An Integrated Structure for a Virtual Networking Laboratory

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Abstract—**A virtual laboratory is a virtual space where students are able to carry out practical activities. This paper presents an integrated structure for a virtual laboratory consisting on nine resources divided into pedagogical, human, and technological factors. Such a structure is based on the experience gained in design and development of virtual laboratories during the past 11 years in a virtual university. The proposed structure has been applied to different virtual laboratories, and this paper presents the special case of a virtual networking laboratory (VNLab) where students can access real networking devices. The VNLab structure described in this paper has been used at the Open University of Catalonia for the Cisco Networking Academic since 2001. Its suitability has been evaluated by the students using a Web questionnaire, and its correctness for the industrial electronics field has been analyzed.**

Index Terms—**Cisco NETLAB+, networking laboratory activities, remote laboratory, virtual laboratory, virtual learning environment (VLE), virtual networking laboratory (VNLab).**

I. INTRODUCTION

NOWADAYS, networking technologies have become of great importance in the world. As the popularity of networking technologies increases, so does the need for people with the necessary skills to design and create functional telecommunication facilities.

One of the companies that realized this fact early on was *Cisco Systems* [1]. To create new networking experts to satisfy the increasing demand in this field, the *Cisco Networking Academy* was created in October 1997.

Although *Cisco Networking Academy* courses rely on Web-based content and assessment to better supervise and organize updates to the curricula, it puts great emphasis on hands-on practice skills and in making students familiar with real networking devices. This is to ensure that new experts not only have theoretical knowledge but are also able to face real-life environments. For this reason, it was initially planned as a fully face-to-face course.

The Open University of Catalonia (UOC) [2] is a fully virtual university that uses a virtual campus to teach in a virtual learning environment (VLE). Currently, more than 37 000 students are enrolled in the different undergraduate and postgraduate programs at the UOC. The UOC joined the *Cisco Networking Academy* in 2001 to incorporate the courses into its postgraduate programs. As a fully virtual university, the courses could not be held face-to-face and had to be adapted to a VLE. Because of their practical characteristics, this proved to be an interesting challenge. New virtual spaces were required in a VLE to find a solution to carry out practical activities. Such virtual spaces are called virtual laboratories.

The term virtual laboratory is defined in different ways in the literature. Some authors [3] take a simple vision of a virtual laboratory as a local computer hosting that may include some simulation capabilities [4], [5]. An accurate definition can be found in [6], where virtual laboratories are defined as "*leverage modeling, simulation, and information technologies to create an immersive, highly interactive virtual environment tailored to the needs of researchers and learners*." Other authors introduce other important aspects like pedagogical and academic factors into a virtual laboratory [7], [8].

A virtual networking laboratory (VNLab) is a special case of a virtual laboratory where networking activities are carried out. An accurate comparative literature review and assessment of the effectiveness of VNLabs is found in [9] and [10].

One of the components of a VNLab is the remote laboratory. A remote laboratory is a technological resource that consists of one or more computers and/or devices installed and set up to allow remote access [9], [11], [12]. Remote laboratories provide students with a real environment to carry out practical activities. They are different from simulators because the latter are not real environments, as shown in [10] and [13]. In a VLE, a remote laboratory is a key resource since it is the only solution that allows students to work with real devices since it cannot be assumed that students will have such devices at home.

This paper presents a general structure for a VNLab that allows students to perform practical activities in the field of networking. The proposed structure is based on the experience gained in design and development of virtual laboratories during the past 11 years in a virtual university. The VNLab structure described in this paper is the one used at the UOC for the *Cisco Networking Academy*. Its suitability has been evaluated by the students using a Web questionnaire. The results show that all nine resources proposed for the VNLab, as well as their integration, are essential in a VLE. The key to success in a VLE is to integrate all these nine resources in a transparent and efficient way for the student. Furthermore, this paper maps the proposed virtual laboratory structure into different virtual laboratory proposals in the field of industrial electronics to verify its correctness as a general virtual laboratory framework.

