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A SYNCHRONOUS REMOTE LABORATORY AS AN ALTERNATIVE TO MECHATRONICS ENGINEERING PRACTICAL CLASSES DURING THE COVID-19 PANDEMIC

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ABSTRACT

The COVID-19 pandemic impelled many universities worldwide to temporally shut the door on in-person education. As a matter of fact, some education institutions opted to keep up the remote classes. Engineering programs, however, rely on educational technology laboratories to conduct practical activities. In this way, virtual experiments and a remote laboratory for synchronous classes were proposed as educational technologies in the Mechatronics Engineering undergraduate program. Given the described scenario, the present paper provides a proposal for a remote laboratory and carries out a research into the educational technology and student commitment. Results indicate that the remote laboratory in synchronous practical classes worked well towards the educational objectives of the Programmable Automation Controllers course. Additionally, students kept themselves committed throughout the academic semester.

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INTRODUCTION

In 2020, universities around the globe were required to suspend in-person activities given the outbreak of the COVID-19 pandemic. Education institutions that decided to move on with academic operations remotely held synchronous classes in an attempt to keep up the usual daily routine (Venable, 2010). Alternatively, they offered asynchronous activities, suggesting a study plan and leaving it up to the student to organize his/her weekly activities. Either way, professors were challenged to plan and develop engaging activities that managed to draw students' attention, even when in-person education incentives were not available, e.g. in-class group activities and laboratory practical activities. The already popular online meeting applications experienced a significant boost and became the computational tools institutions chose to conduct expository classes and group activities (Diogo *et al*., 2021). Professors and students switched to communication over microphones and cameras. But, what about practical activities?

Considering that active learning and laboratories are essential for engineering education, how can practical, professional, and personal skills be developed outside the university walls? Virtual experiments and remote labs were developed and had been improved even before the COVID-19 pandemic broke out (Grodotzki *et al*., 2018; Kagami *et al*., 2020; Kruse *et al*., 2016; Meya *et al*., 2016; Ortelt *et al*., 2016; Terkowsky & Haertel, 2013; Uhlmann *et al*., 2018). Online and hybrid engineering programs are the main users of such educational technologies (Das *et al*., 2020; Hartono *et al*., 2018; Kassab *et al*., 2020; Richert, 2015; Schiffeler *et al*., 2018). Nevertheless, most face-to-face programs were not prepared to dive into remote education unexpectedly. Courses with practical activities had to be re-planned, in an attempt to maintain the teaching quality level. The Programmable Automation Controllers (PAC) course from the Mechatronics Engineering and Control and Automation Engineering undergraduate programs is an example of the abovementioned scenario. The course consists of six classes per week, of which two-thirds include practical activities. The remaining third was easily covered by the real-time online meetings and recorded classes. For the practical classes, however, two educational technologies were employed. A web-based platform was chosen for pneumatics and electropneumatics virtual experiments (Algetec Corporation, 2019). The platform was provided within the virtual learning environment

(VLE) of the course. In this way, students were able to go through the activities as many times as necessary, even at out-of-class time. On the other hand, the second educational technology used, a remote lab, allowed only synchronous practical activities under the professor supervision. Considering the remote lab was adapted to the synchronous, remote practical classes, a survey was conducted with students to measure the effectiveness of such educational technology in the context of the course. Materials and methods, survey results, and discussions are presented next.

MATERIALS AND METHODS

The present paper was based on an adaptation of the Programmable Automation Controllers course during the 2ndsemester of 2020, i.e. during the COVID-19 pandemic, as the university was shut for face-to-face classes. In this way, the course theory classes consisted of brief expositions presented by the professor, group researches, and brief explanations given by the students. As per the practical classes, electropneumatics virtual experiments and a remote lab were proposed. By the end of the course, a survey was conducted with the students to check whether the classes and the remote lab were effective for the teaching-learning process. Next, a detailed description of this section is presentedin: real-world problem, objectives, virtual experiments, remote lab, and survey with students.

