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Cyber-Physical System for Predictive Maintenance in HVAC Installations in Hotels

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***Abstract*—This paper describes a framework for predictive maintenance in Heating Ventilation Air Conditioning installations in hotels using a Cyber-Physical System. Predictive maintenance implies high costs for the hotel sector, so that a low-cost energy-efficient design is essential. The proposed framework is based in the general framework proposed by the National Institute of Standards and Technology and is inspired in the three-layer IoT architecture. This fact also provides the system with interoperability and flexibility. Finally, an application of the framework in a real installation – a five-star hotel - is also presented.**

Keywords—Predictive maintenance, Cyber-Physical Systems, Heating Ventilation Air Conditioning, Internet of Things, hotel sector.

I. INTRODUCTION

Tourism is one of the most important sectors in the world economy. In 2019, more than a billion international tourist arrivals were registered [1]. In Spain, tourism is one of the main economic activities, reaching 12.4% of the country's GDP (Gross Domestic Product) in 2019 and providing close to 3 million jobs [2]. Although, due to the COVID-19 pandemic, the sector has suffered a serious blow, it seems clear that this should be a transitory situation.

Heating, Ventilation and Air Conditioning (HVAC) emerge as one of the largest sources of energy consumption in hotels. Energy demand due to HVAC systems in buildings was estimated at 40% of total energy consumption in Spain in 2017 [3]. Other studies have yielded similar results all around the world [4]. Thus, it is essential to improve the maintenance of the facilities and the use of systems that allow them to maximize their energy efficiency.

Traditional preventive maintenance must guarantee the operation throughout the lifetime of the elements of the HVAC systems, which represents a great cost on the part of the maintenance companies. For this reason, predictive maintenance arises. Predictive maintenance usually allows to optimize costs and meet the needs of the hotel sector. However, the costs involved in its implementation with current commercial products are high, as each installation must carry out an individualized strategy, which means that, in many cases, predictive maintenance systems are not used. In sectors such as nuclear energy [5], or manufacturing processes [6], there is already a long experience in predictive maintenance since a failure in these sectors implies high costs. However, the costs of implementing these systems are not justified for HVAC systems in the hotel sector. Consequently, there is a need new products and services that allow offering a low-cost predictive maintenance with a clear orientation to increase energy efficiency of the facilities.

As it is necessary to measure a large number of signals, corresponding to the elements of the facilities, it is essential to use low-cost sensors. The data that is extracted from these sensors must be processed to help make decisions about when to carry out maintenance. Thus, predictive maintenance is performed based on the knowledge transmitted by the experts. Also, a system accessible by customers must be created, allowing the display of information. The representation of the information should be graphic or in a dashboard format, where it is easily interpretable. In addition, a persistent data storage

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system, where historical data can be consulted, is necessary. This way, the concepts of the Internet of Things (IoT) and Cloud Computing (CC) come to the spotlight [7]. In addition, the acquired information must be processed. Artificial Intelligence (AI) comes into play in predictive maintenance [8].

For the application of the above mentioned techniques and the integration of sensor networks and CC, a very interesting conceptual structure appears: Cyber-Physical Systems (CPS). CPS bring digitization and intelligence closer to physical productive elements and make it possible to close a control loop. Unlike the IoT paradigm, where data is sought to be recorded and stored locally or on a platform, in CPS, loops in production processes are closed using the acquired data.[9]

Since this is a new field, many proposals are being produced and the National Institute of Standards and Technology (NIST), in the United States, has published a common framework to mark the CPS guidelines [10].

Cyber-physical systems constitute a key technology in the development of Industry 4.0 [11]. CPS integrates the monitoring of the equipment, by sensors and computer-based algorithms, with the IoT [12]. CPS comprises a great collection of technologies, such as Wireless Sensor Networks (WSN), embedded systems, control systems, IoT, CC, Big Data, and data analytics [13].

