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Control learning: present and future

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Abstract

This paper presents some personal reflections on how information technology is moving towards effective and efficient application in control education. The time has arrived for virtual and remote labs to make use of the facilities that the World Wide Web (WWW) provides. The replacement of traditional laboratories with virtual or remote laboratories is presented. Their advantages and disadvantages are evaluated from a critical point of view.

Keywords: Education; Control education; Interactivity; Web-based simulation; Virtual laboratory; Remote laboratory; Teleoperation

1. Introduction

There is no need to talk about the importance of control engineering. Automatic control has become a major field in almost every engineering subject, and automatic control courses are part of the respective engineering curricula. The IFAC Symposium on Advances in Control Education (ACE), sponsored by the Technical Committee on Control Education (EDCOM), has been held every 3 years since 1988. Right from the start, the ACE Symposium has been a place that has provided an international open forum for the discussion of recent developments in control education and the exchange of information about new ideas on control curricula advances, teachware including software and innovative laboratory experiments, ongoing education and training.

In this context, we should highlight two excellent reviews (Antsaklis et al., 1999; Kheir et al., 1996) on control education. The first paper is not only an extraordinary overview about what control systems engineering education means but it also offers motivating ideas on how our field must play an important role in the training of our future engineers. The second paper contains reflections taken from the "NSF/CSS Workshop on New Directions in Control-Engineering Education". Its basic objective was, on the one hand, to improve coordination among various control organisations and control disciplines throughout the world so that control systems education issues receive the attention that they deserve. On the other hand, the workshop's main interest was to show how important control systems technology has become in our current society.

For the last 60 years automatic control has flourished as an interesting and successful subject. The growth of the field has been very active and control systems technology is one of the most significant examples of a subject that goes beyond the frontiers of conventional engineering disciplines. Automatic control is the cornerstone of the new automation revolution and can be considered fundamental in such broad areas as household appliances, consumer electronics, production and manufacturing systems, chemical, mechanical and electrical processes, civil, aerospace and transportation systems and it even has cross interaction links with economic, social, biological and medical systems. Basic control systems principles influence all these areas of application. As a consequence, industrial requirements for well-prepared control systems engineers are evolving, due to marketplace pressures and progress in technology (Åström, 1994). Arguably, mathematical systems theory is one of the most significant achievements of 20th century science, but its practical impact is only as important as the benefits it can bring (Goodwin, Graebe, & Salgado, 2001).

The need for the control of systems and processes exists in many areas of human endeavour, from technology to medicine and economics. However, the laws of control for systems, with complicated dynamics and measurement uncertainties, are not well understood. Both basic and applied research (Schmid, 2001) is needed to make further progress

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possible. Basic research or "Newtonian research" (research in response to curiosity about the workings of nature, with no other pragmatic motivation) in control-engineering seeks to understand, in precise mathematical terms, the fundamental principles of control and the limitations on achievable results. This quest for fundamental understanding is in the spirit common to all basic sciences.

Applied research or "Baconian research" (application of existing knowledge on behalf of a sponsor with a specified problem to solve) in control engineering is focused on the development of methods for analysis and design of advanced automatic control systems, including translation of control laws into computer control algorithms and software. Many of today's smoothly functioning systems are the successful engineering implementations of mathematical principles of control theory, with modern computer technology as an enabling tool.

The gap between basic and applied research could possibly be filled in by a complementary third type of research, the strategic research or "Jeffersonian research" (basic scientific study of the best sort with no sure short-term payoff but targeted in an area where there was a recognised problem affecting society or technology).

The present scientific and technological environment offers unprecedented challenges and opportunities in order to apply control technology. As recently developed methods have found their way into standard practice, they have paved the way for more complex applications.

Recent mathematical advances and new computer technologies have greatly expanded the range of problems that can be solved. Above all, the current generation of applications raises new kinds of control problems. In many cases, new mathematical results and even fundamentally new approaches will be required.

The "registered trademark" of our field can be summarised in the following facts (Fleming, 1989):

- Control engineering is an inherently interdisciplinary field.
- Mathematics has played and will increasingly continue to play a fundamental role in the development of control engineering.
- The interrelation between mathematics and control engineering has been closely intertwined right from the start.
- Advances in the control field are made through a mix of mathematics, modelling, computation, and experimentation.

We need to consider how education in our field is changing and how recent technological breakthroughs can influence it. How can we help teachers to continue developing their role as key elements in teaching with the necessary flexibility that technology provides? I am convinced that as educators we must have an open attitude and that we should sensibly incorporate technological development, because otherwise we may risk teaching the students of today how to solve the problems of tomorrow with the tools from yesterday. However, although technology changes quite fast, control-engineering education develops more slowly.

The paper is organised as follows. First, there are some reflections about technology-based instruction from a general perspective. Next, the importance of interactivity and visualisation in control education is analysed. Following this there is a discussion of the implications of the World Wide Web (WWW) for instructional development. Then, control-engineering experimentation environments are classified. The idea of Web-based simulation (WBS) is considered in the context of control education. WBS is today successfully showing its great potential and how current technology can support it. The next section presents the concept of remote labs in control engineering, and their advantages and disadvantages are evaluated from a critical point of view. Finally the challenge that lies ahead to transform our discipline from a "hidden technology" to an "open technology" is considered.

2. Technology-based instruction and control education

The answer to the question what will be the effect of new technologies on teaching in 20 years from now is a wholly non-scientific task, but it is highly entertaining and extremely interesting.

We do not need to explain what we mean by non-scientific. We all know that it is not possible to foretell the future without a proper scientific foundation. The fact that the task is entertaining is a consequence of its non-scientific nature, since the idea of a lack of scientific rigor means that we feel immediately liberated, knowing that we shall always be excused if our forecasts are not right. The fact that the task is also interesting is because people who devote time to thinking how things might be are more prepared to assume what may happen than a person who has never thought about what the future holds in store.

Having said this, I believe that there are some other undisputed observations. The first is that in 20 years' time the new technologies will no longer be new. This apparently obvious remark is not a truism but a basic reflection from which we must deduce that in 20 year's time many of the things that today seem innovative and revolutionary will have become an integral part of our daily lives. The second observation is that the new technologies will change some aspects of teaching; we do not know precisely which ones, but we do know for sure that there will be new problems. The third observation is that life is repetitive, thus when we imagine the future we must not forget the past, after all this is the real significance of history.

We must not forget these initial premises when we refer to new technologies in relation to teaching because they indicate two directions. On the one hand, how these developments in computing will affect didactics and, on the other, the effect that these developments will have on creating new intercommunication models.

As regards the computer from a didactic point of view, I have to confess that I do not find any essential differences between a printed book and a Web page, or between a computer screen and a blackboard. Recognising that not all the cases are the same, the only difference between using a printed book and a blackboard or a Web page and a computer screen is that you need to learn how to use this technology, and that the learning is more complicated than opening a book or writing on the board. In fact, if we talk about choosing between a computer and a blackboard, the truly revolutionary fact lies in what we load into the computer or what the contents of the board are. As regards teachers' ability to adapt to new teaching technologies, time or retirement age will take care of this, which is in fact the same thing.

About 2300 years ago Aristotle defined man as a social animal by nature, and today we know that our condition as human beings or, if you prefer, as intelligent beings is fundamentally due to our contact with other intelligent human beings. In fact, in our education process, the self-consciousness that allows us to define ourselves as individual beings is only acquired by contact with others, with others who like ourselves, want to assert their individuality. We should point out that it is not possible for us to develop our intelligence without developing our language with which we communicate with fellow humans and which is learnt in society. It is thus no mere coincidence that the system that allows our computer to work is called precisely this, language.

The historical path of technology in education is full of controversy. In other times there was even a certain resistance to books and paper because they were thought to impair human memory skills. Educational philosophy evolves in response to the needs of each era and in harmony with available technology. The ancient Greek image of the teacher sitting at one end of a log facing just one student at the other end seems quaint and appealing, although inadequate in a modern context. The common practice of medieval students, copying manuscripts or compiling mathematical tables, is now regarded as not creative enough. The industrial age teacher standing in front of a classroom with rows and columns of orderly separated desks is possibly a too rigid figure. Mid-century scenarios of computer-based instruction or TV-based lecturing have never been fully developed but they are still useful supplements. As technology evolves, we must busily re-negotiate the methods and goals of education.

Studies of cognitive psychology and countless classroom research studies clearly demonstrate that people acquire skills by doing things and reflecting on the outcome, not by watching and listening to someone else telling them what they are supposed to know. The old adage "learning by doing" is today valid. Students may learn on lecture-based courses, but little or none of the learning beyond simple factual recall is provided in the lectures. Certainly, you can do more harm than good with technology and cooperative learning if you do not know what you are doing. If instead of taking advantage of the interactive capability of technology you use it to make students even more passive than they are in the normal classroom—delivering lectures entirely by hypertext or streaming video, for example, or converting class sessions into complete Power Point slide shows, little learning will result. If you just give students homework and then put them in groups in class to discuss it, you are probably wasting everyone's time, and if you ask them to complete an assignment in groups and do nothing to hold them individually accountable or to help them learn how to function effectively in teams (two defining conditions of cooperative learning), you may well be doing more harm than good.

On the other hand, if you spend some time in workshops or on the Web finding out how to (and how not to) implement technology-based instruction or cooperative learning before trying it, you will start to see the results that you are looking for. Doing it right is not necessarily easy—like every meaningful activity, it involves a learning curve. It is not rocket science, however, and the potential benefits to both students and instructor are definitely worth the effort.

Basic skills are learned not in isolation, but in the course of undertaking (often on a collaborative basis) higher level "real-world" tasks. The student assumes a central role as the active architect of his/her knowledge and skills, rather than passively absorbing information delivered by the teacher. Technology alone can never be a solution, but in the hands of a knowledgeable teacher, appropriately designed technology can become a useful tool. The WWW and other information technology cannot be a solution to educational needs unless the creative component is included (Copinga, Verhaegen, & van de Ven, 2000; Poindexter & Heck, 1999).

An innovative idea that has emerged with vigor in recent years and that incorporates creative components in the learning processes has been the *just-in-time teaching* (JiTT) concept (Novak, Patterson, Gavrin, & Christian, 1999). This is a teaching and learning strategy consisting of two elements: classroom activities that promote active learning and WWW resources that are used to enhance the classroom component.

