

A fully integrated open solution for the remote operation of pilot plants

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Abstract— Nowadays remote access to systems in the instrumentation and measurement fields is both a reality and a challenge. There is a growing interest in replacing manual actions performed on site by remote actions carried out from anywhere around the world. To do that, besides the availability of suitable communication networks, it is necessary for the elements involved in the network to recognize each other, this latter task perhaps being the most complex one of the two. Integrating different hardware/software from different manufacturers into a single system with controlled remote access is not a trivial task. This paper presents a fully integrated open solution for the operation of pilot plants (scaled down, laboratory level industrial plants operated in university and other environments) using open access hardware/software on public networks. The proposed solution is independent of the nature of the pilot plant and its elements and can therefore be considered standard. In order to illustrate the capabilities of the proposed solution, two different types of pilot plant are presented.

Index Terms— Remote access, instrumentation, remote sensor, remote pilot plant.

I. INTRODUCTION

Like other sectors, [1], [2], industry today requires the capacity for remote measurement, monitoring and control of its systems. In fact, this is already possible in domestic life and even in the field of education, [3]. However, solving the problem of remote access and control is a challenge for instrumentation and measurement. Indeed, in many cases, manual devices are no longer useful, so the availability of sensors, meters, actuators and other remotely controlled devices is absolutely essential.

However, the availability of such devices is not the only necessity for the development of remote monitoring and control system. The integration of the relevant hardware/software into a communication network is also required. The more complex the task, the more open the required solution needs to be.

Hence, if the remote system supports devices from a single manufacturer or compatible software, all of which are connected to the same local area network (LAN), [4], the system can be considered a closed or proprietary: level 1 of openness as shown in figure 1.

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The system is a little more open if it is accessible via the Internet, although the devices must remain compatible, [5], [6], level 2 in figure 1.

However, if the system can communicate devices from different, mutually incompatible manufacturers and is accessible via the internet, then it can be considered fully open, level 3 in figure 1.

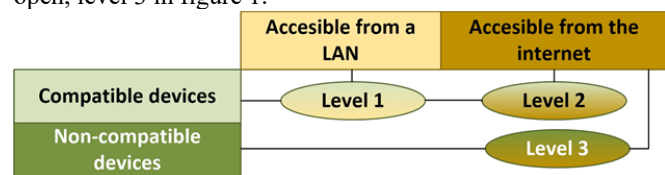


Fig. 1 Solution's level of openness.

Some systems in this latter category can be found in the literature, but not many. Moreover, they are usually local solutions and tend to be ad hoc [7]–[9], that is non-transferrable from one system to another. For example, [10] presents a procedure based on instant messaging (IM) application architecture but this procedure is only valid for plants controlled with LabView. Further, there is no access control through methods such as time reservation or user profiles and the system recognizes only those protocols adapted to http.

In the field of research and higher education (and also in industrial environments, especially for testing, checking and scaling), industrial plants are usually managed at laboratory scale, using pilot plants (PPs), [11]–[13]. For remote operation of plants, at both industrial and laboratory scale, it seems highly desirable to take advantage of the developments made in the field of remote laboratories (RL), [14].

In other words, the monitoring and control of a PP via the internet can be approached as an RL.

Regarding the state of the art of RLs, the last few years have seen the development of a great many across various engineering fields, from electronics, [15]–[17], to automatic systems, [18]–[21]. Robotic is also an area where RLs have been extensively developed, [22], [23]. In addition, there are some physical, [24], [25], mechanical and chemical engineering experimental setups, [26]–[28].

In [29] a power engineering and motion control RL is presented, which offers 18 complete online courses with remote experiments and the corresponding documentation. Within the electrical engineering, there are some other remote platforms, [30]–[32].

Actuators are electric machines with stringent safety requirements. It is essential to avoid the over-acceleration and

overheating, both of which can lead to the destruction of the machines. These safety requirements are more easily met if they are managed remotely and it is therefore essential that remote operating systems include appropriate protection. In addition, the remote management of electric machine requires the design of secure interface modules for the control and measurement of the voltage and current, and the effect of the electromagnetic field created by the electric machines on the PP control boards must be also taken into account.

With respect to photovoltaic system, there are multiple studies into the use of remote transmission systems to monitor them, such as [33] and [34], among others. Within the educational field, the possibilities have been explored of virtual labs, [35], and RLs, [36]–[38]. In [36], a photovoltaic remote system, implemented in LabView, is presented. In [37], the authors consider solid-state photovoltaic cells characterization using several photovoltaic systems. In [38], a remotely triggered photovoltaic solar cell experiment is presented, in which the user is able to turn a number of light bulbs on and off, adjust the load voltage of the solar cell, and view the experiment in real time via a webcam.

Using concepts deriving from RLs, the authors of this paper have gone further and have designed and developed a fully integrated open solution for the remote operation of any PP via the internet, regardless of its characteristics. The solution, based on open-source hardware platforms and free software, covers not only the remote interaction with the PP but also solves communication problems. It has been used to enable the remote access of several pilot plants at the University of Huelva including the automation plant of a commercial PLC and communications plants, among others. These projects can be accessed at <http://sarlab2.uhu.es/sarlab/> and many of them are in operation in several universities. Some other remote PP in operation in those universities have been implemented using the solution proposed in this paper as for example an air levitation system to control the position of an object lifted without mechanical support.

Two of the PP accessible through the URL indicated above are described in this paper. The first, denominated electric machines remote pilot plant (EMRPP), involves actuators located in various industrial plants. The second, the photovoltaic remote pilot plant (PRPP), concerns photovoltaic panels. Although these plants are simple relative to the potential of the solution, their particular characteristics allow different technical details regarding implementation to be illustrated. Indeed, our intention is to show the potential for the remote operation of plants, rather than the complexity of the plants themselves. In fact, the solution allows the inclusion of as many sensors and actuators as necessary, regardless of the complexity of the plant, as well as providing the procedure and tools for the plant remote management of the plant.

