed in this section.

Hyperconnectivity is based on the convergence of three fields of knowledge: cybersecurity, interoperability, and human interaction with the digitized environment. The union of these three concepts provides a new vision in information and communication systems, achieving a greater integration across systems.

The integrity of data content for the communication among systems, services and people is essential to ensure that the information transmitted is authentic and secure. This is achieved through the use of tools such as two-factor authentication, security or data encryption protocols, etc. In addition, these tools help to ensure the authenticity and confidentiality of data, as well as to prevent tampering or unauthorized use.

Furthermore, interoperability enables the effective exchange of information between two heterogeneous systems. This means that two systems can communicate with each other regardless of platform, programming language, operating system, network protocols, etc. To achieve interoperability, an intermediate layer can be created between the systems, where data is analyzed for effective and transparent information exchange. This intermediate layer based on syntactic interoperability structures the information for its presentation according to the standards of the different communication protocols. In this way, information from one protocol is extracted for structuring it in a suitable manner for another protocol.

Furthermore, functionalities can be added to the interoperability layer depending on the case study. For instance, it is possible to manage communications by being able to request information from other devices. In addition, this layer can also be used for data management, storing data in a database or table temporarily for forwarding to other devices on request. Depending on the communication method, data can be requested or received without request.

Therefore, interoperability provides systems with greater flexibility and adaptability, allowing one system to access the resources of another without having to make changes or adaptations to the programming or hardware of the equipment. Another aspect of hyperconnectivity is the representation of information to the human. The reality of the environment is captured by measuring physical variables (e.g., vibrations (sound), visible spectrum (images), temperature, etc.).

In this digitization process, the perception of reality is transformed into data that can be transmitted electronically. However, when the digitized data is represented to the human being, it is represented by interfaces which convert the data into sensory stimuli that can be interpreted by the human being.

Nevertheless, the representation of reality does not have to be of the same kind as it was acquired. In this sense, humans may attain information that they cannot capture with their sensory capabilities but which, through digitization, is transformed for their direct interpretation. In addition, humans can interact with the digitized production environment generated through hyperconnectivity by including information captured by their human senses that cannot be obtained through CPSs and/or by adding processed data through their intelligence that can anticipate future states of the industrial plant and can be helpful for decision-making.

According to Figure 1, the three principles on which hyperconnectivity is based are transversal to all information systems and are independent of casuistry and consequently of technical requirements such as communication networks, computing, or hardware. Therefore, each case study has to satisfy their needs by employing different technologies for each principle. For example, in communication networks, aspects such as the number of devices, bandwidth or physical transmission media will vary depending on the application. Likewise with architectures defining the location of computing equipment operating the interoperability layer (e.g., cloud, edge) or the definition of the kind of interaction between technologies and humans (e.g., interfaces, augmented reality, virtual reality). As a consequence, there is no single technology or methodology to achieve hyperconnectivity because depending on the case study the requirements of the principles can be heterogeneous.

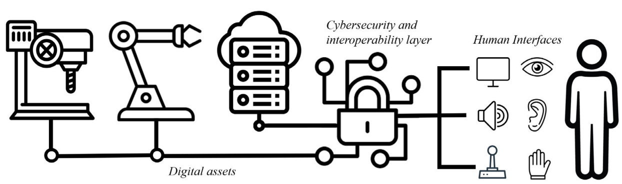

FIGURE 1. Diagram of hyperconnectivity where cybersecurity, interoperability, and human interaction with the digitized world are represented.

In Section V, the authors demonstrate hyperconnectivity in a case study for intelligent manufacturing using technologies specific to the industrial sector and the particularities of the case study.

V. HYPERCONNECTIVITY DEMONSTRATOR

Hyperconnectivity has multiple application cases since CPS, humans, and communication networks are common to most industrial processes. Considering the extent of manufacturing processes, a case study is proposed where all the criteria of hyperconnectivity are addressed. Nevertheless, for the development and implementation of the case study, multiple technologies can be used. In this context, the combination of an automated and a manual part inspection process is proposed where connectivity between cloud assets, machines, and operators is required. The hyperconnectivity demonstrator has been physically implemented in the E3 Laboratory of the School of Engineering of the University of León.

