Current Trends in Remote Laboratories

Luís Gomes, *Senior Member, IEEE*, and Seta Bogosyan, *Senior Member, IEEE*

***Abstract*—Remote laboratories have been introduced during the last few decades into engineering education processes as well as integrated within e-learning frameworks offered to engineering and science students. Remote laboratories are also being used to support life-long learning and student's autonomous learning activities. In this paper, after a brief overview of state-of-the-art technologies in the development of remote laboratories and presentation of recent and interesting examples of remote laboratories in several areas related with industrial electronics education, some current trends and challenges are also identified and discussed.**

***Index Terms*—Laboratories, learning systems, remote laboratories, student experiments, telerobotics, virtual laboratories.**

I. Introduction

LABORATORY tests and experimentation are essential components for education and research in all fields of engineering. Hands-on laboratories are the most common forms of such laboratory environments, offering students opportunities of experimentation with physical, or real, systems related to the research or education material in consideration. While offering the "actual" experience whether in research or education, hands-on laboratories are also known for their high costs associated with the required equipment, space, and maintenance staff. Considering electrical engineering areas of interest, it would be accurate to say that those costs increase even more in areas where the quality of education also calls for a large variety of laboratory equipment and experiments, as in robotics, control, mechatronics engineering, etc., or necessitates several rather costly equipment, as in micro–nanosciences, automotive engineering, etc. High investment, as well as maintenance and safety costs related to those laboratories, poses important limitations and calls for serious consideration to be given to the choice of equipment and design of experiments in such laboratories. Resorting to sharing of resources via off-site experimentation facilities with the use of the Internet, or utilizing the simulated/emulated versions of the physically unavailable test beds, is the next best options to address the earlier limitations. Fast-paced technologies and the undeniable need to stay abreast with the best that is out there, whether in college or in life-long learning, have an important role in the attraction of web-based laboratory activities as an enhancement or alternative to conventional education and research tools. Another obvious benefit is the flexibility such laboratories can offer in terms of time and place to students or even engineering professionals in their continuing education needs.

The aim of this paper is to provide a discussion of web-based experimentation approaches and act as reference for the state-of-the-art technologies and applications, particularly in hands-on remote laboratories in areas relevant to industrial electronics. While some recent books provide comprehensive discussions of a wide variety of technologies and experimentation environments for web-based laboratories [1]–[3], most journal or conference articles that discuss existing web-based laboratory technologies and applications concentrate on one particular laboratory, or emphasize, either mostly educational or technological aspects. This paper attempts to fill this gap by providing a more multipurpose multiangle overview of the state-of-the-art remote laboratories, concentrating on technologies as well as educational aspects. This paper also provides an overview of remote laboratory examples from industrial-electronics-related literature as well as a discussion of current trends and challenges related with remote-laboratory development and usage.

The concept of web-based laboratories was promoted with the invention of the Internet in the 1970s and the powerful rise of the computer networks initiated in the U.S., hence the establishment of the World Wide Web (WWW). The resulting impact of information and communication technologies has led to a number of large educational networks, such as MIT OpenCourseWare, iLab, European Schoolnet, and PROLEARN, besides many other individual and collaborative distance laboratory efforts all over the world [1], [2]. Currently, a Google search for words, such as "remote labs," "web labs," etc., will return over 100 functional remote laboratories all around the world established by world-renowned universities in the U.S., Canada, Europe, and Australia in various areas of engineering as well as multipartner, national, international, and intercontinental remote-laboratory collaborations (or so-called collaboratories).

Considering all engineering and scientific disciplines, a recent analysis demonstrates that the most widespread use of remote laboratories is in electrical and mechanical engineering, among which electronics, robotics, automation, and mechatronics are the most frequently encountered applications in the given ranking order [4]. Hence, in this paper, remote-laboratory applications in the aforementioned popular areas and related publications will be discussed in further detail in Section IV (where several different groups of remote laboratories will be discussed) also due to their strong relevance to industrial electronics areas of interest.

Remote-laboratory architecture relies on the client–server paradigm, where Internet technologies (and web 2.0) are in the center of current development frameworks. Even using different technologies, most remote-laboratory solutions rely on

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L. Gomes is with the Faculty of Sciences and Technology, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal, and also with the Center of Technology and Systems, UNINOVA, 2829-516 Caparica, Portugal (e-mail: lugo@ieee.org).

S. Bogosyan is with the Electrical and Computer Engineering, University of Alaska Fairbanks, Fairbanks, AK 99775-5915 USA (e-mail: s.bogosyan@uaf.edu).

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common simplified software architecture based on the experiment and a computer that allows experiment control and connectivity to the net, acting as a laboratory server at the remote end. On the other end, the user will use a client application (a web browser for most of the applications) that offers remote control and monitoring capabilities to the experiment. Integration or collaboration with learning management systems (LMSs) is foreseen in several remote laboratories, supporting their effective impact within the learning processes.

The next section addresses general issues about remote laboratories and their usage within engineering education, while Section III is devoted to briefly introducing supporting technologies and topologies. Section IV presents some state-of-the-art remote laboratory examples selected according with their relevance to industrial electronics education. Section V identifies several current trends and challenges within remote-laboratory development and exploitation frameworks and gives the conclusion.

II. Remote Laboratories in Engineering Education

A. Characterization of Remote Experimentation

One open issue related to remote laboratories is associated with the specific semantics of the term. Definitions provided in the literature are inconsistent and confusing, and very often, different terms are used to define the very same concept, i.e., e-labs, web-labs, virtual-labs, online-labs, distributed learning labs, and so on. In order to avoid ambiguities in this paper, three major classification criteria are identified for the experiment at hand as follows:

1) type of interaction of the user with the experiment;
2) type of experiment in terms of its nature;
3) type of locations of the user and the experiment.

Regarding the first criterion, two types of user (or experimenter) interaction are possible:

1) directly controlling the devices and instrumentation equipment, which corresponds to a traditional laboratory;
2) controlling the devices and instrumentation equipment through a computer interface, using virtual instrumentation or virtual-reality environments.

The other two criteria are often combined, resulting in the definition of four kinds of experiments, as shown in Fig. 1, where two types of experiments can be considered concerning the nature of the experiment, based on whether it involves physical devices (and equipment), or simulated/emulated models for the devices (and equipment). Two types of situations can be considered for the locations of the user and of the experiment, namely, at the same location or at different locations.

As already mentioned, this paper will focus on experiments which involve different locations for the user and experiment (right column of Fig. 1). Distance experimentation or web-based laboratory facilities are offered in three forms.