It should be noted that the solution presented in this paper, which is characterized as fully integrated open, is the result of several years' work during which we have presented partial results within the RL field, always in terms of their educational value. Thus, [39] presents a RL for electric machines, and [40] one for photovoltaic systems. It is from

these that the current EMRPP and PRPP originate. Following the educational approach, in [41] a comparative analysis of both RLs is presented. Finally, [42] displays a solution for transforming a laboratory experiment into a remote experiment. Building on these conference papers, this one describes a fully integrated open solution for operating PPs via the internet, using open access hardware/software. It describes the two parts comprising the solution, one general and valid for any RPP, and the other, significantly smaller, specific and dependent of the nature of the PP.

This paper is organized as follows: section II provides a detailed description of the solution we propose for the remote operation of PP is summarized. In sections III and IV, two operation of PPs. Sections III and IV discuss two examples of PP working under the control of the system, the first concerned with electric machines and the second with photovoltaic panels. Finally, in section V, some conclusions are drawn.

II. DESCRIPTION OF THE FULLY INTEGRATED OPEN SOLUTION

In this section the proposed framework for the design and implementation of RPPs is presented. Figure 2 shows the general scheme of the complete scenario. The RPP shown here serves only as an example, as it could be substituted for any other type.

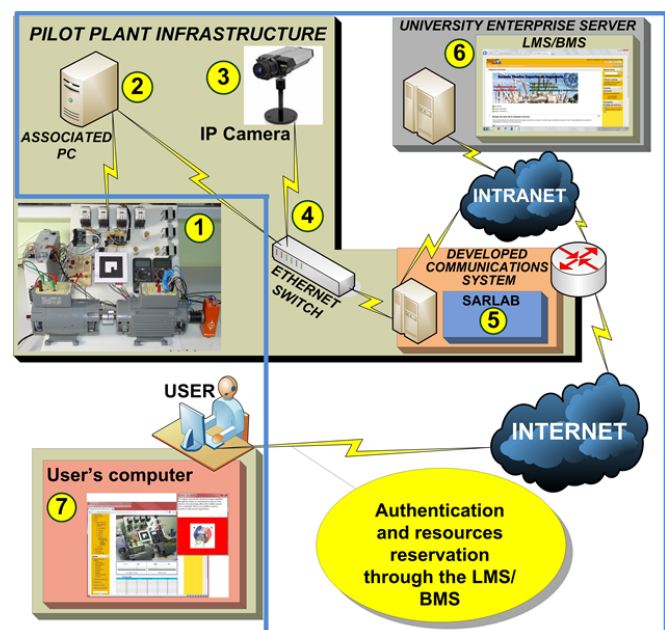


Fig. 2. General scheme of the proposed fully integrated open solution for the remote operation of any pilot plant via internet (RPP).

Fig. 2 shows the infrastructure of the RPP. The PP (1), via an associated PC (Personal Computer) (2), and an IP (Internet Protocol) camera (3) is directly connected to the University LAN by means of an Ethernet switch (4). The PC (item 2) can be replaced by a single-board computer (SBC). For example, in the PRPP, the PC functions are carried out by a Raspberry Pi, [43]. In the same way, the IP camera can be replaced by a

USB (universal serial bus) camera connected to (2).

Continuing with Figure 2, the communications system which has been developed (5) is a server running specific software designed to automatically generate the necessary communication channels (tunnel) to facilitate transparent access to the PP via the internet. This communications system, denominated SARLAB (an acronym corresponding to its Spanish name, Sistema de Acceso Remoto a LABORatorios, or Remote Laboratory Access System in English), has been designed and developed by the authors of this paper. All remote PPs (RPPs) at the University of Huelva are ready to be operated through a learning management system, LMS, (in this case Moodle, this being the university's LMS of choice) (6). In this way, the academic issues are optimally solved by the LMS. For example, and of particular importance in the case of PPs operated by students, the LMS includes a reservation system which allows for orderly user access 24 hours a day, 7 days a week. Moreover, the proposed solution also facilitates concurrent access.

In the same way that access to our PP is granted from an LMS, based on the solution presented here, access to other industrial plants can be granted from the business management system (BMS) of a company, or simply from a content management system (CMS).

The user accesses the RPP through the LMS/BMS/CMS, via a web browser. This is achieved via a user interface (UI), (7), which runs in the user's computer and includes the following elements:

- Live video stream from the IP camera located at the PP scenario.
- Augmented reality (AR) features, [4], synchronized with the live video stream to enhance the UI.
- Monitoring and control of the PP actuators/sensors.
- Required safety features for ensuring correct operation of PP devices.

The UI is created using EJS (easy Java simulations), [44], a free authoring tool written in Java (although compatible with the constraints of the new generation of browsers), which facilitates interactive simulations, and overcomes the limitations of the proprietary software used by applications such as Matlab or LabView.

With the fully integrated open system described and presented in this section, a PP can be remotely accessible whatever form it takes. The procedure to carry out the general scheme in Figure 2 would be as follows:

1. The PP (1), generally different in each case, must be equipped with sensors and actuators that can be monitored and operated by computer. This will be addressed in more detail later in this section.
2. The fulfillment of the previous condition allows the plant's sensors and actuators to be connected either directly to an associated PC (2) or SBC, or indirectly through the Ethernet switch (4).
3. The camera (3) can be an IP camera directly connected to the network through the Ethernet switch (4), or an USB camera directly connected to the associated PC (2).
4. Through the Ethernet switch (4), all incoming and

outgoing PP signals can travel to or from the specially developed communications system (SARLAB) (5).

5. SARLAB is hosted on a server (5) and connected to both the company/institution LANs (through the Ethernet switch) and to the internet.
6. The UI corresponding to the PP is activated (7), providing user with all necessary commands and registers to monitor and control the PP, including video stream (and audio if needed) and required safety controls.
7. The UI is integrated into the company's/institution's CMS/BMS/LMS (6), and runs on the user's computer.

Elements 2, 3, 4, 5 and 6 in Figure 2, frame in the blue box, constitute the fully integrated open solution and are common to any RPP. Elements 1 and 7 are obviously specific to each PP, although in the case of 1, the presented solution develops a general conditioning/signal processing/communication architecture. Thus, a good part of 1 is common to all plants and can therefore be considered part of the proposed fully integrated open solution.