Given the great power consumption in HVACs, CPS have focused on maximizing energy efficiency [14]. Different techniques have been used to manage data, such as Machine Learning (ML) [15], Deep Learning (DL) [16] or Fuzzy Logic (FL) [17]. Unfortunately, most of the literature about CPS and energy efficiency in buildings is referred to residential buildings, forgetting the special idiosyncrasies of the hotel sector, where there is a great variety of equipment arranged in a wide typology of installations, including guest rooms, convention rooms, restaurants, cafeterias, employee dining room, office halls, and sports facilities.

Thus, we are introducing a low-cost energy-efficient framework, provided with flexibility and interoperability, thanks to its design, based on standards. This fact is key, considering the great variety of equipment inside a hotel and the big difference between hotel installations.

This paper presents a low-cost energy-efficient CPS-based framework for predictive maintenance in HVAC installations in hotels. Section I introduces the need of a CPS framework to obtain low costs and energy efficiency using predictive maintenance, and the state of the art in the application of CPS to predictive maintenance, and more specifically, in HVAC installations in hotels. Section II presents the created framework, aligned with the NIST recommendations. In Section III, the application of the conceptual framework to a specific case of HVAC installations in a five-star hotel is shown. Finally, we present the conclusions of our work in Section IV.

II. METHODS

This section introduces the proposed framework. It is divided in three sub-sections. The first one presents the general architecture of the proposed system, while the next two sub-sections deal with the description of two of the most important modules, the acquisition system and the application server.

A. General Architecture

The common framework for CPS defined by the NIST contains a reference manual to standardize the creation of CPS. According to the reference manual, a CPS must be defined from three different facets: conceptualization, realization, and assurance. These facets must be defined based on different aspects, such as functionality, business model, timing, and others. Nevertheless, the NIST framework does not contain the definitions of the blocks that are needed for the creation of an application, so the creation of a specific framework is necessary.

According to the NIST framework, a CPS is made up of interacting digital, analog, physical and human components [18]. Thus, we are creating a framework for HVAC installations, aligned with the NIST standard. Fig. 1 shows the conceptual model of CPS, applying the NIST standard [18]. Nonetheless, this model can be followed by a system in many different ways but developing the different components in any case.

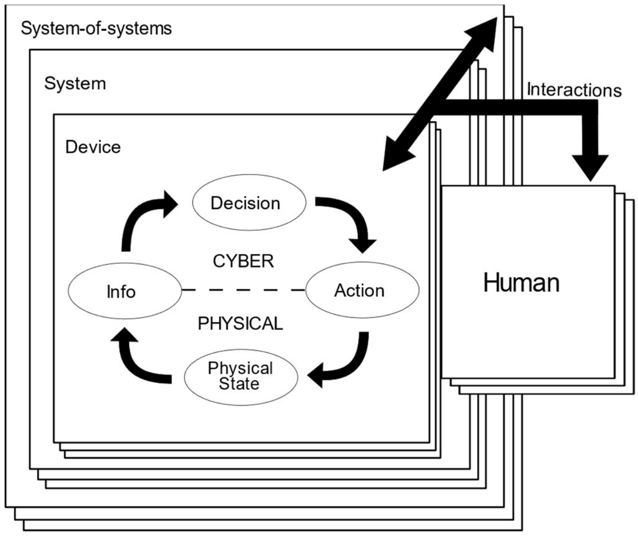

Fig. 1. CPS conceptual model based on the NIST standard

First, physical state of the equipment must be acquired. It is necessary to define some variables of interest to model the equipment and estimate the device conditions. Once the variables of interest are identified, sensors to measure these variables are needed. Thus, sensors acquire information of interest from the HVAC equipment.

Then, an acquisition system is deployed to obtain and process sensor data. Processing consists of digitalizing data and converting them to useful information for the application of the CPS. Acquisition system also manages the communication between the cyber-module and the sensors of the HVAC equipment.