Many industries use *just-in-time methods*; they combine high-speed communications and rapid distribution systems to improve efficiency and flexibility. The use of JiTT is analogous in many ways. JiTT combines high-speed communications on the Web with our ability to rapidly adjust content; this makes our classroom activities more efficient and more closely tuned to our students' needs. The essential element is feedback between the Web-based and classroom activities. JiTT is a strategy that combines the use of the Web with a collaborative learning environment to improve students' learning of various content areas and attitudes towards them. The JiTT pedagogy exploits an interaction between Web-based study and an active learner classroom.

3. Interactivity in control education

What is visualisation? The following story illustrates better than any analysis what visualisation is. The anecdote usually has Norbert Wiener as protagonist, but there are many control-engineering students who would be able to recognize the same attitude in some, or perhaps many of the teachers that they have had throughout the course of their studies.

Wiener was developing a complicated demonstration in front of his class at MIT. The blackboard was full to overflowing with intricate formulae. Suddenly, he got stuck; he stared at the last formula and became statue-like for a good while. Everyone gasped as they thought he was in a jam. Yet, Wiener, without uttering a single word, went to the corner of the blackboard where there was a bit of space left and drew some figures that no one could see because his back was hiding them from view. Suddenly, his face lit up. Without uttering a single word he rubbed off his mysterious figures and went back to the point where he had got stuck, and continued faultlessly to the end without any problem.

Automatic control ideas, concepts and methods are really rich in visual contents that can be represented intuitively and geometrically. These visual contents can be used for presenting tasks and handling concepts and methods, and manipulated for solving problems.

Control specialists have visual images, intuitive ways of perceiving concepts and methods that are exceedingly important for effectively carrying out their creative work and mastering the field in which they work. Using visual images and intuition, they are able to relate constellations of facts that are frequently highly complex, and the results of their theories in an extremely versatile and varied way. Furthermore, via these significant networks they are able to naturally and effortlessly choose the most effective strategies to attack and solve the problems facing them.

The basic ideas of automatic control often arise from very specific and visual situations. All experts know how useful it is to go to this specific origin when they want to skilfully handle the corresponding abstract objects. The same occurs with other apparently more abstract parts of automatic control.

This way of acting with explicit attention to potential specific representations to explain the abstract relations that are of interest to the control expert is what we term *control visualisation* The fact that visualisation is an especially important aspect in the control expert's activity is something completely natural if we bear in mind the applied mathematics feature of control theory.

Broadly speaking, mathematics tries to explore the structures of the reality that are accessible using this special manipulation that we call mathematisation, which could be described as follows. The first perception is that tangible things have certain similarities and we recognize from these perceptions what is common and can be abstracted. We then subject this information to rational and symbolic detail in order to handle more clearly the underlying structure of these perceptions.

Our feeling is primarily visual and it is thus not surprising that visual support is so present in our work. Control experts very often make use of symbolic processes, visual diagrams and other forms of imaginative processes in their work and they acquire what could be called an intuition of what is abstract.

Visualisation thus appears to be something profoundly natural both in the origins of automatic control and the discovery of new relations between mathematical objects, and also of course in the transmission and communication of our control knowledge.

Personally, I believe that one of the important tasks for teachers in control engineering is to transmit to students not only the formal and logic structure of our discipline but also, and certainly with much more emphasis, the strategic and intuitive aspects of the subject. These strategic and intuitive aspects are probably much more difficult to make explicit and assimilate for students precisely because they are very often in the less conscious substrata of the expert's activity.

Given the nature of visualisation, it will have many highly subjective elements. The ways of visualising and making automatic control ideas closer and intuitive in order to implement them in certain situations, and apply them to specific problems, depends a lot on each individual's mental structure. The degree of visual support certainly varies considerably from one analysis to another, and what for one person is helpful for another person is possibly a hindrance. Yet, these differences must not hamper our attempts to generously offer those instruments that are so useful for us in our work and without which our work would be much more difficult, abstruse and boring.

The mathematical language used by control specialists is a mixture of natural language and formalised language, a strange jargon consisting of natural language elements, more or less esoteric words and logical and mathematical symbols. In this strange language reference is explicitly made, or not so explicitly, to scientific conventions that have been established in the course of time and that are laden with intuitive, visual and implicit connotations. It is not surprising that mathematical and communication work using this tool produces mistakes, confusion and obscurities that may lead to error.

One very recent example, which received a lot of public attention, was the "demonstration" of the famous Fermat theorem by Andrew Wiles in June 1993. His demonstration convinced even the best experts in the field for several months, until gaps were noticed in the demonstration. More than a year elapsed between Wiles' work and that of other specialists in the subject, until finally in November 1994 experts reached the conclusion that we had a genuine demonstration of the Fermat theorem.

In this sense, I imagine that a lot of us, as teachers, have had the following experience. After attempting to make one specific mathematical situation absolutely clear to our students by using visual constructions, some or many of them may ask, "Now could you please give us a real mathematical demonstration?"

What is a demonstration? For those followers of Pythagoras who played with stones it would probably be "Look!" For

Littlewood, a demonstration is an indication, a suggestion. “Look in this direction and believe me!” For René Thom “A theorem is proved when experts raise no objection”.

Naturally, the student who asks for a mathematical demonstration possibly has the preconception transmitted by many of his/her teachers that only the result coming after a sequence of some logical quantifiers can be called a mathematical demonstration. This is what I have already asserted; in our scientific education we have not really bothered to instill the habit of interpreting and decodifying our visualisations, and translating them, when it is appropriate, into their formal language.

Bearing in mind these general considerations, the computer can be regarded as a tool that allows us to visualize, and manipulate in an interactive way control objects. The ultimate goal is to facilitate comprehension of the concepts that we are trying to transmit to our students.

Because of the amazing progress made in computer technology, today it is possible to design “control education tools” with the following characteristics:

- Better man–machine interaction,
- Natural and intuitive graphical user interfaces,
- High degree of interactivity.

In order to design technical systems or simply to understand the physical laws that describe their behaviour, scientists and engineers often use computers to calculate and graphically represent different magnitudes. In control engineering, these quantities include among others: time and frequency responses, poles and zeros on the complex plane, Bode, Nyquist and Nichols diagrams, phase plane, etc. Frequently, these magnitudes are closely related and constitute different visions of a single reality. The understanding of these relationships is one of the keys to achieve a good learning of the basic concepts and it enables students to carry out control systems design accurately.

Traditionally, the design of the systems is carried out following an iterative process. Specifications of the problem are not normally used to calculate the value of the system parameters because there is not an explicit formula that relates them directly. This is the reason for dividing each iteration into two phases. The first one, often called synthesis, consists of calculating the unknown parameters of the system taking as a basis a group of design variables (that are related to the specifications). During the second phase, called analysis, the performance of the system is evaluated and compared to the specifications. If they do not agree, the design variables are modified and a new iteration is performed.

It is possible, however, to merge both phases into one and the resulting modification in the parameters produces an immediate effect. In this way, the design procedure becomes really dynamic and the students perceive the gradient of change in the performance criteria for the elements that they are manipulating. This interactive capacity allows us to identify much more easily the compromises that can be achieved.

Many tools for control education have been developed over the years. Many interesting ideas and concepts were implemented by Prof. Åström and colleague at Lund. In this context, we should highlight the concepts of *dynamic pictures* and *virtual interactive systems* introduced by Wittenmark, Häglund, and Johansson (1998). The main objective of these tools is to make students more active and involved in control courses.

In essence, a dynamic picture is a collection of graphical windows that are manipulated by just using the mouse. Students do not have to learn or write any sentences. If students change any active element in the graphical windows an immediate recalculation and presentation automatically begins. In this way, they perceive how their modifications affect the result obtained. Dynamic pictures cannot only be effective in presenting engineering concepts in the classroom but also beneficial in extending student experience in analysis and design assignments. This invitation to creativity can be most useful where specialised control-engineering student projects are concerned.

This strategy causes us to “think small and simple”. This is justified by a frank assessment of our limited knowledge for designing educational software as well as practical considerations about how to manage incremental innovation. As dynamic pictures are fairly easy to create and deploy, they provide a means for rapidly prototyping and testing control principle ideas. In particular, they can be used as sharp tools for investigating precisely what it takes to get a control concept across to students. In this way, the “virtue of simplicity” becomes an issue in learning research on the design and use of these kinds of tools.

Interactive tools, which are accessible to students at any time on the Internet, are considered a great stimulus for developing the student’s engineering intuition. These interactive tools attempt to “demystify” abstract mathematical concepts through visualisation for specifically chosen examples. At the present time, a new generation of software packages has created an interesting alternative for the interactive learning of automatic control (Garcia and Heck, 1999).

These tools are based on objects that allow direct graphic manipulation. During these manipulations, the objects are immediately updated, so that the relationship among the objects is continuously maintained. *Ictools and CCSdemo* (Johansson, Gäfvert, & Åström, 1998; Wittenmark et al., 1998), developed at the Department of Automatic Control at Lund Institute of Technology, and *SysQuake* at the Institut d’Automátique of the Federal Polytechnic School of Lausanne (Piguet, 1999; Piguet, Holmberg, & Longchamp, 1999) are good examples of this new educational philosophy for teaching automatic control.