A. Architecture of the general conditioning/signal

As indicated above, the network can only send data structures (data packets) from one end to the other. Sensors and actuators must therefore have an interface to send the actions in data packages from the network on the PP and vice versa. This is essential for SARLAB to be able to control communication.

With this in mind, in order to convert any PP into an RPP, the first step is to consider the physical PP as a black box with the required number of inputs/outputs, whether analog or digital, depending on the nature of the PP (see Fig. 3). Outputs are sent from the sensors and inputs are received by the actuators. All signals (analog or digital) must be normalized to standard formats: 0/5 V, 0/3.3 V, PWM and so on (Signal conditioning stage). In general, when there are signals that have to go through an A/D and/or D/A conversion process, they have to be conditioned to cover the entire range of the converter's input window, which provides the largest possible dynamic range. The hardware/software solutions to implement the signal conditioning stage and the A/D and D/A conversion stage may be different in each PP, but the purpose of these stages remains the same.

The stages analysed thus far (framed in red above) form part of element 1 in Figure 2.

Once PP is completely monitored, the rest of the process does not absolutely depend on the nature of the PP. It may be chemical, mechanic, electric or whatever nature.

Thus, from here, the data processing/computing stage (2 in Figure 3) is carried out by an associated PC or SBC (2 in Figure 2), which connects the PP (1 in both Figures), through the network interface (4 in both Figures), to the company/institution' LAN. The PP controller can be hosted in stage 2 of Figure 3, or in a higher level, or even distributed across different levels.

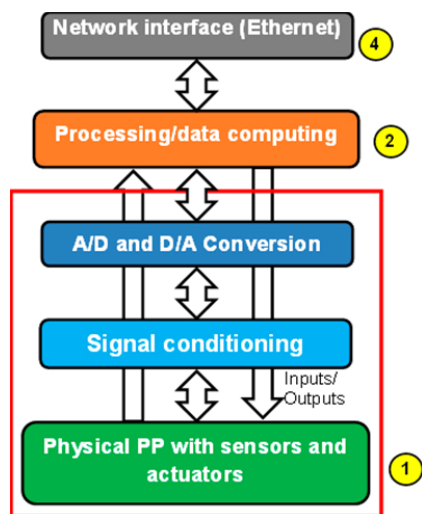


Fig. 3. Stages for managing any pilot plant remotely.

Whatever the particular case, the fully integrated open solution proposed here largely consists of solving a communication problem, the core of which is SARLAB, outlined briefly in the following subsection.

B. SARLAB

Although SARLAB is a pure communications system and is, therefore, outside the scope of this journal and this study, as it is a key part of the proposed solution, a brief description is of interest.

The SARLAB server runs the LINUX open operating system and links the company/institution LAN, to which the PPs are connected, to the internet, to which the user is connected. It thus controls the data flow between the user and the PP, but, importantly, creates a secure frontier between the LAN (a secure network) and the internet (a public network).

The use of the internet imposes the use of a specific family of protocols in the communication structure that govern the flow of data: TCP/IP protocols. These have become the standard of any type of network because in order to connect to internet, LANs have had to adopt these same protocols. Consequently, the data packages that allow the monitoring and control of a RPP in the proposed solution will be transmitted from the user's PC to the PP and vice versa encapsulated in this family of protocols.

In a network with TCP/IP technology, every communication node is identified by an IP (Internet Protocol) address. SARLAB must thus have two Ethernet interfaces - one connected to the internet and the other to the company/institution LAN to which the PP is connected. This means that on the LAN side, SARLAB has a range of private IP addresses and, on the internet side, at least, one public IP address.

The end of the tunnel located in the LAN is identified by the IP and the port which corresponds to the device to be accessed. This means that the user at the other end of the tunnel will gain access only to that device and none of the

others connected to the LAN.

In addition, SARLAB turns on the power when the PP is in use and shuts it off when it's not. This enables the RPP to optimally manage its energy consumption 24 hours a day, 7 days a week.

Furthermore, SARLAB allows the following goals to be met:

- Internet access to devices connected to different LANs.
- Access control by means of different user profiles, including concurrent access.
- Unification of the access control to devices with different access protocols.
- Access to several commercial devices with proprietary software, in addition to devices whose access procedure is implemented in open platforms with low cost software.
- Abstraction of the complexity inherent in communication programming for the PP designer and user.
- Overcoming of limitations associated with the new generation of browsers, whereby their capacity for interaction with the physical system on which they run can be restricted or even eliminated.

III. THE ELECTRIC MACHINES REMOTE PILOT PLANT

Figure 4 illustrates the complete EMRPP, which is comprised of all the components of the general scheme shown in Figure 2. (1) is the PP detailed at blocks diagram level. The associated PC (2) collects the signals from the sensors of the PP and sends orders to its actuators. In this case the PP and associated PC are directly connected, through connection by means of an Ethernet switch is also possible. The axis camera (3) is directly connected to the Ethernet switch (4) and sends the video and audio streams to the UI (7). SARLAB (5) solves the communication problem. (6) is the company/institution server, which hosts the CMS/LMS/BMS. Finally (7) is the UI, which is included in the CMS/LMS/BMS, but runs on the user's computer during access. Access to the UI is available 24 hours a day, 7 days a week via the browser, using the corresponding user profile.

The following section describes the two specific elements of the EMRPP: PP and UI.

As mentioned above, the PP is detailed in Figure 4, framed in the red box. The core is an electric machine bench, comprised of a synchronous generator (A) driven by a DC (Direct Current) machine (B). The nominal values of the generator are 360 W, 380/220 V AC (Alternating Current), 1500 rpm with a power factor of 0.72. The DC machine nominal values are 440 W, 220 V DC and 1500 rpm. Both electric machines are coupled to an analog tachometer (C), which sends the rotational speed signal to an I/O (input/output) board, [45], (D), with analog inputs and digital outputs. This I/O board is directly connected to an USB port in the associated PC (2). Its functions are:

- Rotation speed measurement.
- Field current measurement from the current source (E).
- Switching the current source on/off (E).
- Turning the RPP supply on/off, according to the orders received from the PC, through a set of optocoupled

relays (F).

