Active Learning Environments For Automatic Control Courses

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Abstract — *Over the last 6 years, different learning strategies have been tested in the Automatic Control course at Universidad de Los Andes, in Bogotá, Colombia. Problem Based Learning, Teaching for Understanding, virtual peer evaluations of student's project using Internet, Matlab simulations, and hands-on labs have been the main strategies. As a result of these experiences, the current automatic control course uses a variety of pedagogical approaches, adapting each of them to one specific course goal, and covering different learning methods on the part of students, thus improving the overall results. Course objectives are structured around understanding goals, defined as 'student performance'. This concept resembles that of 'competence'. The proposed evaluation system conforms to the selected philosophical approach. In general, no lectures are given during this course.*

Index Terms — *Automatic control courses, active learning, hands- on inquiry.*

INTRODUCTION

Throughout most of the twentieth century, engineering education was fundamentally based on pedagogical proposals centered on the following main principles:

- Knowledge is transmitted.
- Course objectives are basically defined in terms of information, statements, formulae, and procedures to be taught to students.
- A good professional/researcher makes a good teacher.

Although it may be the case that these statements do not explicitly appear in institutional documents, a close examination of what actually takes place in both undergraduate programs and engineering courses reveals their continual presence. It is only towards the end of the century that curricular proposals showing departures from these three central tenets started to surface.

These changes are the product of evidence—more and more numerous and conclusive, emerging from research in different fields—that shows that these three pillars of twentieth century education were fundamentally erroneous, that they fostered an inefficient, costly and superficial learning process.

Even though teaching practices based on the three pillars responded to the needs of twentieth century society, in present times the requirements seem much more difficult to fulfill. As a reference, see ABET Criteria 2000 [1], in particular the section on attitudes and abilities common to all engineering programs. The acquisition of this set of abilities and attitudes cannot be guaranteed within the framework of the three above-mentioned pillars.

The new proposals are fundamentally based on new pillars, more in agreement with scientific research results related to the ways in which people learn [2]:

- Each individual builds knowledge starting from what he/she already knows. Learning takes place in the borderline between what is known and what is not known. It is fundamental that what is learnt make sense for the person who is learning. *Just in case* learning is replaced for *just in time* learning.
- In educating professionals, abilities, attitudes, and competences end up being more relevant than information and procedures. More than learning, the objective then becomes understanding, being able to transfer knowledge into new problems, contexts and fields of knowledge.
- Active learning, understood as the transference of control in the learning process from the professor to the learner, calls for a faculty with specific and important pedagogic competencies. These are not achieved in the mere exercise of the profession or of research in the discipline to be taught.

In particular, Automatic Control System courses have been taught using classical teaching approaches based on lectures complemented by laboratory practices oriented to a limited design of control systems and a verification of the theory, using educational lab equipment. Normally, this type of course is supported in one textbook selected from a big offer of books available in the market. These books are frequently more structured around the discipline—in a deductive approach—than around a learning process of the knowledge of the subject in a more inductive approach. As a consequence, they are more appropriate as reference texts than as texts guiding the learning process.

In the case of Control courses, there was a slow shift from courses initially based on experimentation and the empirical methods of the 1930s towards courses that followed a fundamentally deductive procedure and had a strong abstract mathematical content. Here, students would learn the central principles—in a specific framework—starting from algebraic and mathematical developments, using the lab only as a less valued complement. This frequently gave rise to students who could answer theoretical exams with questions about concepts, or exams where they were expected to actually carry out, in paper, a design that they normally were able to validate in non-realist simulations. But these students were unable to address real problems. They could not solve more open problems related to control. Moreover, they were also incapable of transferring the acquired knowledge to other fields of knowledge. For example, very seldom would a student educated in this methodology be able to identify, in the configuration of an operational amplifier as an inversor amplifier, a feedback system that, depending on its feedback sign, may or may not be stable. Similarly, he would hardly identify an unstable behavior in a real process.

