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An International Overview of Teaching Control Systems During COVID-19 Pandemic*

JOSÉ LUIS GUZMÁN[1]**, KATARINA ZAKOVA[2], IAN CRAIG[3]**, TORE HÄGGLUND[4]**, DANIEL E. RIVERA[5]**, JULIO NORMEY-RICO[6]**, PAULO MOURA-OLIVEIRA[7]**, LIUPING WANG[8]**, ATANAS SERBEZOV[9]**, TAKAO SATO[10]**, and ANTONIO VISIOLI[11]**
[1] ** University of Almeria, Spain, Ctra. Sacramento, s/n, E-04120, Almería, Spain.
[2] Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovičova 3, 841 04 Bratislava, Slovakia.
[3] University of Pretoria, University of Pretoria, Private Bag x 20, Hatfield, 0028, South Africa.
[4] Lund University, Ole Römers väg 1, 223 63 Lund, Sweden.
[5] Arizona State University, ENGRC 425, TEMPE, AZ 85287-6106, USA.
[6] Universidade Federal de Santa Catarina, 88040-900 Florianópolis, SC, Brazil.
[7] INESC TEC, Universidade de Trás-os-Montes e Alto Douro (UTAD), Vila Real, Portugal.
[8] RMIT University, 124 La Trobe St, Melbourne, VIC 3000, Australia.
[9] Rose-Hulman Institute of Technology, 5500 Wabash Avenue, Terre Haute, IN 47803, USA.
[10] University of Hyogo, 2167, Shosha, Himeji, Hyogo, 671-2280, Japan.
[11] University of Brescia, via Branze 38, 25123, Brescia, Italy.

This paper aims to provide an overview of the impact of the COVID-19 pandemic on control engineering education worldwide. The authors, who are educators in the control education field from various countries across all continents, first summarize their experiences to present a global perspective on the different solutions adopted in control education during the pandemic. Afterwards, collected information from the international community through a questionnaire enabled insightful comparisons between pre-pandemic and during-pandemic educational resources and methods, which are shared in this paper. The feedback from the authors' experiences, along with the questionnaire responses, serves as a valuable resource for learning and improving teaching activities. The questionnaire was distributed among the international control engineering community in collaboration with the International Federation of Automatic Control (IFAC) to explore the diverse alternatives employed globally for conducting online educational activities during the pandemic. These activities include methodologies, tools, theoretical exercises, laboratory experiments, exam types, simulators, and software for online lecturing.

Keywords: control system education; online teaching; COVID-19 pandemic; learning

1. Introduction

In February 2020, the COVID-19 pandemic was declared around the world. Different decisions with different levels of lockdown were established in every country. This situation had dramatic impact on our lives, impacting all human activities. In fact, the COVID-19 pandemic revolutionized our society in every way, socially, economically and in terms of health [1–3]. Nowadays, everyone accepts that our lives have changed somehow after it. There are of course many negative issues and situations around the pandemic that we will never forget and that will stay with us for a long time. However, there are also many other positive aspects and variations in our style of life that could be important to keep and to exploit. This is the attitude that the authors of this work would like to transmit from a general point of view, and particularly from an educational perspective: analyze what we have learned because of the pandemic in the field of control education, and preserve what we can positively use in the future [4].

Clearly, teaching and learning processes were highly affected during the pandemic at all levels (primary school, high school, university, ...), where teachers and students had to adapt suddenly to new ways of education [5–11]. Technology became the main protagonist, where any type of digital resources started to be spread out worldwide. Many education centers were used to work with digital solutions and online platforms as support to education before the pandemic. However, many others had to learn from scratch and adapt their teaching methodologies to the digital world. So, most teachers in the world had to modify their teaching style and look for new solutions based on online lectures, remote activities, video recording, online polls, web-based methodologies [12–14], etc.

All those changes were important in most of the disciplines, but the impact was larger in those disciplines with a high practical component, as it is the case of engineering studies. In engineering, exercises and experiments in laboratories are a fundamental part of the learning process [15]. Moreover, theoretical lectures are usually mixed

** Corresponding author(s). E-mail(s): joseluis.guzman@ual.es

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with practical exercises and simulations to be discussed with students face-to-face. Thus, during the pandemic period, it was not possible to perform all these teaching tasks in classrooms or in laboratories, and new solutions were required [16].

The control engineering field is one example of an engineering topic where important changes were performed not only for practical lectures, but also for theoretical ones [17, 18]. Therefore, this paper is a joint work of lecturers in the control education field around the word, where the idea is to analyze the methodologies, tools, solutions and platforms used in control education before, during, and after the pandemic. In cooperation with International Federation of Automatic Control (IFAC) Technical Committee 9.4 on Control Education, we prepared and discussed a general questionnaire to collect data and opinions about the teaching experiences in control education during the pandemic. This questionnaire was distributed worldwide and this manuscript summarizes the obtained results.

In the survey preparation, we understand that educational activities are organized in a different manner in each university and in each country. On the other hand, we also understand that education for undergraduate and postgraduate students are different, and thus, we suggested to fill out the questionnaire combining the experience from both perspectives. Hence, the proposed questions were formulated from a generic point of view to cover lecturing, laboratory tasks, exercises, homework, exams, and so on. In this way, the questionnaire can be filled out from a global perspective according to the experience of each teacher. The preliminary results from this study was presented in [19], as part of the 13th IFAC Symposium on Advances in Control Education, IFAC ACE 2022.

Moreover, this work also includes a summary of the experiences of the authors in their respective countries, where personal and collective experiences are described. This also gives an international overview on the different decisions that were taken during the pandemic and how similar problems were dealt with in different ways around the globe. The combination of both the questionnaire results and the experiences of the authors provide a very powerful instrument to improve our teaching activities as educators. We strongly believe that this information can be very useful for the whole control education community and that it can help all of us to learn from each other's.

2. International Experiences

This section summarizes (control) teaching experiences during the pandemic period in different universities around the world where each author of this paper is affiliated. Each subsection is devoted to one country represented by one or several authors of these universities, where the insights of the authors are expressed.

2.1 UTAD University, Portugal

In Portugal, the Portuguese Association of Automatic Control (APCA) and the Portuguese Society for Engineering Education (SPEE) have organized several meetings and panel discussions involving other field experts regarding the impact of COVID-19 pandemic in engineering education. While there are some reported studies about educational aspects of teaching and learning during COVID-19 times in Portugal, regarding university studies in general (e.g., see Flores et al. [20]), similar studies focused on control engineering education do not exist.

There were two major confinements in Portugal which required the University emergency teaching to become on-line. The first one started at mid-March of 2020 and continued into the second semester of 2019–2020. The second one started in January 2021 and lasted until the end of the first semester of 2020–2021. The first confinement forced both teachers and students to become fully digital in a period of two-weeks [21]. Some outcomes of this first confinement are:

- First on-line lecture for most teachers and students: the great majority of university engineering courses in Portugal are based on face-face teaching. So, most lecturers and students in Portugal had their first on-line class in March 2020. It is important to state that: (i) this was the confinement novelty phase; (ii) teachers and students started the semester in a face-to-face teaching mode. These two factors helped to soften the drastic transition to the emergency on-line teaching.
- Theoretical Classes: teachers reported that the most difficult issue to deal with compared to face-to-face teaching is the lack of visual contact with the class, not being able to perceive if students were following, or not, the introduced topics. Many teachers reduced the theoretical exposition period and increased the use of simulation software such as Matlab/Simulink.
- Laboratory Classes: this was the most difficult issue to deal with as well as a great opportunity to try new learning/teaching approaches. Given the circumstances, most practical classes had to be replaced by simulation experiments. However, some interesting experiments were conducted using portable take-home laboratories [21, 22], or virtual and remote accessed laboratories. Interesting feedback was received from the use

of breakout rooms among groups of students, particularly regarding for simulation and programming assignments.
- Assessment and exams: these were the most problematic issues faced by teachers, namely on how to ensure that remote assessments carry out by students in learning management systems were performed by those students without fraud.

Regarding the second confinement, the novelty phase was partially lost and motivating confined university students became harder. The black screens become more frequent and the obtained evaluation results become worse. After the confinements, the number of meetings with students, research project meetings, academic juries, etc., which are performed on-line increased significantly, compared with the period prior COVID-19. As a concluding remark if "what does not kill you makes you stronger", we are more prepared now than before COVID-19 to face new control education challenges.