- Configuring the connections suitable for each test of the synchronous generator (vacuum or short circuit tests, among others), through several contactors (G).

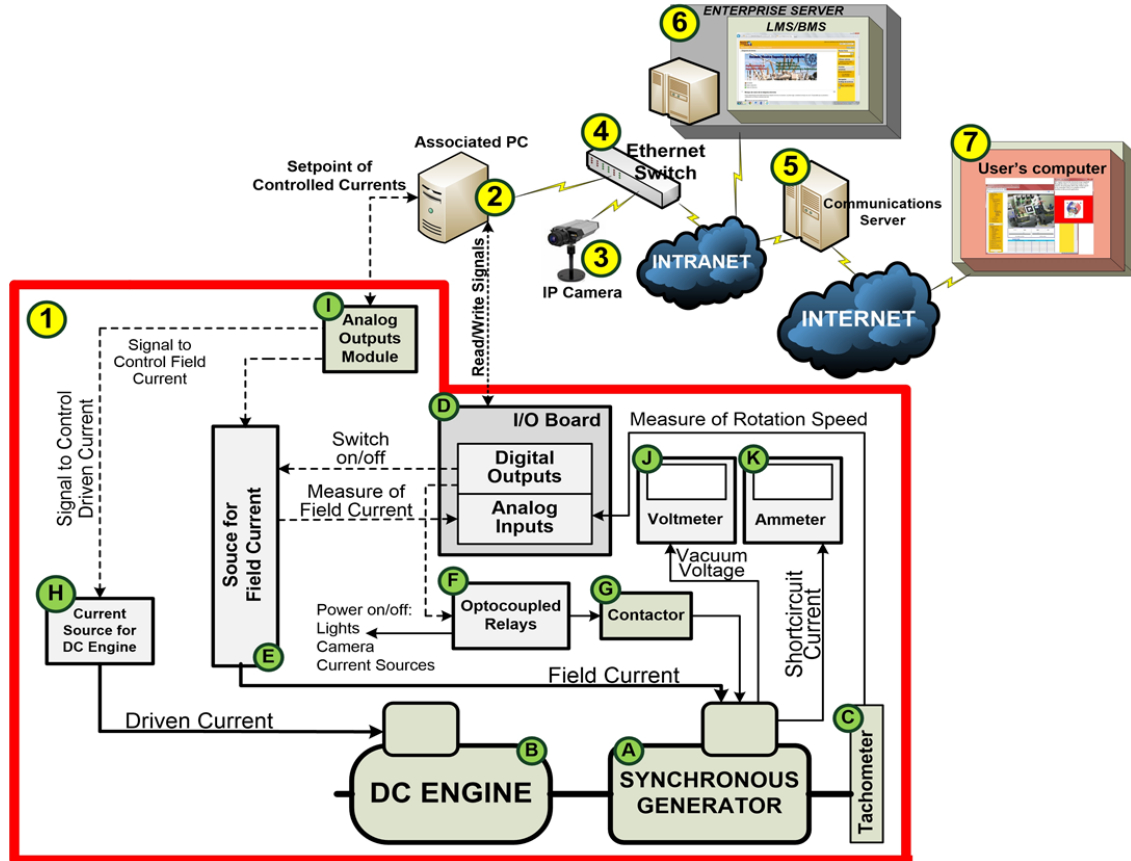


Fig. 4. Diagram of the Electric Machines Remote Pilot Plant including the different elements that composes it.

The current going into the rotor of the DC machine is supplied by a current source (H), which is controlled by an analog output board (I) [46]. This device also controls the field current supplied by the current source (E).

Finally, a voltmeter (J) is used to show the voltage measurement and an ammeter (K) to show the current at the generator input.

The physical PP is shown in Figure 5, where the devices named in Figure 4 are indicated.

The following section describes the other specific element: the UI shown in Figure 6. The central part of the display shows the video stream enriched with AR objects in the form of interactive tabs providing useful explanatory information about the nature and function of the PP. The pop-up displayed when the user selects the DC machine tab is shown at the top right of Figure 6 while at the bottom right, a graph illustrates the evolution of the actuators' signals.

In addition, in order to enhance the user's involvement in the PP scenario, the video stream is reinforced by an audio stream, since the variations in rotational speed have a direct effect on the sound produced by the electric machines. Hence, the availability of audio boosts the feeling of being engaged with physical elements, albeit remotely.

Finally, in the case of this RPP, the UI incorporates the required safety measures, which are of particular relevance.

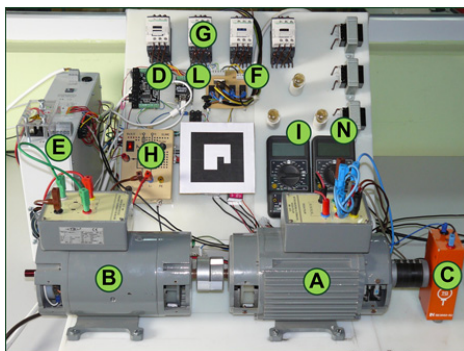


Fig. 5. Actual PP; (I) in Figure 4.

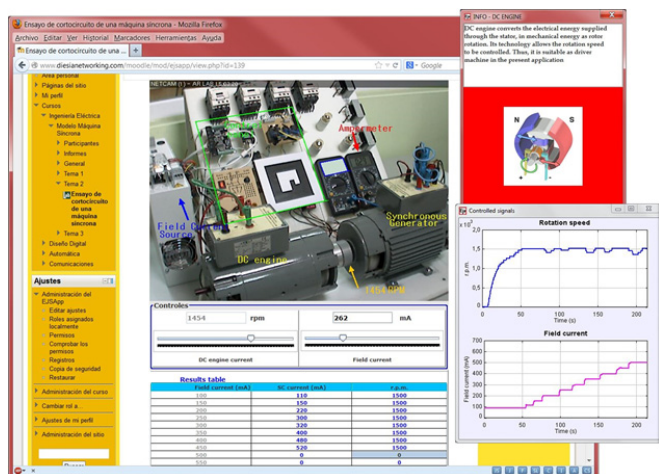


Fig. 6. EMRPP user interface.