This article presents an alternative learning proposal for courses about automatic control systems, within an "Active Learning" modality that combines different types of didactics. The following section sketches the conceptual design framework, while the third section introduces a brief account of the various versions of the course taught in recent years.

ACTIVE LEARNING IN AUTOMATIC CONTROL SYSTEMS TEACHING

As already mentioned, the different modalities that grant the students control over their own learning process can be classified as Active Learning. In the "classical" proposals, it is the professor who holds much of such control: the professor decides what is learnt, when it is learnt, and how it is learnt; the professor also evaluates what the students have learnt. When the students assume control over their learning process, they must necessarily assume most of the activities oriented towards the evaluation of their own process. The students also have to define strategies for solving any difficulty. They are not only aware of what they are learning, but also of the learning process they are actually carrying out.

Within this framework, not any environment where the student carries out many activities can be labeled as an active learning environment. Even though it is true that there may be similarities between the two, what actually takes place from the point of view of the learning process can turn out to be radically different. The two following cases may be examined in order to illustrate this difference.

Case A: The students arrive in a lab where they must test a proportional control system over a position control system. They have attended the theory class, where the professor has explained what a proportional regulator is, and showed how the transference function in close loop is calculated, how stability is theoretically evaluated, and how different systems errors are calculated. In addition, the students have a lab guide where they find indications on the way to connect the lab equipment and the approximate steps they must follow in the course of the practice, as well as the results they must present (analytical calculations, simulated and real result curves, and conclusions). During the whole practice the students remain active, they follow the guide's instructions, collect data, and prepare the report.

Case B: The professor presentes a process requiring a positioning system endowed with a control system meant to guarantee the achievement of certain given specifications. To carry out their task, the students may use whatever elements they deem necessary, and as a final result, they must hand in a report indicating the selected procedure, the chosen teamwork methodology, and the obtained results, showing the fulfillment of the expected requirements. They must also hand in a reflection on the new knowledge and concepts acquired. In the course of the proposed practice, after the problem has been analyzed and the students have identified what they need to learn in order to solve the problem, there may be a session in which the professor, responding to inquiries formulated by the students, presents some issues to the class. The professor may suggest that other students present the issue or prepare a presentation for the rest of the class. Throughout the practice, the students remain active, discussing, searching, assembling models, collecting data, and drafting the report.

An unprepared visitor would only note very few differences between the two classes. In both cases, the professor would probably be ready to answer the students' questions while they work. But a more detailed examination can show some differences such as, for instance, in the second case each team is working on a slightly different process, all designs do not reach the same results, and the sough-after solutions seem different.

There is indeed ample difference between the two cases. In the first one, even though the students are active, the professor is in control of the learning process. In the second one, each student controls a significant portion of his/her own learning process. The professor has not told the students what to study, which exercises from a textbook to carry out. The professor has simply presented a challenge for them to solve, and has asked them to think about what they are doing and the reasons why they are doing it. The evaluation will probably be done with the students examining their own results. Additionally, the students will not only be learning the contents required in the discipline, but also they will be developing transversal abilities and attitudes (learning to learn, working as a team, solving open problems).

As was mentioned in the introductory section, the basically deductive approach of the current offer in system control courses keeps the students away from both practice and the real world. For many reasons, an inductive approach may prove more interesting in view of the consolidation of an active learning environment:

- Starting from a real problem (or one situated on the realist limit), one that is open or poorly defined; the student may find the appropriate context for significant learning. This is one of the fundamental pillars in an effective learning environment.
- A problem that has been adequately presented allows the students to individually identify that which they need to find and learn, thus assuming control over their learning process. Similarly, as they learn they start to use what they just learnt (*Just in time*). The professor's presentations will likely become pertinent, and the students will know what to do with them.
- Working with real problems allows the students to develop concrete professional abilities.
- Evaluation becomes simpler, since it is related to real results that the students themselves may evaluate: the control system works adequately or it does not; specifications are either fulfilled or unfulfilled.
- Since they are being effectively used, the learnt concepts may be better understood, thus facilitating transference to other contexts.