The objective of the case study is the inspection of parts using industrial equipment such as AGVs, Cobots, PLC, an inspection scanner, and a borescope as can be seen in Figure 2.

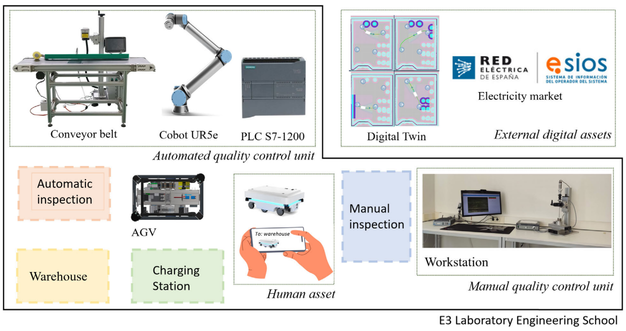

FIGURE 2. Arrangement of the different equipment for the quality control process.

In addition, digital assets in the cloud have been used, such as a DT for governing the autonomous navigation of an AGV and data from Red Eléctrica de España (REE) which publishes the costs of electricity. Given the heterogeneity of the assets, each one is technically described in Section V-A.

A. INDUSTRIAL ASSETS

The main asset of the demonstrator is edge computing, where the applications for interoperability are executed. For this purpose, an industrial computer has been used, which has an Intel Core i7 processor with 16 GB of RAM memory as well as two wired Ethernet interfaces and a wireless one for communications. In the field of communications, a firewall and a router are available for the segmentation of the process network with the external network, as well as a switch and several access points for wireless connections.

The autonomous mobile robot is a device that connects to wireless networks (IEEE 802.11) to communicate its position, as well as to receive navigation missions with the Hypertext Transfer Protocol Secure (HTTPS) using the manufacturer's Representational State Transfer Application Programming Interface (REST API). In this case study, the MIR100 robot is used, which has embedded intelligence for autonomous navigation using Light Detection and Ranging (LIDAR) and ultrasonic sensors. In this way, the navigation and control of the actuators are performed through algorithms programmed in the onboard computer of the industrial robot being able to transport parts autonomously through the industrial plant.

Another industrial robot is the UR5e collaborative robot from Universal Robots, which is equipped with grippers to perform pick and place tasks. This robot is connected to a controller via an ethernet cable which uses the HTTP protocol for external communications. In this way, actions such as starting a program as well as transmitting the status of the cobot are established.

The automated inspection module consists of a conveyor belt which is equipped with a laser scanner that determines the dimensions of the parts to determine whether they meet the established tolerances. In addition, this belt has electro-pneumatic actuators to separate the valid parts from the invalid ones. All this equipment is controlled by a Siemens PLC S7-1200 whose variables can communicate with the PROFINET and OPC-UA protocols to the rest of the equipment in the network.

For human process interaction, an Android application has been implemented for the overlay of process information. The application has been developed with the Unity graphics engine together with the Vuforia SDK for 3D object detection. In this context, a custom API has been created in edge computing to display the information related to the AGV in the developed application using HTTPS protocol. In this way from any smartphone connected to the industrial network that by means of the camera detects the AGV, it will be possible to visualize in an overlapping way the parameters of its status.

In addition, HMI has been implemented for the operator to select which parts are suitable and which are rejected. For this purpose, a web server located in the industrial computer has been programmed. In this web server, a responsive page has been designed where the image of the borescope and the identification of the part are displayed. With this information, the operator evaluates the part as suitable or unsuitable through this same interface.

As for the assets located outside the industrial plant, the DT is in charge of performing the simulations of the navigation times and trajectories, being able to evaluate which is the next navigation target for the AGV according to the parameters of both the industrial plant (e.g., cobot status, AGV status) and the REE market. For this purpose, three simulations are run simultaneously (i.e., one for each possible navigation target) obtaining the times and trajectories. With this information, it is determined which is the most optimal mission that is automatically send to the AGV. The execution of the simulations is performed with ROS using an Intel Core i9 computer with 32 GB RAM.

Given the description of the assets involved in a case of automated inspection of parts in the context of the SM, the heterogeneity of existing equipment and protocols is demonstrated. In this context, the communication incompatibility among protocols makes it difficult to create a collaborative environment which is necessary for the holistic optimization of the proposed production processes.