IV. THE PHOTOVOLTAIC REMOTE PILOT PLANT

Analogously to the EMRPP, the complete PRPP is presented in Figure 7, which shows all the elements of the general scheme included in Figure 2. (1) is the PP block diagram. In this case, a Raspberry Pi (2) acts as the associated

PC and, by means of the Ethernet switch (4), receives the PP sensors' signals and drives its actuators. (3) is a USB camera, directly connected to the Raspberry Pi, which also controls the PRPP on/off switch and the optimization of the PP energy performance. SARLAB (5) is connected to both the company/institution LAN and the internet. (6) is the company/institution server which hosts the LMS/BMS/CMS, and (7) is the UI for this PP. This is included in the LMS/BMS/CMS, although it runs on the user's computer during access. As in all the PPs made accessible remotely by this solution, the UI can be accessed via the browser 24 hours a day, 7 days a week using the corresponding user profile.

In Figure 7, the PP is framed in the red box. Again, the stages for remote management of the PP (PRPP) are those illustrated in Figure 3.

One of the most valuable characteristic of the PRPP is the use of low-cost elements - a Raspberry Pi as the associated PC and Arduino targets ([47], a low-cost, open-source electronics platform) as I/O boards to control both the light and the variable load, and to measure the sensing parameters.

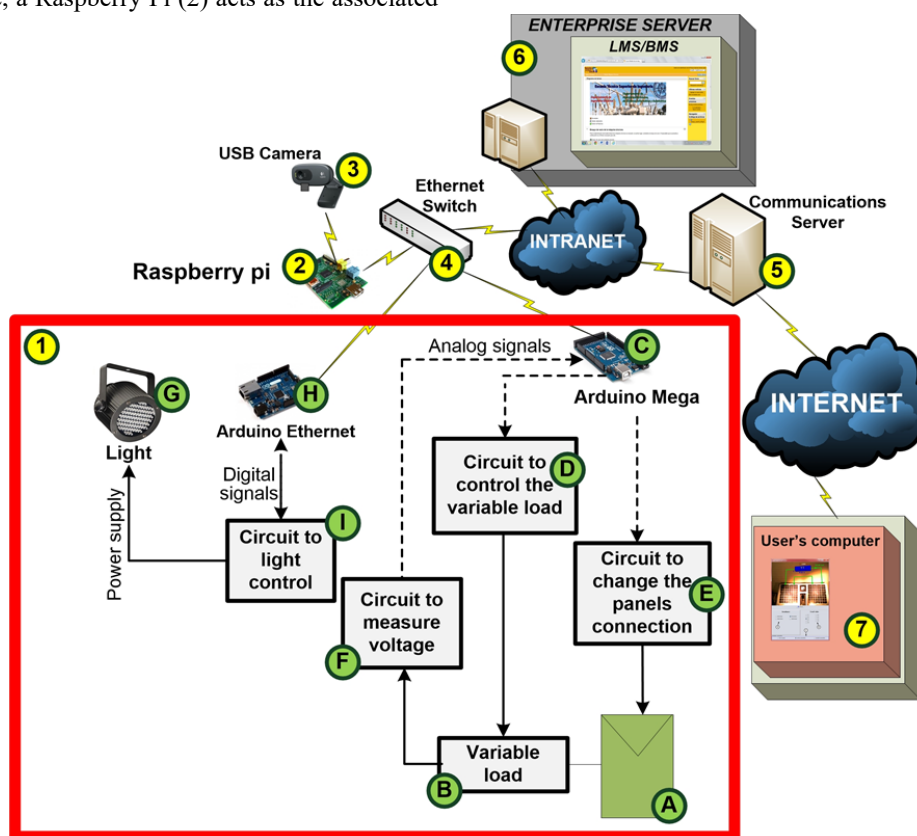


Fig. 7. Diagram of the Photovoltaic Remote Pilot Plant.

The Modbus Industrial Standard protocol has been used to unify the mode of access to all the devices throughout the network. This enables the transmission and receipt of data across all devices and, furthermore, allows them to be monitored by an EJS element with Modbus Master

Architecture. In order to achieve this, a Modbus Slave has been included in all the Arduino boards, [48]. Thus, in this case, Modbus is used to interconnect the I/O boards located in the PP, and the UI accessible from the LMS.

The following provides a detailed explanation of the two

specific elements of the PRPP: the PP and the UI. The physical PP outlined in the red box in Figure 7, it involves the following elements: a set of two photovoltaic panels (A). Each panel's nominal values are 0.4 W, 12 V. The panels are connected to a variable load (B), which is controlled by an Arduino board (C), by means of the corresponding circuit (D).

This board is also responsible for configuring the panel's connection through the circuit (E). The final function of the board (C) is to measure the load voltage, through the corresponding circuit (F). As there are two voltage ranges to measure, the measured voltage is doubled.