A Short History Of The Course

At the beginning of the 1990s, the Automatic Control course at Uniandes (Universidad de los Andes) followed a classic format: lectures about the topics, followed by the solution, on the part of the professor, of some key exercises, eventually complemented by some exercises carried out by students in class or some lab practice. The students were expected to read the materials in advance and then solve a good number of exercises presented in the textbook. This type of course was not very popular among students, who found the topics to be tedious and, probably as a consequence thereof, the general results were not those desired. Additionally, a few semesters later, the students showed a low level of knowledge in the topic, which suggested a superficial learning of the topics.

Towards 1992, some workshops—courses exclusively devoted to the solution of exercises and some more open problems on the part of students—started to be formally introduced. These activities were always carried out after the professor had presented the theory. With these workshops, the students found a course more interesting, eventually achieving better results in exams where they were supposed to solve standard exercises

In 1996, the course objectives were redefined, using the Teaching for Understanding definition of understanding as a conceptual framework[3]. Such a framework evidenced the students' low understanding level, since even though they got acceptable results in solving standard exercises in tests, they received very negative evaluations when solving more open problems where they were required to perform a certain level of knowledge transference.

As a consequence of these poor results, a search for alternatives and new methodologies and didactics was initiated, which might allow for a solution to the problem. Towards 1998, one of the course's sections introduced Problem Based Learning (PBL) in one part of the course, achieving an important shift in the students' attitude: they would get involved, in a permanent fashion, in the course activities. Nevertheless, the lab sessions continued to follow a more or less classical format. Evaluation modalities based on students' portfolios were also tested. [6].

In 1999 an approach promoted by professor Jerry Pine (Caltech, USA) was introduced. Pine had been working in the development of learning environments based on Hands-On practices, where the students learn by doing. This type of experience has also been developed in other institutions, such as the École de Mines de Nantes, where an introductory course for engineers follows this format. At Los Andes, the new lab design was developed in parallel with the classical version, allowing for an evaluation of a control group. The results were largely stimulating. [4].

Similarly, a second experience was carried out, this time with cooperation from Carnegie Mellon University, in which the impact of self-evaluation and peer evaluation on learning was to be analyzed. Again, a control group was involved in the final evaluation. In this instance, results also turned out to be highly positive [8].

By 2002, the first integrative version, which included the various elements and components already tested, was developed. The lab was totally integrated to the course, and in general the hands-on practices preceded the conceptualizing work. With respect to the course taught in the 1990s, the structure had been completely reversed: first the problems and the lab, then formalization.

Notwithstanding, designing a course with these characteristics requires a closer follow-up on the part of the professor. It needs to be more personalized, which turns out to be more expensive and not always easy to implement. Handling the students' paper portfolios remains an important problem in terms of logistics. For this reason, the school decided to complement the course with the support of Information Technologies, which may facilitate the relationship between the professor and the students

In the following sections, this article presents the course design to be taught in the second term of 2003, which will include an impact evaluation.

CONCEPTUAL DESIGN

Table 1 presents the objectives of the automatic control system course. It may be noted that objectives have been divided in three main dimensions:

- *Information, concepts and events*, which may be evaluated either independently or in context, starting from the evaluation of the abilities that require them.
- *Abilities*, susceptible of development and evaluation in their practice.
- *Attitudes*, whose development and evaluation are difficult.

Similarly, each of these dimensions has been subdivided in three categories:

- The discipline: issues directly related to automatic control systems
- Interdisciplinary work: issues related to other areas
- The personal: that which responds to transversal abilities and attitudes

Finally, the desired learning level for each one of the objectives has been classified in two large levels: knowing and understanding. This is an important classification, since traditionally courses are overloaded with content, pretending to address all relevant topics. In practice, the professor eventually manages to present all the topics, but what the students really learn does not match the professor's expectations. The students may even fail to learn central aspects for the sake of learning less important aspects. The chosen option is to previously define the central objectives and the less central objectives, information that is also available to the students. Similarly, the objectives have been phrased in terms of understanding goals [3]. For example, an objective such as modeling (bold in Table 1) may be more precisely expressed in the following manner:

> Modeling: Providing that a simple process (almost invariant and linear dynamics, reduced order) be followed, the students will be able to find their model; to identify the proposed equations' coefficients; to validate and analyze it in its basic characteristics of response time, type of response, stability and frequency response. Based on its possibilities, the modeling may be carried out starting from either balance equations, or from the temporal or frequency response of the process.