Once all the digital assets used in the demonstrator have been defined, the case study is described in Section V-B.

B. CASE STUDY

The quality control process introduced in Figure 2 is based on the automated transport of finished parts to the quality control units. The demonstrator is composed of two modules or units with different locations: one operated by humans and the other fully automated. In this way, the interoperability of the equipment is evaluated, as well as the human-process interaction.

On the one hand, the fully automated unit verifies that the dimensions conform to the design and evaluates the quality according to the allowed tolerances. To do this, the part is fed onto a conveyor belt that, together with a mounted laser, evaluates the part dimensions by separating defective parts from correct ones. In addition, a collaborative robot performs the picking and placing tasks from the AGV to the conveyor belt and vice versa. Therefore, the coordination among the different systems (e.g., AGV, cobot, quality control unit) is necessary for achieving the optimal performance of the production processes.

On the other hand, the manually operated unit is equipped with a borescope to inspect the finishing details of the part. For this purpose, the operator is provided with an assistant that facilitates the identification, evaluation, and decision-making process by integrating it into the production workflow. Therefore, it is necessary to provide the operator with advanced interfaces based on real-time to integrate their tasks with both the quality control process and the rest of the equipment and units, located both in the industrial plant and in the cloud.

The manufactured pieces must have been evaluated by the automated inspection machine and by the borescope operated by a human in order to validate the quality control of the piece. In this regard, the inspection order of each manufactured part is determined by the DT which simulates the navigation of the AGV based on its status (i.e., position, availability, and battery level) and the status of the remaining industrial devices to establish the most optimal navigation mission. Once defined the target, the AGV has onboard intelligence which allows autonomous navigation to move to the objective that the DT has set.

In addition, a third-party service has been used to import data on the hourly cost of electric power. For this purpose, the REST API of REE, which is the Spanish electricity market manager, has been used. This information is sent to the DT to determine, together with the battery level, when the AGV should be charged without significantly interfering in the inspection process.

Therefore, the case study aims to establish communications among all assets for the creation of a collaborative environment that enhances the global productivity. The achievement of this collaborative objective requires the definition of the communications among the assets which is discussed in Section V-C.

C. DATA EXCHANGE IN THE CASE STUDY

This section defines the variables exchanged by the assets to achieve interoperability.

As can be seen in Figure 3, the output variables of one asset are the inputs of another, but with different communication protocols preventing direct communication. Once the variables are defined, it is required to establish the ontologies with the rest of the assets according to the case study process. For this purpose, the assets have been classified into external assets, interfaces and industrial equipment. In the present case study, the communication between the DT and the Spanish electricity market managed by REE is required for the decision-making on the AGV navigation. In this context, from the REE API, the energy costs in kWh of the electricity are sent to the DT to determine when to charge the AGV with the minimum cost.

In addition, the communications between delocalized assets with the CPSs of the production process in the case study, are bidirectional where the DT receives the status of the cobot and the AGV and the DT sends to the AGV the next navigation mission according to Figure 3.

Furthermore, the interaction between the human and the virtual world has been implemented in a bidirectional way using two interfaces. One interface is based on augmented reality where the speed and navigation mission data of the AGV are visualized and obtained from the DT. And another one where the human establishes whether the parts pass the manual quality control.

Moreover, the cobot and the PLC that controls the inspection module have been integrated achieving the automation of the inspection in coordination with the AGV. In this case, when the AGV arrives at the automated inspection station, it communicates to the cobot to start the program of inserting parts on the conveyor belt. Once this program is completed, it is communicated to the PLC which, by means of its analog output to a frequency inverter, starts the belt movement and by means of a digital signal, the scanning process is initiated. Once scanned, the inspection system returns a signal to the PLC to indicate if the part is valid or not, enabling the corresponding electro-pneumatic actuator to separate the correct parts from the invalid ones. After this process is completed, it is communicated to the cobot to start the parts collection program from the inspection machine to the AGV. In this way, the integration of three heterogeneous CPSs for a single process is achieved.