Real-World Problem: The PAC course has been offered mainly to students of the Control and Automation Engineering and Mechatronics Engineering undergraduate programs. Throughout the course, students develop the hardware and software PAC project, selecting the appropriate components that can be tested in the lab environment, e.g. hydraulic and pneumatic equipment. By the end of the course, the student must be able to implement the automation of systems and processes, making use of PAC and adequate programming languages in order to contribute to improving efficiency in the industry. It is expected that students develop competences oriented towards the design of processes and cyber-physical systems required by Industry 4.0 (Assante *et al*., 2019; Borg *et al*., 2019; Ciolacu *et al*., 2017; Jeganathan *et al*., 2018; Makarova, Shubenkova, Bagateeva, *et al*., 2018; Makarova, Shubenkova, Buyvol, *et al*., 2018; OECD, 2019; Ramirez-mendoza *et al*., 2018; Richert, 2015), once the course comprises subjects found at the lowest levels of ISA-95 (Antkowiak *et al*., 2017; Vrielink *et al*., 2018) (Figure 1). For instance, sensors and industrial actuators are present at level 0, while the PACs are at level 1. Therefore, the student must be able to design automated systems. For the implementation of such systems, however, students need engineering stations at level 2. Either laptops or desktops, these machines have the software required to configure and program the controllers at level 1. Among the PAC programming languages, the following can be mentioned: ladder, sequential function chart (SFC), block diagrams, and instruction list. The scenario proposed by the course evinces the need for a practical training environment in which students are in contact with industrial automation components and equipment present in the factory floor. In 2020, however, the COVID-19 pandemic suspended face-to-face activities in many universities worldwide. Some engineering faculties decided to keep up their operations, and thus challenged professors' creativity to maintain an appealing teaching atmosphere. In the Programmable Automation Controllers (PAC) course, the professor proposed virtual experiments for asynchronous online activities, and a didactic remote lab for synchronous practical activities.

Objectives: As face-to-face classes were put on hold, the PAC program had to offer synchronous and asynchronous remote practical classes, using simulation and remote-lab educational technologies. Even though the imposed scenario served to foster a lot of learning in the area, there was the need to see whether students actually achieved the objectives (knowledge) proposed by course. Therefore, this paper aimed to: i) analyze whether the remote lab, as an educational technology for synchronous remote practices, has positively contributed to the learning objectives of the PAC course; and ii) measure the commitment of students.

The Virtual Experiments: Virtual experiments were used in the pneumatic and electropneumatic classes. The virtual bench (Error! Reference source not found.) includes a description of its purposes, files with pneumatic and electropneumatic theory and symbology, a pre-test, a guide for virtual experiments, and a post-test (Algetec Corporation, 2019). Although the guide contains step-by-step instructions of specific experiments, the bench is not limited so other virtual assemblies can be tested. In this way, students were able to conduct virtual practical activities as many times as needed, including the out-of-class time, just by clicking on the virtual bench link provided by the professor on the VLE.

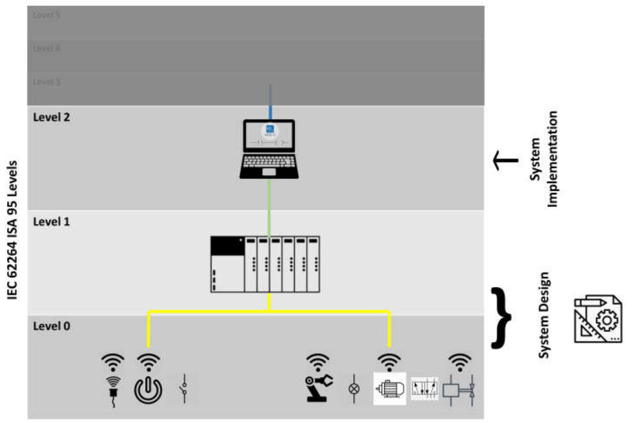

Figure 1. Application domain model of the PAC course based on ISA-95

Figure 2. Bench for virtual experiments: a) virtual bench overview; b) view of the virtual assembly worktable

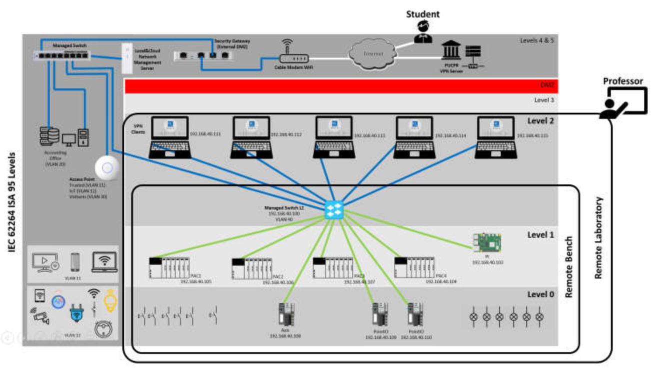

Figure 3. Network architecture for the remote laboratory

By means of the virtual bench, students had the opportunity to learn about the working principles of actuators, directional control valves, sensors, and other pneumatic and electropneumatic components. However, the need to put students in contact with the real technologies for industrial automation was observed. Even though the virtual experiments enable learning through virtual hands-on, the physical hands-on is required so students get a grip on the components' size and how the pneumatic and electrical connections of the components are made.

