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A Cloud-Based Monitoring System for Performance Assessment of Industrial Plants

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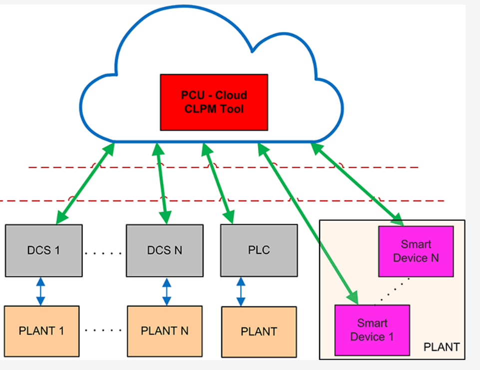
ABSTRACT: The paper presents the realization of a control-loop performance monitoring system operating in a cloud as a single unity for the global supervision of data coming from various industrial plants located in different areas. This is a desirable solution for many companies, because of the costs of local installations (systems, human resources, and their maintenance and upgrading) and is made possible by available Industry 4.0 technologies, although some aspects are worthy of deeper investigation, depending on specific industrial realities. The monitoring system (PCU, Plant Check Up) is described in its basic components and its evolution toward the cloud-based configuration. The entire architecture, as well as the solutions adopted for data acquisition from the field, transmission to the cloud, and web app features, which allow a full remote monitoring, are illustrated. Technical details about the application on a pilot-scale plant are given, and results for significant cases and different types of loop and actuator status are presented.



1. INTRODUCTION

The last several years have been interesting, because of numerous initiatives and fervent activities, both from academia and industry, aimed at illustrating and employing the impressive characteristics and large opportunities offered by Industry 4.0.[1,2] Recalling all characteristics and possible advantages of the nine key enabling technologies (KET), from Advanced Manufacturing Solutions to Big Data and Analytics, would be a heavy and useless burden to carry out.

It is important to recall that, while a first glance would convince one that the advantages are mainly for the manufacturing sector,[3] indeed, the entire process industry can naturally reap the benefits expected from a strong and integrated industrial automation.[4] Thus, the adoption of new methodologies and techniques connected with the Industry 4.0 paradigm can surely lead to a significant return of investment for entire industrial plants and, in many cases, represents a forced choice to survive in a more and more competitive world.

Cloud computing,[5] which is one of the KET, has generally been proven to be very useful for process monitoring, control, and optimization purposes, and, in particular, for control loop performance monitoring/assessment (CLPM/CLPA).[6]

Cloud computing has natural attractive characteristics; it is easily accessible, replicable, distributable, and adaptable. Among other practical advantages, this technology guarantees high power of computation, ability to manage big data storage and analytics, and opportunities for centralized monitoring. Other main features are limited costs and no capital investment, pay-per-use, on-demand usage, elasticity and multitenancy. Nevertheless, cloud computing has also several typical issues; among others, cybersecurity, reliability, real-time operation, setup definition, network topology, and system architecture are critical aspects.[7]

Cloud computing has resulted in the creation of attractive process-related applications for a large number of purposes, including data historians, analysis tools, alarm management, asset management, performance management, training simulators, and remote diagnostics.[8] Several challenges and opportunities of feedback control in cloud computing were discussed in a well-established work.[9]

Nowadays, there are many commercial solutions and technologies that allow one to build an industrial process data analytics platform based on Industry 4.0 paradigms, and on cloud computing, in particular. Among others, the main vendors are cloud services providers (Amazon Web Services, Microsoft Azure, Google, Intel, IBM), enterprise solution vendors (as Oracle and PTC), networking companies (such as AT&T, Verizon, Cisco), and industrial engineering companies (e.g., Siemens, ABB, AspenTech, Metso, Rockwell Automation, Honeywell, Bosch, and General Electric).

Nevertheless, examples of comprehensive implementation of data analytics in the context of Industry 4.0 are not yet so

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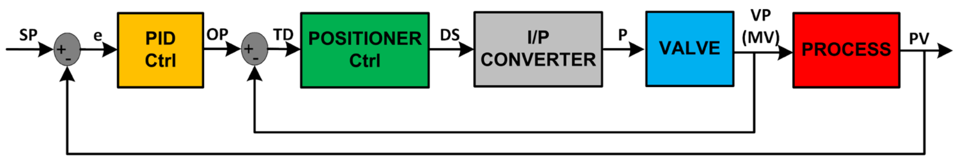

Figure 1. SISO feedback control loop with variables.

common in the scientific literature. Among the few cases, interesting cloud-based solutions for remote monitoring (and control) have been applied to automated electric induction motors,[10] machineries of power plants,[11] and waste-to-energy (WTE) plant.[12]

Regarding CLPM/CLPA, one of the main advantages offered by cloud computing is that centralized systems can be easily implemented, maintained, and updated. Data from different industrial sites can be transferred and analyzed in a cloud by using a single monitoring system. This solution can be particularly attractive when operators must monitor a large set of similar plants or units, and, consequently, must face common issues and faults, or when they must monitor geographically dispersed assets, as in the case of water or energy supply plants.[13] In these scenarios, a single system can be developed and installed in a cloud server and monitor all the various units simultaneously.

Other advantages of a single centralized system are the use of an unified logic without risky duplications on single systems and a minimal involvement of dedicated personnel. For on-site solutions, phases of implementation, maintenance, and updating must be necessarily replicated locally with obvious time consumption for people and resources and with a high risk of errors and omissions.

Therefore, it is beyond doubt that cloud-based solutions for process monitoring and assessment will populate the next future. Nevertheless, our experience of the last 15 years in the area of control engineering, and in CLPM/CLPA, in particular, leads us to note that this process of remotization and centralization may be hard. A real difficulty lies in transferring skills developed over years by operators on individual plants. For example, specific knowledge of processes and equipment cannot be fully generalized and therefore cannot be exported in a completely automatic manner. In addition, one should recall that process data are usually confidential, and industrial companies might not want to move data from local computer control systems to external clouds, as additional issues of cybersecurity and service reliability may arise. Therefore, a strategic decision must be made by the companies on economic bases: the entire cloud-based service can be performed by a pool of internal experts or can be outsourced to specialized companies.

This work aims to present a novel performance monitoring system, specifically devoted to control loops, based on cloud technology by focusing on three different aspects: describe the entire cloud architecture and its implementation issues, illustrate basic techniques and features installed in the updated analytics tool, and then present significant case studies.

The paper then has the following structure: Section 2 presents the evolution over time of our system for CLPM from single distributed units to the cloud. The main features of the basic techniques that accomplish performance analysis and malfunction diagnostics are illustrated; a description of the novel cloud-based architecture is also reported. In Section 3, the various functionalities implemented within the web interface for remote management of the system are illustrated. Section 4 describes the pilot plant used to test the entire cloud-based solution, while Section 5 presents some illustrative examples of application. Finally, conclusions and future steps are reported in Section 6.

2. A SYSTEM FOR CONTROL LOOP PERFORMANCE MONITORING (CLPM) IN THE CLOUD

In the past years, major control engineering companies have proposed their own "traditional", that is, *on-premises*, software package for control loop performance monitoring and assessment to be installed within local computer control systems of industrial plants. In the literature, several surveys have revised the different commercial solutions.[6,14] The most recent comparison can be found in ref 15 within a work of review on valve stiction. Two examples of software packages from the academia are the smart process data analytics platform[16] from University of Alberta and our Plant Check-Up (PCU) system.[17]

2.1. The Evolution of PCU. The PCU tool is now a long-standing performance monitoring system developed in MATLAB within the Chemical Process Control Laboratory of University of Pisa. The first complete release of the system with extensive industrial implementations was illustrated in ref 17. Updated versions with further large-scale applications were then reported in refs 18 and 19. A novel release of the system is now developed for the cloud, as detailed in this paper.