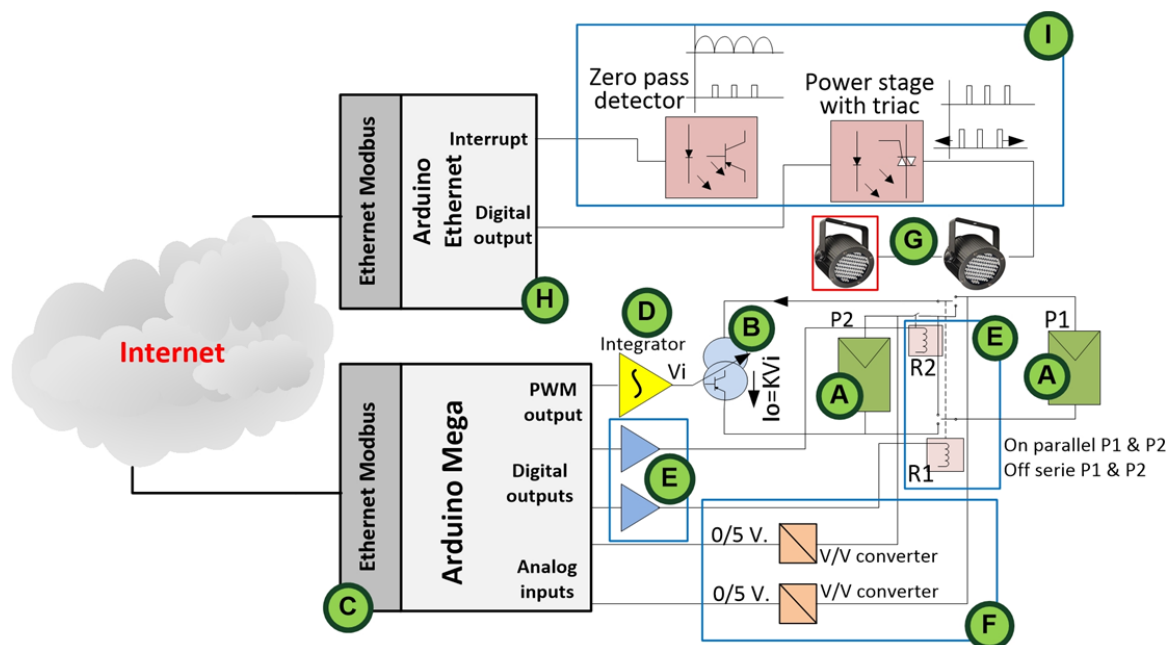


Fig. 8. Diagrams of the control circuits in the PRPP.

Figure 7 also illustrates the use of two 500 W light sources (G) to excite the photovoltaic panels (substituting solar radiation). To study the effect of irradiance in the characteristic curve of the photovoltaic panels, the power of the light sources can be controlled through an Arduino Ethernet board (H).

The control of high power elements by means of an Arduino board is possible due to a novel circuit designed specifically by the authors (I), as detailed in Figure 8. This is basically composed of a module that detects the zero value of the electrical grid and another one which uses this value to establish the trigger point of a TRIAC to control the time in which the light sources are on/off. The resulting circuit is a dimmer switch, directly accessible from the internet using TCP/IP protocol. Therefore, light sources can be controlled by the user via the internet through an Arduino Ethernet board (H).

A second circuit, illustrated at the bottom of Figure 8, manages the load values, which are controlled electronically through a variable current source, connected to the panels. This circuit changes the connection which run in series, parallel, or even single panel, and measures the load voltage with two measurement ranges. The connections are also electronically controlled by relays R1 and R2. Both the connections and loads can be controlled by the user via the internet through an Arduino mega board (C).

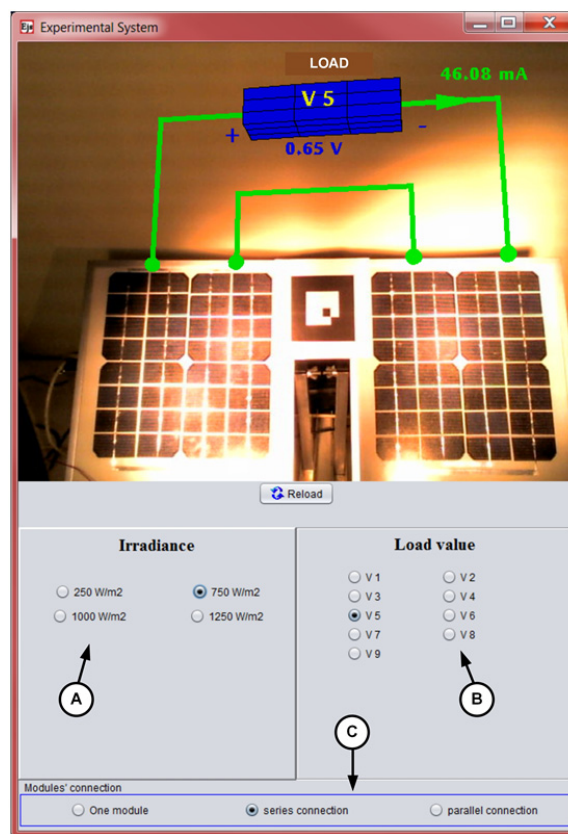


Fig. 9. PRPP user interface.

The PRPP UI is composed of two parts, as illustrated in Figure 9. The PP video image shown at the top displays two photovoltaic panels lit by a variable light source, whose change of irradiance can be distinguished with the naked eye by means of the photographic image. In order to enrich the UI, making it more intuitive and user-friendly, the load, I/V meters and panel connection presented in the image are not the real ones, but have instead been developed through AR to provide the following advantages. Firstly, AR connections are more user-friendly. Secondly, from the user's perspective, the appearance (resistance) of the physical load in the PRPP operation remains unchanged, though it must be remembered that it is comprised of a variable current source (see Figure 8), and, as such, the values can vary (V1 to V8). Voltmeter and ammeter measurements have also been included as AR elements in the UI (0.65 V and 46.08 mA respectively).

The second part of the UI, illustrated at the bottom of Figure 9, contains the control parameters that the user has to manage: the irradiance received by the panel (depending on the lighting power of the scenario, the focus power can be modified continuously, although only four typical values can be selected in the UI) (A), the load value (B), and the panels' connections (individual, two in series or in parallel) (C).

V. CONCLUSIONS

This paper presents a fully integrated open solution for the remote operation of PPs via the internet. The PP can be configured with elements from different manufacturers, despite incompatibility, and from the user's perspective, the solution appears fully integrated open. Thus, the solution is appropriated for PPs of any nature and adaptable to different technologies.

Evidence of the potential of the proposed solution is provided via a URL (uniform resource locator) which grants access to a number of projects successfully utilising the technology, two of which are outlined in detail. These two examples have been selected as they demonstrate the adaptability of the system and allow for the inclusion of different technical details such as innovative problem solving techniques. The first RPP is devoted to the operation of electric machines, whereas the second deals with the management of photovoltaic panels.

The proposed fully integrated open solution facilitates the remote management of the PP via an internet browser, through a friendly UI, 24 hours a day, 7 days a week, using the corresponding user profile. Furthermore, it even switches on the power supply when the PP is in use and whuts it off afterwards.