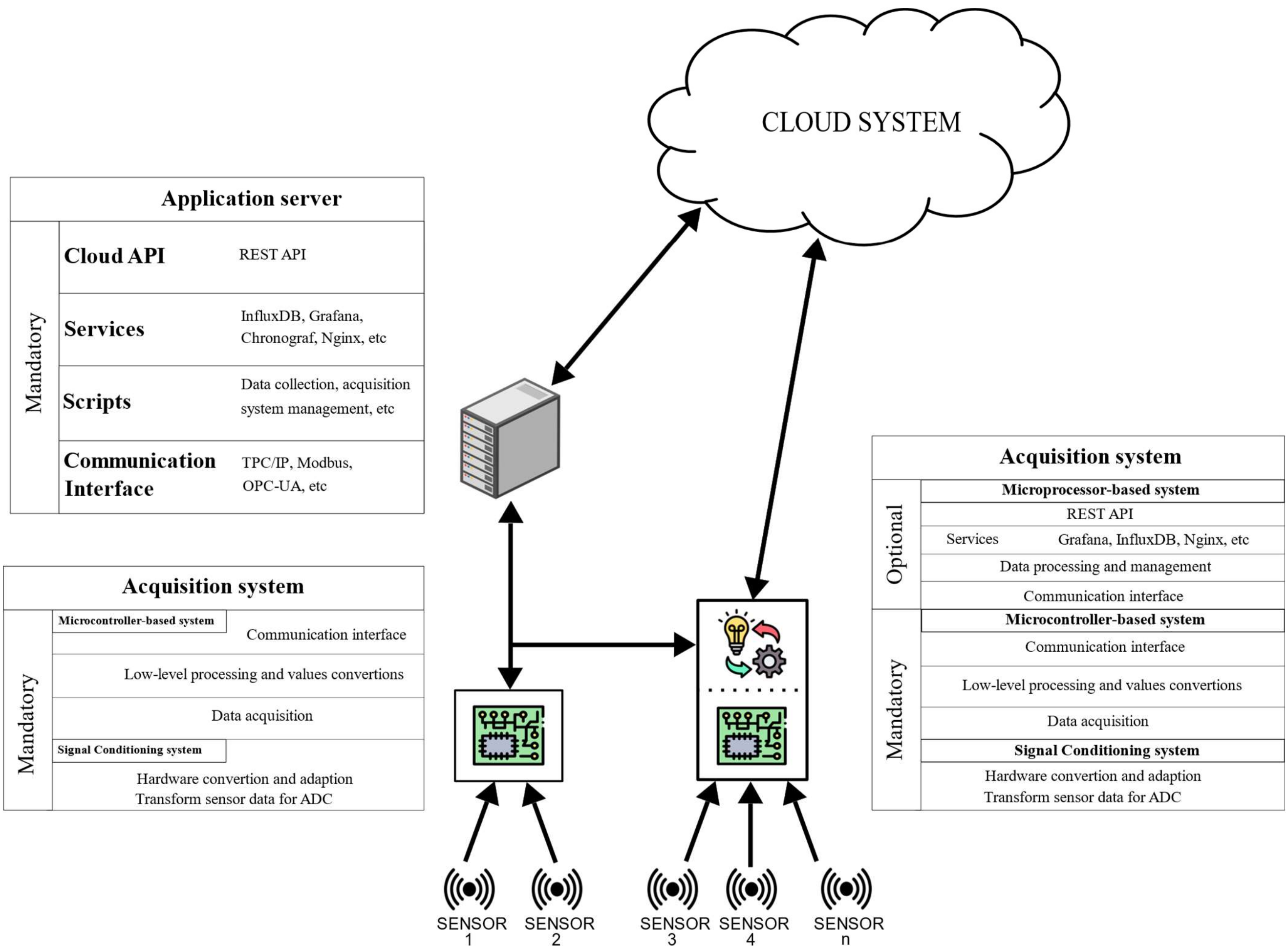

Fig. 2. Conceptual CPS model for HVAC systems in hotels

For the decision-making module, a flexible structure is developed. This structure is implemented in the cloud, in the fog, or even in the edge. This module monitors the HVAC variables, extract some inputs to the system from the acquired information, and sets an output value of the system. Different applications could be implemented in the proposed framework. Thus, a wrapper is needed to integrate the application within the system.