The PCU system is able to diagnose main sources of malfunction of basic single-input single-output (SISO) proportional−integral−derivative (PID) control loops, suggesting actions to be taken. Malfunctions typically induce oscillations in the process variables, and, therefore, their identification is of fundamental importance in order to perform the most appropriate correction. The main causes can be traced to the presence of external disturbances, poor controller tuning, faults of valves and sensors, and interactions from other loops.[20] For these four main malfunctions, actions are upstream intervention, controller retuning, instrument maintenance, and transition to multivariable control, respectively.

Until now, depending on measurements available from the field, the basic version (PCU) or an advanced release (PCU^+) of the program could be adopted (the latter with significantly higher performance). The variables available from a SISO feedback loop with a PID controller are shown in Figure 1.

The basic version (PCU) refers to data made available by traditional industrial plants (that is, only three variables are examined: set point (SP), control variable (PV), and controller output (OP). Such systems have been installed for many years in ENI refinery sites, monitoring up to dozens of plants and more than 1200 control loops.[17]

The latter version (PCU^+) has advanced features, because it employs additional measurements made available by communication systems based on field bus and smart devices, such as valve position (VP), output pressure (P) of electro-pneumatic

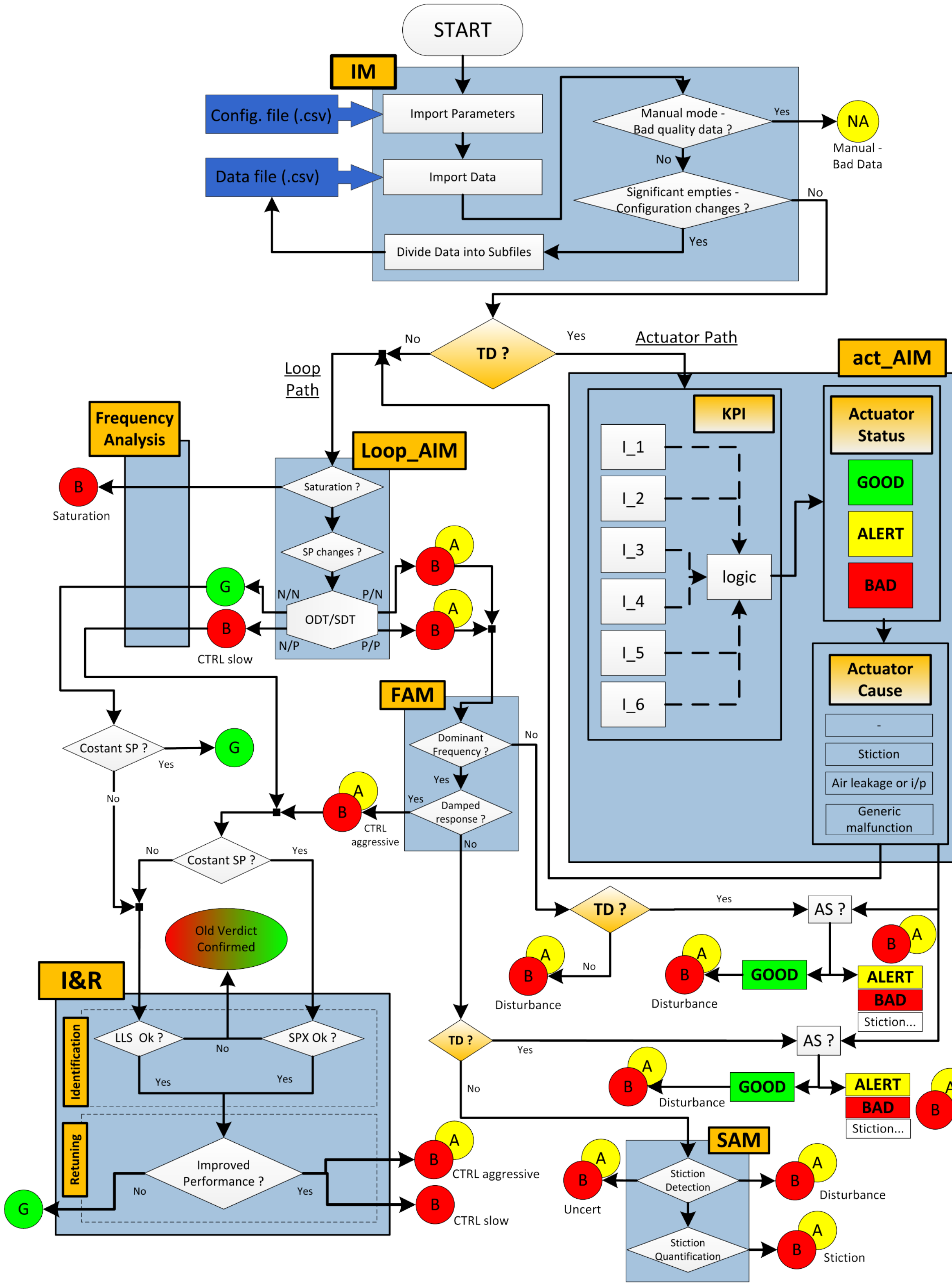

Figure 2. Flow diagram of the updated analysis package within the PCU-Cloud.

(I/P) converter, and drive signal (DS) to valve positioner, as well as safety and state parameters of instruments and actuators.[18] Note that the manipulated variable (MV) is typically associated with VP and corresponds to PV in flow rate control loops. The availability of VP allows one to compute TD (travel deviation), defined as the difference between actual and desired valve position (TD = VP − OP). It has been experimented that, on the basis of different patterns and ranges

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of TD, friction can be clearly detected and also other causes of malfunction affecting the valve actuator (e.g., air leakage, I/P fault, generic malfunction) can be assessed.[18] Therefore, this advanced version allows a more refined assessment of loops and actuators and is now installed in several Italian power plants (property of ENEL) and has been distributed among associates of Automation and Instrumentation Italian End-Users Club (CLUI AS) for testing purposes.

In the wake of the digital revolution of Industry 4.0, a control loop performance monitoring/assessment system based on cloud technology is presented here. The analysis modules implemented into the on-premises versions of the system are now appropriately updated and inserted in a novel analytics tool (PCU-Cloud) within a cloud-based platform, as detailed in the next two subsections. The novel system is then put at service for multiple industrial plants, of the same or different sites, through the transfer of data in the cloud and their analysis by a single supervision unit.

2.2. The Analytics Tool. A brief synthesis of the various analysis modules implemented in the PCU-Cloud is reported below. Figure 2 shows the entire flow diagram of the novel package of analysis operating in the cloud. The main updates, with respect to the previous releases of the tool, regard the initialization module (IM) and the loop anomaly identification module (Loop_AIM). For a more-detailed description of the unchanged modules, the reader can refer to ref 17, where the first version of the on-premises system (PCU) was presented.