1) Virtual laboratories supported by remote simulation are simulated laboratories and hence offer added value to education by providing an experimentation environment without the safety concerns related to actual equipment. Such laboratories could be made accessible through the web for public use or a more interactive version could be developed with the use of a web server, a computer (which may also host the simulated device or system) for the instructor, and remote stations of the students for both on-site and off-site uses. Such a model is utilized for teaching of controls at the University of Maribor [2]. Many other state-of-the-art examples may be found, as in [5]–[7]. A special mention is due to the Special Issue recently published in the IEEE TRANSACTIONS ON EDUCATION devoted to virtual laboratories [8]. Although often viewed not as effective as hands-on experimentation, an obvious advantage of such laboratories could be the added flexibility they offer to learners by allowing them to experiment under diverse conditions with no fear of damage to oneself or to the equipment. Similarly, they can repeatedly go back and forth with the same experiment at their will to learn from mistakes or for further analysis. The functionality of virtual laboratories is often enhanced by online courses and step-by-step instructions to accompany the laboratory assignments.
2) Remote "hands-on" laboratories, or briefly, remote labs, provide users Internet-based access to actual (physical) experimental test beds not available on-site. Supported by a publication-based overall analysis, it can be said that activities in remote laboratories have peaked around 2002–2003 and, after a brief drop, has continued its incline after 2006 [4], demonstrating a geographic distribution that covers the U.S., Europe, Australia, and East Asia. To name only a few of the most cited functional remote laboratories, one can mention MIT's Microelectronics WebLab, Oregon State's Control Laboratory, UC San Diego's WebShaker, the University of Illinois's Integrated Remote Laboratory Environment, the University of Siena's ACT, the University of Maribor's Remote Robotics and Control Laboratory, the University of South Australia's NetLAB, and Blekinge Institute of Technology in Sweden [9]. Besides these individual laboratory activities, there are also interuniversity resource sharing and collaboration examples, such as Cambridge–MIT remote experiment [10] and collaborative projects as referred in Section IV-A.
3) Hybrid laboratories offer a combination of both remote "hands-on" laboratories and virtual laboratories. Among the different types of remote experimentation offered, hybrid laboratories may be considered as the most efficient

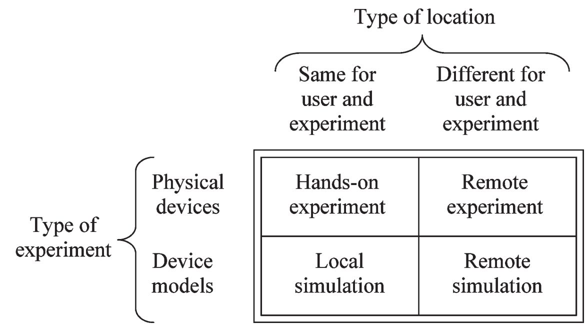

Fig. 1. Characterization of experiments.

for both education and research. While acting as a repertoire enhancer in the face of physical test-bed limitations, the safety concerns of remotely accessed physical laboratories may also be addressed by taking the user initially through the virtual version of the laboratory, hence providing some practice for the use of the actual equipment. Even if the emphasis of this paper is on experiments based on physical devices, it is important to mention that, in many cases, the distinction between a remote physical apparatus and a web-based simulator is not too obvious to the remote user through an Internet connection. Taking advantage of this fact, some remote laboratories resort to an operation mode that can switch from a connection controlling a physical setup to an environment that mimics it through a proper simulation environment. This is the case presented in [11], where the control of an industrial didactic process is possible as well the use of associated MATLAB model instead.

Remote experiments can be categorized in three groups [2], based on the type of provided experiments: batch-, interactive-, and sensor-type experiments. Batch-type experiments allow the remote student to interact with the experiment only indirectly, by entering some system or control parameters and waiting for the result of the experiment from the remote site, with no interaction between the client and the experiment, while it is running. The interactive type, on the other hand, allows for direct communication between the client and the laboratory server while executing the experiment. Finally, the experiment platforms involving only sensors, or sensor networks, return sensor data to remote users, for monitoring and/or analysis purposes. Lowe *et al.* [12] reported on MIT's iLabs Shared Architecture, which merges the batched and interactive components into a single architecture.

B. Benefits of Remote-Laboratory Usage

Each experiment type has firm advocates and detractors, as referred in a recent literature survey [13]. Advocates of simulation argue that simulation can circumvent needs for university space and gives additional flexibility regarding students' time (as far as the experiment can be accomplished in less time).

On the other hand, advocates of hands-on experiments voice their belief that no other approach can take the place of actual physical experiments in engineering education, further mentioning the following added values of remote labs:

1) Remote laboratories can offer similar flexibility benefits as simulation-based experiments, when laboratory space and students' schedules are considered;
2) Unlike conventional lab sessions, access to remote experiments can be 24 hours, 7 days a week;
3) Students can use remote labs also as a supplement or replacement for "regular" laboratory assignments;
4) Overall better scheduling of activities;
5) Better return of investments in equipment due to shared resources;
6) Enables education and research collaborations between individuals and institutions all around the world;
7) Enables and supports autonomous learning;
8) Enables students with some disabilities to conduct their experimentation needs;
9) Prevents damages to equipment via the integration of practice sessions on virtual labs prior to experimentation and ensures user safety at all times;
10) Meets the experimentation needs of distance education and distance courses.

C. Evolution of Remote Laboratories

The number of papers found in literature addressing remote laboratories has been increasing during the last years, as can be concluded from [13], even if in [4] a decay after 2003 is identified. The number of technical or scientific events focusing on remote laboratories also demonstrate a boom in recent years, either as the central subject of the event, as in [14], or as an important subject receiving special attention, as in events devoted to education in general and to e-learning in particular. Recently, books devoted to the subject of remote laboratories and associated e-learning experiences [1], [2] are also available, providing a comprehensive overview on several aspects of remote-laboratory development and usage within selected e-learning experiences.

In [13], the conducted literature survey grouped laboratories into three groups: hands-on, simulated, and remote laboratories. Several major observations were presented, namely, that "*there is no standard criterion to evaluate the effectiveness of labwork*." Several contributions to overcome this observation can be found in the literature and in public initiatives all over the world (within mechanisms for education assessment and evaluation conducted by government or multinational initiatives, as ABET in North America or the Bologna Process in Europe), but no conclusion is reached (maybe this is just one never-ending discussion, as the technologies and sciences continuously evolve and new arguments can be added to the discussion).