Finally, an action is required to change the physical state of the equipment, with the aim of closing the loop. We propose that this action should be made by the maintenance technicians, who has the knowledge and certification to modify the installation.

Based on this scheme, according to the NIST standard, we propose a more specific framework for HVAC installations in hotels. Fig. 2 represents the conceptual model of the framework.

As explained above, the acquisition system gathers data from the sensors and generates information for the decision-making process. The acquisition system is connected to the decision module to send that information, and communicates with a private cloud, which executes the applications, stores the equipment information, and creates a Graphical User Interface (GUI). Regarding the physical connections of the elements, the sensors are wired directly to the acquisition system. The acquisition system is connected to the Internet by means of a router that is deployed in the installation. The proposed system should be installed in an electrical control panel. For each room, there is an acquisition system which gathers the sensors data of the room. There are rooms for heat generation, heat distribution room, chilled water generation, and chilled water pump. Each acquisition system must be connected to the others either with a physical or a wireless connection to a router to be connected to the internet. There are several acquisition systems for each sensor, and different sensors communicate with an acquisition system.

Moreover, mandatory and optional fields have been defined for the acquisition system. The optional part of the acquisition system is the microprocessor-based system. The microprocessor-based module is defined as a processing unit that handles low-level communications, using an industrial communication bus. The microprocessor-based system is capable of handling several acquisition systems and the communication with the application server, which can be an application system or a cloud system. Besides, the application server could be inside the installation or outside of it. Where to deploy the server depends on the acquisition system composition. If there is no microprocessor-based system, the application server must be installed inside the installation. Nonetheless, either if the protocol chosen for the microcontroller is TCP/IP or a gateway is used, remote access is possible. In this case, the application server could be either inside or outside the installation.

The acquisition system is inspired by the three-layer IoT architecture [19-21]. The three-layer structure is widely used in the field of the Internet of Things. In the lowest layer of the model, there is a perception layer, where the values of the objects or variables of interest are obtained. The middle layer corresponds to the acquisition layer, which digitalizes the variables gathered by the sensors. The upper layer, depending on the model, is about the coordination or communication of the information. In other models, such as the four-layer model, there is a pre-processing stage before. Finally, there are services or applications, which collect the information and perform a certain function. The service layer is not a part of the three-layer structure.

Depending on the variables of interest of the equipment, the system needs different sensors to monitor the values. They could consist of an interface, a bus connection, or even an analog value, corresponding to electrical magnitudes (currents or voltages).

The acquisition system adapts the values obtained from the sensors and transform them to create relevant information. This system is made up by the following modules:

- Signal conditioning module. It is responsible for adapting the voltage levels and the signals obtained from the sensors so that the next module, the microcontroller-based system, is capable of processing the data.
- Microcontroller-based system. It gathers the tailored data from the sensors, makes the necessary digital adjustments, and then sends the data to the microprocessor-based system via a communication bus.
- Microprocessor-based system. It decodes the messages gathered from the bus. In addition, it performs data processing for a specific application, such as database storage or the obtention of aggregated data.

The comparison between the three-layer IoT architecture and the acquisition system is shown in Fig. 3. Comparative between the acquisition system and the IoT model . The system should operate without the upper layer, which does not correspond to the three-layer architecture. The signal conditioning system would be active even if the microcontroller is not connected.

The decision of having an intermediate microcontroller-based layer is related to the fact of reducing the acquisition system cost and data processing time. The microcontroller has a higher processing rate, so the microprocessor delegates to the microcontroller for low-level tasks.