2.2.1. Initialization Module. This first module (IM) receives data imported from the field, loop parameters, and additional information. When not specifically defined, most parameters are set to default values. This module performs several preliminary checks: if the quality of input data is overall bad or the control valve is permanently operating in manual mode, the loop receives a definitive label (NA, meaning "not analyzed") and the analysis does not proceed further. If significant null values in data are detected, when the transmission from the field to the cloud has been accidentally interrupted, the system provides a way to separate input data file into corresponding subfiles. Something similar occurs when a change of control configuration (manual, automatic, cascade) is registered, so that segments in manual mode are discarded. Finally, the performance assessment can begin. Note that the loop path to the actuator path is subsequently activated when the travel deviation (TD)—that is, the valve position error—is available; otherwise, only the loop status is evaluated.

2.2.2. Loop Anomaly Identification Module. This module (Loop_AIM) gives a first assessment of the loop status with diagnostics verdicts. Preliminary, the presence of valve saturation and significant changes of the Set Point (SP), in terms of amplitude and frequency, are investigated. If saturation is detected, after a brief frequency test, a label B (BAD) is assigned. Otherwise, techniques to detect sluggish (SDT) and oscillating (ODT) loops are performed. Slow responses are evaluated by a modified version of the standard technique of Hägglund.[21] Whereas, oscillating responses are detected by a recently improved submodule, specifically implemented in this novel version of the tool. Now six different techniques are adopted:

- Hägglund method[22] with suitable modifications of internal parameters, based on field experience and plant calibration,[17] to assess the magnitude of oscillation;
- two indices (E_{PV}, E_{SP}) based on simple norms of the control error (e = SP − PV), to further evaluate magnitude;[23]
- the regularity factor (r)[24] and the decay ratio (R)[25] of autocorrelation function (ACF) of the control error to test the regularity and stability of oscillation, respectively; and
- a revised version of the method based on empirical mode decomposition (EMD)[26] to detect multiple sources of oscillation.[27]

Each detection technique evaluates a specific oscillation characteristic on the basis of three levels: GOOD (G), ALERT (A), and BAD (B), as shown in Figure 2. A global verdict on loop oscillation and sluggishness, positive (P) or negative (N), then is emitted by weighting single responses.

2.2.3. Identification and Retuning Module. This section accounts for process identification and, whether successful, controller retuning and assessment of performance improvements. Loops labeled by Loop_AIM and FAM modules as BAD (because of improper tuning), slow, or aggressive are sent to Identification and Retuning (I&R). Loops with constant and variable SP values are analyzed differently, by simplex (SPX) and linear least-squares (LLS) methods, respectively.[28] Note that the second scenario is typical of secondary loops under cascade control.[29]

2.2.4. Frequency Analysis Module. The objective of this module (FAM) is to separate irregular and regular oscillations on the basis of a power spectrum that computes dominant frequencies. Loops with similar frequency of oscillation can be gathered to investigate the possible presence of interactions. Irregular loops are labeled as Disturbance (with the status of "ALERT" or "BAD", depending on Loop_AIM), without any further analysis, regardless of whether TD is available or not. Note that these loops are not simply affected by field noise, being otherwise filtered and considered as GOOD by oscillation detection techniques. Regular loops, if with damped response, are sent to the I&R module. Otherwise, when loops show stable oscillations, the module for valve stiction versus disturbance detection (SAM) can be activated.

2.2.5. Stiction Analysis Module. When TD is not available, only on the basis of controller output (OP) and process variable (PV) data, four well-established techniques for valve stiction detection are applied: the relay-based fitting of PV data,[30] the improved qualitative shape analysis,[31] the Cross-Correlation Test,[32] and the Bicoherence method,[33] which detects nonlinearity in loop data. A global verdict is emitted by weighting the single results. Once clearly detected, the amount of stiction is also quantified. Various methods developed recently in our laboratory are used.[34,35] Once again, an overall response is emitted by weighting single estimates.

2.2.6. Actuator Anomaly Identification Module. When TD is available, the actuator path is activated and six key performance indices (KPIs, I_1−I_6) based on simple metrics of TD with low and high thresholds, are employed. By using field-tested logic, it is possible to evaluate the actuator status (AS) on three levels (GOOD, ALERT, BAD) and then diagnose specific causes of fault (stiction, air leakage or I/P fault, generic malfunction).[18] These verdicts are definitive and may alter the corresponding loop status, as represented by the converging arrows in the southeast corner of Figure 2.

2.3. The System Architecture. A description of the entire cloud-based architecture of the novel system for control loop

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Ind. Eng. Chem. Res. 2020, 59, 2341−2352

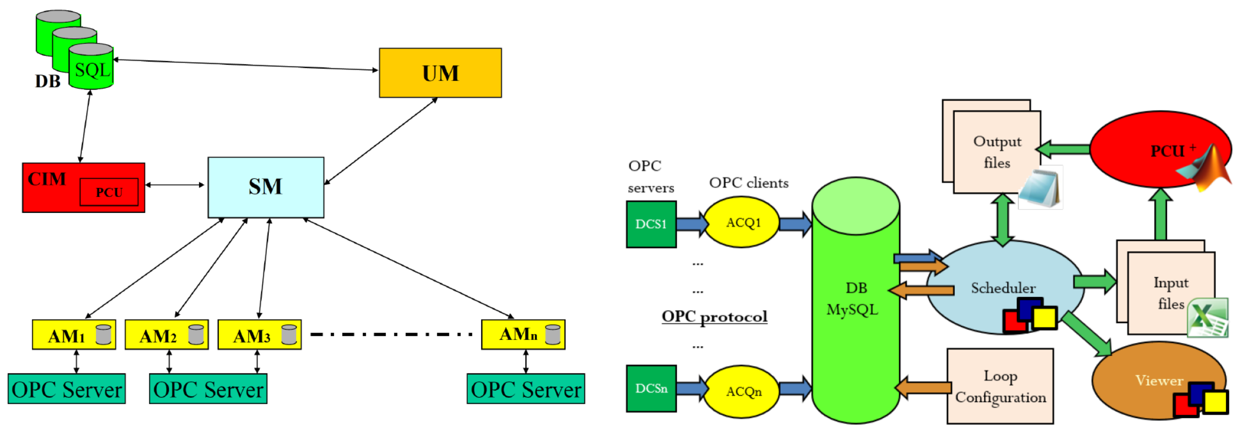

Figure 3. Two examples of on-premises architecture for CLPM systems: (left) with PCU and (right) with PCU^{+}.