2.2 University of Brescia, Italy

The COVID-19 pandemic affected Italy first in Europe and, in particular, the town of Brescia has been very seriously hit by the pandemic for many months. In fact, the University of Brescia was the first in Italy to stop in-person lectures just after the beginning of the second semester in February 2020. The control courses of the Department of Mechanical and Industrial Engineering were immediately adapted to be online for the first time. The year after, courses were again conducted fully online but, of course, both teachers and students were more prepared for this situation. With the general idea that this experience has in any case had a large impact on the learning paradigm even if the pandemic will no more affect our lives, a survey has been conducted with the students in order to know their opinion regarding the advantages and disadvantages of online lecturing and what are the positive aspects that should be kept for the future [23].

It has to be taken into account that, in general, for engineering courses in Italy, there is no compulsory attendance and the student should be fully free to organize themselves in order to fulfill the requirements to pass the exam at the end of the course. Then, it is worth stressing that, in the normal situation, the Italian law requires that for classic (non-online) universities, traditional programs should not have more than 10% of the lectures given online. This means that after the pandemic, in Italy and in Brescia lectures are held in person again. The results of the survey indicate that, although having the option to attend the lectures online can imply a significant saving of time and money, the poor relationship and interaction between the students and between the students and the teacher is perceived as a really significant disadvantage. This means that students who can attend courses in person do so. However, recording the lectures is also seen very positively by the students, as this allows them to watch again an explanation in case something is not clear, and to organize their agenda according to specific needs and to speed up or slow down the learning pace.

Overall, it appears that there is a need to keep a high interaction between the people involved in the education process but, at the same time, there is the need for control resources available online that can be used by the students to improve and to personalize their learning curve. The combination of teaching activity in the classroom and availability of online resources will also foster the learning of soft skills that are essential for a control engineer, like team work on the one hand and autonomous problem solving on the other.

2.3 Universities in Brazil

From March 2020 until the end of 2021 most of Brazilian Universities had to adopt remote activities in order to maintain teaching activities during the COVID-19 pandemic. In particular, different virtual/remote solutions were adopted for control engineering courses, mainly for the practical control educational activities, usually developed in the laboratories of the different institutions [24, 25].

It is important to mention that, even before the COVID-19 pandemic, there was a national initiative to increase the use of remote practical activities in the control education area, as a way of improving the teaching-learning process, and to facilitate the access to the labs, considering the demands of the National Curriculum Guidelines, defined in 2019. Because of this, the Technical Committee on Engineering Education of the Brazilian Society of Automation promoted some special activities, that become more important in 2020 because of the COVID-19 pandemic. A book titled "Remote pedagogical practices in Engineering" was elaborated with the contributions of many Brazilian professors and researches focusing on several important subjects, such as virtual and remote laboratories and their implementation in Brazil, strategies for active methodologies in remote engineering teaching, experiences in the transition to remote emergency classes during the pandemic, industrial control and instrumentation approaches for remote teaching, etc. Also, several special sessions were organised in the two most important Brazilian Control Conferences, that were virtual events in 2020 [26] and 2021 [27] with more than one thousand participants each, in order to promote the exchange of experiences during the pandemic.

In terms of results, new virtual labs were created, many free software platforms were developed to allow remote access to the real labs, simple and cheap lab kits were designed to allow easy access of the students to real experiments even working at home, recorded lectures in YouTube were made available, etc. All these efforts were used to define activities that complemented the traditional ones (lectures, exercises and tests) which were adapted to the remote-virtual mode.

Another important aspect that had to be considered during the COVID-19 pandemic, was the economic situation of the universities and many students. In the first case it was the necessity of paying for new learn management systems and software tools used for online lecturing, including the possibility of online-lecture recording and the simultaneous connection of a big number of users. Also a high quality internet connection was necessary, that is stable when many users connect simultaneously. The real situation was that many universities have problems to pay for the software/hardware infrastructure to allow for remote activities. Students required a good internet connection at home and a personal computer with minimal configuration. To face this problem, universities created strategies to loan equipment and internet access kits to the most economically disadvantaged students.

2.4 Universities in Japan

In Japan, elementary, junior high, and high schools were all closed for three months from March 2020 due to the spread of COVID-19. On the other hand, the university closed in April, but began offering online classes in May. Since the new semester begins in April in Japan, it was necessary to prepare for online classes in about one month.

To investigate the actual state of online control education during the pandemic, a survey of control education in Japan was conducted by sending a questionnaire to the Control Technology Committee, the Electronics, Information and Systems Society, the Institute of Electrical Engineers of Japan (IEEJ). Responses were collected from 28 respondents, with universities and companies representing 89.3% and 10.7%, respectively.

The survey results show that before the pandemic, almost all lectures and experiments were conducted in a face-to-face format, and blackboard/whiteboard or PowerPoint presentations were used in the majority of lectures. During the pandemic period, most of the classes were either online lectures or own video recordings.

The most commonly used platforms for online lectures, in order, were Zoom, MS Teams, their organization's system, and LMS Moodle. The other minority were Cisco Webex, YouTube video, and MS Stream. The results indicate that in Japan, platform decisions are made by the institution to which one belongs. The results also suggest that Zoom is a relatively common choice for faculty. Another analysis was done regarding the functionality required for each platform. The results of this survey indicate that the respondents want not only a simple video streaming function, but also multiple functions such as attendance confirmation and assignment submission.

2.5 Universities in Sweden

Several research reports treating the education during the pandemic in Sweden have been published. In [28], the main conclusion is that even though the pandemic posed many challenges for both students and teachers, the distance mode made it possible to continue the education without any drastic disruption. They also point out the importance of being prepared for this kind of emergency remote teaching in the future.

In Sweden, the teaching is more or less back to the situation before the pandemic, where most of the teaching that was performed on campus now is back on campus again. There are, however, some changes that have appeared because of the pandemic that are interesting and worth noting.

Many video lectures were produced during the pandemic, and many of these videos are still available on internet. Even though lectures now are offered on campus, some students prefer to stay at home and follow the videos instead. Reasons for this are that it is more flexible, they can take the lectures when they want, they can stop, repeat and change speed of the lectures. The main drawback is that they miss the human interaction with teachers and other students. Most people would probably agree that the disadvantages outweigh the advantages. Another change is that since there are so many lectures available on internet, some student look for lectures given at other universities if they are not satisfied with those given at their own university.

During the pandemic, teachers and PhD students had to work from home for some of the time. Most of them are now back at the universities, but some of them prefer to continue working from home. At some departments, where many have chosen to stay at home, this has become a problem and since many have chosen to stay at home, there is even less reason to go to work because there are so few colleagues present. The fact that so few teachers are at the campus means that it is more difficult for students to get in touch with them, which is of course a disadvantage.

2.6 RMIT University, Australia

RMIT university belongs the group of technological universities in Australia and is ranked in the middle level among all Australian universities. The same as other Australian universities, RMIT experienced a rapid growth of international students in the pre-pandemic period. The two key challenges confronted Australian as a result of the pandemic are:

- Learning to perform remote teaching.
- Learning to cope with the drastic reduction of international students.

The second challenge was manifested into academic staff redundancy in a severe degree and farewell of friends and colleagues using Teams. To confront the first challenge is a relatively easy task because they are related to our teaching skills, teaching commitments and our caring for our students. These factors are within our control, which is unlike the consequences of the drastic reduction of student numbers.

As an example, we consider two control courses in the combination of fourth year undergraduates and postgraduates that typically had large classes with student numbers between 150 to 200 students in the pre-pandemic time. These control courses were designed to get student work-ready. The first course is focused on PID control system design, implementation, cascade control and automatic tuning and the second course is focused on model predictive control with constraints. Both courses are electives across the entire engineering school. During the pandemic, both courses were taught online using Collaborate Ultra and all control hardware laboratories were replaced by simulation laboratory using Simulink. Although the courses were taught online, the teaching results were very good with excellent student feedback. One reason could be that the additional efforts were put into designing the courses so that they were more interesting to students and more contact hours were allocated to help students. The students particularly liked performing control system design and simulation using MATLAB and Simulink in real-time and in a step-by-step manner. The students did very well in terms of control system design and simulation, however they missed out on the experience of control system implementation using hardware.

2.7 Slovak University of Technology in Bratislava, Slovakia

The initial term in 2020 started at the Slovak University of Technology in Bratislava without any signs that it could be disrupted in any way, i.e. classical face-to-face classes were taking place. Three weeks later the university was closed (see also Stefancik and Stradiotova [29]), the full-time education was interrupted and self-study and distance learning were recommended. Only staff members were allowed to enter the faculty in exceptional cases on the basis of a special permit. Individual subjects started to be taught online within 1–2 weeks, depending on the computer skills of the teachers. The mathematicians had the most problems, as they were used to explaining the subject only on the blackboard and with minimal use of computers. Teachers used Discord, YouTube and Google Meet according to their preferences. Since the first control course is running in the second part of the academic course, it was not confronted with this situation at the beginning.