On the other hand, one major finding in [13] is that the computer-mediated experiments are demonstrating an increasing trend in engineering and science education, even for an on-site hands-on experiment can be achieved directly by interacting with equipment and instrumentation (as in a traditional experiment) or through a computer (as in a virtual-instrumentation-based experiment). This is not surprising at all, as it is also a well-known and sustained tendency with sophisticated instrumentation to have, in many cases, some kind of an embedded personal computer (PC).

Different from the "old-fashioned" way of preparing an (physical based) experiment for an engineering and science student, where selection of the devices under test and associated instrumentation play a major role, the "modern" way also considers the use of instruments (in the sense of instruments with a user interface supported by a computer).

The use of computers as mediators between users and the experiment not only brings new capabilities that were not possible before (like introducing guidance on how to conduct the experiment or mechanisms to prevent damages) but also introduces a whole new set of paradigms to be considered when developing new experiments.

This is particularly true for remote laboratories, which can be analyzed from a multitude of points of view, emphasizing different aspects, ranging from didactical, supporting technologies (hardware and software), development environments, and communication support, among others.

In this sense, one of the major evolutions associated with remote laboratories is the extensive use of Internet technologies, where web 2.0 and service-oriented architectures and web services play a major role. This evolution has been widely reported in the literature [15]–[17]. Therefore, as in so many other areas, the importance of the software part of the system has been increasing.

D. Integration With LMSs

In close relation with this issue, it is important to mention the ability of remote laboratories to be integrated with specific LMSs and content management systems (CMSs), where they can be seen as additional resources available to the students, as in [18].

However, very different from a common resource available in an LMS or CMS, a remote laboratory has different constraints, namely, those associated with the exclusive control of one user at a time. To assure this exclusive access by one user, it is necessary to use a booking system, like the one described in [19], where the booking of the remote laboratories is integrated within the modular object-oriented dynamic learning environment system (Moodle) (http://moodle.org/).

In addition, in order to allow an easy integration of the remote laboratory within specific LMS, it is necessary to describe the remote laboratory in terms of its metadata, as well as to rely on specific standards allowing the interface with the remote laboratories, as Shareable-Content Object Reference Model (SCORM) and IEEE 1484 Learning Objects Metadata (IEEE LOM). These are open issues, being addressed by different initiatives, which will not be covered in detail in this paper.

E. Remote Laboratories Supporting New Learning Methodologies

The integration of remote laboratories within LMSs and CMSs also allows the support for innovative pedagogic methodologies and attitudes, as project-based learning [20] and problem-based learning [21], supporting collaborative work [22] and shifting the emphasis in order to put the student in the center of its own learning process.

This shift of paradigm toward a student-centric teaching approach is completely supported by availability of remote laboratories, where the student has the possibility to become more autonomous. This could also have some implications with the Bologna Process, currently under implementation in Europe, where a shift in the structure of the courses emphasizing the learning outcomes is expected in the learning process (as opposed to the "traditional" way of guiding students through subjects and activities to which they have been exposed).

We consider that this shifting of paradigms, which can also be seen as the shifting from a "faculty-centric" to a "student-centric" teaching approach, can adequately be supported by remote laboratories [1].

III. Supporting Technologies

A. Components of Remote Laboratory

The number of existing remote-laboratory solutions is huge, however often not assuring compatibility with other solutions. Even in this very heterogeneous situation, it is possible to identify a set of typical components of a remote laboratory, where some of these components can be duplicated, namely, the following items [23], [24].

1) The experiment itself.
2) Instrumentation devices and equipment allowing the control of the experiment as well acquiring results from the experimentation; this equipment could be based on standard equipment or custom-made interfaces.
3) A laboratory server that will assure the control and monitoring of the experiment, through the control of the instrumentation devices and equipment.
4) A server that will assure the link between remote users and the laboratory server, normally through the Internet; the solution for this server varies a lot, ranging from dedicated applications and very "naïf" web servers (normally presenting a simple description of the experiment and containing additional learning materials) to a complex LMS handling the users and time allocation for the use of the experiments (booking system). In that sense, this component could be decomposed into a set of web servers (or layers) with specific functions, namely, performing the presentation of related materials (experiment information, theoretical background, and so on), user authentication, experiment booking, management of the learning path, and so on. Not surprisingly, the referred functionalities can be accessed through a web portal, acting as the front page for experiments established by an institution or by an interinstitution consortium, providing access to a pool of remote experiments.
5) A webcam server that can be used by remote user to get a visual and audio feedback of the experiment status; this functionality could also be included in the previously referred web server, but it is common to rely on a dedicated hardware–software platform to accomplish this goal.
6) Collaborative tools allowing audio, video, and chat communications between users.
7) Client workstations assuring remote users to be connected to the experiment and associated resources; it is important to stress that some remote laboratories rely on a simple web browser, while others will need to have specific plug-ins or download client programs in order to get proper access to the experiment (this is the case when using LabView-based server platforms).

It is important to note that it is not necessary to have all the referred components to establish a remote laboratory with a strong impact on the learning process. However, it is also necessary to emphasize that when one wants to shift from a remote laboratory based on a single experiment to a remote laboratory offering several experiments to a large number of users, several complex issues need to be addressed, starting with the development phase and integrating very diverse subjects, such as how to handle scalability, security issues, multiple access and other accessibility issues, maintenance, and so on.

In the following sections, two major characteristics associated with the referred list of components are presented, namely, those related with topologies and platforms, and communications.

B. Topologies and Platforms

One key characteristic that determines the technologies that one can use to implement a remote laboratory is associated with the type of experiment, which can be roughly divided into two groups [25]:

1) remote laboratories associated with expensive setup experiments and representing a "one-of-a-kind" experiment type (common in process control);
2) remote laboratories associated with low-cost experiments that can be replicated without a severe impact in terms of costs (common in digital systems and basic electronics experimentation).

In the first group, it is common to have "one-user-at-a-time" and the need to rely on a booking system allowing the reservation of time slots to have access to the experiment. The computer-mediated characteristics of the remote laboratory can accommodate tutoring and guidance through the experiment, in order to allow its autonomous usage during a wider period of time.

In the second group, the scalability problem becomes of ultimate importance, and the use of clusters of similar experiments can be a solution to support usage by a large set of users during the same time period. In this situation, selecting specific web 2.0 technologies will allow an easy replication and integration of additional experiments. In this case, it is possible to take advantage of experiment redundancy to improve quality of service, allowing simultaneous usage by several users at the same time.