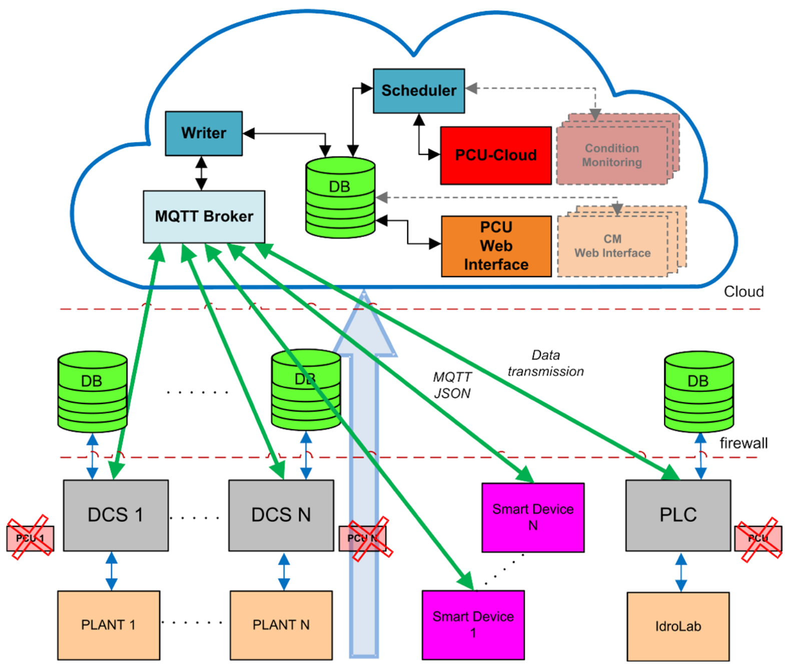

Figure 4. Architecture of the novel system for cloud-based monitoring of different field elements.

performance monitoring and assessment is reported in this section. As a premise, we recall that the typical structure of a computer control system in industry is formed by three different network layers: a distributed control systems (DCS) network at the bottom, a process management network (PMN) in the middle, and a corporate local area network (LAN) on the top.[36] The architectures of traditional on-premises systems for CLPM/CLPA comprise various modules interacting with each other and all physically installed within the local computer control system. The various components belong to one of three categories, in terms of overall functionality, that is, interface, assistant, and application components.[36] This is also the case of our two recently developed on-premises CLPM systems.

2.3.1. On-Premises Systems. A first architecture implements PCU as an analytics tool (see Figure 3, left). A Scheduling Module (SM) is the core component, which leads the various operations (e.g., it establishes hierarchy, order, and frequency of acquisition). The User Module (UM) allows the operator to configure loops, check the progress status, and query the relational SQL database (DB) for viewing and reports. Once activated by UM, SM gives commands to the various Acquisition Modules (AMs) to collect real-time data from OPC servers. Once acquisition is terminated, the SM receives data files from the AMs, which are then sent to and stored in the database. The Causes Identification Module (CIM) program, which includes the PCU tool, is run by the Scheduling Module and acts as the analysis application: it surveys the database, acquires input data, and emits verdicts.

In a second on-premises system, the advanced version of the tool (PCU^{+}) is implemented. A similar architecture is employed (Figure 3, right): a Scheduler manages data acquisition and processing operations; real-time data are collected from various OPC servers via different OPC clients running acquisition applications; analysis results with plots and verdicts are managed by the Viewer application. Loop configuration is performed by editing an interface of the database.

2.3.2. The Cloud-Based System. Our novel process monitoring system based on cloud technology has a

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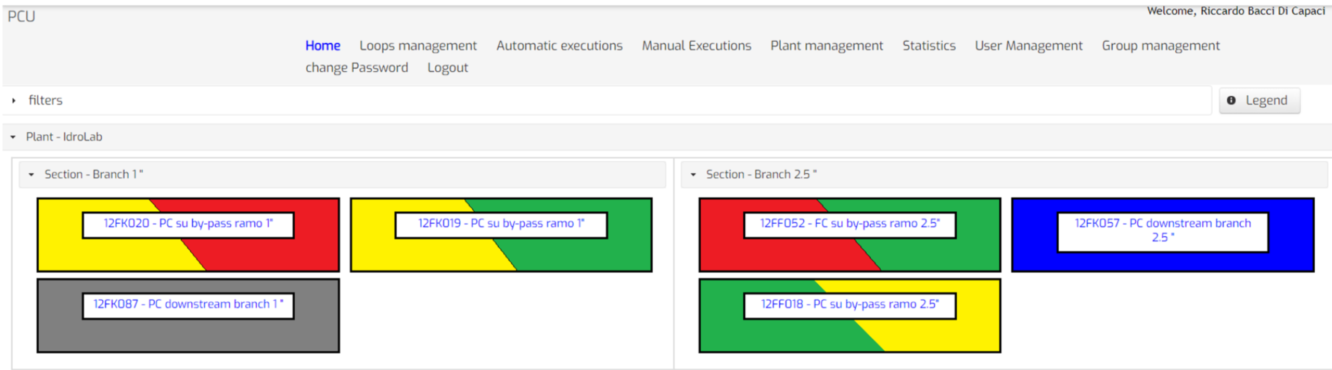

Figure 5. Depiction of the web app homepage.

completely different architecture, as shown in Figure 4. Indeed, no module is on-premises (that is, installed within the computer control system of the various industrial sites under supervision), but all elements reside in a single remote Linux cloud server located in Pisa. Once transmitted via an Internet connection, data are then written and stored in the cloud database (DB), which acts as the star center of the entire network. A web interface queries the database and allows visualization of the results, but also many aspects of loops setting and all phases of analysis management. Nevertheless, note that residual routines of configuration may need to be completed within local computer systems, when peculiarities of industrial sites prevent full remotization. The updated analysis package (PCU-Cloud) works as a single executable program activated by a light scheduler module.

The system employs standard features of cloud technology: JavaScript Object Notation (JSON) data format and Message Queue Telemetry Transport (MQTT) protocol. JSON is a data interchange format, which is now very widespread, since it is particularly simple when used on JavaScript. MQTT is the most common and interoperable messaging system for Internet of Things; it is ISO-standard, based on TCP/IP, and possesses intrinsic cybersecurity features.

With a publish/subscribe structure, MQTT is designed for lightweight machine-to-machine communications and is useful for limited band situations. A client/server model is used, where every smart field device acts as a client and connects to a remote server, known as a *broker*. Every message is published to an address, known as a *topic*; clients may subscribe to multiple topics, and every client subscribed to a topic receives every message published to the topic.

In our novel centralized cloud system, the MQTT broker can collect all the messages directly published by the various field elements from different industrial sites, regardless of the type: DCS, PLC, or even single smart devices, as sensors and actuators (see Figure 4). Therefore, with respect to on-premises architectures, such a solution does not require standard acquisition modules. Note that the same cloud-based architecture can be easily extended by implementing other monitoring applications and corresponding web interfaces. For example, a condition monitoring system that is used to supervise other plant machineries as pumps, compressors and motors, with the objective of preventive and predictive maintenance, can be included by measuring and transmitting specific variables from the field, such as vibrations, rotation velocity, temperature, and power absorption.

In the case of the pilot plant IdroLab (see Figure 4), a PLC has been programmed to collect all data of control loops and, protected by local firewall, send data to the cloud by using a defined JSON string, as later detailed in Section 4.

In the proposed solution, high levels of cybersecurity are ensured: the cloud platform is intrinsically safe as guaranteed by the server provider; the communication channel is protected by a three-level security system, based on a secret alias for the broker, and unique username and password to identify various clients. In addition, MQTT protocol security can be improved by easily turning to a MQTTS solution (where the S suffix stands for secured), that is, employing a certificate on server side during Transport Layer Security (TLS) handshake, which avoids "man-in-the-middle" issues.

Obviously, industrial companies are still in charge of additional safety requisites within their local networks, such as firewall, protected ports, etc.

Note that the proposed platform has been programmed to be totally scalable and industry-oriented. For example, no issues actually involve the software side, since core codes are general and can be easily exported to different monitoring applications. When the number of messages published into the cloud becomes high, since numerous sites or large plants with hundreds or thousands of elements have to be monitored, only physical architecture limitations may need to be overcome, by augmenting the transmission band, computational processing unit (CPU), random-access memory (RAM), and so on. Otherwise, during the configuration of local client systems (PLC, DCS, or single devices), one may reduce the transmission frequency to limit data traffic and then data size, to save cloud space.