The online classes continued in the next school year. In this period two online environments (Google Classroom together with Google Meet and MS Teams) were recommended for all courses. Teachers could choose the environment according to their preferences.

In the basic control course PowerPoint presentations and virtual whiteboard were used for lectures. The disadvantage was that almost all students had the video turned off and therefore the teacher had very poor feedback. There was usually no one to answer the questions that were asked by the teacher during the lecture. Later better feedback was achieved by using simple online polls.

During laboratory classes it was not possible to use the experimental equipment that is located at the university. Of course, students could use simulations in Matlab/Simulink without problems, some problems were illustrated using online interactive examples available on the website. However, as we also wanted to give the students at least basic practical skills in system identification and control, we tried to provide them with the opportunity to do experiments at home. Each student had an Arduino, a breadboard, and components to build a simple RC circuit, on which it was possible to measure basic characteristics, obtain its mathematical model and design a simple controller. In addition, another experiment with termo-opto-mechanical plant was available through a remote experiment, which students could book at a time that was most convenient for them to perform the experiment. They were asked to solve the same tasks as for RC kit.

The exam was done using online test, which contained not only classical multiple choice questions, but mostly short-answer questions that did not allow students to guess the answer at random. Results had to be solved and computed. Since the examples were randomly generated and were not the same for all students (they differed in numerical values), the possibility of cheating was minimal.

At the end of the pandemic, the form of teaching was switched again to face-to-face it is planned to continue using the online interactive examples and the remote experiment, as they allow to supplement practical knowledge even when the university building is closed. Nevertheless, it is hoped that this situation will not happen again, because despite the fact that students have been provided with the course content thanks to information technologies, there was a lack of personal feedback and, above all, social contact, both for students and for teachers.

2.8 *University of Almería, Spain*

Teaching activities were stopped in Spain in March 15th 2020, when the national lock-down was announced by the Spanish government. Most educational centers decided to stop all teaching activities for a period in average of two weeks, in order to face the situation and to analyze how to proceed for the rest of the academic year. At the University level, these two weeks were dedicated to intensive meeting among lectures, deans of faculties, heads of departments, and vice-rectors in order to evaluate the situation, the availability of resources, and re-scheduling of the teaching period. Fortunately, the good news were that most of the Spanish universities already had a Learning Management System (LMS) as support for on-site lectures. Thus, it was not too complicated to continue giving theoretical lectures using the online capabilities of the LMS. Of course, lecturers needed a quick introduction to the videoconferencing tools, but it was a task that was relatively easy to handle.

The main problem in Spain was that the government did not provide any general guideline or recommendation for this situation, and each University was responsible to manage the problem independently and according to their own resources [30]. This resulted in the implementation of many different methodologies and experiences across the country, resulting in a heterogeneous impact on teaching activities [31–33].

In the control engineering community, we had many different meetings with colleagues across the country and under the umbrella of our national control engineering association, the "Comité Español de Automática (CEA)", which is the IFAC National Member Organization in Spain. General solutions were discussed to cover the requirements for theoretical lectures, such as the use of LMS, tablets with electronic pencil to mathematical analysis, or the use of videoconference tools such as Zoom or Google Meet. However, the main concern was about how to replace the practical or lab lectures with students in the current situation. The lockdown affected of course all teaching activities in any discipline, but the impact was higher on those areas with a relevant practical content, such as engineering studies. So, those meetings with other colleagues across the country were very productive and many ideas came out from them:

- CEA has a very active group on control education since 20 years ago, which was originally led by Prof. Sebastián Dormido. This group has been working hard to develop new educational tools to support control education, mainly virtual/remote labs (https://unilabs.dia.uned.es/), benchmark problems based on simulators (http://servidor.dia.uned.es/~fmorilla/CIC2017/), and interactive tools (https://w3.ual.es/personal/joguzman/material_docente_itools.shtml). Thus, all these resources were suggested to be used for the control engineering community as support for practical lectures.
- Another interesting idea was the access to the lab computers using remote desktop applications. So, for instance, DC motors and PLC devices connected to those computers could be used by students remotely according to a given access timetable. This solution was very productive, because it allowed the use of real devices in a very simple way and without requiring the development of new ad-hoc software for remote access. This option was possible thanks to the help of the lab technicians, who had permissions to move to the University to prepare and to maintain all the required material for teaching activities.

The use of these resources helped a lot to motivate students by exploiting one of the most attractive element of the control engineering field, which is to put control theory into practice.

The lockdown in Spain finished on June 21th 2020, and then, a very strong discussion was held on how teaching activities should continue for the next academic year. The decision was very different around the country, and every university made their own decision. Most of the universities decided to apply an hybrid format, and students could decide to attend the lectures on site or remotely. This situation made the problem even harder, because classrooms and labs were not really prepared for a hybrid format. So, lecturers had to be seated in the classroom to teach everything thought the computer screen to be share on the on-site project and on the Internet. When this problem was moved to the lab, the problem was also that some students were at home working remotely with the lab devices or simulators, and some other students were on site in the lab. So, the coordination was really complicated.

At this point, because of the problems experienced with teaching and conduction labs in a hybrid format, the University of Almería decided to buy more than 300 hundreds TCLab kits (https://apmonitor.com/pdc/index.php/Main/PurchaseLabKit) and follow a take-home lab methodology. So, one of those kits was given to each student, and they could perform the lab activities at home and without any time restrictions. Then, the lab sessions were dedicated to discuss the results and solve problems. The experience was very positive and very well accepted by the students, and nowadays the same methodology is still used in lab lectures for most of control engineering studies [34].

2.9 University of Pretoria, South Africa

Universities in South Africa faced similar challenges when the COVID-19 pandemic struck in 2020. More detail on what transpired at the University of Pretoria is given in what follows.

In response to the COVID-19 pandemic, all academic activities, i.e. lectures, assessments, laboratory work and assignments were suspended at the University of Pretoria from 16 March 2020. A severe national lockdown was implemented from 27 March 2020 [35], and after much deliberation, the University of Pretoria decided to continue with online only teaching from 20 April 2020. Lecturing staff therefore had about 5 weeks to pivot to online teaching, online laboratories, and online assessment. Care had to be taken to do this in an equitable manner, so as to consider students who come from a disadvantaged background that lack the required infrastructure for online coursework.

Face-to-face lectures for undergraduate students only resumed on 25 July 2022, the start of the second semester of 2022. Students did, however, return to campus during the first semester of 2022 for laboratory work, semester tests and exams. Attempts were made in 2021 to get students into the laboratories on campus, but this was hampered by lockdown levels that changed due to the emergence of new COVID-19 variants. The 2020 and 2021 academic years were fortunately completed within the respective academic years, albeit a few weeks later than normal, despite the many logistical challenges that resulted from pivoting from face-to-face to online only courses.

Two undergraduate control related courses are taught in the Department of Electrical, Electronic and Computer Engineering of the University of Pretoria. An introductory control course (EBB320) is presented to about 250 third-year students. This is followed by a fourth-year course on automation (EBT410) which is presented to about 120 students. During the COVID-19 pandemic online lectures for these two courses were presented in an asynchronous manner. Videos made by the lecturer were posted online at the beginning of each week which students could follow, along with the course notes, in their own time. Regular course evaluations indicated that the video lectures were very well received with student comments such as "the benefits of this is the ability to pause videos as well as watch the lecture whenever it suits me best" and "the video lectures are clear and one could thoroughly understand the concepts". The video lectures are also very helpful post the COVID-19 pandemic in that they help the lecturer when preparing for lectures, and they can be used by students to reinforce concepts described in class.

An interesting aspect to remark on was the introduction of the COVID-19 modelling into the control systems curriculum. [36] is used as textbook for EBB320 in which HIV/AIDS modelling and control (described in [37]) is covered in each chapter in the form of "Progressive Analysis and Design Problems". Students who complete EBB320 are therefore familiar with the modelling of infectious diseases. The follow-up automation course (EBT410) has a significant component on obtaining plant models for control purposes. Models for sensors, actuators and processes are obtained from first principles, including the use of the principle of conservation of a quantity S (see [38]). The latter is e.g., used in the automation course to model the dynamics of a thermocouple (see e.g., [39], [40]). The principle-of-conservation approach was also used to model the disease dynamics of HIV/AIDS in [32], a model by now familiar to EBT410 students.