In this sense, we have carefully selected a real case study that requires diverse forms of connectivity such as cloud-cloud, cloud-CPS, CPS-CPS or, human-cloud. All these communications forms are critical to enable the generation of a hyperconnected environment in which every decision is based on the overall information extracted from the manufacturing plant by CPS and humans using the cloud for decision-making.

Cloud-based decision-making is addressed through the help of a DT of an autonomous mobile robot in which decisions are dependent on other external information services. In addition, the real industrial equipment used in the case study employs different communication protocols such as Profinet, MQTT, HTTP or HTTPS preventing direct communication among devices.

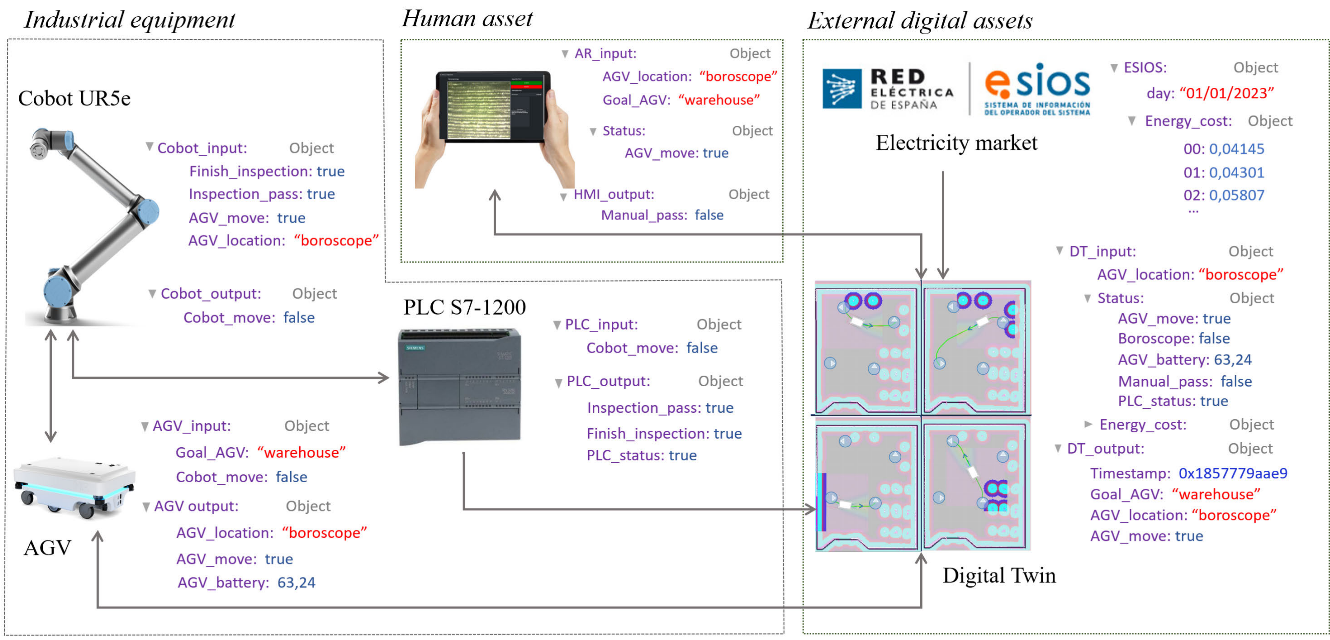

FIGURE 3. Variables of the devices involved in the interoperability process of the case study.