This type of objective definition offers the additional advantage of suggesting the type of test that the students should be able to successfully pass. In turn, the students will have a clear working framework, since they will know, with a high degree of precision, what is expected of them.

The active learning environment is presented in Figure 1. Two working environments structured by the professor support the course: the virtual environment and the classroom environment. Moreover, either in groups or individually, the students must carry out learning activities outside of both working spaces. The learning process is framed in the interaction of three central activities: problems and projects, hands-on laboratory practices, and real-time simulations, being the latter a support tool for the development of the former two. On the other hand, despite the fact that the students carry out most of the work in groups, individual autonomous work is also required, especially in the advanced conceptualization stages.

For the realization of the whole course, a protocol has been developed which induces a guided inquiry process where students must achieved the proposed objectives within a context made up of problems and projects. This inquiry protocol is presented as a set of learning experiences. Each one of these learning experiences is a unit structured around one problem or one project, to be developed in one or several class sessions.

Figure 2 presents the various learning experiences (or sequences) currently proposed in the working protocol. As may be observed, each sequence has an associated problem, a number of sessions during which it is to be developed, and a set of objectives.

In turn, figure 3 illustrates the development of a typical two-session sequence. It can be noted that the proposal presents the initiation (presenting a challenge) and the end (final construction of meaning and conceptualization) of each sequence in the virtual space of the course. Some components of such virtual space can also be appreciated.

Similarly, this figure presents some elements of the proposed evaluation system. Simulation and ranking is one of the components of the virtual system, one that allows each student to introduce the proposed solutions in order to evaluate his/her performance and also to obtain a ranking of his/her solution in relation to the solutions proposed by other students, by means of a previously defined criterion for each problem.

Moreover, the virtual environment facilitates portfolio follow-up activities. As a registry of the various tasks and papers including all corrections and observations, the portfolio serves as evidence of the learning process.

The concept album faces the students with the fundamental concepts of the course, allowing them to individually identify those central concepts that have not been fully understood. Self-examination and the generation of relationships between concepts should support this space.

Finally, in a merely indicative spirit, Table 2 presents the basic outline of the first proposed sequence, which illustrates the way in which each learning activity is designed.

INFORMATION TECHNOLOGIES – VIRTUAL ENVIRONMENT

The course is supported by information technologies, with a virtual learning environment developed in WebCT ; Matlab is used as simulation and control specialized software, and LABVIEW for setting and testing some regulators. In particular, the virtual environment in WebCT is built on a space of interaction between the various actors: students-students, students-professor, and all of them with knowledge. The environment is created with the purpose of enriching presential activity in a way such that it is integrated to the class' rhythm and activities. This environment offers opportunities for:

- Continuing the conceptualization initiated during the presential session, both in groups and individually.
- Interacting around the course's learning sequences.
- Following the learning process of working teams.
- Following the individual learning process of each student registered in the course.

The virtual space offers components apt for group interaction (sequences, concepts), individual interaction, interaction with the professor (portfolio), communications, resources, calendar, and general information about the course. The following section offers a description of some of the components of the proposed virtual space:

Sequences: As noted above, a sequence or learning experience corresponds to the work around one problematic situation which will be solved by a team of students, and an interaction protocol for the construction of the solution. The sequences line up in the virtual space as the course advances, in a way such that they parallel advance in the presential sessions. Each sequence contains interaction sub-spaces: challenge, resources, group construction, discussion of the topic, simulator, ranking tool, solutions. Figure 3 presents the virtual interaction throughout one sequence, which is iniciated with the challenge or problematic situation, and continues in the following manner:

- Each group has access to the sequence's resources, which have been arranged by the professor (readings, links, interactive control book).
- Each group undertakes the collective construction of the solution. In this space, each team must leave trace of its contribution to the construction process: initial hypotheses, team strategies, selected solution. The professor accompanies the groups' construction process by asking questions or by offering contributions that stimulate group dynamics
- The groups may have recourse to the related discussion space in order to solve conceptual questions emerging from the process. The professor participates in this space and embodies the possibility of interaction among the various groups.
- Each group must test its solution in the simulator. All sequences allow for teams to be able to introduce their solution and receive feedback on its efficiency and performance.
- Based on simulator results, the ranking system provides the groups with information about the efficiency of their solution (through comparison with other proposed solutions).
- Each group must finally state its solution in the solution space.

Concept album: In this space, the students may consult the different concepts constructed and tested throughout the course. The album includes a permanent conceptualization forum, intended to facilitate conceptual dialogue among course participants (students and professor) about the various experiences related to the sequences. The students may find different resources associated both to the concepts and to the learning sequences where these concepts have been constructed.

Portfolios and concepts: This is the space devoted to individual construction and conceptualization. It is also the space for individual learning process registry and follow-up. Through portfolio activities, each student reflects on what has been learnt and undertakes the concept construction task. This space includes the following sub-spaces: reflection, concept album, conceptual self-evaluation, and conceptual map:

- After the experience, all students must work on the reflection and conceptualization.
- They must register, in the concept album, the concepts that become clear in the course of the semester.
- By means of the conceptual self-evaluation, any student may test him/herself against conceptualization.

- As a means to evaluate both individual learning and conceptualization, the students must elaborate a conceptual map in which they establish connections between concepts, and an essay.

Additionally, the course's virtual environment includes sections such as Resources, Calendar, Communications, and Course information.

CONCLUSIONS AND FUTURE PERSPECTIVES

Through the last 10 years practice concerning the automatic control course in UNIANDES has suggested strong improvement evidence of learning efficiency when an active learning approach is chosen. In general students find more interesting and challenging this kind of approach, working in a more continuous way during the course. Some evidence about deep learning has been found. Depending on selected strategies it is possible to manage courses up to 60 students. Most of the teacher's work is used before and after class time in a more detailed design and evaluation.

For the second term of 2003, the course will be developed using the complete set of developed tools, including follow-up and evaluation strategies. The results of this new format will be compared with those of former versions. It is worth noting that in the past this course has been the subject of several institutional follow-up and observation studies.

In addition, this venture will enable an evaluation of the impact of guided inquiry in undergraduate level courses, which has been successfully used in innovative science education projects in several countries.

At present, the School of Engineering at Universidad de los Andes is committed to an ambitious curricular innovation project that not only includes a thorough revision of the desired profile of engineers—one that fulfills the new requirements of both society and industry at the same time that it complies with ABET2000 criteria—but also involves the development of efficient learning spaces in an Active Learning approach, supported by new physical classroom and laboratory spaces adequate in terms of such new needs. As a consequence, this type of courses will, in the near future, rely on the physical spaces and technologies required for the development of pedagogical methodologies such as the one here presented.

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FIGURES AND TABLES

TABLE 1
AUTOMATIC CONTROL COURSE OBJECTIVES

		Knowing / Doing / Notions	Understanding / Strategies / Concepts
Information, norms, concepts, laws, notions	Disciplinary	Use of norms and standards, Automatic control history, Robust Control, Available technologies, Sensors and drivers	Transfer Function, State Representation, Modeling, Stability, Feedback, Time Response, Frequency Response, Simulation, Error, Dynamic Systems
	Interdisciplinary	Basic laws governing thermic, chemical, hydraulic, mechanical, biological, and electric systems Systemic thought	Feedback in other disciplines
Abilities, procedures, strategies	Disciplinary	State space control, Phase and gain margin, Nyquist. Programming a regulator in a digital control system	Stability, Bode and root locus analysis, System Simulation, PID Design, lea-lag and Algebraic Design, System Modeling, Error Calculation and Reduction. Assembling a control system.
	Interdisciplinary		Matlab and LABVIEW use in control problems solution
	Interpersonal	Teamwork, presentation preparation, communication, circuit and system assembling, failure detection	Learning to Learn
Attitudes	Interdisciplinary Interpersonal	Systemic thought Responsibility in project development	