Nowadays, as previously mentioned, the most common topology for remote laboratories is based on client/server applications and often exploit web technologies, as the client is also often a simple web-browser.

The topology could be classified into two main groups, as referred in [26]:

1) web-based applications;
2) dedicated remote computer control applications.

Dedicated remote computer control applications have the benefit of supporting powerful interfaces, taking advantage of specific characteristics associated with equipment used in the remote laboratory, and their full integration into the desktop environment (allowing specific capabilities, such as complex graphics and data logging); unfortunately, this solution lacks flexibility and universality.

On the other hand, web-based solutions can benefit from being universal and nonintrusive in the sense that they use no resources at the client side.

From this point of view, client-side technologies can be classified into two groups [26].

1) Intrusive applications, which need to have the same access privileges as the local user of the machine; this is the case for (dedicated) desktop applications and other types of web-based applications.
2) Nonintrusive applications, where it is assured that no damage to any local resource is possible and where two subgroups can be identified, those depending on specific plug-ins (as for Adobe Flash) and those not depending on any plug-in (as for "regular" HTML and for asynchronous javascript and XML).

Roughly speaking, intrusive applications would provide a better interface with the user but may present some deficit in terms of security (as long as client computer local resources are used and users would need to download some parts from the server, it is necessary to assure that this communication is completely secure, which is not always the case when using web technologies).

C. Communications Among Components

Considering a simple remote laboratory, as described in Section III-A, different technologies can be used to assure communications at the different levels.

Starting from the bottom, the communication between the laboratory server and the instrumentation equipment may vary, including standard communication interfaces, as TCP-IP, RS-232, IEEE-488, among others as well as *ad hoc* and OEM interfaces. Coming to the software part of this connection between the experiment and laboratory server, it is common to find several types of solutions:

1) based on proprietary solutions; most of them in his category emphasize graphical representation, as in LabView, VEE, and MATLAB/Simulink;
2) based on general-purpose programming languages, as C, C++, Basic, or Python.

It is also worth mentioning some efforts to merge referred types of solutions, namely, the virtual instrument software architecture, commonly known as VISA, and the interchangeable virtual instrument (IVI), allowing users to define instrument drivers using several languages.

As for the communication between the user and the laboratory server, taking the client–server paradigm as a reference, several technologies are available as mentioned in the previous section. Different languages have been used to support this link, ranging from HTML, Java, Virtual Reality Markup Language, C, C++, C#, CORBA, among others.

Issues on accessibility are very important as different platforms have been considered for the client side, ranging from regular PCs and workstations to PDAs and mobile phones [27] (in order to support m-learning).

IV. Case Studies

A. Institutional Collaboration Opportunities and Transnational Project Programs

As already mentioned, the number of recent publications in remote laboratories and related subjects is large [13]. As usual, the number of collaborative activities and projects is somehow related with this figure. As a matter of fact, the number and nature of funding mechanisms for launching collaborative actions and projects is diverse to assure the evolution and contribution of remote laboratories for an improved quality of education.

Taking European Union as a case study, the funding mechanisms have been scattered for several different programs managed by different Directorate-General of the European Commission (EC-DG) [24] and include support for regional, European level, and intercontinental networks. Typical consortia are composed of institutions of higher education, as well as companies and enterprises, from more than two or three countries. As examples of specific programs, one can mention Socrates and Leonardo da Vinci programs, within EC-DG Education and Culture, several specific programs within the "Framework Programmes" (FP)—supporting research programs as well as several cooperation programs within EuropeAid—Cooperation Office, supporting cooperation with institutions from other world regions, namely, ALFA (cooperation between European and Latin-American institutions), ASI@ITC (cooperation between European and Asian institutions), and EDULINK (cooperation between European and ACP institutions).

On the other hand, it is important to mention that in the other parts of the world, the scenarios are somehow similar. For instance, in North America, cooperations between the university, industry, and government are also very common [28]. The iLab Project at MIT (http://ilab.mit.edu/) is an example of how the initiative of one institution can support the collaboration among several institutions all over the world (including North America, Europe, Asia, and Africa).

The number of supported and ongoing projects is huge, and despite the fact that it is not easy (and unfair) to pick only a few projects, a few of those projects (and results) will be discussed in the following section.

B. Remote-Laboratory Applications for Engineering Education and Research

In this section, some state-of-the-art functional laboratory examples encountered in recent literature will be discussed, referring to the associated publications, which describe the laboratory and its relevance to research and education, often accompanied by a discussion of related architecture, management, and maintenance issues. There are also publications concentrating purely on recent technological developments in remote laboratories, e.g., Casini *et al.* [29] introduce the use at the University of Siena of a bootable (live) device on the server side of a remote laboratory, to greatly reduce maintenance time due to hardware/software failure.

1) Remote Laboratories for Electronics and Microelectronics: The fast-paced developments in electronics and microelectronics technologies have affected all other technologies considerably, also raising the standards for education and practical training demands in this area. While breadboards and wiring are still considered part of the training process as in [30], the changing skill needs of digital design also call for a more effective use of time and other means of training. To this aim, various virtual-laboratory environments have been developed. Limiting the list to currently functional laboratories, the following examples can be mentioned: WinLogiLab as a teaching suite for the design of combinatorial and sequential logic circuits, which is composed of a set of tutorials aiming at bridging the gap between theory and practice by mixing together tutorials and simulators (see http://132.234.129.50/WinLLab/WinLLab.html), MIT's Digital Simulator (see http://www.mit.edu/people/ara/ds.html), Circuit Shop (see http://www.cherrywoodsystems.com/cshop1.htm), EasySim (see http://www.researchsystems.com/easysim/easysim.htm), Logisim (see http://ozark.hendrix.edu/~burch/logisim), and Digital WorkShop (see http://www.cise.ufl.edu/~fishwick/dig/DigSim.html). While these laboratories concentrate on certain subjects in electronics, a more recent example [31], Digital Electronics and Design Suite (Deeds), offers three simulators covering combinational and sequential logic networks, finite-state machine design, microcomputer interfacing, and assembly programming.

Among current remote laboratories offering access to actual electronics equipment, one can mention MIT iLab's NIELVIS platform, offering an all-in-one electronics workbench. The system is recently expanded in order to enable students to test and debug digital and analog circuits, also with the use of a digital multimeter with remote-switching capabilities [32].

