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Overview and future trends of control education

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Abstract: Control education is a mature area in which many professors and researchers have worked hard to face the challenge of providing a versatile education with a strong scientific base. All this without losing sight of the needs of the industry; adapting the contents, methodologies, and tools to the continuous social and technological changes of our time. This article presents a reflection on the role of automatic control in today's society, a review of the traditional objectives of control education through seminal work in the area, and finally a review of the main current trends.

Keywords: Cultural and social issues of control education; challenges for control engineering curricula; pedagogy in control engineering.

1. INTRODUCTION

In September 1952, Scientific American published an entire issue devoted to automatic control. The role that this discipline was playing in the new advances of the time, particularly in manufacturing processes, was highlighted. Since then, control has become less and less visible to the general public, perhaps in part due to its success. People use numerous control applications without being aware of it, from electronic amplifiers, tuners, and filters in television and radio, to congestion control algorithms that allow fluid communication over the Internet, through control systems for commercial aircraft to cite just a few examples. For this reason, automatic control is known as the hidden technology (Åström (1999)).

Control is not only widely used in production processes to improve their functionality, performance, and efficiency, but has also been able to address new fields of application that were unthinkable until not long ago, such as collaborative robotics, autonomous driving and space exploration vehicles. This implies that automatic control is not only critical to improve today's products, solutions, and systems, but it is also a critical technology for carrying out future visions in emerging areas such as biomedicine, renewable energy, critical infrastructures and industrial cybersecurity.

Table 1. Five major shifts in 100 years of engineering education

1	A shift from hands-on and practical emphasis to engineering science and analytical emphasis.
2	A shift to outcomes-based education and accreditation.
3	A shift to emphasizing engineering design.
4	A shift to applying education, learning, and social behavioral sciences research.
5	A shift to integrating information, computational. and communications technology in education.

The evolution, great challenges, theoretical advances, maturation, and success stories that have occurred in the field of automatic control education have been documented over the years in numerous articles, reports, and reviews. These challenges have been the subject of debate over time, but many of the most influential works are generally little known by the community.

One of the fundamental challenges, since the beginning of the discipline, is how to unify the training needs of the industry, normally marked by a strong technological component of immediate application and therefore specific to the field of interest, with a theoretical based general training of a transversal field like control. The work of Bristol (1986) reflected on this dilemma.

Later, to address emerging challenges and opportunities, the IEEE Control System Society organized a seminar to

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Table 2. Conclusions of the "NSF/CSS workshop on new directions in control engineering education"

1	Control systems technology is the hidden science that underlies virtually all aspects of modern society.
2	Common conception of control,even among many scientists and engineers, is too limited to encompass the scope of the control systems field.
3	Applications of control systems technology will increase dramatically in the future with advances in technology.
4	Internet represents a major opportunity for control systems education.

identify future needs in control education (Antsaklis et al. (1998)). Its main conclusions are summarized in Table 2.

The report Murray (2003), funded by the US Air Force Office of Scientific Research (AFOSR), analyzed trends in control and dynamic systems to provide a fresh look at the challenges and opportunities in this field including the main issues of control education.

The review Åström and Kumar (2014) provided a comprehensive historical account of the development of the field, as well as an outlook on future opportunities and reflections on the interplay between theory and practice. In addition, Samad and Annaswamy (2013)'s report provided an overview, success stories, and research challenges that the field faces.

Finally, according to Froyd et al. (2012), in the last 100 years there have been five major shifts that have marked the evolution of engineering education. These shifts are detailed in Table 1. The first two shifts can be said to have been successfully completed in the last century and the remaining three are still under development and, in a certain sense, will be the subject of analysis in the following sections.

2. REDUCING THE GAP BETWEEN ACADEMIA AND INDUSTRY

Education, training, and dissemination of automatic control ideas must evolve and adapt to the requirements demanded by the society of the future.

A key element is the development of new content and courses that emphasize feedback concepts as well as the mathematics necessary for their understanding, without requiring students to come from a traditional engineering background. As more students in biology, computer science, environmental science, physics, and other disciplines want to learn and apply the methods and techniques of automatic control, new ways to provide the necessary knowledge should be explored.

It is important that students are provided with a balance between theory and application, so they are capable of solving real problems from the conceptual design to the final implementation and commissioning. This implies that these skills need to be considered as an integral part of the control engineer's training.