Below, some possible future developments for the centralized cloud structure of Figure 4 are briefly discussed. The adoption of fog computing is advisible to build a preliminary layer, close to the plants and the various smart devices, where performing a preliminary step of storage and computation (e.g., for data check and filtration, alarms managements, and critical and confidential analyses). Other communication protocols (e.g., Web of Things, with CoAP) may overcome Internet drawbacks and increase system scalability and flexibility. In addition, data mining algorithms can be used to manage big-data analytics, from the perspective of predictive maintenance. These functionalities will be taken into consideration in the next industrial applications, once some problems may arise in their realization or alternative approaches will be considered more efficient.

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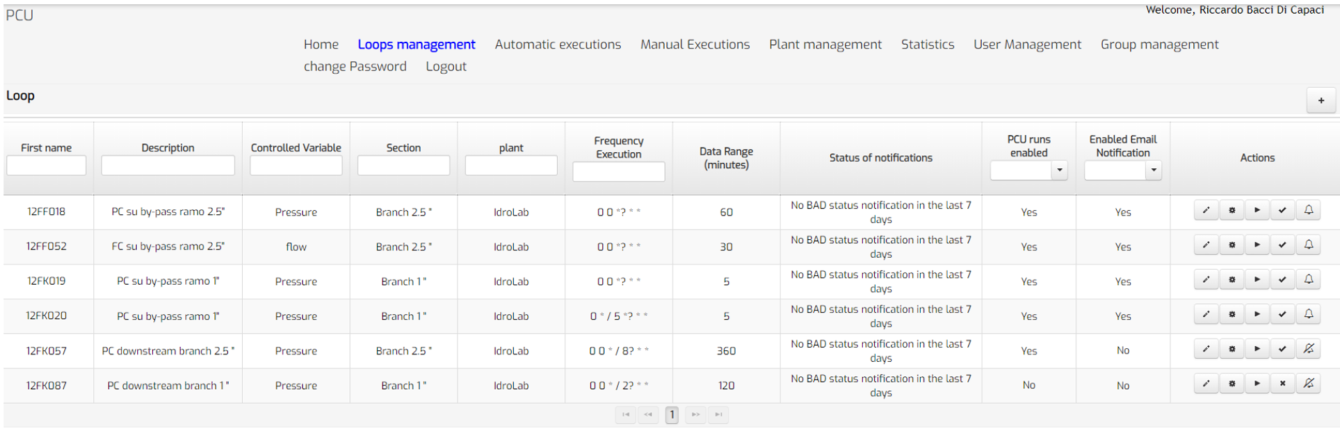

Figure 6. Screenshot showing the loop management page.

3. THE WEB APP

The updated analytics tool (PCU-Cloud) for CLPM in the cloud is interfaced with a Java web application. *Spring*, as an open-source framework, and *Eclipse*, as an environmental tool, have been used for the development. Any interested guest reader can get access and manage the application with a reader level once a username and password has been obtained. The main functionalities are briefly presented in this section. For deeper information, the reader can request the user guide.

The application has a simple, quick, and friendly layout. The monitored plants are organized on the homepage within a cascade list (see Figure 5). Once a plant is selected, the corresponding sections and control loops are shown. Loops can also be filtered and displayed according to that plants and sections to which they belong. Each loop is displayed inside a box with two colored fields, associated with the last issue of the tool: the Loop Status is shown on the left, and the Actuator Status is shown on the right. The following color legend is used to indicate the status: red, BAD; yellow, ALERT; green, GOOD; blue, Manual Mode; white, None (loop not yet analyzed); gray, Disabled (loop not currently monitored).

3.1. Execution Modes. The system allows two different modes of execution: automatic and manual. Automatic mode performs, in fact, an online analysis at predetermined time intervals. Nevertheless, control loops can be reanalyzed off-line in manual mode, that is, by setting a user-defined data interval and specifying a start and end date/hour.

3.2. Results. The outcome of the analysis are presented at various levels: trends, cycles, and output.

3.2.1. Trends. "Trends" involved temporal plots of the loop measurements. A first plot includes the Set Point (SP) and Control Variable (PV); a second plot shows the PID output controller (i.e., desired valve position (OP), and actual position (MV, that is, VP)); and a third plot shows Travel Deviation (TD) (that is, valve position error).

3.2.2. Cycles. "Cycles" involved polar plots of the process and valve. The PV(OP) diagram relates the control variable to the output controller; a loop with regular and stable oscillation around a fixed set point shows a well-defined limit cycle, that is, a circular or elliptical path. The MV(OP) diagram relates desired and actual valve position; a sticky valve produces nonlinear hysteresis limit cycles, i.e., paths with rectangular or parallelogram shape; this allows a clear distinction, with respect to a healthy valve, which does not show cycles.

3.2.3. Output. "Output" involves the main results of the analysis. This represents a selected list of all detailed fields reported in the output file issued by PCU-Cloud. In section 5, three significant examples of application are illustrated.

3.3. Users. There are three levels of users with different roles and privileges:

Reader: basic user with very limited possibilities; one can access only automatic mode executions, and then display verdicts, figures (trends and cycles) of the various loops.

Configurator: user with intermediate possibilities; to get access and also manage manual mode executions, with the possibility to modify the data period to be analyzed. One can configure only loop details (name, description, plant, section, type of control variable), and also insert and configure new loops, but not threshold values for analysis techniques. Finally, one can download a.zip folder with input and output files related to automatic and manual mode executions.

Administrator: user with full possibilities; to access all the functions of configurator and additionally modify configuration parameters of core techniques to run sensitivity analysis. Furthermore, one can manage plants and users. In particular (see tabs at the top of Figure 5):

- in *Plant Management*, add and modify plants and sections to be monitored;
- in *User Management*, add and modify user profiles and enable/disable the receipt of periodic notification e-mails with a results summary;
- in *Group Management*, associate a user to a group (administrator, configurator or reader level) and to a role (that is, a level for a specific plant or section).

3.4. Loop Management. Analysis parameters can be extensively configured within the web app (see Figure 6). *Frequency Execution* sets the frequency with which the input files in .csv format are generated and, consequently, the frequency of analysis execution. *Time Interval* sets the duration of single acquisitions (that is, data length inside input files). This time range refers only to the last minutes of data between two consecutive execution times. *Maximum empty in data* sets limit the value of the time interval between two consecutive data to consider the presence of an interruption in the transmission to cloud and, consequently, cause a split of the original data file into two subacquisitions.