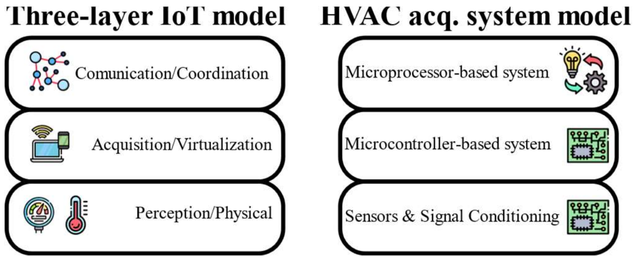

Fig. 3. Comparative between the acquisition system and the IoT model

If the three-layer structure of the acquisition system is compared with the three-layer IoT architecture, the equivalence of the sensors and signal conditioning system to the physical or perception level is shown. The microcontroller represents the acquisition or virtualization layer. Finally, the microprocessor plays the role of the coordinator or communication module. Due to the flexibility obtained by this structure, different components could be used in each level. This fact provides interoperability to the system, considering the possibility of using different devices.

The details of the different modules of the system are addressed in the next two sub-sections, which present the how-to-use of the proposed framework. First, we describe in detail the different modules of the acquisition system, the signal conditioning system, the microcontroller-based system, and the microcontroller-based system. Then, we also describe the application module.

B. Acquisition system

1) Signal conditioning system

The values of the signals obtained from the sensors must be converted to digital, so that they can be processed by the microcontroller. Thus, it is necessary to make a circuit that allows the conversion. The signal conditioning system is very dependent on the sensors used.

2) Microcontroller-based system

This system controls low-level operations, which are necessary to adjust the information for its digital processing in the microprocessor system. A scheme of the system is shown in Fig. 4. For the sake of flexibility, there are two connections with the high-level system, a data interface and a programming interface. Thus, the microprocessor communicates with the microcontroller, acquiring the processed data that is gathered from sensors. Moreover, a connection between both systems is open to change the running code of the system. This fact brings the possibility of changes in sensors without a human intervention to the station. A wide flexibility and adaptability are addressed with the programming interface.

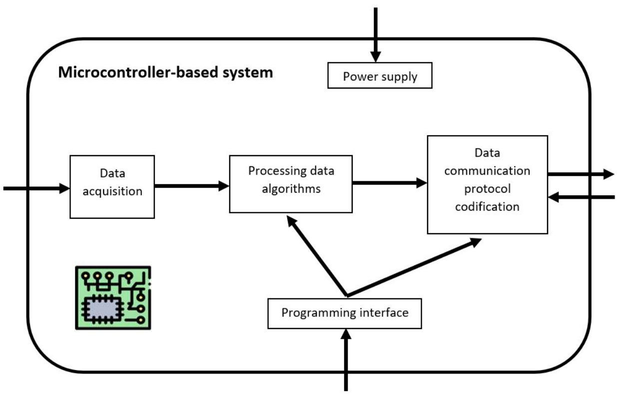

Fig. 4. Microcontroller-based system conceptual model CPS

Regarding the model of the microcontroller, changes are possible either on the processing data algorithm or the communication protocol, by re-programming the microcontroller.

3) Microprocessor-based system

The microprocessor-based system communicates with the microcontroller, acquiring the processed data that was gathered from sensors. A scheme of the proposed system is shown in Fig. 5. The information is codified in a communication protocol, so decoding must be performed by the microprocessor system. Then, the system executes their algorithms to process the incoming information. Once the information is processed, it could be used either in special services deployed in the system or communicating with an Application Program Interface (API).

The system has an on-demand interface to program the microcontroller, used when the API or the microcontroller itself order it. This fact provides an additional degree of freedom to the framework, adding new applications and functionalities without hardware changes.

An API was considered to communicate with other systems. Thanks to this interface, it is possible to access different functionalities and to the data of the microprocessor. The proposed API is a REST (REpresentational State Transfer) API, which is a form of software architecture that is used for the description of interfaces of HTTP-based systems. The REST API allows the final user the degree of freedom of defining his or her requests.

Regarding the microprocessor provided services, which add functionality to the system, such as data storage within a database, or the presentation of the information to the techniques. In addition, these services are deployed under software containers, which give adaptability and interoperability. Thanks to the container virtualization the deployment phase time is reduced. Moreover, containers bring an interface to communicate with. Users and systems could use these services by means of the TCP/IP protocol suite. TCP/IP communication possibilities provides a strong interoperability between systems, and ubiquity.