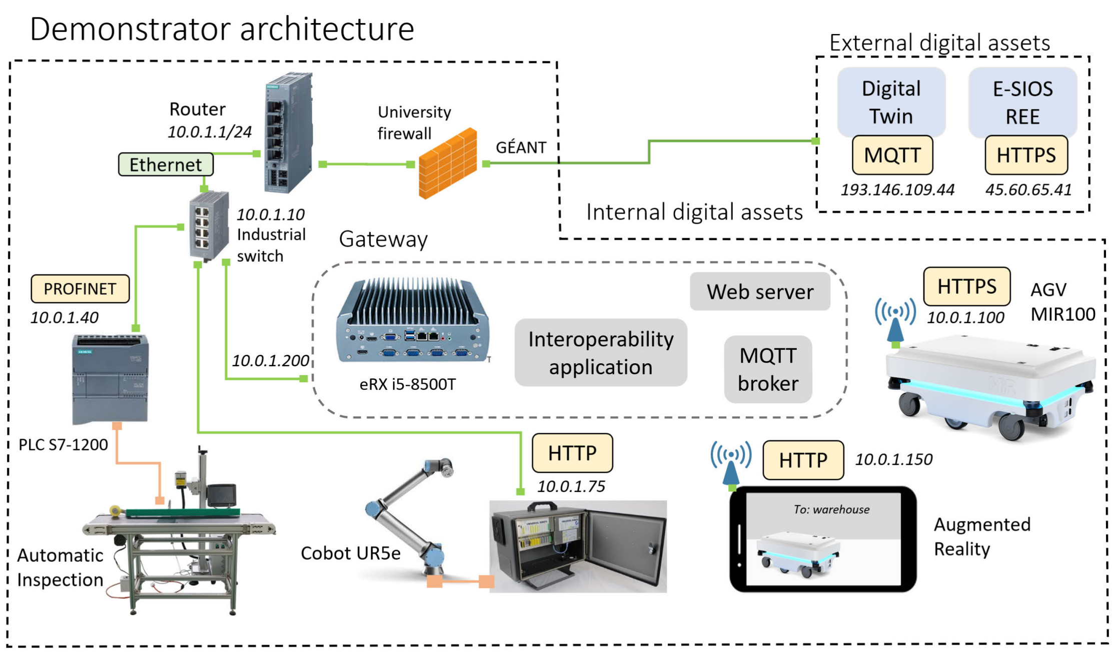

FIGURE 4. Demonstrator architecture with real industrial equipment for interoperability.

Human interaction with the digitized environment which is critical to enhance the proposed hyperconnected environment of this paper is provided through interfaces and AR enabling, for instance, the communication of the DT data with humans or integrating the manual and automated inspection process through an HMI.

To exchange the above information between all the described assets, an architecture is proposed as detailed in section V-D.

D. PROPOSED ARCHITECTURE

For this case study, an Ethernet-based communications architecture is presented which is compatible with the industrial protocols of the demonstrator. For this purpose, a network has been created using an industrial router for the inspection process in the plant and a switch to communicate all the devices by cable. In addition, there is an access point for wireless communications for the AGV and the AR application.

E. INTEROPERABILITY APPLICATION

As for the interoperability layer, it is located within the private network of the production process so that data can be exchanged with lower latency between the CPSs. However, the DT and REE data are located outside the industrial process due to computation and storage needs. These services are connected to the process through a firewall to provide further cybersecurity to the private network of the production process.

Figure 4 shows the devices used in the demonstrator and the connections between them. Application layer communication protocols and the IP addresses used for this case study are also shown. In the case of the gateway, three applications are running: the MQTT broker, the web server for monitoring the production process, and the interoperability application which is described in section V-E.

The interoperability application runs on the industrial computer located at the edge to reduce times compared to running it on cloud servers. This application aims at exchanging information between different application layer protocols in order to provide interoperability among assets. In this case study, levels one and two of the Levels of Conceptual Interoperability Model (LCIM) are required for information exchange [56].

Level one corresponds to technical interoperability, which aims to establish an infrastructure for data exchange. In this context, Ethernet-based networks are employed in accordance with IEEE 802.3 standards where the different physical layer media are specified. However, different physical media have been used due to the nature of some equipment such as the AGVs which requires wireless communications, which is why the IEEE 802.11 standard has been adopted in the case study. In this way, wide compatibility is achieved with most assets both in the industrial plant and externally.

But, this level of interoperability results insufficient since data is not structured in an understandable way for all devices, which is why level two interoperability based on the syntax of data is required. To restructure the information, the gateway has an Ethernet interface where the transport-oriented layers decapsulate the packets to serve the application-oriented layers. In this case, an application has been developed to encapsulate the data to each protocol. In addition, it is necessary to identify the source device of the packets as well as the communication protocol for the extraction of the information for its subsequent encapsulation for the destination protocol. For this purpose, a table has been programmed to establish the data flow, relating the variables of the source and destination protocols.