For those that begin learning in this field some concepts are initially difficult to grasp, due to the fact that their properties are expressed in two different domains: time and frequency. Transient behaviour, such as settling time, overshoot, and the risk of saturation are analysed typically in the time domain; while concepts like stability, noise rejection,

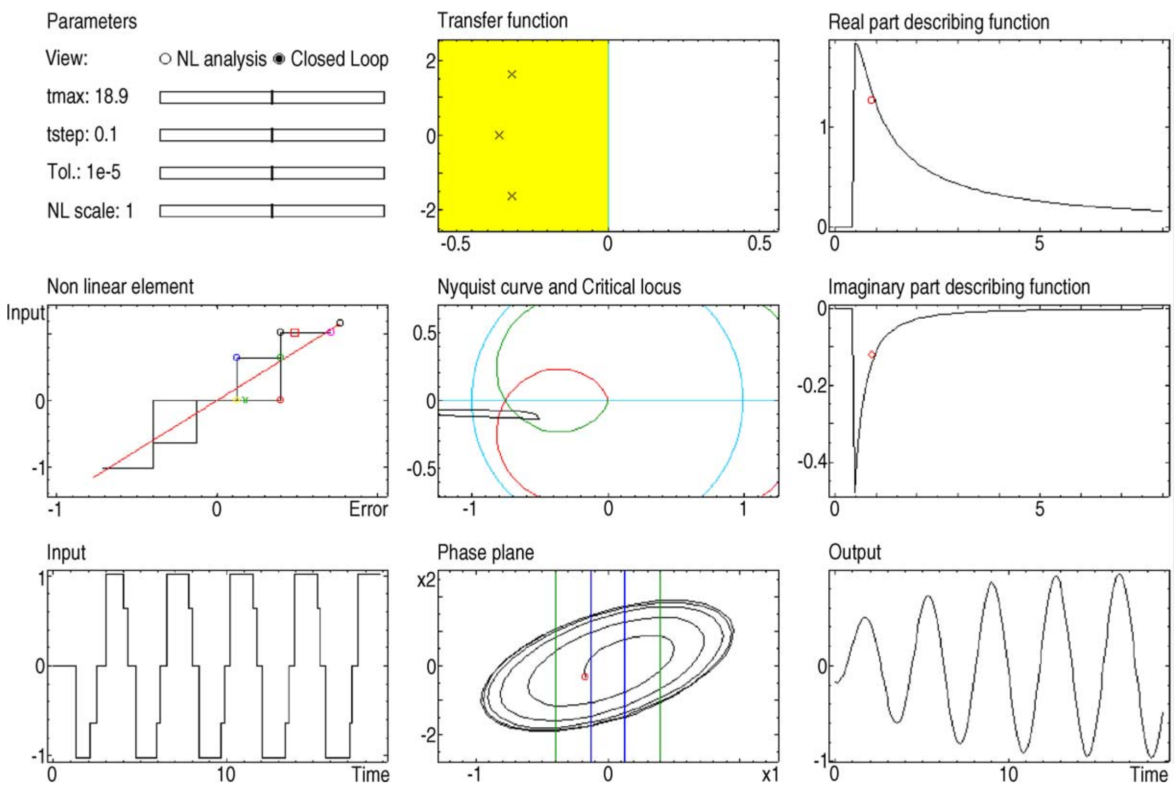

Fig. 1. Multiple views that illustrate the describing function method.

and robustness are expressed more easily in the frequency domain. The basic mechanisms that relate them and other phenomena like, for example, the effects of sampling and non-linear elements, to mention just a few, can be illustrated in a very effective way using these tools.

Fig. 1 shows an example of how this new way of interactive control education provides practical insights into control systems fundamentals (Dormido, Gordillo, Dormido-Canto, & Aracil, 2002). It is a dynamic picture in the sense mentioned earlier, and when the student manipulates some active element in the figure the new result is automatically produced.

In this case the objective is to explain the scope and limitations of the describing function method to the student. Unfortunately, the practical application of the describing function has not received enough attention from control systems analysis and design software. It is well known that the describing function method is very helpful as an analysis tool for an introductory non-linear control course. However, it does not give any conclusive results, although it helps to predict some global phenomena that should be confirmed by simulation. In fact, it is not a true analytical method making exact predictions. This is a good reason why it should be used in connection with an interactive tool. Interplay of simulation and the use of the describing function allow the student to understand many non-linear control problems of great practical interest.

The role of this new interactive computer learning experience in control-engineering curriculum is twofold: (1) To provide a new method for delivering classroom material whereby real-world control system engineering concepts are introduced via an interactive package, and (2) to provide an opportunity for innovative laboratory assignments where students can analyze, design, and modify control-engineering systems via interactive tools.

The combinations of an interactive environment plus animation bring visualisation to a new level and aid learning and active participation by control-engineering students. We are at the threshold of a new era in which advanced information technology is finding its way towards effective and efficient applications in control education (Kheir et al., 1996).

4. The World Wide Web: implications for instructional development

The widely spread WWW has produced a real revolution in educational institutions. At present many subjects are being critically reassessed in terms of their own methods, techniques and philosophies. If we had to select an innovation in computer technology that characterises the late 1990s, many scientists would recognize the tremendous impact of the Web.

Educational institutions and organisations worldwide continue to experience changing learner expectations fuelled by technology innovation and the expanding possibilities for personalised learning. With the development of the Web as a viable medium for learning and self-directed study, education providers are increasingly able to provide learning opportunities in a more flexible and customer-aware manner. Yet, many continue to replicate traditional educational models using the new medium.

While the Web world focuses its attention on knowledge management, customer profiling, and e-business practices, many educational institutions continue to automate traditional instructional and administrative practices. For most institutions, courses continue to be the standard units of instruction, the "one-size-fits-all" building blocks of academic credit, even within the virtual education arena. Very few have considered the idea of component-based instructional units, "learning objects", and complementary business systems and student service models that have the potential to revolutionize instructional practice.

The growing currency of distance and distributed learning practices has made learners believe that educational institutions can provide them with personalised study options at home or their workplace (Aktan, Bohus, Crowl, & Shor, 1996; Maly et al., 1997; Syed, 2001). Software developments, such as the music distribution system Napster, have demonstrated that Web-based environments that are accessible to everybody can build an enormous following of loyal users, provided that they give them what they want in a convenient and Web-centric manner. The challenge for educational institutions offering virtual programs is similar, yet few seem able to achieve the promise of education for everybody in a convenient and user-driven manner. Very few educators or institutions understand the concept of learning object. Fewer still have even attempted to apply pure Web-centric thinking in their approach to virtual learning.

Too many traditional institutions offer learners hierarchical views of their organisational structure at the main entrance to their buildings, through their academic calendars, or even through their Web sites. Instead of identifying a learner's goal and then describing potential pathways for achieving it, many institutions deal more with their own institutional requirement to qualify the learner to be enrolled. This position can be attributed in part to the historically autonomous nature of institutions of higher learning, where power resides in the hands of the institution.

There are some object lessons from the Web that educational institutions need to learn if they expect to use the medium effectively. In educational terms, the analogue would be the provision of access to instructional units, learning resources, and assessment and accreditation mechanisms using a common package schema for the granular components of learning. Building an educational repository that provides access to learning objects requires standards and structures that can facilitate object storage, retrieval and aggregation to suit the needs of learners or the pedagogical intentions of instructional developers.

As a consequence of all this and, in parallel with the different initiatives for establishing integral plans of telematic tutoring, the need arises to pursue further research, development and exploitation of new experimentation environments more in line with the Web-based teaching model that is being used.

5. A classification of the experimentation environments

Under the label of experimentation environments there are several modalities that must be briefly described in order to ascertain which new systems we are referring to. There are two criteria that allow us to establish a clear classification from the point of view of student use:

1. The way of accessing the resources for experimental purposes.
2. The nature of the physical system.

As regards the first criterion, there is *remote access* through the Internet, and *local access*, that is to say, no connection with the Internet is necessary to interoperate with other components. As far as the nature of the resource is concerned, there are *simulated models* or *real plants*. From combining these two criteria, we obtain four kinds of environments that are very different but encompass all the possible ways of experimentation (see Fig. 2):

- *Local access-real resource*. It represents the traditional practical laboratory where the student is in front of a computer connected to the real plant to carry out the given practical.
- *Local access-simulated resource*. The whole environment is software and the experimentation interface works on a simulated, virtual and physically non-existent resource, which together with the interface is part of the computer. This configuration would be defined as a *mono-user virtual laboratory*.
- *Remote access-real resource*. It represents access to a real plant equipment laboratory through the Internet. The user operates and controls in a remote way a real plant through an experimentation interface. This approach is

NATURE OF THE RESOURCE

ACCESS TO THE RESOURCE		Real	Simulated
	Local	Hands-on lab.	Mono-user virtual lab.
	Remote	Remote lab.	Multi-user virtual lab.

Fig. 2. Experimentation environments.

named *remote laboratory*, *telelaboratory* or *teleoperation* through WWW.

- *Remote access-simulated resource*. This form of experimentation is similar to the one above in as much as a model replaces the physical system. The student operates with his/her experimentation interface on a virtual system reached through the Internet. The basic difference is that several users can operate simultaneously with the same virtual system. As it is a simulated process it can be instantiated to serve any person who asks for it. We thus have a *multi-user virtual laboratory* or WBS environment.

Of the two ways of access to the resources, local or remote, the latter has a greater demand at present: access to virtual or real experimentation resources through WWW and, even more interesting, access to and control of real systems. This possibility, teleoperation, is the one that really allows you *to take the lab home*, because if the system is correctly built, it is possible to experiment in any computer connected to the Internet, any time of the day and any day of the year.

Yet, remote experimentation need not be limited exclusively to the educational world. In industry, as in research centres, the remote control of devices through the Internet represents a unique opportunity to solve scientists' and engineers' needs to access given equipment. The reasons are obvious: costs. In some cases, the acquisition of equipment to carry out experiments is not possible and the equipment available in other centres has to be used; in other cases it is necessary to reduce costs and traveling expenses, as in the case of machinery supervision, something which can be frequently carried out easily via the Internet. On the other hand, and from the economical point of view, the concept of teleoperation gives way to a new sales-service market that in a near future will allow companies and universities to hire their equipment to others.

However, given the drawbacks that Web-based study and experimentation can produce (loneliness, isolation, lack of motivation, etc.), these new experimentation environments must meet certain requirements in order to minimize these effects. The basic requirements are:

- *Simple installation and use*. The experimentation environments must be inherently easy to install and use. This should not prevent the student from working with precision and detail. The environment must provide the necessary means to make up for the absence of a tutor.
- *Access through the Internet*. Access to remote environments must be carried out exclusively via the Internet. This aspect together with the point above means that a WWW navigator is the only necessary software tool that students will need when undertaking a practical.
- *No cost*. Students need not acquire any additional software. The only expense that they will have is access via the Internet, and when they work in the computer room at the study centre they will have no expense.
- *Interactivity and realism*. The environments must promote students' interest and motivation when they obtain real and coherent responses irrespective of whether they are using a real or simulated plant. The dynamism of the system is important so that the environment reacts in real time to any action from the student.
- *Total availability*. There should not be any time restriction as far as the use of the environments is concerned. The only limitation should be the one created by the other user when he/she occupies the experimentation environment or when maintenance work is being done.

6. Web-based simulation

In this general context *control education* is no exception. Thanks to many simulationists throughout the world, who took the risk and experimented and incorporated Web-based technologies, a new simulation area was born.