Seeing that COVID-19 was dominating the headlines, it was decided to introduce COVID-19 modelling into the control systems curriculum in the form of the COVID-19 model described in [35]. This model uses the same principle-of-conservation approach as was used for modelling thermocouples and the HIV/AIDS model, making it easier for the EBT410 students to follow. Students appreciated the fact that the material that they covered in the automation course had a direct bearing on the COVID-19 pandemic that they were experiencing.

2.10 Rose-Hulman Institute of Technology, USA

Rose-Hulman Institute of Technology is a small private undergraduate engineering college located in the Midwest region of the United States. The total enrollment is 2,400 students, with an average class size of 20 students. In the Chemical Engineering program students are required to take an introductory control course in the December–March term of their junior or senior year. During the COVID-19 pandemic years, 2020–21 and 2021–22, approximately 120 students took the control course. Most of the instruction was in person, except for the first 3 weeks in 2020–21.

Based on experiences with other courses taught earlier in the pandemic, the control course instructors identified student engagement and motivation as the most critical element of the course. Prior to the pandemic, there was only one active learning component in the course, the LOOP-PRO TRAINER simulator, [36]. During the pandemic, two additional active learning platforms were incorporated: Kahoot interactive games [42] and TCLab take-home kits [34].

Kahoot games provided an engaging and stress-free environment for students to test their knowledge. They also gave immediate feedback to the instructors about the level of understanding of the topic at hand. Kahoot games were played every other lecture and took 10 to 15 minutes to complete. Student feedback was overwhelmingly positive with some students commenting that "every course should adopt Kahoot."

The TCLab kits were used as a take-home laboratory. Students completed two labs on model identification and three labs on controller tuning. Each lab took 2 to 3 hours to complete. In the first pandemic year, 2020–21, when most extracurricular activities were cancelled, students did not comment on the length of the labs. In the second pandemic year, 2021–22, when most of the social restrictions were lifted, students complained about the time it took to complete the labs.

The addition of the Kahoot games and the TCLab modules significantly increased the preparation time for the instructors. But at the same time, these new elements provided more opportunities for the instructors to engage with the class on an individual level. Instructors' enthusiasm and high level of time commitment were greatly appreciated by the students, who voted one of the instructors as the outstanding professor for 2020–21, based mainly on the introductory control course.

2.11 Arizona State University, USA

Arizona State University (ASU) is a large state university, with multiple campuses located in various parts of the Phoenix metropolitan area. The Fulton Schools of Engineering is the largest engineering college in the nation, with over 30,000 students enrolled. In the chemical engineering program, approximately 150 students a year enroll in ChE 461: Process Dynamics and Control, a required course for fourth-year chemical engineering students (seniors), which is normally offered in the first semester of the final year in the BS program of study.

In mid-March 2020 (following the official declaration of the pandemic), all instruction at ASU went online. Subsequently, significant investments were made at ASU to equip all classrooms with cameras and equipment to create "ASU Sync" [43], a learning modality meant to facilitate both in-person and remote instruction. In fall 2020 (the first semester that ChE 461 Process Dynamics and Control was offered during the pandemic), ASU had returned to in-person instruction, but only for classes with enrollments under 100 students; consequently, ChE 461 had to be taught remotely. The course historically has made substantial use of MATLAB w/Simulink through dedicated computer modeling assignments (CMAs); the COVID-19 pandemic provided the opportunity to develop two completely new CMAs devoted to epidemic open-loop modeling and closed-loop control, respectively. The experience is described in detail in [44]. All major concepts in ChE 461, ranging from dynamic modeling using conservation and accounting principles, linearization, state-space and transfer function model representations, and model-based tuning of PID controllers using Internal Model Control, were applied using these CMAs to a chemical reactor analogy of the Susceptible-Infected-Removed (SIR) epidemic model. Consequently, the students' understanding of modeling and control concepts was improved in the context of a major world event that they were currently living through.

The experience in ChE 461 with SIR modeling and control was subsequently used in ChE 561: Advanced Process Control (an elective course that includes advanced undergraduates and graduate students); this has included extensions of the problem to Model Predictive Control. Training activities with graduate students in data-centric predictive control paradigms has also improved through exposure to the epidemic control problem.

2.12 Summary

As can be observed from the above experiences, a wide and different variety of solutions were observed and proposed by the different authors around the word. It is really fascinating to see all the effort made at the different countries to face the problem and to restore the teaching activities in a record period of time. On the other hand, it is important to highlight the enthusiasm and creativity observed by the different universities and educators, with the re-usability of old material, discovering of new resources, or even the development of new ad-hoc resources to cover the urgent online teaching demands. Notice also how beside the different cultures, similar approaches were applied worldwide.

Regarding the above summaries, one can realize the high workload suffered by the educators during that period, and it is a clear example of the pressure we were all under during the pandemic. Anyway, the positive issue was that all the solutions and experiences gained, and how many of the methodologies, tools and resources used during the pandemic are still in use today. In particular, the importance of digital tools to foster the students engagement have to be highlighted, and also that of take-home kits (and/or virtual laboratories) that allow students to have practical experiences and, in general, of having a variety of online resources that can be fruitfully exploited also in the post-pandemic period for new ways of teaching [45].

The next sections present the responses obtained from colleagues around the world based on the questionnaire prepared by the authors. The aim of this study was to obtain a quantitative and wider analysis of the above summarized experiences about the impact of the pandemic on the control engineering field.

3. Discussion

The questionnaire distributed to the international community is described in the Appendix. The questionnaire was completed by 240 individuals from 30 countries. The detailed distribution among countries is shown in Figs. 1 and 2. Fig. 1 shows countries where the questionnaire was completed at least by 2% of the total participants. Countries with smaller number of respondents are covered by the joint name "Other" that is shown in more details in Fig. 2.

As a first result, our interest was focused on knowing what tools/platforms/resources lectures were used before the pandemic. Fig. 3 shows the obtained results for the most often used tools. Moreover, some other material out of our proposals was provided by the participants, including the following ideas:

- examples and simulation in MATLAB®/Simulink®,
- own (standalone) demonstration tools,
- textbooks,
- computer exercises,
- own audio recordings,
- Git,
- Facebook study groups.

These answers were compared with the situation when lectures were taught online during the pandemic. Although at first glance it might seem that the blackboard with chalk and whiteboard with pen will not be used in such conditions, the opposite was true. People started to use "virtual blackboard/whiteboard", i.e. handwriting distributed via Internet. In spite of this, as it is evident from Fig. 3, the blackboard/whiteboard and PowerPoint-like presentations were partially substituted by the tools that are more appropriate for online teaching. The big increase in own video recordings was due to the use of prerecorded lectures (asynchronous lecturing) that started to be quite popular. Furthermore, from the extra comments, we also obtain examples based on interactive sessions with screen sharing or using classical communication tools such as cellphone or email.

The pandemic period also brought higher use of LMS. Fig. 4 shows that approximately two years ago Moodle was the most common LMS. COVID-19 enabled the increased use of MS Teams and partially also of Google Classroom. The increased use of MS Teams is very relevant. An important issue mentioned by the respondents was that the selection of the LMS was mostly done by the institution and educators rarely use other platforms.

However, LMS solutions only facilitate sharing of teaching materials and presentations, testing or administration of courses and students. In most cases, they do not allow synchronous online teaching where students can also ask questions. For this

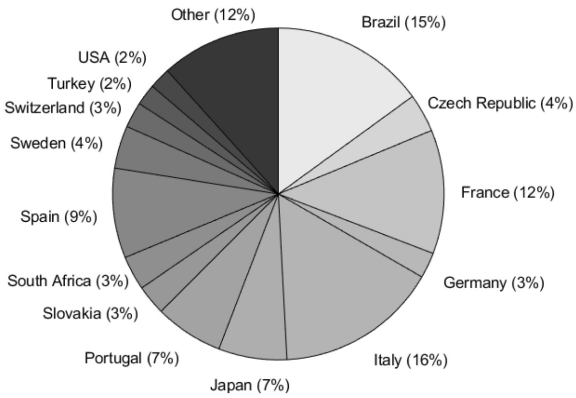

Fig. 1. Distribution of questionnaire answers among countries.