A recent remote-laboratory activity at Darmstadt University of Technology offers the possibility of executing simulation models as well as the capabilities of field-programmable gate-array (FPGA) platforms in prototyping digital electronics circuits. Different from other such examples, this remote laboratory not only provides measurements or predefined experiments but also the flexibility of FPGAs to allow designers and students to completely configure the remote laboratory as a prototype of the system that they are designing. The prototyping is also rendered completely interactive; hence, its execution can be controlled and monitored, which is ideal for both design and education purposes. The laboratory has been used in a number of industrial and educational projects involving wireless communications, cryptography, automation, and multimedia [33].

A remote laboratory in Hong Kong offers students the opportunity to learn by observation of electrical circuits phenomena. The involved interactive human–machine interface was created with the use of open-source software, LabVNC, for conducting remote experiments [34].

The remote optical circuits' laboratory at the University of Houston provides both simulations and physical experiments for light-source characterization using the optical spectrum analyzer with bandwidth comparison and fiber-link attenuation characteristics for multimode and single-mode fiber [35].

Warsaw University of Technology also offers a remote laboratory which facilitates studying CMOS physical defects. The equipment is based on an educational chip that contains different manufacturing defects, hence providing students advanced training on manufacturing defect modeling, detection, and diagnosis [36].

A remote laboratory in France, the National Test Resource Center (CRTC), provides support in integrated-circuit testing via the remote use of industrial test equipment. The center has been established in connection to the Commitee National pour la Formation en Microelectronique to meet industrial demands in engineering curriculum in terms of design and test competences. Currently, CRTC is being hosted by the University of Montpellier [37].

A remote laboratory for microelectronics has been developed at the University of South Australia, which allows students to test their circuits directly on the silicon wafer under a microscope. The advantage of this approach is that the system is completely independent of the circuit design and does not require any prewiring. An interesting aspect of the laboratory is the high-precision positioning of test probes to be controlled remotely via the Internet [38].

Some other well-established remote laboratory examples in the area of microelectronics, as referred in [3], are WebLab [39] at MIT, AIM-Lab [40] at Rensselaer Polytechnic Institute, LAB-on-WEB [41], Next-Generation Laboratory [42], [43] at Norwegian University of Science, and RETWINE [44] at the University of Bordeaux, France, the University Autonoma of Madrid, Spain, and the University of Applied Sciences of Münster, Germany.

2) Remote Laboratories for Power Electronics and Electrical Drives: Education in power electronics requires a background in a wide range of disciplines, such as physics, electrical circuits, analog and digital electronics, as well as informatics and automatic control. Valuable training experiments will also involve the addition of loads to the power-electronics circuits, such as different electric machinery. Hence, most power-electronics laboratories, remote or on-site, will also involve electrical drives. These subjects have been gaining increased attraction among students and researchers nowadays due to escalating need for alternative energy sources and related generation and distribution efforts.

While some universities have tried to address the educational needs of power electronics via virtual laboratories as in [45]–[47], Lunghwa University of Science and Technology offers a reconfigurable power-electronics test bed, a web-based distance laboratory, and a user-interactive e-learning platform. The reconfigurable power-electronics test bed can be configured by the students via a web-based interface to construct a wide variety of converters and inverters remotely. A matrix switch module PXI-2529 from the National Instruments Corporation is utilized for this purpose. The matrix switch module can be used to connect any input to any output; hence, the system has the capability to dynamically change the internal connection paths without any external manual intervention [48].

Another power electronics and drives example is offered at the University of Alcalá, where a multilevel converter is made available to be controlled and supervised remotely in a secured way. This remote laboratory provides access to a wide variety of laboratory experiments, from grid connection to ac-motor control. Users can choose the control structure, control parameters, and the kind of load and get the graphical results of the measurements, all in real time [49].

The Center of Technological Innovation in Static Converters and Drives, Technical University of Catalonia, has developed a remote laboratory which offers a programmable-logic-controller (PLC)-based electrical-drive platform. Hence, unlike other platforms which merely train in PLC programming [50], this laboratory focuses on the control of electrical drives as well as PLC programming. The platform can be accessed through the Internet without the need for a server and therefore allows the student to operate in the same environment as if s/he were dealing with a real industrial process. Part of the hardware (PLCs and inverter) and software (CoDeSys software) components are typically used in real industrial applications [51].

Pires *et al.* [52] present another web-based laboratory aiming the study of electrical-machine dynamics. A mechanical load simulator is presented to this aim, which allows testing the behavior of an electrical machine under different load types, such as load torque depending on time or speed. The remote laboratory uses MATLAB and is based on an I/O interface controller and client–server architecture.

Turan *et al.* [53] describe the remote power electronics and drives laboratory at the University of Alaska Fairbanks (UAF). The lab provides on-site and remote access to buck-and-boost-type dc–dc converters and inverters as well as the control of permanent-magnet dc, permanent-magnet synchronous, and induction-motor motor-load sets for power electronics and electrical drives, electrical machinery, and motion-control courses.

3) Remote Laboratories for Control and Automation: The highly theoretical and abstract concepts of control engineering can only be overcome by allowing students to put these theoretical concepts into practice on diverse and interesting test beds which are preferably also similar to those seen in industry. Virtual and remote laboratories in particular can have a lot of use for the education of control, whether within the context of servo control, robot control, process control, or automation. In this section, interesting examples and practices in web-based control education will be discussed with examples from the areas mentioned earlier. However, examples related to robot control will only be discussed here if the purpose of the laboratory is control of the robot. Web-based robot laboratories also involving robot kinematics and dynamics education will be discussed in the upcoming section devoted to remote robotics laboratories.

Huba and Simunek [54] aim to teach control theory, with concentration on the PID controller, as the most popular control algorithm in industries and academia. This paper provides a relevant discussion of difficulties faced in control education and presents the implemented approach as a solution, entailing the use of e-learning material, interactive electronics course material in Moodle, the virtual laboratory, WebLAB, and remotely accessible plants.

A thoughtful discussion on control education and an interesting remote-laboratory solution is offered in [55]. This remote laboratory at http://www.cremona.polimi.it/crautolab offers access to two main plants, namely, a thermal control plant and a velocity control plant with the use of the LabVIEW web-server technology to access the experiments with only a web browser and an *ad hoc* communication layer designed to allow for remote access to real-time control loops.

Most existing remote-control experiments provide the users with a variety of experiments and allow them to change control or system parameters. One such laboratory is the University of Maribor's DSP-based remote laboratory, based on an in-house developed embedded controller and two commercially available software packages, namely, MATLAB/Simulink and LabView. MATLAB/Simulink is used for experimental control algorithm development, while LabVIEW is used for the user front-end and remote control. The developed control test beds (dc motor control, SCARA robot control) allow the users to change predefined system parameters on the provided control algorithms, i.e., a cascade controller, proportional–derivative (PD) controller, and computed-torque controller, to track a predefined reference trajectory. System responses can be observed in textual, graphical, or video format. This remote laboratory also includes a booking system, which enables remote users to book experiments in advance [56].