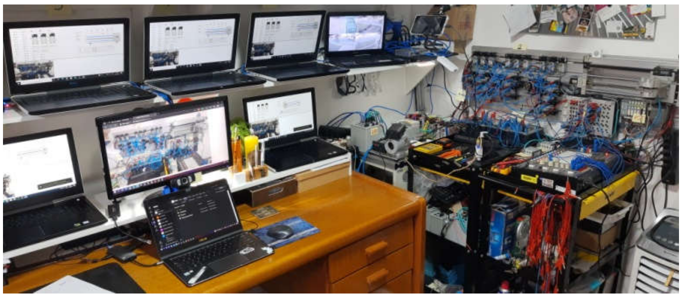

Figure 4. Remote lab overview, with remote bench to the right and engineering stations to the left

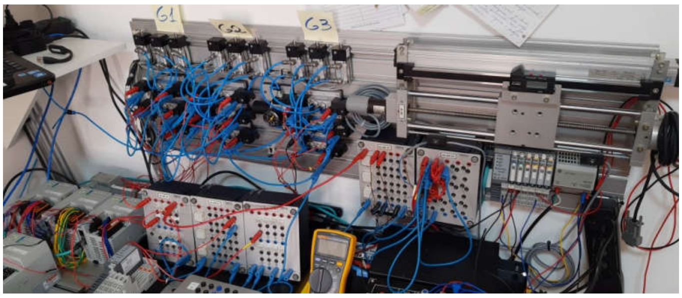

Figure 5. Set of sensors, valves, cylinders, and LEDS for the PACs

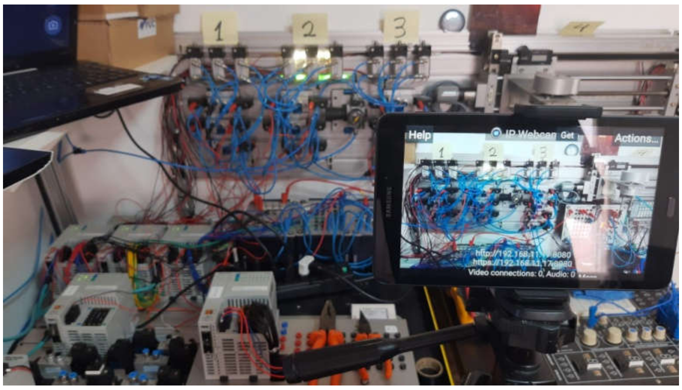

Figure 6. Webcam for the remote bench

In a virtual bench, students have no clue about the force required by pneumatic and electrical physical connections, for instance.

The Remote Lab**:** In its turn, the remote lab was conceived for synchronous practical classes, deploying real components and equipment used in industrial automation. In order to do so, a network architecture was considered to provide connectivity, given the network and Internet structure available at the professor's residence (Figure 3). The residence was equipped with 4 PACs (Level 1), which were connected to 5 engineering stations (laptops at Level 2) via a managed switch. Additionally, 3 IO remote units (PointIOs at Level 0) were connected to the switch. Notice that the 3 levels and the DMZ do not contain any equipment in the architecture. This was due to the fact that, even though the remote lab was conceived as an alternative to practical classes during the pandemic, the duration of social distancing was not expected to be so long. Also, there was not enough space at the professor's improvised office. The engineering stations, VPN Clients in Figure 4, included licensed software for PAC programming. Therefore, a VPN had to be configured to access the university corporate network, and thus the licenses were found in the license server (VPN Server).

Ideally, there should be virtual machines for students to use. However, given the urgency to suspend face-to-face classes and start the remote mode, there was no feasible time for the server reconfiguration. A set of software was used in the configuration of drivers for communication between the engineering stations and the PACs. Additionally, applications for the programming of the PACs were used, mainly in Ladder and Sequential Function Chart (SFC) languages. For PACs 1, 2, and 3 there was a set of magnetic sensors, electrically actuated directional control valves, double-acting pneumatic cylinders, light bulbs, and LED tapes (Figure 5). The sensors were connected to the digital inputs of the PACs, while the solenoids, bulbs, and LEDs were connected to the digital outputs. PAC 4 did not include local IOs. For this PAC, the remote unit "Axis" included a set of magnetic and inductive sensors, a direct current motor to rotate an axis, an analog sensor to measure movement, anelectrically actuated directional control valve, a double-acting pneumatic rotary cylinder, light bulbs, and LED tapes. So that the students were able to test and observe their experiments, a tablet was configured as webcam (Figure 6). Images were sent to an IHM developed for the remote bench.