WBS outlines new paradigms of distributed and remote teaching. Control education is typically a domain where WBS is successfully showing its potential and how current technology can support information sharing among large dispersed groups (Sánchez, Morilla, Dormido, Aranda, & Ruipérez, 2000). The great flexibility and functionality in the dissemination of information and the efficient mechanism that it offers for integrating tools into a unique interface are the main reasons for using the Web concept with educational aims (Copinga et al., 2000).

The area of on-line simulation is certainly in its infancy and needs much further investigation (Antsaklis et al., 1999). The only real uncertainty here is which new Web technologies will be available in the next 5 years for us to exploit. Whatever their capabilities are, they will radically change the way in which we view simulation and control education. Neither of them will ever be the same.

WBS allows us to outline, within the extensive field of simulation, new paradigms of distributed and remote teaching that have been emerging with vigor over the last few years due to the explosion of new information and communication technologies and, in particular, the WWW. The official presentation of WBS was at one of the work sessions at the Winter Simulation Conference in 1996 in San Francisco. More specifically, the paper by Fishwick (1996) presented at this session is regarded as one of the first to describe this new issue as a reality that was already present in the ideas of many computer simulation researchers. This event aroused interest in the scientific and industrial community, and it is thus now common at international congresses organised by different international scientific associations (IFAC, IEEE, SCS) where sessions devoted solely to the numerous aspects of WBS are normally held.

Fishwick defines WBS simply as "*the connection between the Web and the field of simulation*". WBS is not an existing field but rather an idea that represents an interest by simulationists to exploit Web technology. There are two aspects where the convergence and interrelation of both these fields must be complete:

1. *Teaching*. As in other scientific disciplines, in the field of simulation the WWW is considered a key medium for distributing and universalising the information contained in modelling and simulation tools (aids, data and technical references). There is also the need to promote the use of the different technologies associated with the Internet (virtual reality, video conference, multimedia) to promote the didactic aspect of the educational materials and thus facilitate the learning process to students.
2. *Simulation programs*. It is here that the Web and the simulation field are in perfect symbiosis. Thanks to the Internet, graphical interface with simulation software can be manipulated from anywhere in the world with just a navigator. Even the possibility of doing distributed simulations and possibly parallel ones acquires a meaning with a vast world network of computers interconnected with non-proprietary protocols. Let us imagine, as Fishwick suggests, reusing small models to construct large systems. With the Web and current object-oriented programming techniques, the distribution of components throughout the Internet is perfectly viable so that each computer simulates the behaviour of a specific part.

Another common feature of WBS, as a result of the WWW, is that they use *client-server architecture* as a data transmission link to the client from a remote place. Although this will be dealt with in more detail below, it can be said that this information can consist of the simulation program transmitted to clients to be executed within their WWW navigator, or of the client or server simulation results for subsequent analysis.

More specifically, WBS can be defined as the use of resources and technologies offered by the WWW for interaction with client and server modelling and simulation tools. Therefore, the common characteristic of all WBS applications is that they use WWW navigators as a support for graphical interfaces connecting the user with simulation. It is important to note that the downloading of a simulation package from a server to the client's computer and its execution as an application wholly independent of the navigator and the net is not included in the WBS category: a WWW navigator always has to play an active role in the modelling or simulation process, either as a mere graphical interface or, additionally, as a container for the simulation numerical engine.

Therefore, the main design idea of the system is to use the WWW as a communication structure and a Web browser as the user's interface. The Web browser provides a platform for transmitting information as well as an environment to execute the client's software. A Web server provides the interface between the client and the experiment. The Web itself provides the infrastructure to exchange the necessary information.

6.1. Classification criteria

Although the definition of this emergent issue may seem quite simple, it is necessary to study it in more depth by classifying the different ways of designing WBS according to four criteria:

1. The location of the mathematical calculation engine.
2. The nature of the simulation kernel.
3. The design capacities.
4. The degree of simulation interactivity.

6.2. Location of the mathematical calculation engine

In accordance with the first criterion, the *location of the calculation engine* can be either *local* or *remote*. Local simulations mean that the calculation engine is transmitted to the computer where the client is working, so that the graphical interface and the numerical kernel coexist in the same environment, i.e., within the navigator. For the development of these simulations, Java is currently the only real possibility for providing a wholly independent hardware platform (Alfonseca & de Lara, 2001; Alfonseca, De Lara, & Pulido, 1999; Carlson, Guzdial, Kehoe, Shah, & Stasko, 1996; Chatterjee, Paramasivam, & Yakowenko, 1997; Crutchfield & Rugh, 1998; Salazar-Silva, Martínez-García, & Garrido, 1999; Torres et al., 2001), although there is some study on the viability of using multimedia tools, such as Macromedia Flash, for the simulation of real processes (Planas, Hernández, & Gomilla, 2001). There are also researchers who, although working in local mode, separate the engine and interface (Copinga et al., 2000; Esquembre, Härtel, Martín, & Zamarro, 1996; Schmid, 1999, 2000), i.e., the interface is on an HTML page whilst the calculation engine is outside the navigator.

Remote simulations means that the numerical kernel is executed in a remote computer and the graphical interface does not need to be in the computer from where the HTML page has been unloaded, although it usually is. In any case, the graphical interface and simulation are executed in different computers, and they can both communicate via CGIs (Erkes et al., 1996; Fishwick, 1995; Georgiev & Hogenboom, 1999; Lindfors, Yliniemi, & Leiviskä, 2000; Morilla et al., 2001; May, 1996; Szafnicki & Michau, 2000; Diez et al., 2001), via sockets (Narayanan et al., 1999), Java RMI (*Remote Method Invocation*), JavaBeans, CORBA (*Common Object Request Broker Architecture*), *RPC* (*Remote Procedure Call*) or via *front-end* applications for simulator software, in this instance, both front-end and server applications are in the same computer because it would make no sense otherwise (Dormido, Sánchez, & Morilla, 2000; Kóvacs et al., 2000).

All these approximations are characterised by the existence of a server that receives orders from the different client interfaces. These orders are transmitted to the process where the simulation instance created for each specific client is

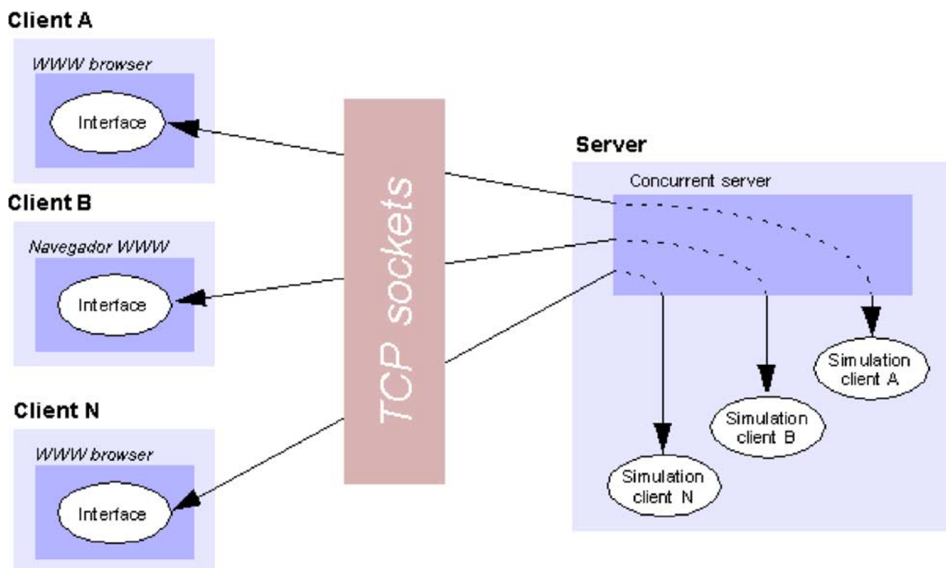

Fig. 3. Remote simulation environment with concurrent clients.

executed (each client has his own workspace in the server) and the server receives the data generated by each instance so that in turn they are delivered to the corresponding client (Fig. 3).

An aspect to be considered in every WBS when the calculation engine is located in a remote computer with server functions is the number of users that can be doing experiments at the same time.

Owing to computational overload from the concurrent simulation of various models, the restriction on the number of students working simultaneously is imposed by the numerical power of the server where the simulation model is executed. The current capacity of processors, the existence of work stations with multiple processors or the creation of low-cost multicomputers with PC interfacing (Sima, Fountain, & Kacsuk, 1997) means that the disbursement necessary for the provision of a WBS multi-user service with a remote calculation engine is not prohibitive.

6.3. Nature of the simulation kernel

The second classification criterion is the *nature of the simulation kernel* irrespective of whether its location is local or remote. This criterion refers to the fact that the very simulation has been constructed with a modelling or simulation-oriented tool (Matlab, Simulink, LabView, ACSL, etc.) (Copinga et al., 2000; May, 1996; Morilla et al., 2001; Schmid, 1999, 2000; Szafnicki & Michau, 2000; Valera et al., 2001), or it has resorted to general purpose high-level languages (C, C++, Fortran, Java) using specific simulation-oriented libraries (Alfonseca et al., 1999; Crutchfield & Rugh, 1998; Erkes et al., 1996; Georgiev & Hogenboom, 1999; De Lara & Alfonseca, 2001; Narayanan et al., 1999; Salazar-Silva et al., 1999; Torres et al., 2001).

In accordance with this classification criterion, the first approximation can be considered the right one since the versatility, power and features of the different modelling and simulation graphical tools are unlike those obtained from direct programming in general purpose high-level languages.

6.4. Design capacities

The criterion *design capacities* refers to the fact that the client cannot only modify the numerical intervals of the system parameters to be simulated but also the model architecture. Thus, the client not only introduces the parameters for configuring the simulation behaviour but also participates actively in constructing the very model. Examples of these environments can be found in works by (Boroni, Goosey, Grinder, Ross, & Wissenbach, 1997; Chatterjee et al., 1997).

6.5. Degree of simulation interactivity

The fourth and final criterion for the different approximations for WBS is the *degree of simulation interactivity*. There are basically two kinds of interactivity: *pseudo-batch* and *on-line*. By *pseudo-batch simulation* we mean non-immediate response from the time when the simulation process is initiated. In some instances the system response corresponds to intermediary steps in the simulation process, so it is possible to introduce some parameters and repeat some of these steps. Some examples can be found in (Copinga et al., 2000; Fishwick, 1995; Georgiev & Hogenboom, 1999; May, 1996; Morilla et al., 2001; Szafnicki & Michau, 2000).