This application executed on the industrial computer structures the data in JavaScript Object Notation (JSON) due to its ease of writing to be parsed. In this way, a new datagram compatible with the destination communications protocol can be created, as shown in Figure 5.

In addition, with this methodology, it is possible to introduce information from several sources in a single package, especially for cloud services where large amounts of information can be processed. This facilitates the massive storage of information, or even customize the type of information for a specific application resulting more efficient. In addition, in case a communication protocol does not have the necessary data to create the datagram in another protocol (e.g., type of variable, destination address), it is completed by the information stored in the server or received by other assets.

VI. HYPERCONNECTIVITY DEMONSTRATOR RESULTS

The creation of an experimental environment with real industrial equipment for interoperability enables the demonstration of the hyperconnectivity concept proposed by the authors.

For this purpose, the case study mentioned in the previous section is implemented in the E3 laboratory of the School of Engineering of the University of León, as shown in Figure 6.

In this sense, key performance indicators (KPIs) [57] can be obtained and analyzed for the evaluation of interoperability in a real application environment. In this demonstrator, wireless communication is required due to the fact that there are two mobile devices (i.e., AGV and AR applications).

Therefore, to achieve technical interoperability, the physical layer protocols shown in Table 1 are used.

TABLE 1. Physical layer-oriented protocol used for each asset of the interoperability demonstrator.

Device / Protocol	IEEE 802.3	IEEE 802.11
AGV MIR-100		X
REE	X	
Digital Twin	X	
Cobot UR5e	X	
PLC S7-1200	X	
AR application		X
Gateway	X	X

Since the gateway used has two types of network interfaces, the IEEE 802.3 standard has been selected to obtain the KPIs because it is the most widely used for these case studies and has better performance. Therefore, wireless communications have been carried out through an access point with the IEEE 802.11ac standard, which allows technical interoperability among wireless devices and those connected by cable.

According to the case study, interoperability is performed between external and internal assets to automate the DTs' decision-making. For this reason, the communicative relationships between elements have been defined in Table 2, where the addresses as well as the location of the assets are shown.

Once technical interoperability has been achieved among all the assets, syntactic interoperability is required in order to organize the information of the different protocols in the application layer. Table 3 summarizes the protocols supported by each device and shows that the gateway, which acts as an interpreter, is compatible with the demonstrator's communication protocols.

For the case study, the messages transmitted via MQTT protocol are carried out with a Quality Of Service (QoS) of level 0, where there is no acknowledgement (ACK). In this