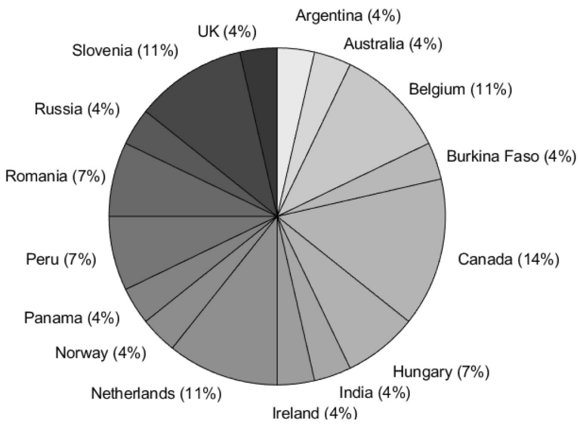

Fig. 2. Distribution of questionnaire answers among countries that are covered in Fig. 1 by the name "Other".

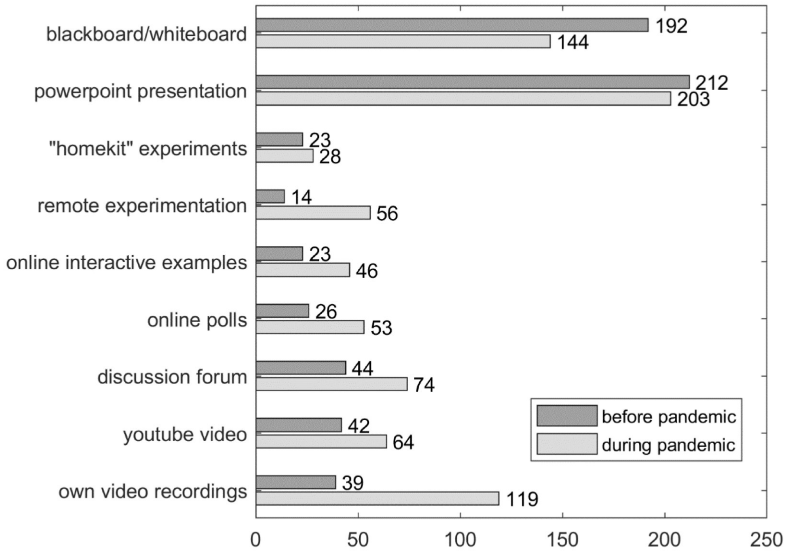

Fig. 3. Overview of different tools used before and during pandemic.

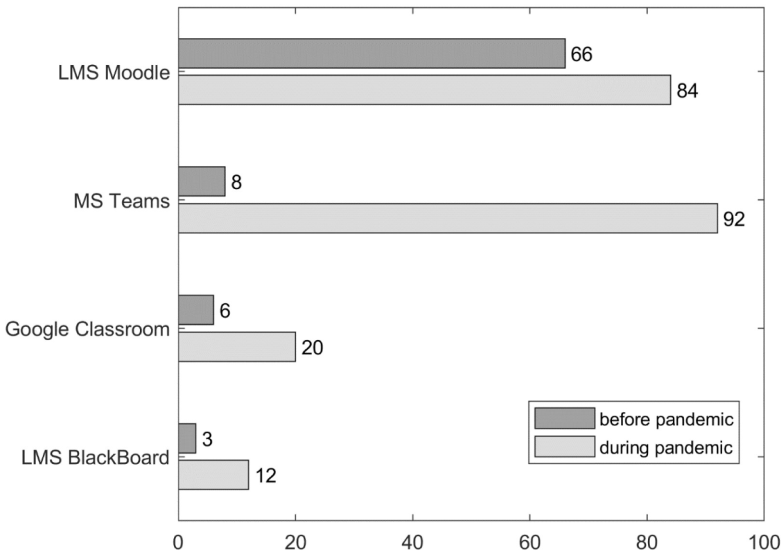

Fig. 4. Overview of the most used LMS before and during pandemic.

reason, a large number of teachers were looking for online streaming opportunities. As can be seen from Fig. 5, several software solutions were used for this purpose. Zoom, MS Teams, and Google Meet were the most often used.

Since teaching via the Internet requires the use of other ways of attracting students, we were interested in methods that teachers used to keep students engaged and motivated. Fig. 6 shows the questionnaire replies, where it is observed that for motivation purposes, teachers mostly used various forms of assignments: projects, open-ended assignments, additional take-home assignments, regular quizzes (online or offline), competitions, or games. Moreover, the following examples were also given by the questionnaire participants:

- practical experiments,
- encouragement to create discussion sessions among schoolmates,
- quizzes,
- polls,
- exercises and simulations in MATLAB®/Simulink®,
- more frequent communication via email,
- splitting seminars into shorter time slots with smaller number of students.

One respondent mentioned that normally students found jokes enjoyable, but together with this answer there come also several comments saying not to try it online because it is a disaster if you do not hear or see the smiling audience.

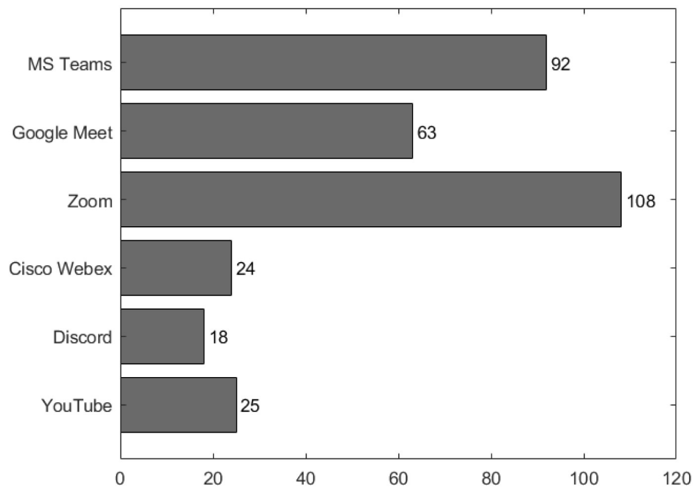

Fig. 5. Overview of the most used software for online lecturing.

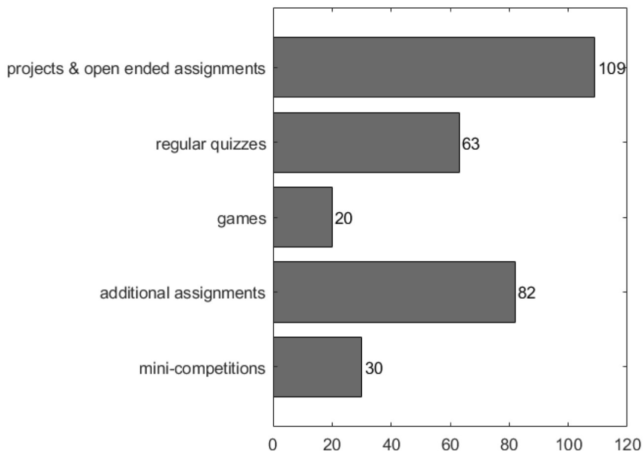

Fig. 6. Overview of methods used for engaging and motivating students.

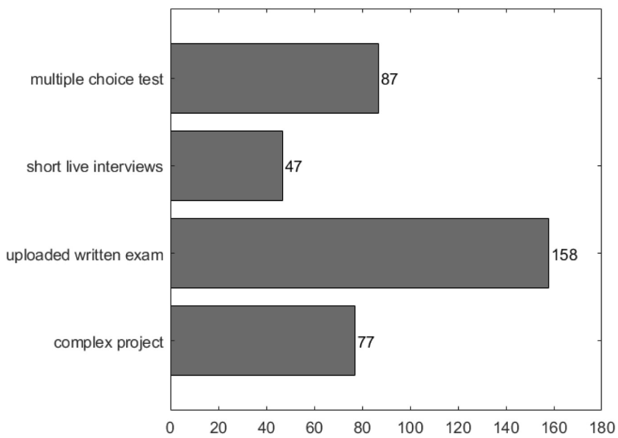

Fig. 7. Overview of methods for exam realization.