On the other hand, a capital sin of automatic control is to believe that the systems to be controlled are given a priori. The traditional approach of developing sequentially and separately the design of the system and the control of its components, equipment, and machines is no longer sustainable, in view of the increasing complexity and the need for optimal use of resources. Very good arguments for the integrated design of a process and its control system were already exposed very eloquently in the initial works of Ziegler and Nichols (Ziegler et al. (1942)) where a special emphasis is made on the fact that too often the control engineer is faced with a process that is very difficult to control properly. A good controller can never mask a bad design of the system. Flight control is a good example of integrated system and control design. The Wright brothers succeeded where others had failed because they made an unstable airplane that was maneuverable. Modern fighters reach their high performance this way (Stein (2003)).

2.1 Curriculum issues

Traditionally, the control curriculum has been characterized by being quite homogeneous throughout the university spectrum, especially in the first year courses, however, the technological changes that have occurred recently have led to the development of new teaching tools that have motivated changes in the methodologies used in the curriculum.

Different scientific associations linked to the automatic control area, such as IFAC, CEA-IFAC, EUCA and IEEE, have carried out activities and events related to control education in their respective international congresses and journals. In these discussion forums, two questions that are considered essential have been analyzed: 1) How to optimally apply the new teaching methodologies and 2) What is expected to be the future of automatic training and what should be its orientation.

In this sense, sponsored by the control education committees of both IFAC and IEEE, an important study is presented in Rossiter et al. (2020) on what should be the approach for a basic control course. Based on a broad and elaborate questionnaire, which was debated and discussed in different IFAC congress panels in 2018 and 2019, approximately 500 surveys were carried out among professionals, both in the academic field (84%) and in the industrial field (16%) from 47 countries. In the conclusions of this work, despite the wide diversity of degrees, nationalities, and different roles of the professionals considered, it can be said that a broad consensus was obtained regarding the main thematic blocks, although, given the transversal nature of automatic control training, the curriculum should be nuanced and adapted to the career in which the course is taught, since the scope of application is very different from industrial engineering to aeronautical engineering, or to the fields of robotics or process control.

Regarding the practical curriculum, the available information is not as homogeneous or generalized as in the theoretical curriculum, since depending on each degree and each university, the available practical resources are different (and scarce in most cases). This has caused practical training to be addressed in very different ways, but with a common characteristic such as the widespread use of computer simulation tools, which, although they provide the student with important help for the acquisition and settlement of basic concepts of control, do not cover, in general, all aspects of control systems and do not allow addressing the problems associated with the implementation of control systems.

Another key issue related to the above, is the acquisition by the student of skills and practical abilities on real laboratory equipment, not simulated, that facilitate not only the establishment of the theoretical and practical concepts of control but also of the knowledge necessary to handle the instrumentation associated with this type of experimentation, so that they are capable of acquiring, treating, recording, processing and representing, both with electronic instrumentation and with software tools, the data linked to each trial/experience.

2.2 Lifelong learning and industry

Providing control training for workers in industry and general engineering graduates has always been an important activity in the area of systems engineering and automatic control. This activity has facilitated the transfer of up-to-date knowledge and innovation towards the production sector. Nowadays, it can be assured that these activities will have to be reinforced as a consequence of the strong technological changes that are going to be experienced and due to the lack of skills in key new technologies in the available human resources.

Indeed, in the future, the transfer of knowledge to the productive sector from the field of control will have to be focused, not only to cover the needs of the workers as a result of the evolution of the technology itself, but also, in providing the necessary digital skills on which these training activities will be based and for which there are serious shortcomings.

Another important challenge that will have to be addressed as a result of the transformation of production structures will be what is known as industrial cybersecurity. This must be understood and applied as an additional and essential tool, already at this time, in the implementation and deployment of any type of automation, control and supervision strategy, taking into account the aspects of secure software development and with the validation, testing and auditing of the algorithms and programs used.

As in other disciplines today, automatic control requires data management and its algorithms wherever it is applied, both for the extraction and management of knowledge from systems, and for their operation, presentation, and visualization in modern industrial supervision systems in which it is increasingly necessary to have more holistic and complex representations. The industry has been obtaining and accumulating data from its processes for years, but making basic use of them, since, in general, it has difficulties to have the necessary and qualified human resources that can tackle these tasks.