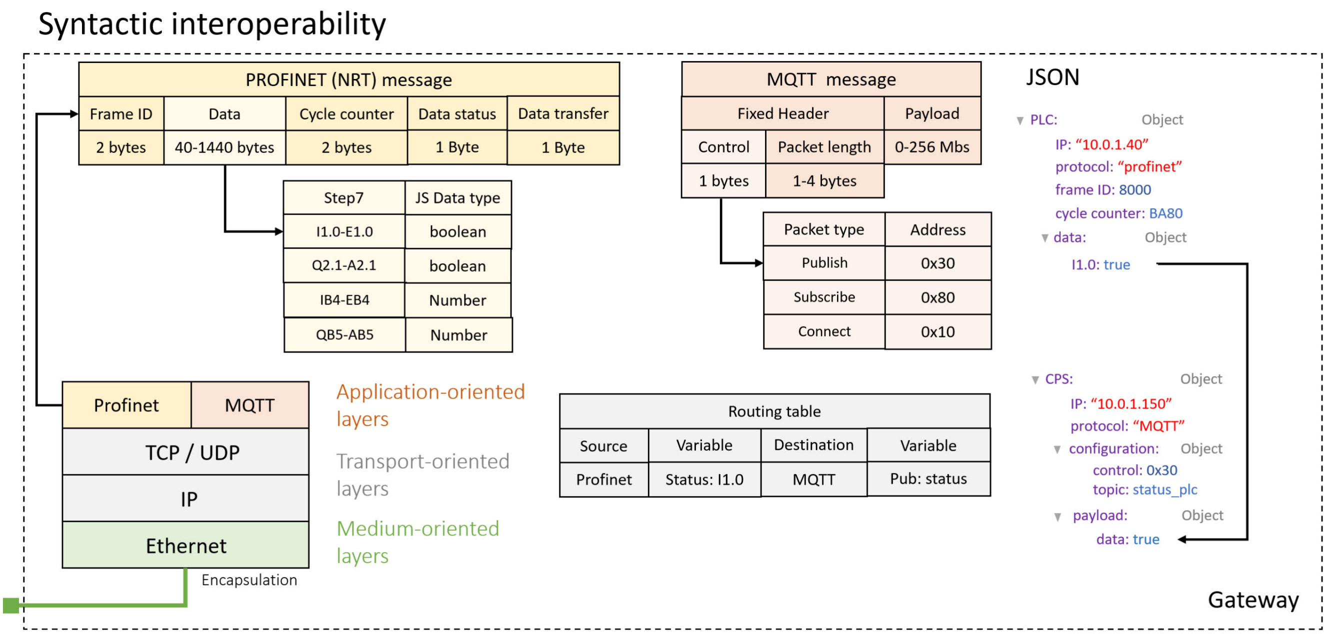

FIGURE 5. Data flow in the gateway application for syntactic interoperability among industrial protocols.

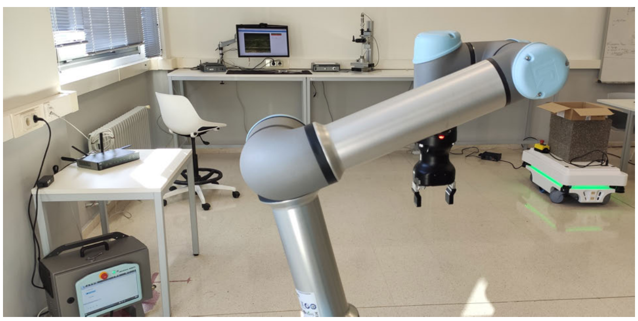

FIGURE 6. Real experimentation environment for the interoperability demonstrator based on an industrial Internet platform.

TABLE 2. Interoperability relationship between demonstrator assets for the case study.

Asset	IP source	Location	Asset	IP Destination	Location
REE	45.60.65.41	External	DT	193.146.109.44	External
DT	193.146.109.44	External	AGV	10.0.1.40	Internal
AGV	10.0.1.100	Internal	DT	193.146.109.44	External
DT	193.146.109.44	External	AR	10.0.1.150	Internal
AGV	10.0.1.100	Internal	Cobot	10.0.1.75	Internal
Cobot	10.0.1.75	Internal	AGV	10.0.1.100	Internal
Cobot	10.0.1.75	Internal	PLC	10.0.1.40	Internal
PLC	10.0.1.40	Internal	Cobot	10.0.1.75	Internal
PLC	10.0.1.40	Internal	DT	193.146.109.44	External

case, the gateway runs EMQx w hich is the selected broker due to the low latency according to the comparison made by Koziloek et al. [58].

Once the communicative relationships between the assets have been established, as well as the different protocols of

TABLE 3. Compatibility of application protocols among the assets used in the demonstrator.

Device / Protocol	MQTT	PROFINET	HTTPS	HTTP
AGV MIR-100			X	
REE			X	
Digital Twin	X			
Cobot UR5e				X
PLC S7-1200		X		
AR application				X
Edge gateway	X	X	X	X

each one, interoperability is evaluated by obtaining KPIs. In this context, the systematic review of the evaluation of interoperability by Serapião et al. [23] establishes performance indicators at the conceptual and technological level. At the conceptual level, the most relevant KPI is the total time of information exchange between assets, while at the technological level, the percentage of failed connections is evaluated, as well as the times related to message translation for data syntax.

For this purpose, the Wireshark protocol analyzer was used on the gateway to evaluate the performance of the proposed interoperability system by obtaining the latencies. However, to obtain the processing times related to the syntax of the data (i.e., syntactic interoperability), it has been done by querying the clock time without the need to create new variables to the application. In this way, the application layer processing time metrics have been obtained, as well as the response time to requests from client-server-based protocols (e.g., HTTP and HTTPS). Therefore, the response time derived is the sum of the propagation time through the physical medium, the queuing time, as well as the processing delay of each layer of both the server and the client.

Table 4 results have been performed on a network devoted only for this case study and averaged over four measurements

TABLE 4. Latencies and data processing time for the case study variables.