Expert users, with administrator privileges, can also manage all threshold values of the various performance indices of analysis techniques. As already mentioned, such operation is

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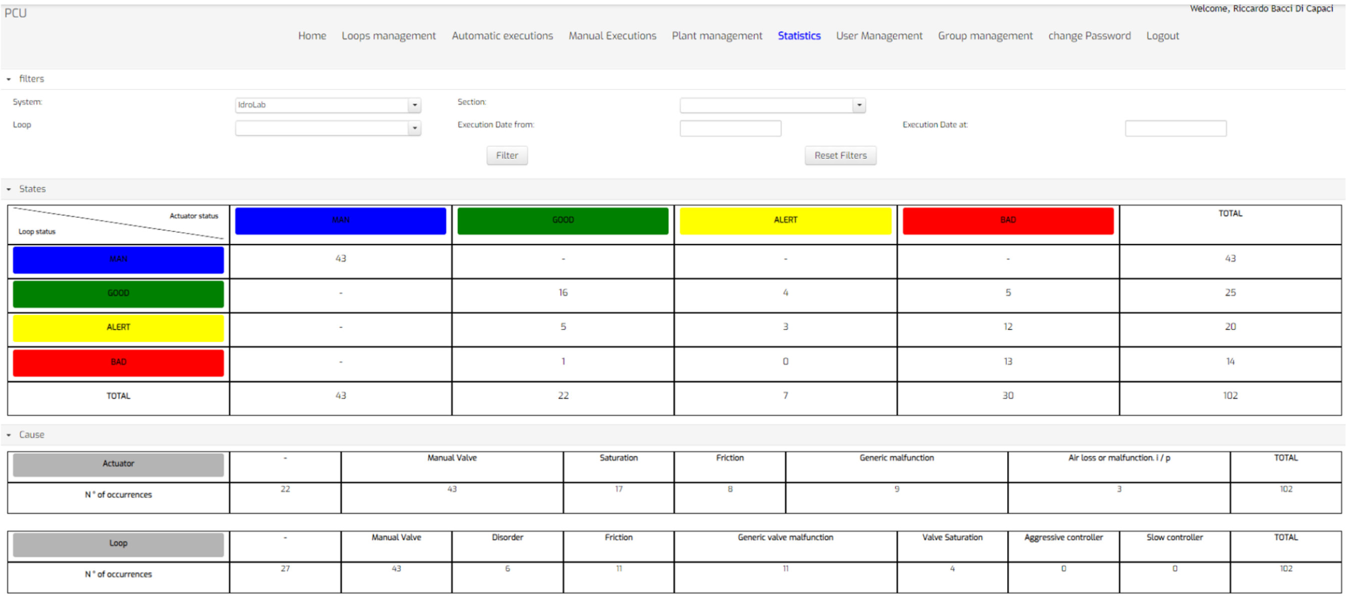

Figure 7. Screenshot showing the statistics page.

critical and experience and skills are required. Therefore, a single figure who performs calibration for all control loops and plants of one or more sites may be a suitable solution, which is only possible with a cloud-based monitoring system. Among others, it is possible to set:

- TD_{lim}, which is the acceptable range for Travel Deviation, with a default valve operating range of 2%;[18]
- SAT_{lim}, which is the limit used to assess valve saturation, as a percentage of the data length;
- AB_r, which is the ratio between threshold values of ALERT status and BAD status for oscillation detection techniques;
- a, which represents the amplitude of oscillation for computation of IAE_{lim} in Hägglund's ODT;[17,23]
- lower and upper thresholds for indices E_{SP} and E_{PV}, which are specifically dependent on loop type, according to ref 23; and
- UI, which is the upgrading index ($UI \in [0,1]$), to accept controller retuning proposed by the system.[17]

3.5. Statistics. This features allows one to evaluate the overall performance of a plant, a particular section, or even a specific control loop over a defined period of time. Two tables with aggregated results can be examined (see Figure 7):

- *States*, which reflect the total number of different states—MANUAL, GOOD, ALERT, BAD—for the loop and the actuator; note that, crossing rows and columns, it is also possible to assess the number of times that a combined verdict occurred.
- *Causes*, where, besides the number of healthy actuators and loops, different causes of poor behavior are summarized: e.g., valves in manual, controller issues, valve problems, disturbances, etc.

3.6. Periodical and Event-Based Notifications. The application sends periodical E-mail notifications with summary performance of the various plants and details of the last verdict for each loop under supervision. The notification frequency and information degree of detail can be customized in order to limit message flooding. In addition, it is possible to enable a class of *critical* loops (which is key, with regard to safety or productivity) for which, as soon as the loop or actuator status changes to BAD, a specific E-mail is immediately sent and an alarm icon is activated. The company user can acknowledge the alarm and then make suitable corrections.

4. THE IDROLAB PLANT

IdroLab is a pilot plant recently revamped to become a demonstrator facility of Industry 4.0 technologies in the framework of a project developed by (CLUI AS) (see Figure 8). The plant is also proposed for training purposes and demo for users. Recently, a novel PLC (Siemens, Model Simatic S7-1500) has been installed and configured with the Simatic Step7 TIA Portal program to control operations. The plant is composed by a double hydraulic circuit equipped with a centrifugal pump under inverter control, as shown in Figure 9. A pre-existing set of latest generation actuators and sensors allows process operation and variables measurement (pressure, flow rate, and level). Fieldbus communication from smart devices to PLC is accomplished with Profibus protocol; communication from PLC to the cloud server occurs with MQTT protocol, as detailed in Section 2.3.

Figure 8. Photograph of the IdroLab pilot plant.

Five PID control loops are programmed into the PLC; their features and parameters are listed in Table 1. PLC operates each loop with a sampling time of 1 s, collects and stores data in its local database, and then sends data to the cloud server.

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Ind. Eng. Chem. Res. 2020, 59, 2341−2352