TABLE 2
FIRST SEQUENCE

Time & groups	3 sessions, 4 students per group.
Concepts	Model, simulation, continuous time and discrete event systems
Objectives	Finding out what students know about differential equations, transfer function, physical models, system approach and control. Introducing the course: virtual environment utilization, problem and project learning environment dynamics, systems, continuous time control and discrete event control, control strategies, simulation.
Working elements	Paper problem on a hybrid blending system where students have to design a control strategy and test it using virtual tools (Students have to manually control a simulated process).
Sequence overview	Session 1: Problem presentation and analysis, teamwork formation, learning needs identification, solution strategy Session 2: Workshop on utilization of virtual tools, course presentation Session 3: Presentation of solutions by some groups. Review of learning objectives (modeling, transfer function,simulation)
How to start	The problem and the methodologies are presented. Teamworks are conformed. It is important to indicate to all students that they must find out a control strategy. This strategy will be tested by means of the simulator.
Sequence details	During the first session, students work on the problem. In the second session, we expect students to use the simulator and load in the virtual environment some part of the solution in HTML format. In the last session, some groups are asked to present their results.
Evaluation	In general, the simulator conducts the evaluation. When their proposed control strategies have problems, the students will find out by themselves. On the other hand, the ranking system allows for a relative evaluation. The ranking system will be supported in a quadratic error integral between desired values and real values.

FIGURE 1
LEARNING ENVIRONMENT ARCHITECTURE

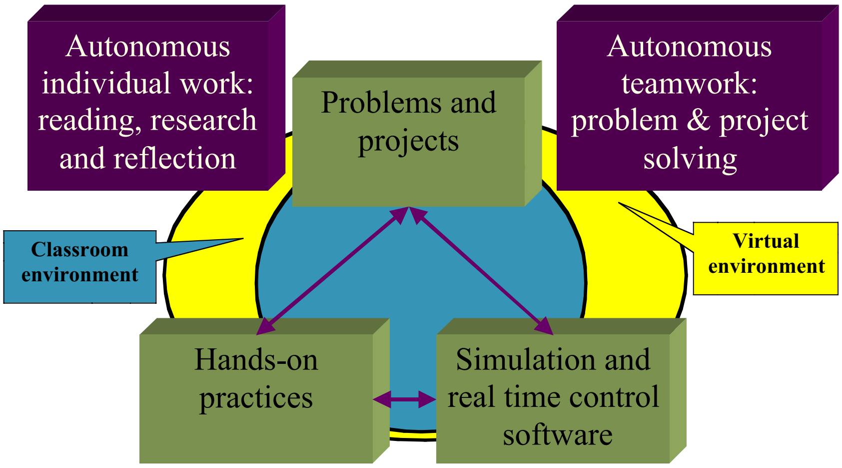

FIGURE 2
GENERAL STRUCTURE BY SEQUENCE

What do we know about	A blending problem	3 sessions	CT:4
A basic model	One bottle	2 sessions	CT:2.7
A second degree problem	Interconnected bottles	2 sessions	CT:2.7
A complete system	The Thermal process	1 session	CT:1.4
An unstable system and its control	OPAMP circuit	2 session	CT:2.7
ON/OFF control	Thermal process	2 session	CT:2.7
A non linear system	Human body and heart rate	2 session	CT:2.7
A PID control	Thermal process	3 session	CT:4
A computer control	Thermal process	3 session	CT:4
A robust control system	Chemical reactor	3 session	CT:4
A final challenge	Lab helicopter	4 session	CT:5.3

CT=Course time

FIGURE 3
TYPICAL SEQUENCE STRUCTURE