On-line simulation is the opposite extreme but also the most attractive one. In this instance the simulation pro-

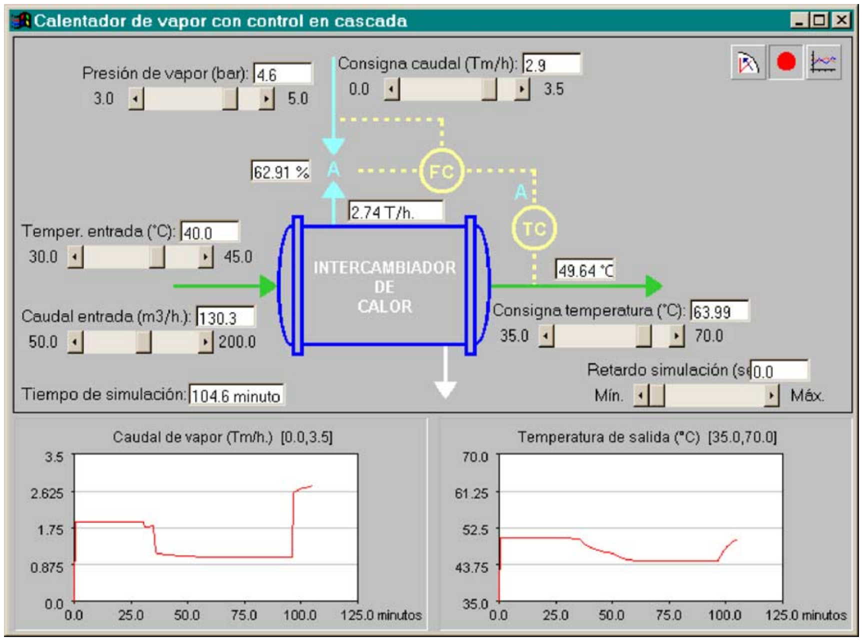

Fig. 4. Interface for cascade control of a heat exchanger.

cess advances continuously and dynamically, and the user obtains the results in the form of a continuous flow of numerical values or graphics steadily developing in each sampling period of simulated time. Another great difference with pseudo-batch interactivity is that, when a parameter is modified in the interface, the system response is immediate (obviously, the speed of the reaction depends on the size of the change and the dynamics of the model).

The simulation environment is completely interactive and dynamic (no batch or off-line simulations). In this way, the qualitative aspects are immediately highlighted graphically and numerically as a response to the user's actions. Students are not expected merely to tune sliders and controllers, to run the simulation, to examine the "scopes" (visualisations), and to repeat all the steps if they want to change some of the data. During the experimentation phase, changes in parameters and variables are immediately reflected in the graphical user interface (GUI). Thus, users can visualize on the fly how the model behaviour evolves according to the values of the interactive variables.

Fig. 4 shows a simulation environment that has been developed to convey a feeling of realism, as if the users are in an actual control room and their attention is focused on a basic element of the process (Sánchez et al., 2002). Additionally, this characteristic gives the tutor/instructor a priceless tool for the on-line explanation of certain concepts without having to repeat different simulations. A glance at the scopes allows students to understand how the plant behaviour is changing when the parameters are varied.

Interactivity is essential for imparting some realism to the experiments that the student carries out with the simulation environments. To emphasise the dynamism and qualitative aspects, the experimentation system GUI is closely integrated with the simulation, providing features, such as dynamic visualisation, animation of elements, and logging of variables and events. The GUI is composed of the following parts: the process diagram, the control panels, univariate scopes, the multisignal scope, and the historical log.

Given the characteristics of these simulations, the tool par excellence is Java language, although it is also possible to find some developments with ActiveX controls (National Instruments). Other examples can be found in (Alfonseca et al., 1999; Carlson et al., 1996; Crutchfield & Rugh, 1998; Esquembre et al., 1996; Narayanan et al., 1999; Salazar-Silva et al., 1999; Torres et al., 2001).

With this philosophy we should mention the works of Schmid developed at Ruhr University (Schmid, 1999, 2000), where part of the on-line interactivity with the experimentation environment is done with a three-dimensional interface developed in VRML. Thus, its environment, VCLab, needs to be studied in depth in order to see how three-dimensional worlds can contribute to the field of teaching and simulation, and even more so if we look at interaction with physical objects whose characteristics are difficult to transmit to a static two-dimensional view.

To summarize, irrespective of the design and degree of interactivity possibilities, the three most frequent WBS environments are:

- *Monolithic approximation*. The graphical interface and the simulation engine are a monolithic application that is executed within the WWW navigator and resides in the client's computer (see Fig. 5a).
- *Semi-distributed approximation*. The graphical interface and the engine are independent applications and they both reside in the same computer, i.e., in the client computer

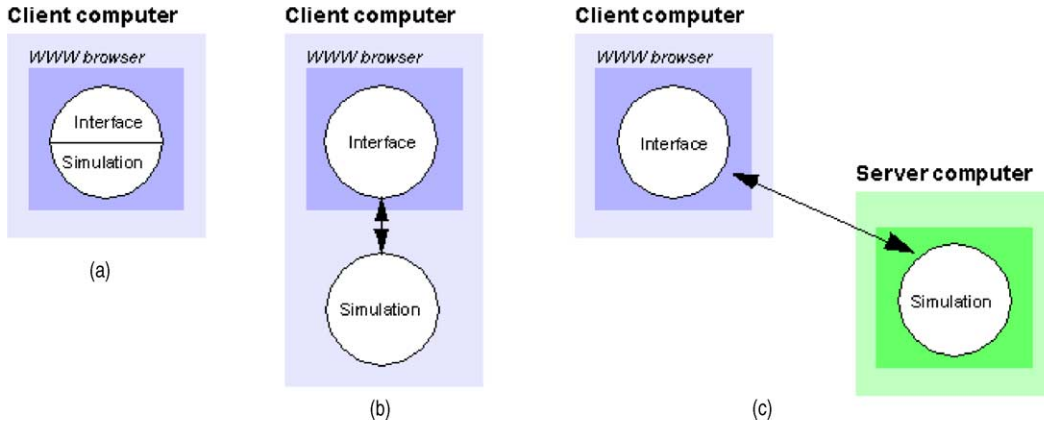

Fig. 5. Most usual Web-based simulation.

(see Fig. 5b). The interface is located in the WWW navigator, whilst the engine is usually a Matlab/Simulink, Labview or ACSL simulation environment.

- *Distributed approximation*. The graphical interface and the engine are independent applications and they are physically separate (see Fig. 5c). As in the previous approximation, the interface is located in the client WWW navigator but the simulation resides in the remote server, and it may consist of an application developed for this purpose, or of modelling and simulation tools. In both instances, communication with the interface can be in one of the ways described earlier: front-ends with CGIs or ad hoc servers for their communication with the interface, sockets, etc. Within this category we should also consider the possibility of many users working independently with the same server.

The tools for the development of graphical interfaces are usually ActiveX controls (limited to Windows platforms), Java applets (any kind of navigator with Java support), VRML models (any navigator with its corresponding plug-in for the interpretation of VRML) or Java 3D for the development of three-dimensional graphical interfaces, and script languages like JavaScript or JScript when communication is done with remote-simulation forms and CGIs (characteristic of pseudo-batch simulations).

Obviously, the previous definitions and criteria try to present in a structured way most of the different ways of doing a WBS, but there are some cases that do not exactly match these definitions. For example, can we consider in this paradigm the independent applications that are directly connected via the Internet with a remote computer containing a calculation engine, as occurs in (Gillet, Salzmann, Longchamp, & Bonvin, 1997). In our opinion, we can. The reason is that, although the interface is not part of a Web navigator, this does not mean that the system architecture is not based on the same fundamental principles and ideas as the WBS. Furthermore, since Java language has become standard de facto in these developments, its use for user interfaces very easily allows the same file to behave as an independent application and an applet incrusted in a navigator HTML page.

6.6. Principal application areas

We have presented what this new WBS field consists of and we now analyze some of the areas where the synergy between the WWW and modelling and simulation tools is complete. The areas are the following:

1. *Upgrading of hypermedia documents by incorporating simulations*. In this case, HTML page educational contents do not just have to be static texts, video recordings, animations with no interactivity, or off-line voices by a teaching team. The inclusion of interfaces for interaction with simulations representing the concepts to be explained provides the student with the basic tool for practising with the theoretical concepts transmitted via traditional information channels on the Web (audio, video, text, graphics) (Patton & Jayanetti, 1996). In order for a particular computer simulation to be effective and receive widespread use, three conditions have to be met: (a) The simulation has to be *authentic*—that is, it must address real educational issues. It has to allow something to be taught in a way that the students who are going to use it can understand. (b) The simulation has to be *adoptable*—that is, it must be easy for instructors to put into their classes and easy for the students to learn to use. A heavy learning curve—for teachers or students—severely impedes its adoption. (c) The simulation has to be *adaptable*—that is, it must be easy to modify to fit a particular instructional setting.
2. *WWW integration of simulated models previously generated for other courses*. Currently, and given the length of time during which simulation has been used as a didactic resource, numerous models have been developed. Many of them, almost all of them, are used locally in university laboratories and classrooms, i.e., in a specific computer with specific software. Sometimes this software is not available for students to use in their per-

sonal computer or the hardware resources are so high that they do not have this computational power in their own home, so the only solution they have to gain access to the simulation at any moment is the WBS. We can find an example of this in (Alfonseca et al., 1999; Alfonseca & de Lara, 2001). The authors have developed an object-oriented simulation language called OOCSMP (*Object-Oriented Continuous Modeling Program*), an extension of CSMP simulation language, which allows the development of object-oriented models when the system to be simulated consists of several similar parts interacting among themselves. A compiler called COOL (*Compiler for the OOcsmp Language*) has been created together with this language, which semi-automatically converts the models developed with OOCSMP into Java/HTML or C++ skeletons. Thus, all the earlier developments in OOCSMP can easily migrate to Java-based WBS.