The Internet-based teaching and experiment system for control engineering (ITESCE) laboratory for web-based teaching and control engineering experiments [57] provides students with online course material, a simulator, and online access to control experiments on a robot arm. The ITESCE is based on standard browser/server architecture with three layers and employs multithreading, Java applets, and Java database connectivity. The real-time control experiments are handled by background control subsystems, while a network server handles communication with clients and with background control subsystems. The ITESCE can be accessed at the following Web site: http://mrobot.csu.edu.cn/ArmRobotWeb/armrobotindex.htm.

Another web-based laboratory example is the one for a 2-DOF helicopter [58], providing four different predefined controller types, of which the remote users can change the parameters.

Unlike the previously mentioned control laboratories, the Automatic Control Telelab (ACT) of the University of Siena at http://act.dii.unisi.it enables students to design their own controller, besides allowing them to choose from the provided list of controllers, of which they can change the parameters online through the MATLAB/Simulink environment. Using ACT, the remote users can design a custom controller and reference signal on a local PC and, after successful simulation, upload it to the ACT server and verify the performance against the actual remote system. The ACT laboratory provides access to several interesting nonlinear systems, such as magnetic levitation and water tank control, as well as dc motor control, and a helicopter simulator. The ACT architecture is based on a bootable CD.

The UAF Remote Robotics and Control Laboratory also allows users to implement their own control algorithms as well as predefined controllers, such as PID, PD, and sliding-mode controllers, to track predefined trajectories on various robotic systems. The available robot systems are open for control and consist of an open-architecture 6-DOF PUMA 560 manipulator and two hardware-in-the-loop (HIL) robotic simulator platforms [59], one for geared-type and one for direct-drive robots. The users access the test beds through a web browser and do not need to download any software on the client side. The connection between the remote user and the experiment is provided by a database server [53].

Another control laboratory allowing for users' own algorithms is the Networked Control System Laboratory in the University of Glamorgan, U.K., at http://www.ncslab.net. The laboratory provides a unified and flexible web-based interface to access test rigs, i.e., magnetic levitation, servo motor, etc., located in different countries of the world. This distributed facility is organized using a three-layer structure, consisting of the main server, subservers, and test rigs. The laboratory also allows for remote users to implement their own control algorithms for the test rigs using the MATLAB Real-time Workshop and a template file as proposed in [59]. The web interface is designed using Java JSP/Servlet [60].

There are also educational game activities to motivate students in the area of automatic control. One such interesting web-based game is a simple submarine game developed at the University of Stuttgart. The game involves trajectory tracking of submarines using state feedback, output feedback with a state observer, and PID controller [61].

Automation systems entail the control of various local and remote systems composed of many actuators and sensors. A quality education and training in the area requires the use of real industrial systems and components which are often difficult to adapt for education [62]. A web-based laboratory using emulated models for automation systems education can be found in [63].

A remotely accessible automation system is offered at the University of Reims Champagne-Ardenne both for teaching discrete-event systems and PLCs. The automation system, PRODUCTIS, is an industrial integrated manufacturing system that hinges around a pallet-based free-transfer system designed to bottle-pack medicine tablets. Two validation filters have been developed to address safety concerns involved with the remote (or local) use of automation systems in education [62].

The Technical University of Valencia's remote laboratory also provides an environment to instruct students in the aspects of the design, development, and validation of applications for process control, automation, industrial informatics, and embedded systems. A remote-laboratory architecture, SimPROCes, developed to this aim not only permits the teleoperation of simulators/real prototypes but also allows control applications be remotely tested and validated. The simPROCes is precisely specified to be independent of the model of computer, data-acquisition card, programming language, and operating system and is transparent to the programmer and easy to use [64].

Another remotely accessible automation laboratory is at the University of Technology, Sydney, offering access to six setups, namely, PLC experiments, coupled water-tank experiments, shaker-table platform experiments, as well as FPGA, embedded system, and beam-deflection experiments [12]. The Technical University of Catalonia also offers education in automation via an e-course based on a flexible manufacturing cell, resulting from the collaboration between the university and Schneider Electric and its training center. In this remote course, students perform the automation of the cell with commercial (PLCs) [54].

INSA-Lyon in [65] also offers a technological platform featuring modern controllers and industrial networks in an aim to illustrate the concept of the transparent factory, which entails Internet-based technologies that provide seamless communication between plant-floor and business systems to improve collaborative management. This shared platform is put in the use of all academic and industrial users and centralized for education and long-life learning.

Another interesting remote laboratory example is the remote computer numerical control (CNC) lathe system, located 70 mi away from the Instituto Tecnológico y de Estudios Superiores de Monterrey Campus Toluca in Mexico. The system has been set up with a three-component piezoelectric dynamometer, piezoelectric accelerometers, and an impulse hammer in order to receive force, acceleration, and stiffness measurements in real time. Through the use of computers in class, it is possible to send a CNC program to the lathe and retrieve the current program loaded from it, using Internet and wireless communications for the data exchange [66].

Escola Superior de Tecnologia de Setúbal also offers a remote laboratory example, contributing mainly to education in automation engineering. The laboratory integrates PLCs and oscilloscopes into the same industrial network combined with a supervisory-control-and-data-acquisition supervision system. The system is highly reconfigurable, supporting several working benches with different experiments, and due to the developed PLC/Ethernet-based architecture, it can easily be extended to other engineering fields. The Internet integration of fieldbus systems enables information from supported devices to be exchanged across equipment and users [67].

4) Remote Laboratories for Robotics: There are a number of virtual- and remote-laboratory applications aiming for robotics education. Software and hardware platforms in the area commonly use MATLAB, LabView, as well as C/C++ and Java, and often involve mobile robotics as a means to enhance the teaching of basic sensing and intelligent control principles. Other examples of virtual laboratories in this area are given in [68] and [69] for mobile robots. On the other hand, examples of remote laboratories providing physical access to robotic manipulators are few. The capabilities of web-based robotic-manipulator laboratories often provide simulations and 2-D or 3-D animations of robot-arm motion and/or offer practice with motion commands to achieve desired end-effector's positions based on Cartesian or joint space. One such laboratory example is described in [2] and presents a Java-based interface providing both simulation and teleoperation of a robot. A pilot study in [70] presents a comparative evaluation for three training modalities: real, remote, and virtual training on robot-manipulator programming. The manipulator in consideration is a SCARA-type AdeptOne-MV manipulator. For training purposes, an interactive control panel has also been implemented and integrated with the system, providing an exact emulation of the robot's manual Teach Pendant, called *Virtual Pendant*. Another example of remote programming of remote robotic manipulators is given in [71].