As the aim of the course resides in collaborating on the development of student competencies, the execution of just the practical activities suggested by the professor could cause the competence-based learning process to become inefficient. In order to overcome this problem, the professor proposed an automation project that made use of the PACs and the remote bench equipment. The project, called "Christmas Project", initially required students to draw the automation diagrams (electropneumatic). After the assessment procedures of this stage, students moved on to the PACs programming, with the aim to automate the "Christmas Project". Results can be checked on the following video: https://youtu.be/xXPrmooijj0.

Survey with Students: The survey with students made use of a form divided into five question groups: i) resources to access the classes and connect to the remote lab; ii) remote laboratory; iii) instructions and exercises for the practical classes; iv) effectiveness of the practical classes; and v) general assessment. The form was configured with multi-choice and yes/no answers for questions in group i). Groups ii) and iii), in their turn, contained 10-point Likert scale questions, multiple-choice, and one open question. Group iv) contained just 10-point Likert scale questions and one open question. And at last, group v) included 10-point Likert scale, yes/no, and one open question.

RESULTS

In general, from the 16 students who attended the PAC course in 2020, 12 of them participated in the survey. The survey was divided into five question groups. The first group dealt with resources to access the classes and connect to the remote lab (Figure 7). In their turn, the second group covered the remote lab (Figure 8a), the third one included questions about the instructions and exercises for the practical classes (Figure 8b), and the fourth one dealt with the effectiveness of the practical classes (Figure 8c). And at last, a group of questions was proposed as a general assessment (Figure 8d). By the end of each question group, students were encouraged to freely share their thoughts through an open question. One of the questions made was about the type of equipment respondents used to get connected to the remote lab. This question allowed more than one answer. Half of the respondents (50%) indicated that they had used desktops, while 58.3% answered laptops. Just one respondent indicated he also used a smartphone. As per the question about the operational system, 100% of the respondents indicated they had used Windows for the classes, and just one of them also used Android. Regarding the Internet browser, 83.3% used Google Chrome and 16.7% used Microsoft Edge. With regard to the Internet connection type, more than one answer was accepted, too. Due to the remote classes, some students got connected from their houses, but also from work or internship. In some cases when the student came across connection problems or was in transit, 4G connection was used. Eight students used fiber connection, and six also used cable connection. Just two of them made use of 4G mobile connection. Also, there was one case of xDSL connection, and another case of satellite connection.

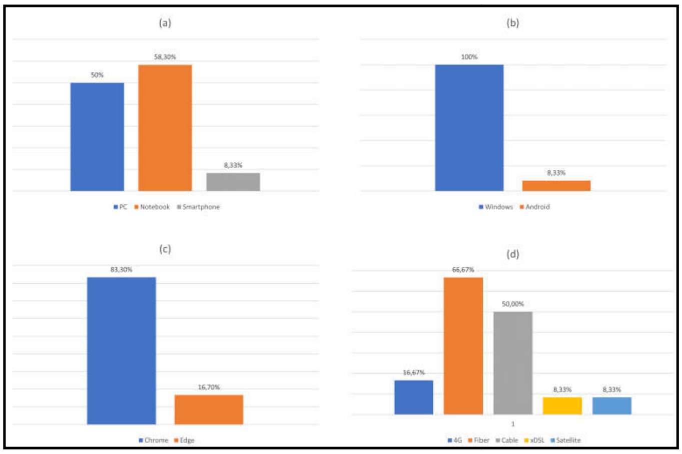

Figure 7. Classes and remote lab access resources: a) equipment; b) operational system; c) browser; and d) connection type