3. *Development of new modelling and simulation methodologies*. In accordance with the observations by Page et al. (1999), the application of Web technology to the field of simulation implies a revolution in the traditional ways of developing, documenting, analysing and distributing simulated models. The Web and its related technologies enable analysis and development to be done in a collaborative and open way between different people irrespective of their geographical situation. Furthermore, the documentation becomes more dynamic, expressive and rich thanks to the multimedia contents, and the simulations are universally distributed as on the Internet. Accordingly, the positive influence of the Web is clear in the field of modelling and simulation, but its potential for introducing changes in the fundamental principles is considerably less apparent except for distributed simulation and modelling, as can be seen below.
4. *Distributed modelling and simulations*. To date one of the great defects in computer simulation has been the non-existence of object models published in a global medium for their distribution and execution; the Internet and its related technologies are presented as the right medium for filling this gap. To achieve this, the design and creation of blocks or atomic digital components is necessary. The latter have standardised interfaces and allow larger distributed models to be constructed from them by taking the net as the linking nexus. Although it is true that this idea may produce a market of distributed simulated components where engineering firms offer the possibility of establishing links with their components and using these components, it is also true that it is necessary to establish some certification mechanisms so that the digital component has the same quality control mechanisms as its physical counterpart. Accordingly, even if a car is built by assembling different parts, it could also be modelled by linking the different components after they have been modelled, resulting in a model of a car distributed throughout the net and ready to be tested. That is to say, the need for a thorough *component-based design methodology* is obvious, and Java can be considered as the ideal candidate for this (Piguet & Gillet, 1997). Without losing sight of this language's characteristics, there are two elements that will have a fundamental role in this new component-based design: *interfaces* and *event-based communication*. On the one hand, interfaces enable components to interoperate and pass messages without having to know the class or class hierarchy inside other components; a component's interface is equivalent to a commitment to incorporate certain methods that operate independently and await the sound of messages and their generation before certain internal events (a change in state) or external ones (the arrival of another message).
5. *New WWW-oriented modelling and simulation tools*. One consequence of the points above is the emergence of new modelling and simulation tools or the adaptation of already existing commercial tools. Taking Java language as a base (Hamilton, 1996), there are numerous packages available for developing discrete event-based simulations, like for example, SimJAVA [SimJAVA], Silk [Silk], JavaSim [JavaSim], SimProd [SimProd] or JSIM [JSIM], giving rise to what in the WBS area is beginning to be called *Java-based simulation*.

On the other hand, commercial simulation and modelling environments for discrete and continuous simulation are striving to incorporate new elements so that their link with the net is much better, and their products and developments are accessible via the net. A very important example is the product offered by the company Mathworks to link its family of Matlab products to the Internet: the Matlab Web Server [MWS]. This tool enables all Matlab applications to be executed in a Windows or Solaris server so that the user can access them via a WWW navigator, using HTML pages as a graphical interface for sending parameters and visualising results. The only disadvantage of this tool is that it is not for on-line interactive simulations since it uses CGIs to exchange data between the user and calculation engine. Yet, even without net-oriented products, nearly all the commercial environments have their own APIs for calculation and simulation engines from other languages (Java, VBasic, C++) that do have possibilities of accessing the network, as occurs in Matlab/Simulink (Matlab Engine, Matlab ActiveX) or in ACSL (ACSL Open API).

An immediate consequence of the reading of this technology's application areas is the development of virtual remote laboratories through simulations. That is to say, *the application of Web-based simulations to the educational field as a direct result of the development of virtual laboratories accessible via the Internet*.

As a summary of the WBS application to control-engineering teaching, we focus on one of the conclusions that appears in the NSF/CSS Workshop summary-report on New Directions in Control-Engineering Education (Antsaklis et al., 1999):

> "The Internet represents a major opportunity for control education, both for the dissemination of instructional material and for the development of remote laboratories, where students can gain practical laboratory experience over the Internet".

7. Web-based teleoperation

Laboratory experiments play and will certainly play an important role in control-engineering education (Horacek, 2000). One important tendency in the field of control practice is the increasing employment of virtual instrumentations. In fact, in major production facilities operators are often trained in plant operation using a simulation environment (instead of the real process) to drive the virtual instruments. These virtual labs mimic this to a certain extent, as the student has a continuously simulated system with the internal details of the plant concealed. Controlled and manipulated variables are visible only through a virtual instrument panel. The experimental data can be exported by the student to a software package for doing control design, and the results applied back to the virtual lab.

What is obvious is that experimentation in situ with a plant or real object cannot be replaced by a simulation or training simulators (Cooper & Fina, 1999; Poulis & Pouliezos, 1997), especially as regards the sensations perceived by the student in the experiment. Practical education needs to be based on errors and irregularities, as occurs in mechanical, electrical or chemical systems in opposition to the ideal icons and environments represented on a computer's monitor.

One vital aspect of control-engineering education is the laboratory and practical work necessary to give engineering students a taste of real situations, measurement and instrumentation, with all the attendant problems (Röhrig & Jochheim, 2000). The idea is for the students to be able to perform real experiments, in real time, on real equipment, but over the Internet.The use of remote labs for supporting and integrating the activity of a control-engineering course is in fact a widely discussed issue. An analysis of the recent solutions developed for remote labs, where different laboratory experiments are run remotely via a Web interface, is reported in (Poindexter & Heck, 1999). Different solutions of remote control-engineering laboratories are presented and discussed in (Bhandari & Shor, 1988; Bohus, Crowl, Aktan, & Shor, 1996) where remote control was applied to a robot arm. A remote measurement lab is also described in (Arpaia, Baccigalupi, Cennamo, & Daponte, 1997). In all the proposed solutions the remote user (a client user) is connected by Internet to a dedicated Web server that interacts with the computers of the laboratory used for controlling (monitoring) the experiments.

The rapid progress of Internet technology and its increasing popularity has prompted several educational institutions to develop Internet laboratories (Ko et al., 2000; Ling, Lai, & Chew, 2000; Overstreet & Tzes, 1999; Sánchez et al., 2001; Shaheen, Loparo, & Buchner, 1988; Sheng, Choo-Min, & Khiang-Wee, 2000). With the help of an on-line Internet laboratory for control experiments, the educator can be encouraged to design control-engineering courses that combine theories without neglecting the practical experiments. Via the Internet, the on-line laboratory could offer the instructors more flexibility to prepare assignments for their students that require some experimentation with the real plant. In addition, an Internet laboratory allows equipment to be better used by both local and remote users since they can access the laboratories from anywhere with an Internet connection. This sharing of resources not only brings down the experiment cost per student, but equipment will also be made available to more students as the time and space constraints normally associated with a traditional laboratory can be removed. In order to give remote users a laboratory experience as close to the one obtained by local users, experiments are based on real systems rather than computer simulations or virtual reality.

This concept of remote labs provides both vertical and horizontal integration of control education and addresses several problems faced by engineering educators, such as the cost of high technology, the duplication of resources that occurs when several departments attempt to offer independent control laboratories, the rapid obsolescence of equipment and the difficulty of providing technical support.

Our point of view is that there is no replacement for real experiences on physical plants, but there are special situations that demand students to have access to virtual experiments. For example, the student may not have access to a laboratory or may be asked to do a virtual experiment before carrying out a real one later at a physical plant.

The equipment in a remote lab must be modified in order to make it suitable for remote control operation (Shen et al., 1999). At first sight this appears to be a relatively straightforward task, simply replacing manually controlled components with remote controllable versions. However, in the detailed implementation many more aspects arise for consideration. Attention has to be paid to ensuring that the equipment always remains safe in the event, for example, of a breakdown in the communications link. A human operator could immediately realize that some situations were wrong and could take action to prevent all these potential occurrences, and ensure that the system failed safely, even in a fault condition. Provision also has to be made to allow the equipment to be easily shut down locally, regardless of what it is being requested to do remotely.

In addition to all this, very often the real experiment's sensory perceptions; visual, auditory and tactile, cannot be reproduced with a simulation or they are, but with a financial or time cost, which does not allow them to be developed by a workgroup in a university department. Together with this there are numerous situations in industrial environments where the operators make corrections in accordance with what they see and hear, and even smell, when they are in front of the device.

Obviously, in face-to-face practical laboratories these sensations are indeed perceived by the students: the device in question is nearby and they can see, touch and hear what is happening at every moment, what the results are or what unforeseen situations are generated. Consequently, we must always accept the idea that *practical experience enriches the student's knowledge in a way that simulations cannot*.

Yet, the practical laboratories, as they are currently conceived, are subject to a series of factors that limit their use, such as:

- *The high number of students enrolled in the subject*. This restriction forces shifts and timetables to be established, with the subsequent detrimental effects for students (no additional time in the laboratories to complete their tasks, not many practical cases) and for lecturers (abandonment of their research work or extra work activities to cover the shifts so that the students are not left unattended in the laboratory).
- *Distance-learning-based educational model*. Distance education offers flexibility for those who are subject to limited time, distance, or physical disability. They can benefit from a more flexible environment that lets them learn in their own time, wherever they choose. Very often these students are forced to enrol in other degrees where experimentation is nil or can be done with a personal computer at home.
- *Insufficient economic resources*. In many instances there are very few laboratory experiments. This, together with the number of students and limited laboratory space, leads to situations where the practicals cannot be appropriately developed.

7.1. The concept of teleoperation in teaching

In order to resolve or alleviate to a certain extent the problems raised above, it is necessary to resort to a concept that is accessible to the student and the general public thanks to the current diffusion of the Internet network: *teleoperation*. Generically, the term teleoperation can be defined as the *possibility of gaining access to the remote manipulation and control of certain resources just as if they were operated upon locally, manually and directly*. Obviously, the definition of the term encompasses many forms of action that can be grouped under the same umbrella: from the control of a cable remote-controlled car to the radio-frequency control of supervision vehicles on Mars.

Another very common concept at the moment is *telepresence*, which on numerous occasions is considered to be a synonym of teleoperation but is more related to virtual reality environments. The term telepresence can be defined as a *situation or environment where we perceive with our senses all the stimuli necessary for believing that objects or places not present in our physical environment are real*. This implies not only the perception of basic sensory stimuli but also the possibility of interaction with the environment, i.e., the environment is not only heard, smelt and seen but it reacts and responds to users' actions. Accordingly, telepresence can be considered as the most advanced teleoperation mode.