The University of Siena's Robotics and ACT is established as an extension of ACT at http://act.dii.unisi.it to allow students to interact with a remote robot manipulator, 6-DOF KUKA KR3 manipulator, for basic and advanced experiments, like inverse kinematics and visual servoing.

On the other hand, UAF's previously mentioned HIL robotic simulator systems [59] allow users to implement the dynamics of any given robotic structure, whether of geared or direct-drive type. The remote laboratory already supports several predefined system dynamics, such as PUMA 560, 2-DOF planar robot, and single-link rigid and single-link flexible arms [53], [72]. Recently, the predefined system dynamics examples have been further enhanced with the dynamics of Acrobot and Pendubot, also implemented on the HIL system both for on-site and remote use.

The Telelaboratory at the University Jaume-I (UJI) in Spain similarly offers access to one industrial and two educational manipulators to train in teleoperation, programming, visual servoing, and speech recognition. The UJI manufacturing cell is also added to the remote-laboratory capabilities to provide training in real-time reconfigurable vision for grasping and a fast protocol for distributed sensors and actuators in an IP wired network [73]. The University of Alicante in Spain also has a remote platform for both virtual and physical access to control the 5-DOF Scorbot ER-I (Intelitek) with a gripper [74]. Another example of remote robot-manipulator laboratories is the remotely accessible Asea IRB-6 robot manipulator in Cuba [75], providing training for students in the fields of robotics and advanced control theory.

There are also remote mobile robot examples: One such laboratory experiment is developed at Utah State University (http://www.csois.usu.edu/people/smartwheel/CompleteInfoPage.htm), providing access to a stand-alone three-axes robotic wheel (Smart Wheel) assembly [76] for education.

There are also multirobot platforms with remote access aiming education and competitions for increased motivation among students for the field of robotics and control. One such platform is Teleworkbench at the University of Paderborn, Germany, offering experiments both with single and multiple robots. The platform provides a standardized environment to achieve benchmarking in robotics, furthermore allowing for scaling the minirobot algorithms up to larger platforms or down to microelectromechanical systems (MEMS) [77], [78].

Another remotely accessible mobile multirobot platform is established for students to remotely program the robots to participate in games to accomplish a set of goals in a remote stadium (the RoboStadium). The platform also provides online training to facilitate the use of the robots, hence contributing to robotics education as well as mechanics, electronics, control, mathematics, and computers at different class levels [79].

5) Microprocessor, Reconfigurable, and Embedded Systems: Embedded systems are now in all aspects of our lives, from home to office, from factories and transportation vehicles to our personal items and clothing. The ubiquitous use of embedded systems combined with the extremely fast-paced technological developments in the area also call for a high quality of education with a lot of hands-on practice. In this endeavor to keep students abreast with state-of-the-art technologies out there, it is also important to assure teaching foundations from Boolean logic and assembly language, complemented with sufficiently advanced topics, such as hardware–software codesign, system-on-chip, and network-on-chip. Gomes [80] proposes the current approach taken at the Universidade Nova de Lisboa based on the use of programmable logic devices as supporting platforms for experimentation, from introductory to advanced courses, including microprocessor-based system design, within a typical "embedded systems track" course structure.

Among other examples in the area of microprocessors, one can mention the "lab-in-a-box" [81]. The system consists of a metal case needing only power supply and network access to provide a complete infrastructure to establish a microprocessor laboratory for embedded-system applications in computer engineering. The laboratory is used in distance teaching, and thus, all instruments and devices are controlled and observed via the net. There are also combined hardware and virtual laboratory examples in microprocessor teaching [82] at http://www4.ncsu.edu/_efg/wcae/2004/.

Unlike digital systems that have predetermined and unchangeable functions, FPGAs can be reprogrammed for different hardware functions, hence are excellent alternatives to custom ICs. Currently, they are being used for applications that were traditionally in the domain of application-specific integrated circuits, also becoming an important component in remote teaching of digital electronics and embedded and reconfigurable systems [83]. Another example is the FPGA-based remote laboratory in [33], offering prototyping capabilities to students and designers for their digital electronic systems, as well as integrating such platforms with a simulation environment. The University of North Carolina at Charlotte also offers a platform for FPGA education, the structure of which is described in [84] and [85]. The platform provides access to 64 Xilinx ML-310 Boards over the Internet. The remote platform gives users the ability to dynamically power on/off the FPGA boards, upload/download files, configure the boards online, and execute synthesized designs while sending input and output through the Internet. A Spartan-3E-based FPGA laboratory is presented in [86] at the University of Bahrain.

Examples mentioned in this section summarize only a few of the recent remote experimentation platforms in most common remote-laboratory application areas. Extending the examples to other disciplines within the IEEE Industrial Electronics Society (IES) areas of interest, one can also mention some recent virtual and remote laboratory examples in mechatronics monitoring and control [87], [88], in sensors and data acquisition [89], and in power systems [90], power quality [91], solar energy [92], and wind energy [93] training and research.

V. Conclusion, Current Trends, and Challenges

This paper has provided an overview of the state of the art in remote laboratories and related technologies, with examples in several selected areas within industrial electronics. In this section, a brief overview will also be provided to discuss identified current trends and challenges. These issues are related to supporting technologies that may open new possibilities for the implementation of new functionalities, while ensuring the proper integration of the developed capabilities with LMSs and institutional portals, also taking advantage of specific teaching and learning methodologies, as well as collaborative activities involving different educational institutions.

A common feature of most existing remote laboratories, whether for educational or industrial purposes, is that they offer stand-alone solutions, with limited or no capability to cooperate with other platforms. Most of these solutions are developed as special or *ad hoc* solutions relying on different types of technologies and both computer and human languages and often use heterogeneous and incompatible hardware and software tools. In that sense, the major challenge in current remote laboratories appears to be the lack of standardization, impeding the modularity, portability, and scalability of solutions, as well as interoperability between different solutions.

From this point of view, future contributions in the area of service-oriented architectures and adequate metamodels (as SCORM and IEEE LOM), as well as open frameworks (as VISA or IVI), could be considered as key aspects to overcome current limitations.