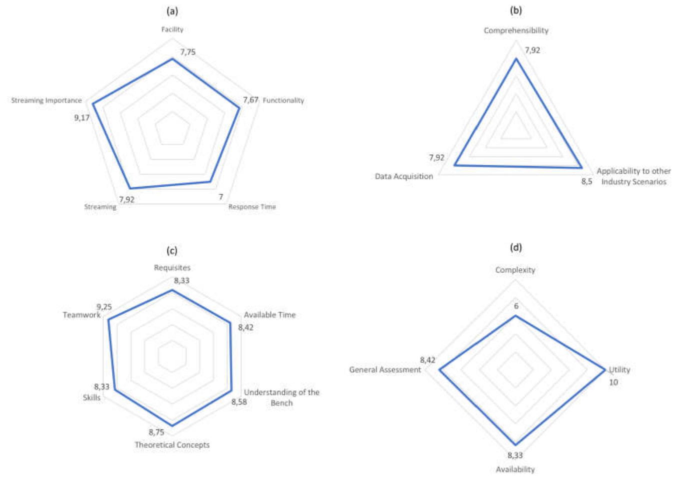

Figure 8. a) Remote lab assessment; b) Remote lab use instructions; c) Remote lab effectiveness to the development of students; d) Remote lab general assessment

Microsoft Teams was chosen as the online live streaming classroom and meeting platform as it is one of the platforms officially in use by the university. When the meeting gathered the whole group, the professor used it for streaming the class and making study materials available, in addition to the LMS. Groups were configured within the platform itself, facilitating the professor follow up, both during the class and out-of-class moments. All students opted to use the desktop version of the application due to its remote access functionality, even though two students also made use of the smartphone version. A second set of questions referred to the remote lab. From the 12 students, 11 of them reported this was their first experience with this educational technology. One of them mentioned a previous experience with another remote lab. Considering the equipment and the IHM, the students assessed the facility for using the remote lab with an average of 7.75/10.00, which was a good rating given the space limitations and the remote lab complexities. On the other hand, functionality got an average of 7.67. Some technical issues occurred during the practical classes, requiring corrective maintenance so that students were able to employ all resources. Delays in the webcam streaming also impacted on the user experience. Students rated the lab system response time a 7.00, while the video streaming got a 7.92. The occasions on which the five groups operated the IHM remotely, 100% of the Internet band was being used in the residence where the remote lab was installed. And although the connection speed of each student was not registered, some of them reported connection issues during the practical classes. In spite of the issues reported, the video streaming was very well rated (9.17) for its importance to make students discern what actually occurred during the tests with the remote bench.

Anydesk was the access platform selected for the laboratory. Even though it is a finished tool, students rated it with an average of 9.00. Additionally, this platform was preferred by 92.67% of the students. Students were also questioned about possible improvements to the remote practical classes, resulting in a few comments from respondents. With regard to teamwork, a student reported that screen sharing interfered with the progress of the activities due to poor connection quality of colleagues. Another student mentioned there could be additional IOs units, instead of just one for the whole group. This comment refers to the PAC and the IOs units of the remote bench movement table, which is just one. A last comment argued that the course fit very well into the remote education model. But, the student claimed improvements could be made to prevent the system from halting so often.

The third group of questions was about the instructions and exercises for the PAC practical classes. The first question inquired whether the exercise objectives were clear. Students rated it a 7.92. Another question aimed to attest whether students were able to replicate the exercises of the tutorial videos provided to demonstrate the use of the system connected to the remote bench. From the 12 respondents, 11 confirmed they could replicate the exercises. The following question was whether the students could perform other tasks based on the tutorial videos. Just like the previous question, only one student was unable to do it. Students were also questioned about the practical classes supervision – whether they preferred to conduct the classes by themselves or with the professor supervision. For 11 of them, the classes could be conducted both ways. As per the applicability of the remote bench equipment to other industry scenarios, students gave it an 8.50. Also, students rated the remote bench data acquisition a 7.92. For this set of questions, there was only one positive comment: the tutorial videos are quite good and should be maintained. The fourth set of questions aimed to measure the effectiveness of the remote practical classes. The first question considered the sequence of practical activities and the requisites to move forward. In this way, students were asked whether the next stage of each activity or project was clear, i.e., whether they were aware of the next steps. This question got an 8.33. As per the time available for the practical classes, students gave it an 8.42. Another question inquired whether the students understood how the remote bench equipment and components were connected and being used. This question got an 8.58. With regard to the comprehension of the course theoretical concepts through the remote practical exercises, students gave it an average of 8.75, while the remote activities as a way to help improve the abilities to apply such concepts to the design of cyber-physical systems and processes received an 8.83. The fact that these two averages were so close demonstrated the effectiveness of the remote activities for the course. As per teamwork and knowledge sharing, students rated it a 9.25.