Yet, moreover, any kind of teleoperation, however basic, has a higher or lower degree of telepresence since it always implies the performance of remote actions similar to those done locally and directly by a human operator. Thus, and to highlight the difference between the two terms, teleoperation is a field of application of telepresence where the quantity or intensity of stimuli that the user receives stretches from ordinary every day (interaction with the remote system using a graphical interface with the mouse and keyboard) to futuristic (virtual reality immersive system).

Although teleoperation based on total immersion is at present a utopia and a leading research topic because of its immediate and direct applications, there are other less sophisticated engineering techniques based on the current communication network which allow the teleoperation of numerous physical systems just by having an interconnection point or a software interface with these networks. Thus, the technology currently available for the average person in his/her own home, that is to say the teleoperation of remote laboratories, is a viable instrument that can be integrated into current distance-learning methodologies.

In accordance with what has already been said and within the context under discussion, we will limit the term teleoperation to *access to practical laboratory elements using the Internet network resources with a sufficient degree of presence to be able to develop the practical activities in exactly the same way as if they were developed in a traditional way on the laboratory premises*. If the term teleoperation is applied to gain access to face-to-face laboratories without any restrictions of space or time, then we have the concept of a WWW-based remote laboratory (see Fig. 6).

7.2. Benefits

But what are the reasons that lead us to believe that teleoperation is a possible solution for reducing the problems that exist in university practical laboratories? Remote access via the Internet has the following characteristics:

- *Laboratories are accessible 24 h a day every day of the year*. Students' time is more personal and free, and they can adjust their pace of study to their working and family life and not the opposite, as presently occurs.
- *Students do not have to travel to the centre to do the practical activities*. Let us imagine distance-learning-based educational models where the distance to the centre is several hundred kilometres and the student has to go there several times a week.

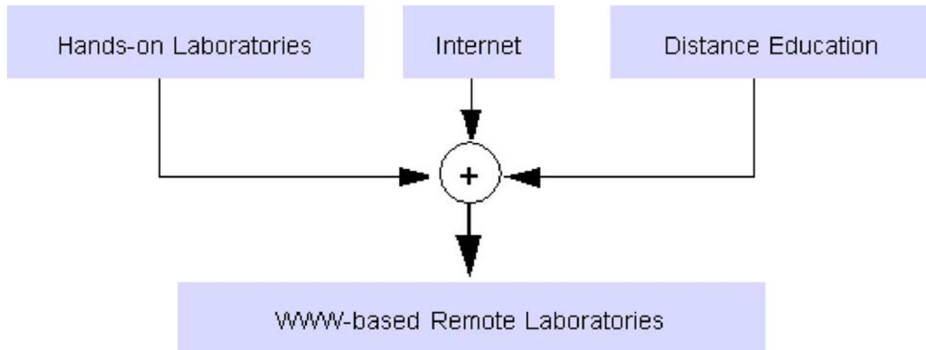

Fig. 6. World Wide Web-based remote laboratory.

- *Optimal exploitation of the resources*. Extending time accessibility irrespective of the location of the operator leads to better exploitation of the laboratory elements. Thus, the ratio *money inverted/time used* obviously improves. We should furthermore highlight that the construction of virtual laboratories does not require large areas since students do not occupy any space; the only room necessary is for the experiment's instruments and the safety distances indicated by the norms for preventing accidents.
- *Accessibility to different kinds of experiments* irrespective of the centre's scant resources.
- *Prior preparation by students of their experiments* if they have to go to the laboratory. The remote laboratory permits a previous preparation phase in those situations where students have to go to the laboratory to show their knowledge. Moreover, preparation or familiarisation time in the laboratory is notably lower because some of the practical activities are done beforehand.
- *The learning process is enhanced, since a constant nexus is established between experimentation and theory*. Students can put into practice the knowledge imparted to them in class without having to wait for the practical. They are not confined to the practical activities set by the teaching team, but can freely innovate.
- *Adaptation and personalisation of the laboratory environment to students with disabilities*. People with disabilities may access the laboratories from their own homes with experimentation interfaces especially adapted to their particular problems.

As occurs in WBS, one consequence of the creation of remote laboratories that deserves particular attention because of its importance, given the model of society and university towards which we are supposedly moving, is the creation of *remote laboratory interuniversity networks*. If the existence of remote laboratories resolves many of the problems raised above, the setting up of consortia considerably increases these benefits. Benefits that are to the advantage of the two parties concerned: students would have a complete battery of activities that had nothing to do with the level of physical equipment, whilst teachers would have different platforms to support their teaching based on the master class, thereby minimising purchase and maintenance costs.

Laboratories, either well or badly equipped would not exist, but only one environment in which to work, to the advantage of all the university since it would be able to offer more integral, complete, varied and up-to-date teaching. As regards this aspect, we should consider the observations in the summary report of the NSF/CSS Workshop on New Directions in Control-Engineering Education (Antsaklis et al., 1999), which are literally as follows:

> "A shared laboratory can mean two or more departments sharing equipment and coordinating the development of experiments. It can mean the development of an integrated network of centralized laboratories . . . , or it can mean sharing laboratories across campuses and across universities. Shared laboratories within individual colleges or universities, as well as shared laboratories among different universities, make more efficient use of resources, increase exposure of students to the multidisciplinary nature of control, and promote the interaction of faculty and students across disciplines. Shared laboratories also facilitate the horizontal and vertical integration of control systems concepts in the curriculum".

Let us imagine the possibilities that a distributed infrastructure could have with just one access point for remote practicals on a subject with a high experimental content as is the case of Automatic Control. A paradigmatic example of shared laboratory is the active portal at the University of Purdue called PUNCH (*Purdue University Network Computing Hubs*) (Kapadia, Figueiredo, & Fortes, 2000). Another collaboration between universities for teaching in mechatronics applied to mobile robotics is the project IECAT (*Innovative Educational Concepts for Autonomous and Teleoperated systems*) (Roth, Schilling, & Rösch, 2000). Finally, two other examples of remote laboratories applied to the field of automatic control are the initiative LearNet supported by eight German universities for the creation of a remote laboratory infrastructure at national level [LearNet] or the project ReLAX as an example of corporate-university collaboration [ReLAX].

7.3. Disadvantages

Obviously, the use of teleoperation environments for practical experiments does have some drawbacks, such as the following:

- *No direct physical contact with the experiment*. The inevitable spatial separation of the student with the laboratory may reduce the sensation of practical realism (Schmid, 2000). The solutions to this demotivating factor are the correct use of multimedia components like live video and audio or three-dimensional scenarios to increase the sensation of telepresence. Another additional factor that is decisive in increasing the degree of telepresence is the use of direct and interactive action strategies on the physical system, avoiding as much as possible the use of batch techniques. An essential requisite for the success and acceptance of the environment is that an operator's actions on the experimentation interface have an immediate effect on the remote system and that, via multimedia components, the user perceives the result of the action in a steady and direct way (always bearing in mind the experiment's time constants), thus clearly and notably increasing the telepresence sensation in the remote laboratory.
- *Inappropriateness of the subject to remote operation experimentation*. It is obvious that not all the scientific and technical subjects, however experimental they are, allow the creation of teleoperation environments. A clear example are the chemistry laboratories where the large number of activities to be developed and elements to be manipulated mean that, for the moment, their integration is especially difficult in teleoperation environments except for very specific parts of these environments. Another example is the assembly of combinational and sequential circuits in a digital electronics laboratory. One solution for these kinds of experiments is to create independent simulator-based virtual laboratories or WBS.
- *Unpredictability and instability of transmissions*. Although these are not important factors in teleoperation systems in restricted environments and with some deterministic service quality parameters, like university campus internal networks, they are indeed demotivating elements when there is access from any geographical point. In Salzmann (1999), the characteristics of transatlantic transmissions via the Internet between Lausanne Federal Polytechnic School (Switzerland) and Florida University (USA) are described in order to establish a model allowing different solutions to be analysed to solve this disadvantage.
- *Need for a change in teacher and student mentality*. In spite of the increasing number of new ways of interaction and communication (mobile telephones, the Internet, interactive television, automatic cash points, etc.) in present society, there is still a high percentage of people that are blind to this blatant situation. One group is university lecturers who, in spite of the enormous effort that is being made, are still not using these technologies as widely as they are used in other areas, such as banking. It is among lecturers rather than students that this change in mentality is really needed. Students are young and more used to these new media. However, lecturers, either because of inertia, fear of change, or not enough experience in these issues, have not taken advantage of this technology in their daily teaching activity. It is because of this that although there are excellent teleoperation environments, their use requires the prior fulfilment of two prerequisites: training in the use of new technologies and adaptation of the didactic materials to the new framework (Copinga et al., 2000; Latchman, Salzmann, Gillet, & Kim, 1999; Poindexter & Heck, 1999).

7.4. Requisites for remote experimentation

Successful implementation of a teleoperation environment to complement or replace a framework of local experimentation must meet the following requisites:

- *Easy comprehension and use*. The experiment is remote and so is the support teaching staff; students can practice at any time and do not have any help in situ to solve the problems that prevent them from advancing. It is because of this that the experimentation interface must be friendly and complete and, as far as possible, it should present the same components that the student would find in the face-to-face laboratory. Accordingly, we can express the following "*An important aspect when a remote laboratory is designed is to make all the hardware components as simple as possible to ensure quick and effective maintenance. The same criterion must be applied to make use of the commercial software packages currently available*" (Schmid, 2000).
- *Adaptation of traditional didactic materials to the new context*. The support material for practices must be self-contained and self-explanatory, exhaustively describing the work environment, the objectives pursued and the action mechanism. Given the characteristics of distance studies, the implementation of telelaboratories requires creating communication channels which make up for the lack of contact with agents involved in the resolution of problems: fellow-students, tutors, lecturers.
- *On-line supervision of the experimentation environment*. Users must know what is happening at every moment both in the physical system and in its environment in order to achieve their objectives and avoid damaging the laboratory material. For this it is necessary to use real-time reception of data, video and audio, avoiding the loss of practical realism with an increase in visual and auditory sensations.
- *Appropriate server and physical system security policy*. The user must not directly access certain private sys-

tem resources (personal data, file system, local network, low-level hardware, etc.). The server software must protect the physical system against any hostile or accidental action that may damage or destroy it. Moreover, it is necessary to find a point of equilibrium between security and flexibility, since the wrong security policy may cause the environment to collapse because it overrestricts users' actions.