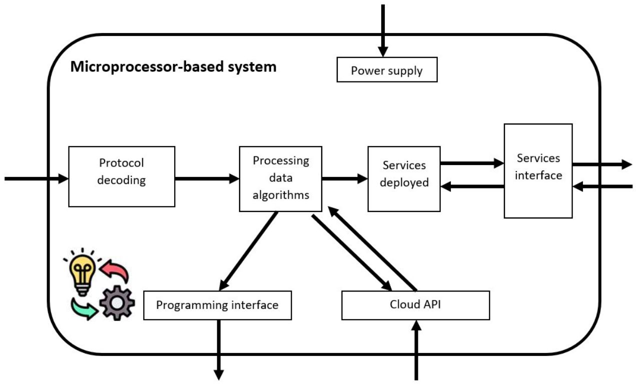

Fig. 5. Microprocessor-based system conceptual model CPS

C. Application module

As seen in Fig. 2, an application server handles high-level application and management tasks, centralizing data on a local server inside the installation. Depending on the case, this conceptual module may be implemented in a separate hardware, or it can be a part of the previously described microprocessor-based system. A scheme of the Application server is shown in Fig. 6.

The app server model contains the algorithms that are required to change the input information. The app module is defined as an artifact to be developed in any technology. Thanks to the proposed model, there is a huge flexibility and not depending on the technology used. The structure can be developed inside software containers, so only the query of the services is necessary. Furthermore, once the app is packaged in a container, it reduces compatibility problems and deploying time.

Concerning to the app results, the API implementation or local services are conceived to save, represent, or even use these results as inputs to other apps.

The flexibility of the containers provides the possibility of deploying the app module in different cases. If the microprocessor-based system is compatible with the container virtualization technology, the app could be deployed in the edge. Moreover, the app may be deployed in the cloud, or even in the fog. The representation module should be accessible by any user, so it might be deployed on cloud.

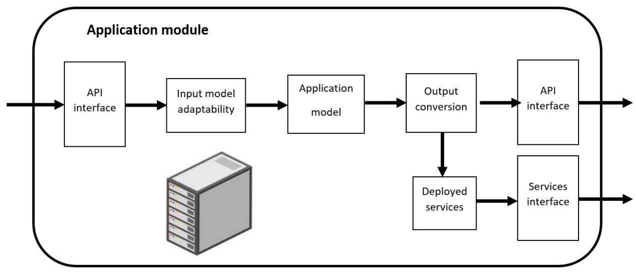

Fig. 4. Application module conceptual model CPS

A conceptual summary of the proposed framework is summarized in Fig. 7, where the relationship between the modules is shown. First, the state of the different types of HVAC equipment is monitored by sensors. Then, an acquisition system, composed of a signal conditioning system, microcontroller-based system, and a microprocessor-based system, digitalizes and obtains equipment information. Finally, an application module processes the information and obtains the results that are used to change the physical state of the devices. The equipment state is changed by the maintenance technicians, who have the know-how of the required procedures.

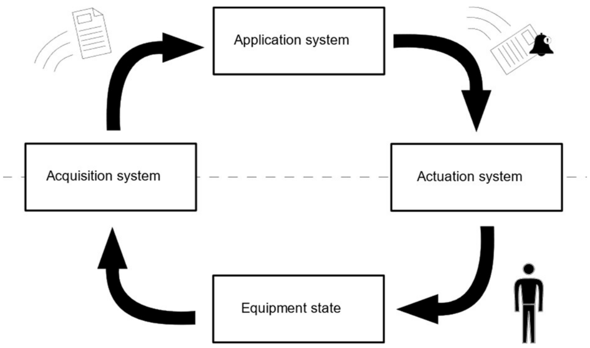

Fig. 7. Proposed Cyber-Physical framework

III. RESULTS

Based on the proposed framework, a system has been developed in a real installation. The installation is the HVAC system for the Barceló Renacimiento hotel, a five-star hotel in the city of Seville (Spain), with 295 rooms, 25 convention center rooms, for a total of 5,000 square meters and capacity for 1,200 attendees, and different common use and employee rooms [22]. Considering the high capacity of guests and attenders to the events celebrated there, the HVAC demand is considerable.