The survey also made a general assessment of the remote lab usability. Regarding the complexity, the question served as a control and considered an inverted scale, i.e., score 1 to be assigned for very easy usability, and score 10 for very difficult usability level. As average, the usability complexity got a 4.00, which means that most students found it easy to use the remote lab via IHM remote access. All students (100%) stated that the remote lab was a useful learning experience, providing the opportunity to connect not only students from the university in question, but also from all over the world, in order to learn about automation of systems and processes. In relation to providing additional remote labs, 83.3% of the students consider it important for other courses. When questioned about an overall rating for the remote lab, students gave it an 8.42. And in order to justify the rating given by each student, the survey included an open question afterward. Among the comments considered, a student suggested the remote lab should be available at out-of-class hours. Another student pointed out stability and Internet connection issues. Additionally, this student declared that even though the lab was aligned with the pandemic reality, the in-person experience cannot be renounced. Eventually, the student proposed a combination between the remote bench and the in-person contact with it.

Thirdly, a student recommended the improvement of the webcam video streaming in order to prevent it from halting often and reducing the remote access "real time".

Other two students rated the lab as a quite interesting idea, although they missed exercises related to circuit assembling and to how components are connected on the remote bench. A student declared he was able to learn better from the remote practical classes than from the theory classes only.

The course evaluation system was composed of formative and summative assessments (Palmiero & Cecconi, 2019). The former aimed to provide feedback about the progress of the projects so that students fixed errors in the automation diagrams before the final delivery, which consisted of the summative assessment. The same sequence was performed for the automation implementation (PACs programming). Additionally, formative quizzes were applied before summative tests. With an average of 9.33/10.00, the pass rate of the PAC course was 100%. And given the social distancing scenario imposed by the pandemic, such result can be considered excellent, once students were able to acquire knowledge, yet limited, during the remote classes.

DISCUSSION

Considering the answers given by students through the survey and the passing rate of 100% of the group with outstanding scores, the virtual experiments can be referred to as good alternatives for asynchronous classes. That is because students are able to access and develop the experiments at any time and from anywhere as long as Internet access is available. Furthermore, the remote lab proved to be a good option for students to have the opportunity to perform practical activities from afar. In this way, physical distances were digitally shortened. As remote classes were being given, it was observed that the pandemic caused many students to return to their family residences, from where they watched the classes and developed the virtual and remote experiments. Savings on transportation and accommodation were pointed out by students during informal talks. Even though practical classes were concluded, the real lab is still required, with its equipment and physical materials. During the pandemic, the handling of tools and assembly materials on the real bench were left behind. The installation and accurate positioning of sensors, valves, and actuators could not be physically carried out. Students were restricted from understanding how the pneumatic and electrical connections were made by the professor. Anyway, students were able to remotely do the actual programming of the PACs and edit the remote IHM, according to the need of each student. Additionally, the remote lab was eventually used in other courses due to its versatility, e.g. in the Industrial Internet of Things (IIoT), which is also a course of the Control and Automation Engineering and Mechatronics Engineering undergraduate programs. In this course, students were also encouraged to comprehend the project planning process of an industrial network architecture and collect PAC data via electronic prototyping boards, e.g. Raspberry Pi. The remote lab was also used in the Industrial Systems course of the Production and Mechanical Engineering undergraduate programs. The same occurred with Industry 4.0 specialization programs. In both cases, the PAC programming and the communication among entities of the industrial network was the focus of the courses and modules.

As future perspectives, the face-to-face and hybrid education can be improved, at the same time that an LMS-integrated system for asynchronous activities can be developed. In this sense, although the compact bench format (Figure 4) brings about flexibility to be carried from a learning space to another, students would be clumped together around it. Therefore, the segmentation into smaller benches, each one with its own equipment kit, clears more space in the classroom. For the remote access, the IHM would require few adaptations. Since it can be made available over a Web server, the IHM can be easily integrated into an LMS. In so doing, the utilization of the lab for asynchronous activities would be possible, as long as a few improvements are made to the compressed air supply system and to the local technical support for occasional corrective maintenance. Given the possibility of accessing practical classes remotely and face-to-face at the same time, they can be designed for hybrid groups, and thus help reduce the impact of transportation on remote students. Augmented and mixed reality could also be added to the remote bench in order to enhance the experience of remote students, including technologies aligned with the Industry 4.0 pillars (Grodotzki *et al*., 2018; Hoffmann *et al*., 2017; Kolbe Júnior, 2022; Makarova *et al*., 2019; Makarova, Shubenkova, & Pashkevich, 2018; Plumanns *et al*., 2015; Schiffeler *et al*., 2018).

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