- *Multi-platform client software*. Students, especially the ones doing experimental sciences, are a group who, in spite of the predominance of Microsoft (Windows), also use a number of other operating systems, such as Linux or MacOs. Consequently, the remote work environment must be developed so that it can be used from a wide variety of operating systems.
- *Easy installation of client software*. Users, in spite of their computer knowledge, are not experts. Besides they do not have a teaching team, and for this reason the installation of the software must be as simple as possible without the need for third parties to install complicated software packages.
- *Client safety*. Clients must be protected against the downloading and execution in their computers of new software. An electronic system company can certify that the software has been developed by a reputable centre and does not endanger the security of their computers. In addition, the use of Java applets as experimentation interfaces is a guarantee of integrity for clients thanks to the security model in the Java specification.
- *Free client software*. A requisite is that clients should only need a computer with access to the Internet for the practicals, and they should not have to buy any additional software. This requirement, together with the previous one, means that the software for the client must consist of applets or Java applications. Similarly, the use of freely distributed educational software is an alternative to bear in mind when selecting development, complementary and support tools.
- *Flexible algorithm formulations*. Even though the elements that intervene in a laboratory can be summarised into a set of equations with a fixed structure, it is necessary to allow freedom in design and only a programming language can provide this.
- *Easy access to a library of algorithms or prior activities*. One way of evaluating the system's advantages and improving the quality of the work developed is by analysing the works elaborated by other system users. An area for storing algorithms and earlier works facilitates collaborative and individual work in distance-learning environments.
- *Object persistence*. The system has to store the work developed by clients in a persistent way. Thus, the workspace owner can access all the experiments that have been developed in the experimentation environment. Similarly, the teachers will have access to these workspaces to test the works done by users and their validity.
- *Downloading of experimental data*. In some instances the complementary use of certain analysis tools may be necessary. For this reason the work environment must allow the gathering of experimental data in formats that are well known in the corresponding area.
- *Maintenance of version management policies*. As in the software engineering area, the design and development of experiment or algorithm files, both individual and collaborative, require appropriate policies for controlling the versions. The inclusion of workspaces in remote laboratories must consider the possibility of controlling versions of the elements in these areas, either automatically or manually
- *Open and modular architecture for the inclusion of new components and exercises with minimum effort and disruption to the service*. The system must be prepared for the lecturer to have the possibility of including new practical activities without any changes in the experimentation environment. Thus, an appropriate navigation interface that allows families of experiments to be practiced is an ideal solution for the inclusion of new experiments in an ordered and structured way. Moreover, the possibility of increasing the experimentation environment features with the inclusion of new basic modules must be a compulsory requisite: the system must be prepared to change and develop together with current technological development; a highly modular design facilitates this development.
- *Appropriateness of the physical system*. The physical system to be teleoperated must be visually attractive to guarantee the sensation of telepresence. Systems with mobile elements (tanks with liquid, pendulums, ball and beams, engines, mobile vehicles, etc.) are ideal because their visualisation makes users sure that their actions are having some kind of effect on the remote system, that is to say, that something is happening. If the sensation of practical realism is to be guaranteed, the inclusion of indicators, graphics, controls and animations is not enough, a real visual feedback of the experiment is necessary.
- *Acceptable parameters for service quality*. Experimentation via the Internet, and more specifically real-time experimentation, is a new net-based application with some requisites different from those in traditional videoconference or data transmission environments (Salzmann et al., 1998). A key parameter determining the success of a teleoperation environment is the speed of the response reception, 5-s response time being acceptable.
- It is obvious that, depending on the kind of teleoperated laboratory or the objectives it pursues, some of the requisites described here may be omitted. The list above does not establish a set of requisites that every telelaboratory must obligatorily fulfill, but enumerates a series of issues that should be considered as a preliminary step to creating any infrastructure for remote access; after analysing each specific situation, the most appropriate decisions should be taken.

7.5. Remote visualisation

Currently and thanks to technological progress, every laboratory that is considered real *telepresence* requires visual and auditory communication, both the plant and process being experimented upon, and the possibility of conversing with the lecturer and fellow students (Bohus et al., 1996; Maly et al., 1997). In accordance with the ideas outlined up to now, the objective pursued is the creation of a work environment that allows *remote visual supervision of a process*. Thus, what we aim to construct is a *remote network sensor* (McDowell et al., 1998), which can be controlled by the lecturer/supervisor and the student/operator, although it is always the lecturer who sets the specifications for the student.

The traditional field for video use is telerobotics, which is a means for prolonging the human sense of sight beyond that allowed by the human condition per se. Thus, in some instances the video allows a human being to operate in dangerous environments (mines, nuclear power stations) (Corke, Roberts, & Winstanley, 1998) or remote environments (external space, great depths) (Sheridan, 1993); in other instances it removes the spatial barriers for the application of an expert's know-how (medical teleassistance, surgical teleoperations) (Kitson, Malzbender, & Bhaskaran, 1997; Sacile et al., 1999); and why not use it for remote experimentation of certain control-engineering aspects (Aktan et al., 1996; Gillet et al., 1997, 2000; Overstreet & Tzes, 1999; Schmid, 2000).

Here are some of the possible applications in telepresence or teleoperation pedagogical environments applied to automatic control teaching:

- *On-line process monitoring*. Direct real-time visualisation of how the control actions on the experimentation interface affect the real plant. Thus, the feedback the student obtains does not only come from analysing the numerical values but also from observing the process.
- *Off-line process check*, that is to say, recording on video all or part of the experiment with the plant, so that, after the teleoperation session, it is possible to focus on a particular aspect of one of the steps in greater detail.
- *Concept reinforcement*. Use of video sequences obtained from some earlier experience that allows some theoretical concept to be reinforced.
- *Problem exercises*. Visual presentation of some situations so that the student can think a priori about what actions must be taken when a particular situation arises during a teleoperation session.

8. Hidden or open technology?

In a really lucid paper Åström coined the term "hidden technology" as a characteristic of automatic control in the sense that automatic control systems are in many instances crucial for the proper functioning of the global system (Åström, 1999). A failure in the control system will lead to a system failure. In spite of all this, automatic control does not generally cause much discussion.

8.1. Control engineering: a broader context

One of the most important issues in contemporary control engineering is the search for one's own identity. As used today, the term "control" or any of its variants refers to feedback control. However, the term control is today much broader than feedback control. It encompasses all the problems of complexity associated with process control in a very general sense. While feedback control plays a fundamental role in these systems, the broader control problem of designing software-based systems to cope with issues of coordination, operator interface, communication, error and exception management and other crucial issues are equally or more important. We barely teach techniques for dealing with these problems but we must recognize that a large numbers of our graduates are working on these problems.

Moreover, it is obvious that the vast majority of IFAC members are engaged in teaching feedback control. Of course, feedback control is a fundamental cornerstone of many engineering systems and, for this reason, I think that we should carefully re-evaluate our introductory feedback control courses in order to see if we are fulfilling these needs and targets (Dorato, 1999). Many people now believe that some of the traditional approaches that have been used for teaching control are no longer appropriate for the target audience. That audience needs to be motivated and must be confident that they could identify and solve straightforward feedback control problems after finishing a course of this kind. Instead, our offerings are abstract and based on nineteenth century mathematical concepts.

In this respect we need to reconsider the application areas of what we teach on the undergraduate control-engineering curriculum. We should remember that many of the pioneers in this area invested a great deal of their effort in social, biological and economic systems as application areas for the emergent discipline of control. We strongly feel that the moment has arrived to shift our teaching focus from "control-engineering principles" to "system dynamics principles". This requires the inclusion of systems analysis, modelling and design aspects that are at the origin of our discipline in areas, such as biology, medicine, economics, social, ecosystems, industrial engineering, etc. In short, any discipline where the concept of "change" is presented.

An introductory course, in my opinion, should be primarily motivational. That is, it should provide students with an appreciation for the role of feedback in technological and natural systems, and an intuitive feeling for issues that affect the design of feedback systems (Bequette, Chow, Li, Maby, & Newell, 1999; Bernstein, 1999; Heck, 1999). Students who take no further control courses should emerge with a feeling that they know how to handle simple feedback problems, and know how to identify difficult ones.

We should mention as a good example to follow in the future, the recent increase in the last few years of the application of control engineering in medicine, and the way in which the range of problems and future prospects for research has expanded. An indication of the increasing emphasis on systems and control approaches to medicine and biology (Ghosh & He, 2001) is the fact the IEEE Control Systems Society has established a Technical Committee on Biosystems and Control (http://www.ieeecss.org/TAB/Technical/biosystems/).

As Bissell (1999) has remarked, the exposure to these approaches can only give students a much broader view of system analysis, modelling and design. This is the challenge that lies ahead: to convert our discipline from a "hidden technology", as highlighted by Åström, into an "open discipline" with its own distinguishing features so that its importance is recognised by society at large and it attracts our most brilliant young students with exciting challenges ready to be tapped. If on the other hand, we decide to continue looking inwardly, an enormous wealth of possibilities will be wasted.

9. Conclusions

Our general recommendation for control-engineering education is that students be made aware of problems and potential solutions arising from the increasing complexity of our technological systems. Laboratory experience is extremely important as part of control learning. The goals of control education that might be kept in mind regardless of the specific choice of material or the structure of the course are the following (Kheir et al., 1996):

1. To provide the basis for lifetime learning so that new control problems can be dealt with.
2. To establish and maintain high standards of excellence for the experience of learning the foundations of control.

Reforming the curriculum will not, however, be done by books alone. It will be done by people: students, teachers, researchers, practitioners, and by market pressures. Moreover, for these efforts to be efficient and sustainable, the control-engineering community will need to communicate their experiences via a host of new books, laboratories, simulations and Web-based resources. Thus, there will be a need for several different and complementary approaches.

In this lecture, we have reviewed the advantages and disadvantages of traditional university instruction versus the new practice of offering instructional material on the WWW. The changing role of instructors, the possibilities opened up by various technologies, and the economic and cultural roadblock of this form of spreading information and teaching are presented.

The change in control education that we propose must bear in mind the following general considerations:

1. Automatic control education currently has a very narrow approach and essentially focuses on mathematical aspects of the controller synthesis.
2. It is necessary to attach greater importance to all the design cycle of a control system.
3. Modelling and identification of the processes to be controlled are a key factor for achieving a good design of the control system.

Good education in automatic control recognises the importance of laboratory experiments and unequivocally balances the theoretical and practical contents.

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