In the installation, there are several HVAC devices, such as pumps, chiller plants and boilers. The state of these devices is obtained by measuring several temperature, pressure, and current variables from them, and according to some thermodynamic equations. The acquisition system was placed on an electric box inside the chilled water pump room. Besides, an application server was installed, together with the application module, inside the installation. This application server was placed in the installation with several applications. Conceptually, it is placed in the fog layer managing the communication with the edge devices, acquisition system, and the cloud. The different modules of the framework are explained in detail in the following sub-sections

A. Sensors

Sensors extract the physical state of the HVAC system, reading temperature, pressure, and current variables. A DS18S20 digital thermometer has been used to measure the temperature of the pumps, heat exchangers, boilers and chiller plants. These sensors provide a 1-wire interface to extract the values. Nevertheless, it has a limited maximum temperature ranged for the boiler exhaust fumes. For that reason, an RTD (Resistance Temperature Detector) technology-based sensor has been used in this case. Silicon-based pressure sensors were used. They offer a 4-20mA output range, following the industrial standard, and reducing noise interferences. Finally, a toroidal current sensor was used to measure currents. It measures the currents of the HVAC system in a non-invasive way, generating an output current, due to induction effect.

B. Acquisition system

First, the conditioning system was build using a hardware soldering of passive devices. It was made over a through hole prototype Shield for Arduino. Additionally, the shield was provided with a screw terminal for easy connection.

For the acquisition system, an Arduino MEGA microcontroller board was selected as the microcontroller-based system. The use of the development board instead of an ad hoc PCB (Printed Circuit Board) reduces the total cost of the deployment. Moreover, thanks to the development platform, there are several standard solutions to integrate the Arduino to DIN-rail or connected prototyping shields to create the conditioning circuits. Several modules inside the microcontroller-based system must be deployed to accomplish with the proposed framework. The data acquisition module was implemented by reading the values of the ADC (Analog to Digital Converter) schedule in periodic tasks. Then, the read values are converted to engineering values and corrected if necessary. Finally, there is a communication module, which converts the measured values to the selected protocol. Additionally, thanks to the Arduino standard platform, there is a programming interface, where the system scripts may be updated. This fact enables changing the communication protocol or input processing. As well as the programming interface, the power supply is also contained in the Arduino platform.

A Raspberry Pi 3 was selected as the microprocessor-based system. This system decodifies the Arduino messages and processes the information. The virtualization technology used is Docker. Thanks to the containerization, it is possible to package software solutions and develop them rapidly. This approach is under the isomorphic systems policy [23], which indicates that a system must be based either on the same virtualization technology or on the same programming language, in order to increase the swiftness in the deployment of systems. Several modules inside the microprocessor-based system must be deployed to accomplish with the proposed framework. The protocol decoding module manages the communication with the microprocessor system. In this case, it takes the Arduino-codified values to fit the standard. Later, the microprocessor runs the scripts to process the values, and the calculations needed for the HVAC equations are done. Furthermore, it prepares the information for the deployed services, if necessary. The deployed services are based on Docker containerization. Chronograf and InfluxDB are the services deployed in this system. Thanks to the Docker, a TCP/IP interface is created but, depending on the service, some data processing may be needed. A REST API must be created to communicate with the services in the cloud.

Finally, there is a programming interface, where a firmware update can be sent to any system. The microcontroller-based system and the microprocessor-based system can be updated with new functionalities from the application system. Moreover, the microprocessor interface manages the programming of the microprocessor, based on commands that comes from the cloud or from the application server.

C. Application module

The application module is implemented in a server with an Intel Core i3-8109U 2-core, 3GHz, 8 GB RAM Processor. This module contains the high-level processing algorithms. The application layer of the Cyber-physical system is implemented in this module. In this case, a fuzzy logic-based system was designed. The system is based on rules that were set up according to some criteria, defined by HVAC expert engineers. The system provides a failure probability as an output, given the calculated values from the acquisition system. If the output reaches a defined threshold, it is considered that there is a formal failure. In this point, the system sends an alarm to the maintenance team, who are responsible of the procedures to repair the equipment. Moreover, the system may recommend possible solutions to the most common failures, based on the experts' knowledge.