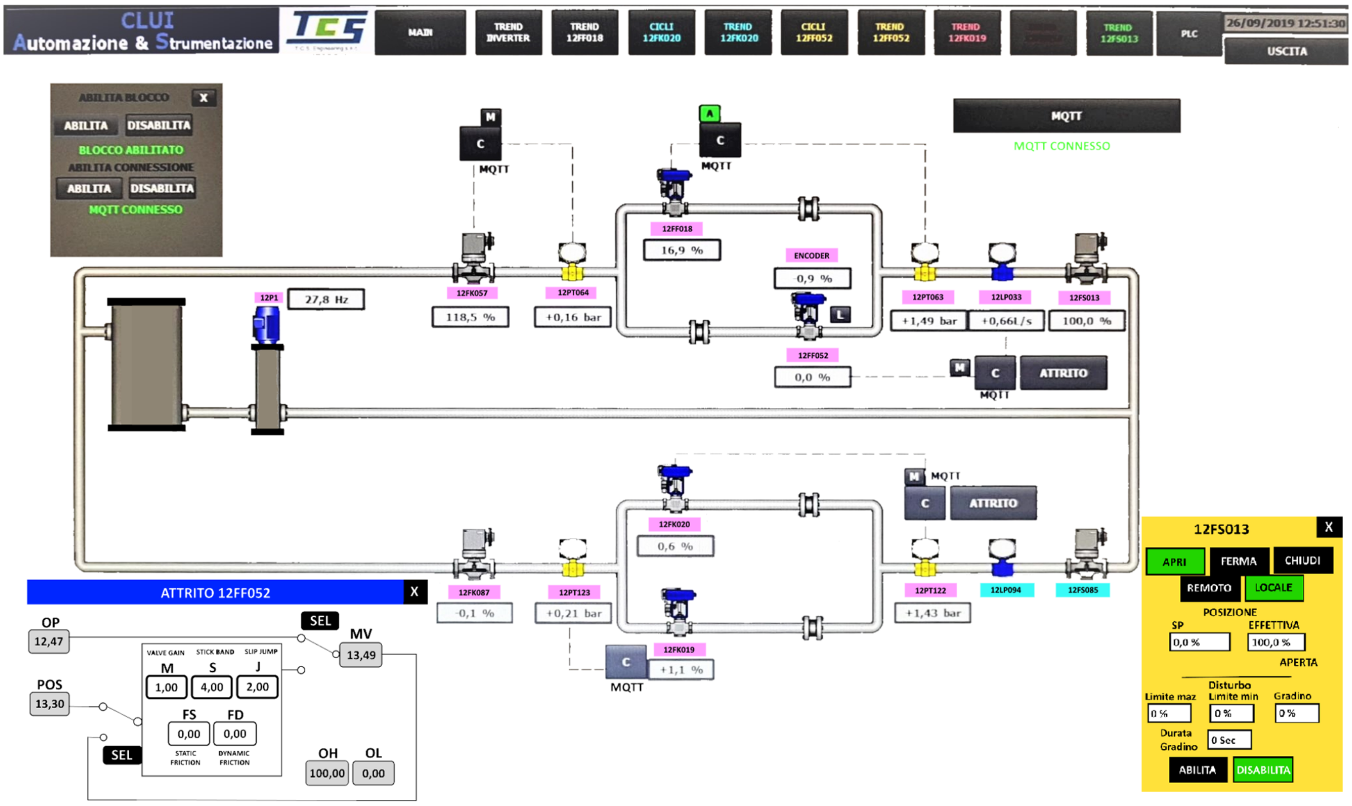

Figure 9. Schematic of IdroLab on the Human Machine Interface.

Table 1. Control Loops Implemented in the IdroLab Plant

valve (tag within PCU)	actuator type	type of PV	PV range	sensor
12FK057	pneumatic	pressure	0−5 bar	12PT064
12FF018	pneumatic	pressure	0−5 bar	12PT063
12FF052	electric	flow rate	0−5 L/s	12LP033
12FK020	pneumatic	pressure	0−5 bar	12PT122
12FK019	pneumatic	pressure	0−5 bar	12PT123

The various data are written within a defined string in JSON format with key and value notation. At each time sampling, the JSON string includes the following fields: name, time stamp, loop measurements (SP, PV, OP, as mandatory, MV (that is, VP), DS, P, as optional), and controller parameters (proportional gain (pidP), integral constant (pidI), derivative constant (pidD), filter constant (pidF), controller mode (pidmode), high and low limit on OP (pidOL, pidOH) and PV (PVL, PVH)).

The main causes of malfunction can be reproduced by means of some physical modular items, as described in ref 37. In addition, faults can be also introduced by the use of dedicated software blocks.

Valve stiction is reproduced by implementing a data-driven model within a customized function block of the PLC (see Figure 9). Valve stiction dynamics can, indeed, be modeled as follows:

$$\mathrm{MV}_k = \begin{cases} M(\mathrm{OP}_k - f_D) + \mathrm{MV}_{k-1}(1-M) & \text{if } \mathrm{OP}_k - \mathrm{MV}_{k-1} > f_S \\ M(\mathrm{OP}_k + f_D) + \mathrm{MV}_{k-1}(1-M) & \text{if } \mathrm{OP}_k - \mathrm{MV}_{k-1} < -f_S \\ \mathrm{MV}_{k-1} & \text{if } |\mathrm{OP}_k - \mathrm{MV}_{k-1}| \le f_S \end{cases} \quad (1)$$

where f_S and f_D are static and dynamic friction parameters, respectively. Note that both standard[38] and semiphysical versions[39] of the well-established He's stiction model can be reproduced, by setting $M = 1$ or $M = 1.99$, respectively. Recalling that parameters of He's model have their theoretically equivalent in Kano's model,[40] the user must set the stick-band plus dead-band ($S = f_S + f_D$ and slip-jump $J = f_S - f_D$), such that $f_S = \frac{S+J}{2}$ and $f_D = \frac{S-J}{2}$. Note that one can also select which signal is recycled as input into the block: the block output (MV) or the actual valve position (POS). In this second case, valve dynamics is mixed with simulated stiction nonlinearity, so that typical wave forms of friction can be altered.[41]

Moreover, external software disturbances are introduced within the inverter and two motored valves. A sinusoidal disturbance can be added to the desired inverter velocity. One can set amplitude and frequency of oscillation around the set-point value. Whereas, the input signal to motored valve 12FS013 is added with a stepwise wave. Here, one can select extremes of oscillation (D_{min}, D_{max}) within a range of 0−100%, step size Δ, and step duration τ (compare the yellow pop-up in Figure 9).

5. EXAMPLES OF APPLICATION

In this section, three examples of application of the analytics tool PCU-Cloud are illustrated. The performance of loop and actuator 12FK020 of the IdroLab pilot plant are detailed below. These cases represent a synthesis of some typical behaviors, but all main types of malfunction have been successfully tested.

5.1. Case (i): GOOD Loop. This first dataset represents a case of good behavior, without any type of malfunction (see

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Ind. Eng. Chem. Res. 2020, 59, 2341−2352

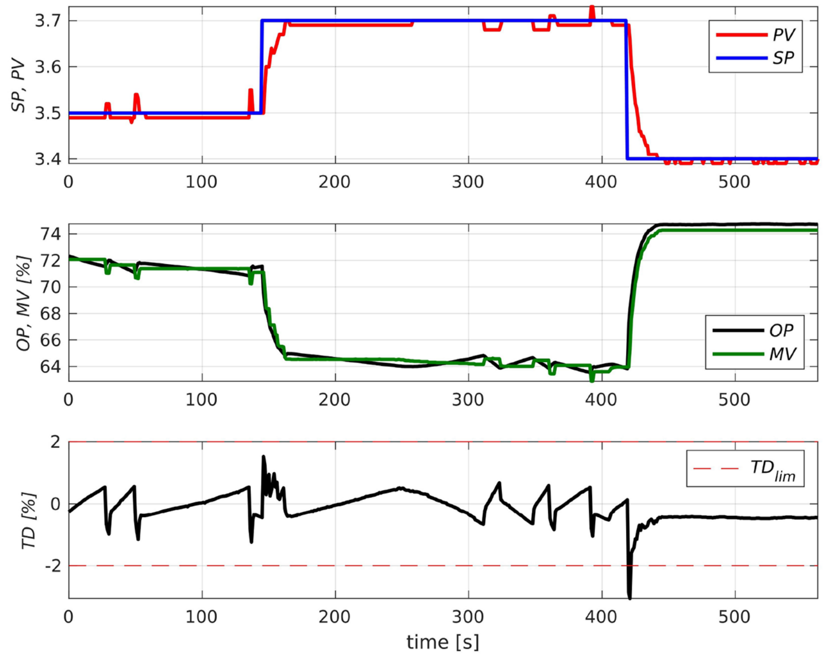

Figure 10. Time trends for case (i): good behavior.