3. REFRESHING THE METHODS

From 1958, the IRE and IEEE Transactions on Education [1], the IEEE Proceedings, and other engineering education journals, such as the Journal of Engineering Education, have focused on many topics that are important in engineering education, including which content should be taught and how it should be taught, accreditation, design, research, and how to use technology in engineering education. How do students learn better? This issue continues to be raised and debated among experts.

In the automatic control area, and probably in most engineering areas, there is a paradox regarding teaching methods. On the one hand, if a bibliographic search is made of studies on different methodologies in the classroom, their applications, and their results, a certain disdain or even ignorance regarding the terminology, resources and current trends is detected. However, this is not representative of the reality, since when consulting the publications of any recent congress, one observes many innovative, ambitious, complex, practical education initiatives with high implementation costs, a clear focus on active learning and the development of competencies, and the use of modern methods such as project-based learning, problem-based learning and other initiatives.

A possible explanation for this fact lies in tradition, or rather in the absence of it. Engineering schools, since their conception during the Enlightenment, have had a journey separate from traditional universities, serving the government or the bourgeoisie since their creation, to deploy and control their domains and infrastructures (Aracil (2015)). They are not limited, therefore, by tradition, but to fulfill a practical purpose. They have lived outside the legacy of great university institutions and have had no choice but to teach based predominantly on abilities and skills.

Starting from these origins, the engineering teaching tradition has remained faithful to a balance between teaching based on direct transmission and teaching based on student activity.

The master class or lectures may be the methodology that has raised the most controversy and rejection in recent times. However, this fact contrasts with the importance of its use. The characteristics of this medium have recently changed substantially and require a review and reflection of its possibilities and limitations in the context of automatic control. In the book Dynamics Lecturing (Harrington and Zakrajsek (2017)) a defense of the lecture as a means of teaching subjects at grade level is made, and in many cases concrete strategies for student involvement are proposed, based on numerous scientific evidences. This work and its references maintain that lecturing is the teaching medium with the greatest bandwidth, that is, with the greatest quantity and quality of the concepts that can be transmitted in a given time. It also excels in psychological and social factors, facilitates the correct ordering of scientific concepts, and allows the transmission of nonexplicit knowledge by observing the skills of the teacher, for example, by building and debugging complex simulations, or adjusting controllers by iterative methods.

The expansion of information technologies, which support the adaptation of learning rhythms, sometimes play an opposite role: the projection of mathematical developments

[1] The Institute of Radio Engineers (IRE) was a professional organization, based in the United States, that existed from 1912 to 1962. On January 1, 1963, it merged with the American Institute of Electrical Engineers (AIEE), thus forming the Institute of Electrical and Electronics Engineers (IEEE).

on the screen, without the pace forced when developed by hand on the blackboard, can be considerably counterproductive. In general, it is considered a good teaching practice to carry out proofs by hand in class, in front of a blackboard or a digitizing tablet, and, if possible, record them for later reference. In this way, the lecture gradually unfolds at an accessible pace, accompanied by spontaneous comments and reflections, iterations, and even controlled errors, which bring the student closer to the learning the process (Rossiter et al. (2018)).

One last mention with respect to lecturing is that the COVID-19 pandemic has made it possible to demonstrate in some detail the differences between teaching a class in person or remotely. In particular, face-to-face communication generates an affective psychological bond between the classroom participants that is difficult to reproduce in virtual form, which in general, is worse.

The problem-based learning methodology has a name that may seem trivial, but it is less common than one might think. It is a methodology that consists of early exposure of students to problems, even if the theory has not been fully developed. By knowing the problem in advance, students receive with greater motivation the concepts and procedures that help solve them. In the field of automatic control, this approach is rarely used, although almost all classic courses and texts on the fundamentals of control begin with one or more motivating examples.

A variant of problem-based learning is challenge-based learning, where the problems that students are exposed to come from real problems that arise in society (Rajkumar et al. (2021)). This paradigm is popular in the area of business administration, known as the case study method, and in certain areas of engineering such as transportation, energy, and the environment. With this methodology, when translating an industrial problem into a series of specifications, the student has to specify a path between many possible alternatives, with a high degree of uncertainty.