Source Asset (SA)	Destination Asset (DA)	Latency gateway-SA [ms]	Data response time [ms]	PT [ms]	Latency gateway-DA [ms]	Total time [ms]
REE	DT	6	105	3	13	121
DT	AGV	13	-	10	23	46
PLC	DT	4	-	2	13	19
AGV	DT	23	211	1	13	225
DT	AR	13	-	5	9	27
AGV	Cobot	23	211	5	1	217
Cobot	AGV	1	35	10	23	68
Cobot	PLC	1	35	2	4	41
PLC	Cobot	4	-	5	1	10

The Processing Time (PT) of the packets whose destination protocol is MQTT or Profinet corresponds to the decapsulation, transformation, and encapsulation of the data. However, the augmented reality application which connects to the HTTP server located at the gateway requests the data as a client. For this reason, the processing time corresponds to the time lapse from the time the request arrives at the gateway until it is sent. On the other hand, for both cobot and AGV, the HTTP or HTPPS protocol server is located at the end devices, so the information is sent using the POST method.

The response times shown in Table 4 for the protocols based on the client-server philosophy have been obtained using the GET method, considering the time elapsed from the request to the data acquisition. For this reason, the total time where the source protocol is HTTP or HTTPS corresponds to the sum of the response time plus the processing time plus the latency time between the gateway and the destination asset.

However, the latencies of the assets connected with the IEEE 802.11 protocol have a higher variability due to the dependencies of external factors such as Line-of-Sight, and channel saturation among others. Nevertheless, according to an investigation [59], AGV latencies for communications with management should be contained between 10 and 100 ms, being 46 ms that of this demonstrator.

According to the data obtained in the interoperability demonstrator, hyperconnectivity has been successfully achieved. Therefore, connectivity between cloud-cloud, cloud-CPS, CPS-CPS, and human-cloud assets has been technically possible using a gateway located at the edge for the modification of the data syntax depending on each protocol. In this manner, production processes have been optimized through external assets which have been integrated with humans and industrial equipment creating a collaborative environment demonstrating the benefits of implementing the proposed hyperconnectivity.

Thus, these results show the successful implementation of the hyperconnectivity concept of this paper in a real application environment. Future research directions for this incipient field may include the study of communication policies among assets, the advanced representation of information considering the heterogeneity of data or the evaluation of the effectiveness of the information transfer among assets.

VII. CONCLUSION

The digitization of production processes through digital assets such as CPSs, DTs or optimization algorithms among others, improves productivity and efficiency being this one of the objectives of SM. To achieve this aim, a collaborative environment where all assets need to communicate in order to be integrated along the entire value chain is required. The new collaborative conception drives a new communication model based on connectivity among all assets in a direct way. Based on this concept, a new term (hyperconnectivity) has been defined referring to the connectivity among humans, equipment, and services.

However, achieving hyperconnectivity entails a number of technological challenges in the field of industrial communications. The heterogeneity of the communication protocols used in the different organizational layers prevents interoperability among human, external and internal assets of the production processes. For this reason, an interoperability demonstrator has been developed and implemented with real equipment based on an industrial internet platform where it has been possible to exchange information between human, external, and CPSs assets located in the manufacturing plant. In this context, technical interoperability has been achieved through industrial ethernet networks, as well as syntactic interoperability by using a gateway located at the edge to act as an interpreter between the different elements involved in the production processes. For this purpose, a novel case study based on automatic inspection has been implemented to evaluate the syntactic interoperability between the different industrial communication protocols at the application layer.

By means of the interoperability demonstrator, KPIs related to the information processing time for syntactic interoperability, as well as the total communication times among assets, have been obtained. The PTs obtained are less than 5 ms, except for the HTTPS protocol whose time is 10 ms due to authentication.

Therefore, it is demonstrated that it is technically possible to implement the proposed hyperconnectivity concept of this paper, achieving an increased efficiency in the case study by using real heterogeneous devices under the Smart Manufacturing paradigm.

Furthermore, this paper establishes a groundwork for hyperconnectivity, with the aim of facilitating its implementation and discussion in future works, which may be applicable to a variety of domains and through alternative technologies.

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