Of course, during online teaching it is also necessary to do exams and evaluation activities. The feedback results for this question are summarized in Fig. 7. In most cases, students needed to write the exam on paper, then scan and to upload to a platform after the exam is finished. Computer-based multiple choice tests were the second choice. These possibilities were followed by complex projects containing various tasks and short live interviews with students. In a few cases, it was possible to

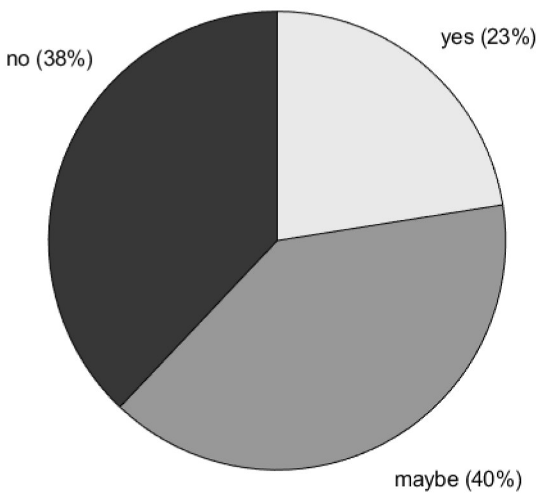

Fig. 8. Answers to the question "Do you think that after the pandemic will you return to the teaching activities in the same way as it was before?"

accomplish traditional face-to-face exams. Other ways also provided in the responses were:

- test with calculated questions in Moodle,
- oral exam via MS Teams,
- time restricted project with individual parameters,
- MATLAB Grader®,
- stack quizzes/questions in Moodle.

An interesting discussion ensued among the respondents. In some cases, when exams were done by hand and uploaded to a platform, students were required to have their remote video-camera switched on to be supervised by the lectures. It was interesting to know that in many universities, this option was not allowed because of privacy reasons. Actually, it was also forbidden to talk with students during online lecturers. However, don't we (as lectures) see the students' faces and what they are doing in person when they perform an exam in a classroom? So, why is it not allowed to require the same for online situations? This question opens an interesting discussion about the quality of distance evaluation.

Probably, everyone is interested in whether, when all the waves of the pandemic end, we will be able to return to the previous way of life and with the same teaching activities. Fig. 8 shows that just 23% of respondents (i.e. less than one quarter) think that teaching will be done in the same way as before. The rest of respondents agree or partially agree that it will not be the same.

In Fig. 3, we compared the tools that were used before and during the pandemic. Since we cannot expect that education will be the same as before, we wanted to know what we can expect in the future. Therefore, colleagues were asked which activities they would like to retain in teaching after the pandemic. Fig. 9 enhances this study and compares the obtained answers to the expansion of tools that were used up to now. Regarding the use of blackboard/whiteboard, it is necessary to say that we were asking about the use of "virtual blackboard/whiteboard" that was used during online teaching. The increase in the item "own video recordings" was due to the fact that it actually includes two video forms – own videos (54 answers), but also prerecorded lectures (113 answers). The most surprising result was the decrease of the use of PowerPoint-like presentations. All other online tools were as expected – reduced use in comparison to the pandemic period but the increased use in comparison to the period before COVID-19. In addition, some

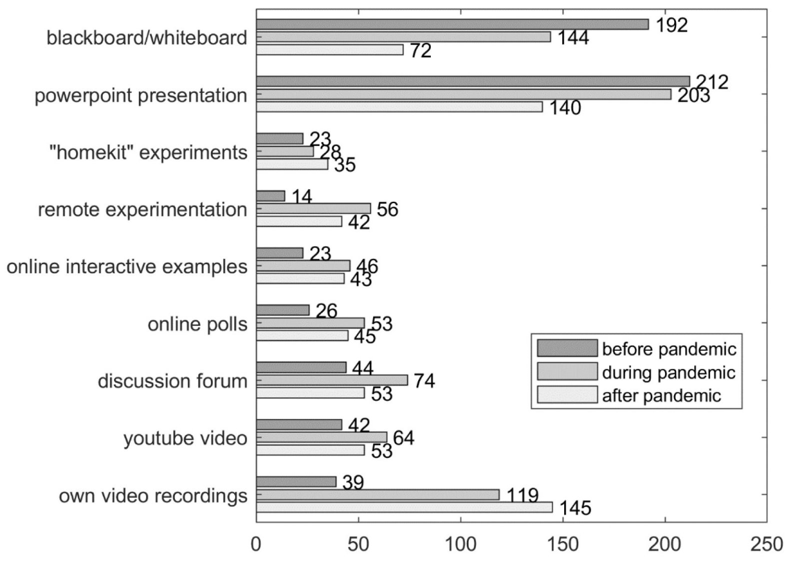

Fig. 9. Overview of tools used before, during and after pandemic.

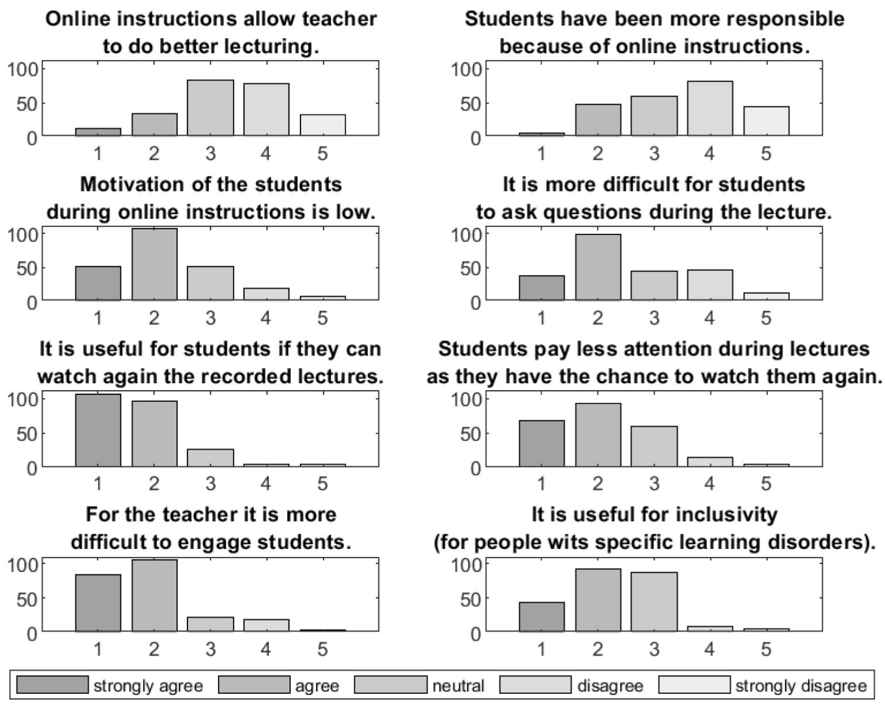

Fig. 10. Main advantages/disadvantages of online lecturing with respect to traditional in-person lectures.

teachers would like to keep the recording of lectures to be later available to students for individual study.

Finally, Fig. 10 shows the opinion about some statements related to the advantages or disadvantages of online teaching. As observed, most of the respondents agree that online teaching is most difficult for students and teachers. For students because they lose motivation and attention, as it is more difficult for them to ask questions and follow the lecture evolution. There is a general concern that being in front of a computer all the time opens many possibilities for distraction. For teachers, it is more difficult to keep the attention of students and get them to participate. Most of us agreed that face-to-face teaching provides live feedback from students which is impossible to observe in online teaching. So, most of us think that online teaching is not a good solution for education from a global point of view. However, some advantages were observed. For instance, to record the lectures can be useful for students to watch and revise the contents again. Also, to create video material to explain some complicated concepts is a very powerful tool for lectures. Imagine, the typical question that is repeated time after time by students. The recording of a simple video about the solution can be of incredible help to students for better understating, and also to reduce the repetitive tasks for lectures. Moreover, online tutorial meetings are very useful to address individual or group doubts, allowing for bigger availability. On the other hand, all the online solutions are demonstrated to be very beneficial for inclusivity situations for students with specific learning disorders.

4. Results

The pandemic period brought problems in experimenting with real devices. The questionnaire showed that some teachers skipped it altogether, some replaced experimental work with simulation experiments, and some tried to find a way to keep laboratory experiments in the classroom. Several teachers allowed students to use classical lab hardware via Remote Desktop software, in one case an assistant staff was available in the lab. Elsewhere, students were asked to send controller code to the professor, who tested it on the device, and feedback was also provided by video camera. Probably the most common way was to use various Arduino Based Kits (e.g., for temperature control or motor control), which were either very cheap or could be assembled at home. In the course on Signal and Systems students also used cheap microphones and speakers.