In the area of automatic control, it is not easy to frame this methodology, since, as previously mentioned, the specialized language is necessary for the description of the problems. However, in more specific topics such as artificial vision or drones, the equipment is becoming easier to operate or program thanks to technological progress, shifting the focus of training from implementation skills to more abstract and practical skills. , of projecting the challenges of reality onto the tasks that these systems can perform.

The learning methodology based on projects and challenges is fully developed when the student can dedicate one or two months to a specific task, developing a sequence of decisions, trial and error tests, assembly and connection of hardware, programming and analysis of results iteratively and cyclically (Frank et al. (2003)). Many take-home laboratory initiatives have contributed to its development, in which students can work with pendulums, quadrotors or robotic systems individually or in groups to reach a functional result.

Another of the pedagogical possibilities that automatic control technology allows is the approach of competitions and games among students, which is a powerful tool for teachers to improve motivation and interest in the discipline (Huang et al. (2020)). For example, in recent years there have been many examples of the use of robotic competitions in teaching at all educational levels, initially in the form of open competition, without specific goals.

As a final reflection, new methodological training strategies must be proposed for an innovative development of the same in the new scenario that has been generated for a few years, such as the digitalization of society and, in particular, in the digitization of university education.

4. THE IMPACT OF NEW TECHNOLOGIES

It is clear that for a few decades the influence of new technologies on the teaching/learning binomial has been enormous in all disciplines of knowledge, and particularly in control. With the arrival of Internet, the possibility of accessing immediately and constantly to great amounts of information has become a reality. From this moment on, student face a different learning problem, in which fundamentally they must be able to build knowledge about the subject from multiple sources of information, in general many more than they were used to.

The changes generated by the technological advances used in education affect all training processes, which for simplicity we will divide into content presentation, development of abilities or skills, and evaluation of learning outcomes.

4.1 Content presentation tools

Without any doubt, one of the great education advances that the development of Internet has made possible is the appearance of online learning management systems (LMS). These systems provide a virtual learning environment in which students, through a computer with an Internet connection, access teaching contents from anywhere and at any time. These systems allow managing, programming, sequencing, and evaluating all activities related to learning.

It is possible to find different capacities in the LMS systems, but all of them have at least some basic elements such as a student registration system, a library of resources with different degrees of interactivity, a verification and/or follow-up system, as well as an evaluation and/or tutoring system.

Recently, in the field of automatic control, massive online open courses (MOOC) have become popular, offering distance learning courses that are accessible through the Internet. Most of these courses are self-contained and teaching is done entirely asynchronously. There are platforms like edX [2], where it is possible to find multiple content courses related to control. Another of these self-learning platforms is Coursera [3] with multiple courses that integrate content and self-assessment that allows asynchronous online learning.

[2] https://www.edx.org/
[3] https://coursera.org/

4.2 Tools for acquiring skills

It is essential to carry out practices and interactive experiences with physical systems to settle and strengthen the knowledge acquired. Providing engaging laboratory experiences is one of the challenges for effective college education in engineering disciplines.

Remote and virtual laboratories have been, and continue to be, a very advanced line of research by different research groups in the area of systems and control engineering, in which numerous interesting results have been obtained, which have produced collaborative and networked experiences on different types of industrial systems (Heradio et al. (2016a,b)).

However, sometimes experience with real laboratory equipment cannot be replaced by simulation. In these cases, in addition to virtual laboratories, remote laboratories have been developed in which the user interacts through the Internet with physical devices located in traditional laboratories. This type of system supposes a notable additional complexity since it is necessary to manage, control, and maintain a real physical device with which the students interact remotely as if they were physically present in the laboratory (Dormido (2004)).

Another variant that has emerged with the advancement of technology in recent years is the use of low-cost laboratories to carry out teaching practices. Although it is true that in some cases these types of laboratories cannot replace the experiences obtained with the experimentation and control of real-scale systems where the student has the option of facing situations that will appear in the industrial environment, on many other occasions they allow practice with real physical elements by accessing much less expensive devices.

Some of the common elements that appear in all these low-cost platforms are the microcontrollers used (Arduino,Raspberry, etc.) that offer powerful calculation capabilities along with seamless integration and communication with calculation programs commonly used by students such as Matlab.