Several modules inside the application module must be deployed to accomplish with the proposed framework. The information is collected by the system using a REST API. HTTP GET messages are used as requests, while JSON objects are sent as responses, containing all the data of the systems of interest. Once the information is obtained, it must be converted to inputs to the application model. Necessary operations, such as type conversion, math operations, or information aggregation take place in this module. Then, the converted information is taken to the application model, where the expert system calculates the failure probability of all the components of the HVAC equipment, offering possible causes and solutions to the failure. Additionally, these results are converted to be communicated to the maintenance technicians. Two mechanisms of communication are defined in the application module. On the one hand, an API REST to send the information by a POST request to a third-party system, such as a GUI (Graphical User Interface), a web-based system, etc., is defined. On the other hand, a module for local deployed services is also defined, using the application system for the representation of the information or with storing capabilities. The deployed services must have an interface to interact with. Following the philosophy of the modular system, the services should be packed in software containers. The proposed services are a graphical interface, Chronograf, and a storage system, InfluxDB.

As an example of data representation, shows several time series stored in the database, which were acquired by the system. The graphs represent the input (red) and output (blue) for the chilled pump pressure evolution. Each graph represents a couple of pumps, that are alternatively working shows an example of the acquisition and application systems, deployed in the Barceló Renacimiento hotel. Inside the electric box of the chilling water pumping room, there are Modbus-based devices. These devices validated the interoperability of the framework, as Modbus devices were fully integrated within the acquisition system that was developed using the proposed framework. Thanks to the layer-based architecture, the communication interface allows the communication using the Modbus RTU standard. With this aim, a hardware device was necessary to communicate over the physical level.

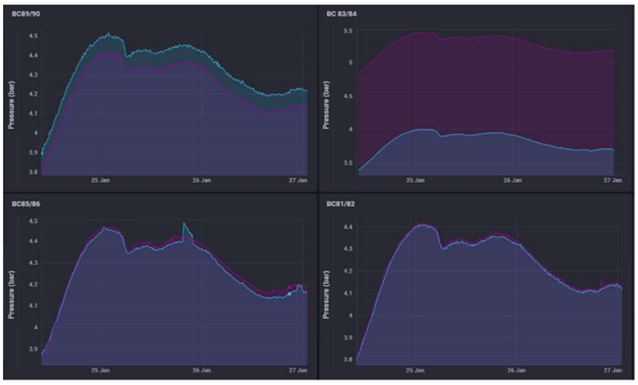

Fig. 8. Time series of several chilled pumps in the hotel

Fig. 9. Real installation in an electric box inside the chilled water pumping room

IV. CONCLUSION

This paper presents a low-cost energy-efficient CPS-based framework for predictive maintenance in HVAC installations in hotels. The proposed framework accomplishes the National Institute of Standards and Technology framework for CPS, while its structure is based in the three-layer IoT architecture.

An acquisition system gathers data from the sensors and generates information for the decision-making process. The acquisition system is connected to the decision module to send that information, and communicates with a private cloud, which executes the applications, stores the equipment information, and creates a GUI.

The acquisition system is structured in three different modules. A signal conditioning system coverts sensor data into a digital format. A microcontroller-based system adjusts and prepare the information to be processed in a microprocessor-based system, which executes some algorithms to process the obtained information from the sensors. An application module contains the programs and services that are needed for the predictive maintenance of the HVAC system.

Finally, the framework was validated by its application within a five-star hotel in the city of Seville (Spain). The proposed framework showed its flexibility and interoperability, while low cost is guaranteed. Energy efficiency is being currently tested, and results will be published in future research. Some interesting topics, such as the details of the expert system for the application module, and the details of the communication between the REST API and the cloud are out of the scope of this paper and will be also addressed in future research.

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