It is only natural that some teachers were not satisfied with the teaching during the pandemic and would like to go back to the way teaching was done before, because "Live lectures could never be replaced". On the other hand several teachers also found advantages to online teaching, e.g., "Online teaching has been rare in the past at our university, but it will help a lot if it is allowed during normal times, especially when the lecturer is traveling." or "Audience Response Systems are great!". Most responses agreed that "a mixed model can be advantageous" and "prerecorded lectures will be combined with live-lectures" because "students really appreciated the chance to watch the lectures again". On the other hand, this approach also raises slight concerns about the difficulty of preparing for this way of teaching – "I fear that students will demand both very soon: polished online resources to be used offline/on demand AND perfect, interactive, engaging live lectures and teaching, in total increasing our stress immensely....". Perhaps the closest to what awaits us in the future was the following answer: "I am very much up for a sharing culture where we don't do anymore so much frontal 'feedforward' teaching, but rather spend our time to give feedback to students that somehow study by themselves much more. And I think that our final objective is to transform ourselves from teachers to mentors of individual students."

Finally, we would like to introduce a few more observations, which were also included among the answers in the questionnaire:

- Most people feel that face-to-face is likely to be more engaging for the majority of students. Also this allows easier informal chats between students and also with staff.
- The worst thing during teaching online is the lack of feedback. You have no idea about initial conditions. You do not see if the students are lost or bored. You don't see whether you already lost their attention. You have no idea about disturbances.
- Nice examples of how advantageous feedback control/teaching is.
- The advantages/disadvantages of virtual classes depend on each teacher, on his or her own vocation for the teaching-learning process. The idea that the teacher should have is, "I want to teach my students" and based on that, manage his or her teaching methodology.
- At a time when screens and remote relations are spreading more and more, I do think that it is all the more important to keep real physical interactions in teaching (and research, by the way).
- The required level of self-discipline and forward-looking action for students during the pandemic is clearly higher than before.
- One thing I noticed is that it became even more evident that students who want to study accept any platform. However, with online classes the performance of those who are not motivated is even worse.
- The amount of cheating increased a lot. This is a cultural problem that is minimized in in-person lectures. In online lectures the students talk through WhatsApp groups during the tests and the teachers have no way to avoid the cheating as it is not right to ask everyone to open their cameras (privacy problems).
- From a personal perspective, remote teaching (or any task for that matter) allowed me to organize my time and be more efficient throughout the day (no time spent on commutes), and in particular, have more time to dedicate to my R&D activities.
- The pandemic has prompted many lecturers to improve their course material. Pre-recorded lectures are a lot of work, but have the advantage that it can be re-used.
- Universities must invest more in remote experimentation systems.

5. Conclusions

Initially, each author provided a summary of their experiences in their respective countries and universities. From these accounts, it is evident that there was a significant and commendable global effort to address the challenges of teaching during the pandemic. Following this, the authors collaborated on designing a detailed questionnaire to gather quantitative data on these experiences, focusing on the technologies, methodologies, activities, tools, and other resources used by educators worldwide during the pandemic. The survey collected the opinions of over 240 educators from 30 different countries. The main insights obtained from this study are the following:

- Permanent Changes in Teaching Methods: Most respondents believe that teaching methods will not entirely revert to their pre-pandemic state. The pandemic introduced new tools and methodologies that are expected to be retained in future teaching practices.
- Shift in Presentation Techniques: There has been a notable decrease in the use of PowerPoint presentations and an increase in the creation of custom videos to explain concepts. This shift highlights a move towards more dynamic and engaging teaching materials.
- Adoption of Remote Experiments: The use of remote experiments and take-home lab methodologies is another trend likely to continue post-pandemic. These methods have proven effective and convenient for students and educators alike.
- Integration of Online Tools: Online lecturing tools have become an integral part of modern educational activities. Their effectiveness and accessibility have made them indispensable in the current teaching landscape.
- Prevalence of Written Exams: Traditional written exercises remain prevalent, possibly due to

the mathematical nature of control engineering, which can be challenging to assess through other methods.

In conclusion, the pandemic has taught us valuable lessons and introduced new educational resources that enhance our current teaching practices. Despite the difficulties and sadness experienced during the pandemic, it has also provided opportunities for positive developments, a sentiment we should convey to our students as educators. We believe that this type of study is a valuable resource for the control education community, and sharing ideas among peers is a powerful way to continue learning and improving.

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Appendix

This section summarizes the questionnaire prepared by the authors in order to collect data about the methodologies, tools, solutions and platforms used in control education before, during, and after the pandemic. The idea was to see and analyze how the different solutions and didactic resources were used before the pandemic, during the more complicated period under the lockdown, and which ones are still used today. The structure of the survey was developed in different blocks of questions. First, basic questions about the country and affiliations of the participants were required. Afterwards, the groups of questions were specifically oriented to determine the tools, methods, activities, exams, and other resources used before, during and after the pandemic.

The first block was dedicated to knowing the tools and resources used before and during the pandemic with the following group of questions:

- What tools/platforms did you use before the pandemic situation came?
  - blackboard/whiteboard and chalk/pen.
  - PowerPoint-like presentations.
  - laboratory experiments.
  - experimenting with "home kits".
  - remote experimentation.
  - interactive examples via web interface.
  - online polls.
  - discussion forums.
  - LMS Moodle.
  - university information system.
  - MS Teams.
  - Google Classroom.
  - YouTube videos.
  - own video recordings.
  - others (providing other ideas).
- What tools did you use during online teaching?
  - pre-recorded lectures (asynchronous lecturing).
  - online live lectures (with any kind of synchronous feedback).
  - "virtual blackboard/whiteboard" (hand writing distributed via Internet).
  - PowerPoint-like presentations.
  - practical experimenting with "home kits".
  - remote experimentation.
  - interactive examples via web interface.
  - online polls.
  - chat.
  - discussion forums.
  - YouTube videos.
  - video recordings (complementary materials).
  - others (providing other ideas).

Then, the interest was moved on the LMS and the software tools used for online lecturing with the next questions:

- What LMS (if any) did you use for online teaching or videoconferencing as support to teaching activities?
  - LMS Moodle.
  - Canvas LMS.
  - university information system. – MS Teams.
  - Google Meet.

– Google Classroom.
– Zoom.
– Cisco Webex.
– Discord.
– video streaming via YouTube.
– video streaming via Twitch.
– other

Afterwards, the focus was on the students' motivation and the different ways to perform online exams:

- What methods did you use to keep students engaged and motivated?
  – projects and open-ended assignments presented to the entire class or submitted as a short video.
  – daily/weekly quizzes that count toward the course grade.
  – games that do not count towards the course grade.
  – additional take-home or virtual lab assignments.
  – mini-competitions among the students in the class (for example, tune a controller).
  – other.
- How did you perform the exams?
  – multiple choice test.
  – short live interviews with students.
  – written exams that students upload to a platform once they finished.
  – complex project containing various tasks.
  – other.

Finally, the interest was focused on the methodologies and resources to be kept after the pandemic:

- Do you think that after the pandemic will you return to the teaching activities in the same way as it was before?
  – yes.
  – maybe.
  – no.
- What activities would you like to retain in teaching after the pandemic?
  – pre-recorded lectures (asynchronous lecturing).
  – online live lectures (with any kind of synchronous feedback).
  – "virtual blackboard/whiteboard" (hand writing distributed via Internet).
  – PowerPoint-like presentations.
  – practical experimenting with "home kits".
  – remote experimentation.
  – interactive examples via web interface.
  – online polls.
  – chat.
  – discussion forum.
  – YouTube videos.
  – own video recordings.
  – others (providing other ideas).
- What do you think are the main advantages and disadvantages of online lecturing with respect to traditional in-person lectures?
  – Online instructions allow teacher to do better lecturing.
  – Students have been more responsible because of online instructions.
  – Motivation of the students during online instructions is low.
  – It is more difficult for students to ask questions to the teacher during the lecture.
  – It is useful for students if they can watch again the recorded lectures.
  – Students pay less attention during the lectures as they have the chance to watch them again.
  – For the teacher, it is more difficult to engage students.
  – It is useful for inclusivity (for example for people with specific learning disorders).

Notice that the idea was to develop a simple and easy questionnaire with the aim of collecting as many responses as possible. For that reason, we designed a short group of questions to avoid having a very tedious questionnaire. There are of course many other questions with a deeper pedagogical perspective that could be asked in future works, but this topic is out of the scope of this paper. The following section summarizes and discusses the results obtained from the collected data.