The conveyed extensive literature review in web-based laboratories has also revealed a high number of publications in the area, with many papers discussing solutions for certain aspects of the related technology and others giving examples of test beds made remotely accessible with the use of the Internet. Even with so many successful experiences on the web, some resulting from international cooperation, an important challenge remains to be ensuring actual benefits for education and research with a given remote laboratory, along with the proper demonstration of benefits achieved with the development of that laboratory. Hence, it is essential to quantify the benefits of using remote laboratories within teaching and learning processes. An effective integration of remote laboratories with up-to-date LMSs is a key aspect in improving the impact of remote laboratories within the educational process.

Accessibility is also a major concern. Providing easy access to remote laboratories from developing countries (where computer access is limited and bandwidth is constrained) is a major challenge as well as a worthy goal, as remote laboratories are expected to be facilitators to get access to resources otherwise unavailable.

In addition, facilitating the use of remote laboratories by disabled or special needs people should be a major goal and yet remains to be a challenge. The Web Accessibility Initiative (WAI) (http://www.w3.org/WAI/), promoted by the WWW Consortium, provides specific recommendations and guidelines to produce accessible sites [94].

In the wider sense of accessibility, the 24/7 availability of remote laboratories also remains to be an issue. Although mentioned in the introduction of almost all remote-laboratory-related publications, solutions for 24/7 accessibility are rarely ensured or even addressed in actual remote-laboratory applications. Most literature examples discussing remote-laboratory applications limit themselves to only a proof of concept for proper and continuous operation, without an adequate discussion of resources or functional plans to address this issue. Hence, accessibility, which is one of the major reasons why remote laboratories have ever been considered, may be worthy of further attention in future studies.

Efforts in addressing accessibility issues also have a severe impact in the remote-laboratory development processes, where the constant evolution of development technologies is a major concern. Model-based development and the model-driven architecture proposed by the Object Management Group (http://www.omg.org/mda/) are important contributions [95] to address accessibility issues.

One other major trend in remote laboratories is related to configurability issues. Clearly, the static structure of most online experiments is of limiting nature. Although motivating as a starting point and initially interesting, providing remote users merely with the capability to configure some parameters in a predefined experiment may not be considered a realistic replacement for hands-on experiments or even a very beneficial learning experience; hence, future studies concentrating on full configurability capabilities would be very much welcome, in accordance with the ultimate goals of remote laboratories in their emphasis and support of student self-learning skills and student-centered approaches as well as life-long learning. Currently, only a few experiments allow changing the experiment setup, most of the time in a very limited way.

Integration of voice-over-IP applications and other collaborative applications are also worth mentioning, as they will increase the interaction among remote users and computer-supported collaborative learning, giving the students with a feeling more similar to that of actual presence in a physical laboratory.

Last but not least, providing all hardware remote laboratories with accompanying computer simulations, animations, and video recordings (online or offline), wherever possible, could have many benefits, i.e., computer simulations could act as an initial "draft" platform before actual experimentation on physical systems, hence addressing some safety and security concerns due to the multilevel use of often rather costly actual equipment. Animations and recordings, on the other hand, could increase the feeling of "realness" and engagingness of remote laboratories, also putting the Internet to the use of science and engineering fields by attracting younger generations (who already spend a lot of time on the Internet) to these areas, which are currently (and unfortunately) underadvertised.

In summary, with the proper addressing of the aforementioned issues and unmentioned many others, remote laboratories have a strong potential to act as facilitator for supporting collaborations between institutions, teachers, students, and researchers worldwide and can have significant contributions to science and engineering at different levels, ranging from the development of new frameworks and experiments to the generation of new technologies put into the use of all mankind.

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Luís Gomes (M'96–SM'06) received the Electrotech.Eng. degree from the Universidade Técnica de Lisboa, Lisbon, Portugal, in 1981 and the Ph.D. degree in digital systems from the Universidade Nova de Lisboa, Lisbon, in 1997.

From 1984 to 1987, he was with the R&D Engineering Department, Empresa de Investigação e Desenvolvimento de Electrónica (EID), a Portuguese medium enterprise, in the area of electronic system design. He is a Professor with the Department of Electrical Engineering, Faculty of Sciences and Technology, Universidade Nova de Lisboa, and a Researcher with the Instituto de Desenvolvimento de Novas Tecnologias, Caparica, Portugal. He is the author of more than 100 papers published in journals, books, and conference proceedings. He was the Coeditor of the books *Hardware Design and Petri Nets* (Kluwer Academic Publishers, 2000), *Advances on Remote Laboratories and e-Learning Experiences* (University of Deusto, 2007), and *Behavioral Modeling for Embedded Systems and Technologies: Applications for Design and Implementation* (IGI Global, 2009). His main interests include the usage of formal methods, like Petri nets and other concurrence models, applied to reconfigurable and embedded-system codesign.

Dr. Gomes has been serving in different roles for the organization of conferences, namely, as General Cochair for the 2nd and 3rd IEEE International Conference on e-Learning in Industrial Electronics (ICELIE'2008 and ICELIE'2009), among other events.

Seta Bogosyan (M'95–SM'06) received the B.Sc., M.Sc., and Ph.D. degrees in electrical and control engineering from Istanbul Technical University, Istanbul, Turkey, in 1981, 1983, and 1991, respectively. She conducted her Ph.D. studies in the Center for Robotics, University of California, Santa Barbara.

She was a Researcher and Lecturer with the Center for Robotics, University of California, between 1987 and 1991. Between 1992 and 2003, she was an Associate Professor with Istanbul Technical University. She is currently a Professor with the Department of Electrical and Computer Engineering, University of Alaska Fairbanks. She has authored over 90 journal and conference publications and a book on modeling and control of induction motors. She is the Principal Investigator of several National Science Foundation, North Atlantic Treaty Organization, and other federally funded research grants. Her research interests are nonlinear control and estimation techniques for electromechanical systems with applications in direct-drive systems, sensorless control of induction motors, hybrid and autonomous vehicles, time-delay compensation in bilateral systems, remote robotics, and sensor/data fusion.

Dr. Bogosyan is the Associate Editor of the *International Journal of Intelligent Automation and Soft Computing*, the IEEE TRANSACTIONS OF INDUSTRIAL ELECTRONICS, and the *IEEE Industrial Electronics Magazine*. She is currently the Chair of the Industrial Electronics Society Education Committee and a member of the Technical Committee (TC) on Education in Engineering and Industrial Technologies and the TC of Motion Control.