Many educational centers are carrying out an additional step, such as the possibility that the students themselves previously carry out the design of the systems to be controlled from these low-cost elements available on the market. This aspect is especially interesting in engineering degrees due to its integrative nature of multiple knowledge imparted in different subjects.

4.3 Tools for the evaluation of learning outcomes

In the current context of limited resources, growing class size, and increased student demand for feedback on their progress, grading automation tools are of particular interest (Rossiter (2019)).

Automated assessment of papers and exams by computer, known as computer aided assessment (CAA), has experienced a notable expansion in recent years (Keady et al. (2012). Multiple choice tests are the most common tool of automatic grading, and yet, in engineering, due to the importance of complex mathematical and open design problems, they are seldom used.

Automatic grading processes have to be programmable to offer the flexibility needed for engineering courses. For this reason, an algorithmic evaluation paradigm has been developed, in which the teacher designs the exercise with the only requirement that the results of the work can be grouped in a data set in a quantitative way so that they can be analysed using some programming language such as C, Matlab or Python. This black box paradigm (de la Peña et al. (2012)) fits naturally many automatic control problems such as design and adjustment of controllers, frequency analysis, pole assignment, predictive control, etc. In the case of interactive tools, many of the developments that have been presented have been reprogrammed, in a way such that they collect information from the student's interaction to carry out an automatic evaluation (Farias et al. (2016)).

5. FUTURE TRENDS

The future of control education is inexorably linked to the application of the new technologies that have emerged and how teachers can take advantage of them for the benefit of university students or those who must face continuous learning of new technologies and emerging knowledge.

One of the most important roles of control engineers is that of system integrators in multidisciplinary projects. In this sense, they must be capable of using new tools and technologies which are in continuous development. This implies that control education must provide students with at least some integrating capacities that facilitate their future work.

In the traditional teaching model, teachers are the main source of knowledge in their subject, and their fundamental role is transmitting it in the classroom. Today, however, presence in the classroom is no longer essential. Virtual environments and office automation tools facilitate the preparation of materials for teachers to support their classes, generally rich in accessible bibliography, multimedia materials, simulations, videos, and complementary contents that abundantly and illustratively contribute to the learning process and of which students can use out of the classroom.

This means that teachers have ceased to be the main source of knowledge in the classroom, becoming a selector of content, acquiring a role of a counselor who provides support materials, in many cases made by other people. Teachers, therefore, must focus on guiding the student's learning through collective and individual guidance so that they can learn more and better by themselves to acquire the skills of the subject being taught. This implies that students must acquire a more active role, since they must drive their own learning based on the guidelines and means provided by the teaching staff. The interaction between teachers and students must become more active and personal, intended not to receive information and content, but to resolve doubts, clarify concepts, and evaluate the evolution of learning.

Another issue to consider is a possible global adaptation in the way of teaching to the online format. The pandemic originating as a consequence of the coronavirus (COVID-19) has caused, at least during this period, a substantial change in the format of teaching, which has been mostly carried out by distance learning through Internet. This crisis has stimulated the use, perhaps prematurely, of all technologies available at this time to continue with the educational process.

The traditional lectures taught in each of the different subjects have been carried out in an online format synchronously, through the incorporation and use by educational institutions and teachers of novel meeting platforms, which were, up to that time, little used. In this sense, it has been necessary to carry out an accelerated learning of these platforms by teachers.

On the other hand, the practical classes that are so characteristic and necessary have had to be carried out by modifying them and adapting their contents since they could not go (at least during the first pandemic stage) to the laboratory. Some of these sessions have been developed using computer tools in the form of simulations, but others have not been immediately adapted. In most of the institutions, the implementation of a dual teaching model has been chosen, in which while there are students who attend in person, fulfilling all required requirements, they coexist with classmates who attend the sessions remotely. In any case, in the future it will be necessary to reconcile and/or modulate these changes, because close and permanent contact between teachers and students is essential and necessary.

Summing up, under these conditions, university professors will have to address great challenges. They will have to change their old points of view of the teaching-learning process, teaching methodologies, technological tools, and didactic approaches. The future must be faced with an open mind, willing to incorporate new ideas, and learn from other experiences launched by colleagues in similar or related disciplines.

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