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REFERENCES

- [1] S. Wang *et al.*, "Augmented Reality as a Telemedicine Platform for Remote Procedural Training," *Sensors*, vol. 17, no. 10, p. 2294, Oct. 2017.
- [2] L. Zhou, N. Chen, and Z. Chen, "Efficient Streaming Mass Spatio-Temporal Vehicle Data Access in Urban Sensor Networks Based on Apache Storm," *Sensors*, vol. 17, no. 4, p. 815, Apr. 2017.
- [3] R. Heradio, L. de la Torre Cubillo, D. Galan, F. Cabrerizo, E. Herrera-Viedma, and S. Dormido, "Virtual and Remote Labs in Education: a Bibliometric Analysis," *Comput. Educ.*, vol. 98, pp. 14–38, Jul. 2016.
- [4] A. Mejías Borrero and J. M. Andújar Márquez, "A pilot study of the effectiveness of augmented reality to enhance the use of remote labs in electrical engineering education," *J. Sci. Educ. Technol.*, vol. 21, no. 5, pp. 540–557, 2012.
- [5] V. L. Lasky, D. K. Liu, S. J. Murray, and K. K. L. Choy, "A Remote PLC system for e-Learning," in *Proceedings of the ASEE/AaeE 4th Global Colloquium on Engineering Education*, 2005.
- [6] M. Domínguez, J. J. Fuertes, M. A. Prada, S. Alonso, and A. Morán, "Remote laboratory of a quadruple tank process for learning in control engineering using different industrial controllers," *Comput. Appl. Eng. Educ.*, vol. 22, no. 3, pp. 375–386, Sep. 2014.
- [7] M. Casini, D. Prattichizzo, and A. Vicino, "The automatic control telelab," *IEEE Control Syst.*, vol. 24, no. 3, pp. 36–44, Jun. 2004.
- [8] N. Faltin, A. Böhne, J. Tutas, and B. Wagner, "Distributed Team Learning in an Internet-Assisted Laboratory," presented at the International Conference on Engineering Education, 2002.
- [9] T. A. Fjeldly, J. O. Strandman, and R. Berntzen, "Lab-On-Web - A Comprehensive Electronic Device Laboratory On A Chip Accessible Via Internet," presented at the International Conference on Engineering Education, 2002.
- [10] Ning Wang, Gangbing Song, and Xuemin Chen, "Framework for Rapid Integration of Offline Experiments into Remote Laboratory.," *Int. J. Online Eng.*, vol. 13, no. 12, pp. 192–205, 2017.
- [11] A. K. Sukede and J. Arora, "Auto tuning of PID controller," in *2015 International Conference on Industrial Instrumentation and Control (IICIC)*, 2015, pp. 1459–1462.
- [12] D. Sachde, E. Chen, and G. T. Rochelle, "Modeling Pilot Plant Performance of an Absorber with Aqueous Piperazine," *Energy Procedia*, vol. 37, no. Supplement C, pp. 1987–2001, Jan. 2013.
- [13] A. D'Angelo, M. Tedesco, A. Cipollina, A. Galia, G. Micale, and O. Scialdone, "Reverse electroanalysis performed at pilot plant scale: Evaluation of redox processes and simultaneous generation of electric energy and treatment of wastewater," *Water Res.*, vol. 125, no. Supplement C, pp. 123–131, Nov. 2017.
- [14] J. M. Andújar Márquez and T. J. Mateo Sanguino, "Diseño de Laboratorios Virtuales y/o Remotos. Un Caso Práctico," *Rev. Iberoam. Automática E Informática Ind. RIAI*, vol. 7, no. 1, pp. 64–72, Jan. 2010.
- [15] S. Marchisio *et al.*, "Starting the study of electronic circuits with VISIR: Viewpoints of college students in a pilot test in Argentina," in *2017 4th Experiment@International Conference (exp.at'17)*, 2017, pp. 18–23.
- [16] M. G. Valls and P. B. Val, "Usage of DDS Data-Centric Middleware for Remote Monitoring and Control Laboratories," *IEEE Trans. Ind. Inform.*, vol. 9, no. 1, pp. 567–574, Feb. 2013.
- [17] J. M. Andujar, A. Mejías, and M. A. Marquez, "Augmented reality for the improvement of remote laboratories: an augmented remote laboratory," *IEEE Trans. Educ.*, vol. 54, no. 3, pp. 492–500, 2011.
- [18] I. Santana, M. Ferre, E. Izaguirre, R. Aracil, and L. Hernandez, "Remote laboratories for education and research purposes in automatic control systems," *IEEE Trans. Ind. Inform.*, vol. 9, no. 1, pp. 547–556, 2013.
- [19] I. Ruano Ruano, J. Gámez García, and J. Gómez Ortega, "PID Control SCORM Web Laboratory with advanced Integration," *Rev. Iberoam. Automática E Informática Ind. RIAI*, vol. 13, no. 4, pp. 472–483, 2016.
- [20] B. M. Al-Hadithi, C. E. G. Cena, R. C. León, and C. L. Loor, "Development of an Artificial Intelligent Lighting System for Protected Crops," *Rev. Iberoam. Automática E Informática Ind. RIAI*, vol. 13, no. 4, pp. 421–429, Oct. 2016.
- [21] J. Chacon, J. Saenz, L. de la Torre, J. M. Díaz, and F. Esquembre, "Design of a Low-Cost Air Levitation System for Teaching Control Engineering," *Sensors*, vol. 17, no. 10, p. 2321, Oct. 2017.