Table 2. Verdict of Six Oscillation Detection Techniques

case	Hägglund	E_{PV}	E_{SP}	r	R	EMD	final
(i)	GOOD (0)	GOOD (0)	GOOD (0)	GOOD (0)	GOOD (0)	GOOD (0)	GOOD (0/6)
(ii)	GOOD (0)	GOOD (0)	ALERT (0.5)	GOOD (0)	BAD (1)	BAD (1)	ALERT (2.5/6)
(iii)	ALERT (0.5)	GOOD (0)	GOOD (0)	GOOD (0)	BAD (1)	BAD (1)	ALERT (2.5/6)

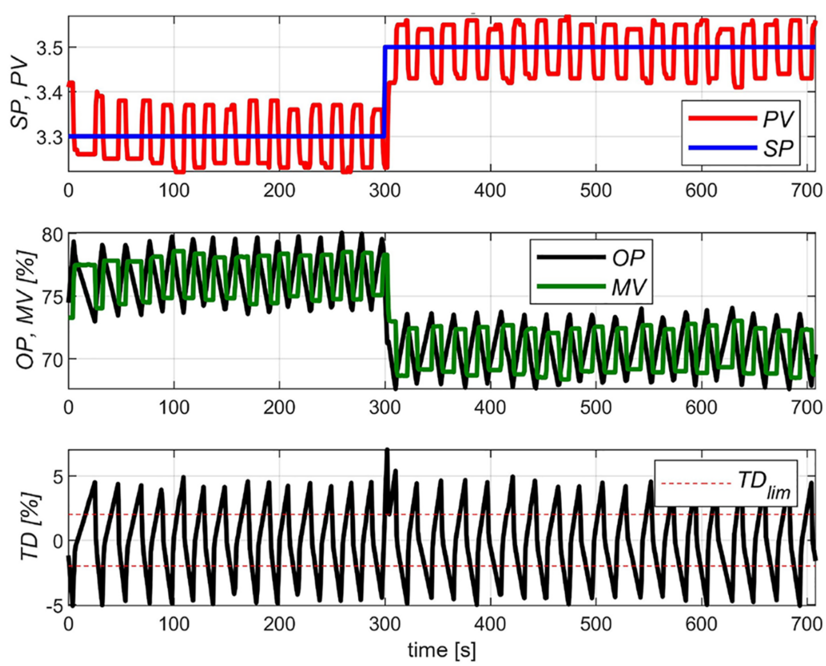

Figure 11. Time trends for case (ii): valve stiction.

Figure 10). Two step changes are imposed to the set point SP, the PID controller has good tuning, and no stiction is introduced into the valve. The PCU-Cloud actually emits a correct verdict of GOOD status, both on the loop and the actuator (compare Section 2.2). In detail, assessment of all six oscillation detection techniques (ODT) reveals no fluctuation in PV data (see Table 2). All six key performance indices (KPIs) for actuator status are below their thresholds, since TD does not exhibit significant sticky movements and lays within its acceptable range TD_{lim}.

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Ind. Eng. Chem. Res. 2020, 59, 2341−2352

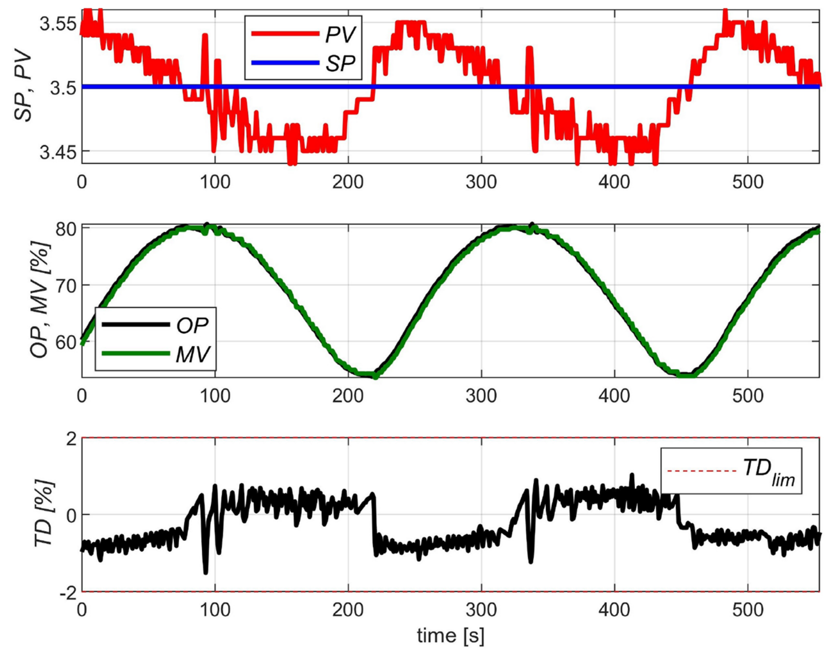

Figure 12. Time trends for case (iii): external disturbance.

5.2. Case (ii): Valve Stiction. To simulate stiction within valve 12FK020, the dedicated software block is activated. The following parameters are set: $S = 4$, $J = 2$, and the output signal (MV) is recycled back as input (see Figure 9). Typical wave forms are shown in Figure 11: PV and MV exhibit squared wave forms, while OP shows a triangular wave form. The cloud-based monitoring system properly evaluates both loop and actuator status. Travel Deviation shows evident stick–slip trend, even outside TD_{lim}, so that the corresponding KPI[18] exceeds its threshold and stiction can be perfectly recognized. Valve malfunction also induces evident oscillations in PV data. The various ODT emit different outcomes, as reported in Table 2. The final averaged verdict of oscillation is ALERT (2.5/6) and also loop status is evaluated as ALERT.

5.3. Case (iii): External Disturbance. In this example, stable oscillations are induced by adding software disturbance to the set-point velocity of the pump inverter. A sinusoidal disturbance, with a relative amplitude (A) of 5% and a frequency (f) of 1/240 Hz, is inserted, whose effects are particular evident in OP data, as shown by Figure 12. The PCU-Cloud emits an appropriate verdict: the actuator and loop status are assessed as GOOD and ALERT, respectively. All six KPIs for actuator status are below their thresholds as TD resides within its acceptable range TD_{lim}. The outcomes of various ODT are reported in Table 2. Also in this scenario, the final averaged verdict of oscillation is ALERT (2.5/6), and then loop status is evaluated as ALERT.

6. CONCLUSIONS

The system illustrated in this paper represents a successful example of a cloud-based platform for performance monitoring and assessment of process plants, specifically oriented to PID control loops. The same approach can be easily taken for the global monitoring of plant performance and equipment efficiency. Details of implementation have been illustrated, in terms of global architecture and modules within the analytics tool (PCU-Cloud) of the system, for the specific case of application to a pilot-scale plant.

The system today employs available technologies of Industry 4.0 and can be built with very reasonable investments to complete the required automation and instrumentation, in large part already pre-existing in the plant. The additional costs of the cloud will be compensated by savings and advantages in the need for a unique monitoring system, with a consequent reduction of skills to be developed and resources to be maintained on each single plant. Open issues, such as cybersecurity, data traffic, and message size, and practical problems, as analysis scheduling and system configuration, must be solved jointly by the industrial firm and the external company. Results of application to several significant control loops, which represent a synthesis of various conditions of good operation and presence of different types of malfunction, confirm the effectiveness of the cloud-based monitoring.

As a future step, the same cloud-based architecture will be extended to other functionalities, e.g., condition monitoring purposes to supervise other plant machinery, such as pumps, compressors, and motors with the objective of preventive and predictive maintenance.

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Notes

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■ ACRONYMS

CIM = Causes Identification Module
CLPM/CLPA = control loop performance monitoring/assessment
DCS = distributed control system
JSON = JavaScript Object Notation
KET = key enabling technologies
MQTT = Message Queue Telemetry Transport
MV = manipulated variable
OP = controller output
OPC = open platform communications
PV = process variable
SM = Scheduling Module
SP = Set Point
TCP/IP = transmission control protocol/Internet protocol
TLS = transport layer security
UM = User Module
VP = valve position

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