José Luis Guzmán received the Computer Science Engineering degree and the European PhD degree (extraordinary doctorate award) from the University of Almería, Spain, in 2002 and 2006, respectively. Currently, he is Full Professor of automatic control and system engineering with the University of Almería, where he also belongs to the Automatics, Robotics and Mechatronics research group. His research interests are focused on the fields of PID control, feedforward tuning rules, MPC techniques, and robust control with applications to biotechnology, solar plants, and agricultural processes. He has written several books, e.g., Feedforward Control (coauthor T. Hägglund), Automatic Control with Interactive Tools (coauthor R. Costa, M. Berenguel, S. Dormido), and Modeling and Control of Greenhouse Crop Growth (coauthor F. Rodríguez, M. Berenguel, A. Arias). Moreover, he is very active in research on teaching/learning methodologies/technologies on control education.

Katarína Žáková is a Professor of Cybernetics at the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Slovakia. She specializes in the automatic control of linear and nonlinear systems, with a focus on the computer-oriented design of controllers and control systems. Her interests include internet-based control applications, the creation of interactive simulators, virtual and remote laboratories, and computer-aided and online education. Her expertise is also focused on the evaluation of open resources to support teaching activities and the application of novel methodologies in the field of control engineering. She served as a member of the executive committee of the International Association of Online Engineering (IAOE) for four years and currently serves as vice-chair of the IFAC Technical Committee on Control Education.

Ian Keith Craig received the BEng degree in electronic engineering from the University of Pretoria, the SM degree from the Massachusetts Institute of Technology, and the PhD and MBA degrees from the University of the Witwatersrand. He heads the control systems group in the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria (UP) which is featured in the April 2024 issue of the IEEE Control Systems Magazine. Before joining UP Ian was part of the Measurement and Control Division of Mintek where he was involved in the design, implementation, and commercialisation of advanced controllers for the mineral processing industry. His research interests include model-based control and optimisation in the process industries. Ian was Editor-in-Chief of the journal Control Engineering Practice from 2005–2010 and the President of the International Federation of Automatic Control (IFAC) from 2011–2014. He chaired the IFAC Foundation Board from 2017–2023, and is currently the Chair of the IFAC Publications Managing Board. Ian is a Fellow of the South African Academy of Engineering and received the exceptional academic achiever award from the University of Pretoria five times.

Tore Hägglund received his MSc degree in Engineering Physics in 1978 and his PhD degree in Automatic Control in 1984, both from Lund University, Lund, Sweden, where he currently is professor. Between 1985 and 1989 he worked for Alfa Laval Automation (now ABB) with development and implementation of industrial adaptive controllers. Tore Hägglund has written several books, e.g., PID Controllers: Theory, Design, and Tuning (coauthor K. J. Åström), Process Control in Practice, and Feedforward Control (coauthor J. L. Guzmán) . His current research interests are in the areas of process control, tuning and adaptation, and supervision and detection, with applications mainly in the pulp and paper industry.

Daniel E. Rivera is professor of chemical engineering and program director for Arizona State University's Control Systems Engineering Laboratory in the School for Engineering of Matter, Transport and Energy in the Ira A. Fulton Schools of Engineering. Prior to joining ASU, he was a member of the technical staff at Shell Development Company in Houston, TX. He has been a visiting researcher with the Division of Automatic Control at Linköping University, Sweden, Honeywell Technology Center in Phoenix, AZ, the University "St. Cyril and Methodius," in Skopje, North Macedonia, the National Distance Learning University (UNED) in Madrid, Spain, and the University of Almería in Andalucía, Spain. His research interests include the topics of robust process control, system identification, and the application of control engineering principles to problems in process systems, supply chain management, and prevention and treatment interventions in behavioral medicine. In 2007, Rivera was awarded a K25 Mentored Quantitative Research Career Development Award from the National Institutes of Health to study control systems approaches for fighting drug abuse. He is a Distinguished Member (2019) of the IEEE Control Systems Section, and is Fellow of the American Institute of Chemical Engineers (AIChE).

Julio E. Normey Rico is graduated in Electronic Engineering – National University of La Plata (1986), Master's in Electrical Engineering from the Federal University of Santa Catarina (1989) and PhD in Automatic and Electronic Robotics – University of Seville (1999). He is currently a full professor at the Federal University of Santa Catarina, Coordinator of the Graduate Program in Automation and Systems Engineering, Senior Researcher of CNPq-Brazil, Coordinator of the National Institute of Science and Technology for Control and Automation of Energy Processes and of several research projects in energy areas, Editor of SBA Press, Associate Editor of Frontiers in Control Engineering magazine, and permanent member of the advisory committee of the IREC-International Renewable Energy Congress. He has experience in the area of Control and Automation Engineering, with emphasis on Process Control, working mainly on the following topics: control of delayed systems and model predictive control, with applications in several sectors of the industry, mainly in oil and natural gas and renewable energies.

Paulo Moura Oliveira received the Electrical Engineering degree in 1991, from the UTAD University, Portugal, MSc in Industrial Control Systems in 1994 and PhD in Control Engineering in 1998, both from Salford University, Manchester, UK. He serves as an Associated Professor with Habilitation at the Engineering Department of UTAD University and a researcher at the Centre for Robotics (CRIIS) in Industry and Intelligent Systems in INESC-TEC institute. Currently, he holds the position of Director of the Pedagogical Council at the Science and Technology School at UTAD. His research interests are focused on the fields of control engineering, intelligent control, PID control, control education, evolutionary and natural inspired algorithms for single and multiple objective optimization problem solving.

Liuping Wang received her PhD degree from the Department of Automatic Control and Systems Engineering, University of Sheffield, UK. Upon completion of her PhD degree, she worked in the Department of Chemical Engineering at the University of Toronto, Canada and in the Center for Integrated Dynamics and Control, University of Newcastle, Australia. In February 2002, she joined the School of Electrical and Computer Engineering, RMIT University, Australia where she is a Professor of Control Engineering since 2007. She has authored and co-authored more than 250 papers in the field of system identification, PID control, adaptive control, model predictive control, electrical drive control, unmanned aerial vehicle control, sensor fusion and control technology application to industrial processes. She is the author and the lead author of five books in the field of systems and control (State Feedback Control and Kalman Filtering with MATLAB/Simulink Tutorials, Wiley-IEEE Presss 2022; PID Control System Design and Automatic Tuning using MATLAB/Simulink, Wiley-IEEE Press 2020; PID and Predictive Control of Electrical Drives and Power Converters

Using MATLAB/Simulink, Wiley-IEEE Press, 2015; Model Predictive Control System Design and Implementation using MATLAB, Springer 2009; From Plant Data to Process Control-Ideas for Process Identification and PID Control, Taylor and Francis, 2000). Her recent book on PID control in 2020 was translated into Chinese and published by Tsinghua University Press in 2023. Dr Liuping Wang is an editor of International Journal of Control, an associate editor of Journal of Process Control and IEEE Transactions on Control System Technologies, and a Fellow of Institute of Engineers Australia.

Atanas Serbezov is a Professor of Chemical Engineering at Rose-Hulman Institute of Technology (Terre Haute, IN, USA). He holds BS and MS degrees in Process Control from the University of Chemical Technology and Metallurgy (Sofia, Bulgaria) as well as MS and PhD degrees in Chemical Engineering from the University of Rochester (Rochester, NY, USA). He has extensive industrial experience at Honeywell, Praxair (now Linde), and Eli Lilly. His main focus in academia is bringing industrial relevance to the Chemical Engineering curriculum. He is a member of the IFAC Industry Committee and the IFAC Technical Committee on Control Education.

Takao Sato received BEng and MEng degrees from Okayama University in 1997 and 1999, respectively, and his Deng degree from Okayama University in 2002. He is a professor in the Graduate School of Engineering at University of Hyogo, Japan. His research interests are in the areas of PID control, mechanical system, and medical engineering. Prof. Sato is a member of the Society of Instrumentation and Control Engineers in Japan (SICE), the Institute of Systems, Control and Information Engineers in Japan (ISCIE), the institute of Electrical Engineers of Japan (IEEJ), and the Institute of Electrical and Electronics Engineers (IEEE).

Antonio Visioli received the Laurea degree in electronic engineering from the University of Parma in 1995 and the PhD degree in applied mechanics from the University of Brescia in 1999. Currently he holds a professor position in automatic control at the Department of Mechanical and Industrial Engineering of the University of Brescia. He is the chair of the TC on Control Education of the International Federation of Automatic Control and the secretary of the subcommittee on Industrial Automated Systems and Control of the IEEE Industrial Electronics Society Technical Committee on Factory Automation. He has served as IPC chair or IPC member of many international conferences. His research interests include industrial robot control and trajectory planning, dynamic inversion based control, industrial control, fractional control, anesthesia control and control education. He is the author or co-author or editor of four international books, one textbook and more than 300 papers in international journals and conference proceedings.