- [22] S. Nayak, P. Vakrani, A. Purohit, and G. N. S. Prasanna, "Remote Triggered Lab for Robotics: Architecture, Design and Implementation Challenges," in *2014 IEEE Sixth International Conference on Technology for Education*, 2014, pp. 214–217.
- [23] J. M. Andújar Márquez and A. Mejías Borrero, "Interaction of Real Robots with Virtual Scenarios through Augmented Reality: Application to Robotics teaching/learning by means of Remote Labs," *Int. J. Eng. Educ.*, vol. 29, no. 3, pp. 788–798, 2013.
- [24] L. de la Torre, M. Guinaldo, R. Heradio, and S. Dormido, "The Ball and Beam System: A Case Study of Virtual and Remote Lab Enhancement With Moodle," *IEEE Trans. Ind. Inform.*, vol. 11, no. 4, pp. 934–945, Aug. 2015.
- [25] D. Galan, O. Isaksson, M. Rostedt, J. Enger, D. Hanstorp, and L. de la Torre, "A remote laboratory for optical levitation of charged droplets," *Eur. J. Phys.*, vol. 39, no. 4, p. 045301, 2018.
- [26] S. Leal and J. P. Leal, "A new chemistry e-lab experiment chemical equilibrium reaction," in *2013 2nd Experiment@ International Conference (exp.at'13)*, 2013, pp. 154–155.
- [27] D. Cmurk, M. Borsic, T. Mutapcic, and S. Rapuano, "A novel approach to remote teaching: Multilanguage magnetic measurement experiment," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 4, pp. 724–730, 2008.
- [28] J. P. S. Simão *et al.*, "A remote lab for teaching mechanics," in *2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REVI)*, 2016, pp. 176–182.
- [29] A. Rojko, D. Hercog, and K. Jezernik, "Power engineering and motion control web laboratory: Design, implementation, and evaluation of mechatronics course," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3343–3354, 2010.
- [30] A. Cardoso, V. Sousa, J. Leitão, V. Graveto, and P. Gil, "Demonstration of identification and control of nonlinear systems using a remote lab," in *2015 3rd Experiment International Conference (exp.at'15)*, 2015, pp. 97–98.
- [31] Z. He, Z. Shen, and S. Zhu, "Design and implementation of an internet-based electrical engineering laboratory," *ISA Trans.*, vol. 53, no. 5, pp. 1377–1382, Sep. 2014.
- [32] M. J. Callaghan, K. McCusker, J. L. Losada, J. Harkin, and S. Wilson, "Using Game-Based Learning in Virtual Worlds to Teach Electronic and Electrical Engineering," *IEEE Trans. Ind. Inform.*, vol. 9, no. 1, pp. 575–584, Feb. 2013.
- [33] K.-H. Chao and C.-T. Chen, "A remote supervision fault diagnosis meter for photovoltaic power generation systems," *Measurement*, vol. 104, pp. 93–104, Jul. 2017.
- [34] T. Köklü and S. Kılınc, "Remote monitoring of photovoltaic systems using embedded system clusters," in *2016 24th Signal Processing and Communication Application Conference (SIU)*, 2016, pp. 1133–1136.
- [35] D. T. Cofas, P. A. Cofas, D. Ursutiu, and C. Samoila, "RELab - virtual laboratory of the renewable energy," in *2013 10th International Conference on Remote Engineering and Virtual Instrumentation (REVI)*, 2013, pp. 1–5.
- [36] R. Blanchard, S. Williams, M. Bliss, M. Clowes, A. Mohammed, and R. Pancholi, "Educating the world: A remote experiment in photovoltaics," in *2014 1st International Conference on Non Conventional Energy (ICONCE 2014)*, 2014, pp. 28–32.
- [37] F. Schauer, M. Ozvoldova, P. Cernansky, Z. Gerhatova, L. Tkac, and M. Kostelniková, "Material science internet remote experiments: Solid state photovoltaic inorganic and organic/inorganic nanoheterostructural cell characterization in teaching," in *Interactive Collaborative Learning (ICL), 2012 15th International Conference on*, 2012, pp. 1–4.
- [38] J. Freeman, A. Nagarajan, M. Parangan, D. Kumar, S. Diwakar, and K. Achuthan, "Remote triggered photovoltaic solar cell lab: Effective implementation strategies for Virtual Labs," in *Technology Enhanced Education (ICTEE), 2012 IEEE International Conference on*, 2012, pp. 1–7.
- [39] M. R. S. Herrera, J. M. A. Márquez, A. M. Borrero, and M. A. M. Sánchez, "Testing Bench for Remote Practical Training in Electric Machines," *IFAC Proc. Vol.*, vol. 46, no. 17, pp. 357–362, Jan. 2013.
- [40] R. S. Herrera, M. A. Márquez, A. Mejías, R. Tirado, and J. M. Andújar, "Exploring the usability of a remote laboratory for photovoltaic systems," *IFAC-Pap.*, vol. 48, no. 29, pp. 7–12, Jan. 2015.
- [41] R. Tirado, R. S. Herrera, M. A. Márquez, A. Mejías, and J. M. Andújar, "Comparing Remote Laboratories from the Student Perspective," *IFAC-Pap.*, vol. 48, no. 29, pp. 176–181, Jan. 2015.
- [42] A. Mejías Borrero, M. A. Márquez Sánchez, J. M. A. Márquez, and M. R. S. Herrera, "A Complete Solution for Developing Remote Labs," *IFAC Proc. Vol.*, vol. 46, no. 17, pp. 96–101, Jan. 2013.
- [43] "Raspberry Pi - Teach, Learn, and Make with Raspberry Pi," *Raspberry Pi*. [Online]. Available: <https://www.raspberrypi.org/>. [Accessed: 13-Jun-2017].
- [44] "Welcome to Easy Java Simulations home page." [Online]. Available: <http://www.um.es/fem/Ejs/>. [Accessed: 13-Jun-2017].
- [45] "Phidgets Inc. - 1018_2 - PhidgetInterfaceKit 8/8/8." [Online]. Available: http://www.phidgets.com/products.php?category=0&product_id=1018_2. [Accessed: 13-Jun-2017].
- [46] "Phidgets Inc. - 1002_0 - PhidgetAnalog 4-Output." [Online]. Available: http://www.phidgets.com/products.php?category=0&product_id=1002_0. [Accessed: 13-Jun-2017].
- [47] "Arduino - Home." [Online]. Available: <https://www.arduino.cc/>. [Accessed: 13-Jun-2017].
- [48] A. Mejías, R. S. Herrera, M. A. Márquez, A. J. Calderón, I. González, and J. M. Andújar, "Easy Handling of Sensors and Actuators over TCP/IP Networks by Open Source Hardware/Software," *Sensors*, vol. 17, no. 1, Jan. 2017.



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