This paper is organized as follows. Section II provides the general structure of the VNLab used at the UOC. The usefulness of the general structure of the VNLab proposal is analyzed in Section III by means of a survey providing student feedback. In Section IV, the specific tool of the remote laboratory, called NETLAB+, is introduced and evaluated. To contrast the correctness of the general virtual laboratory proposal, Section V maps different proposals of virtual laboratories in the industrial electronics field into the proposed nine-resource framework. Finally, a brief conclusion in Section VI concludes this paper.

II. General Structure for a VNLab

This section presents the implementation of a VNLab that has been used at the UOC since 2001. During the 2006–2007 academic year, 421 students used this laboratory while attending a *Cisco Networking Academy* postgraduate course and a computer engineering degree.

Bearing in mind that a VNLab requires special resources to improve the learning process of the practical activities [14], the following elements have been identified.

1) Technological resources
   a) virtual communication environment (VCE)
   b) simulator (SIM)
   c) remote laboratory (REM)
   d) automatic assessment tool (AAT)
   e) support tools (SUP).
2) Pedagogic and strategic resources
   f) learning methodology (MET)
   g) support documentation (DOC)
   h) evaluation (AVA).
3) Academic staff resources
   i) Teacher (TCH).

Next, an overview of each resource is presented.

A. Virtual Communication Environment

The virtual communication environment is a resource that allows communication between the users of the VNLab (students and teachers). It should stimulate the participation of the students in the VNLab and provide better interaction with the teacher. This resource can be implemented using shared mailboxes, public forums, and a teacher's board (e.g., *Blackboard* [15], *BSCW* [16], *WebCT* [17], *LMS Moodle Classroom* [18], and *UOC Classroom*).

In our VNLab, the virtual communication environment has been implemented as a virtual classroom of the virtual campus at the UOC. This space has three main features.

1) Mailboxes: This is a common area with access to students and teacher and corresponds to a traditional classroom. This area contains a teacher's board (where only the teacher has permission to write) and a forum.
2) List of students: The VNLab students and their teacher are listed in this area (photo, names, and e-mails).
3) Monitoring tool: This feature allows teachers to check student connections.

Note that, although the virtual communication environment is classified as a technological resource, it is closely related

to the academic staff. In a VLE, the virtual communication environment is absolutely necessary to create a real feeling of the university community. It is the only way the teacher can reach the students, access subject contents, and communicate and interact with the other members of the university.

B. Simulator

A simulator is a tool that imitates experiments, states, or processes. The purpose of the simulator in a VNLab is to allow the students to understand different behaviors of the practical activities that may be difficult to observe in a real situation. One of the main features of the simulator is its interactive capability that allows users to interact with it. Interactive simulations are quickly gaining importance as a means to explore, comprehend, and communicate complex ideas [9], [11], [19].

In a VNLab, simulators allow students to practice network device configuration from a stand-alone computer, without the need of the real physical device. Thus, even when students lack physical access to routers, they can gain valuable experience. There are several professional simulators available, but they tend to be too complex for pedagogical purposes. Fortunately, some simulators only address the basic needs of a student of networking subjects.

In our VNLab, students use two simulators.

1) *eSIM* [20] provides a closed sandbox, where students may practice router configuration in a preset topology.
2) Once students have eventually mastered the basic configuration, *Packet Tracer* [20] is used to enable open scenarios. Through simulator, it is possible to create any kind of network topology, configure each device, and simulate different scenarios. In each scenario, it is possible to graphically analyze how packets are sent between devices.

C. Remote Laboratory

A remote laboratory provides the student with a real environment to perform practical activities. It consists of computers and/or devices set up to allow remote access [9], [11].

The VNLab at the UOC uses *Cisco* NETLAB+[1] as the remote laboratory. As it is a central resource of our VNLab, Section IV provides a detailed description of the *Cisco* NETLAB+.

D. Automatic Assessment Tool

The automatic assessment tool enables an interactive process between the student and the automatic assessment system that allows the students to learn by an iteration process. This automatic system also reduces the mechanical work of teachers, allowing them to concentrate on other more beneficial aspects. To improve interconnection with other systems, it is very important for any assessment system to follow the standards proposed

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[1]NETLAB+ is the intellectual property of Networking Development Group (NDG; http://www.netdevgroup.com). NETLAB Academy Edition was developed by NDG under contract with Cisco Systems, Inc.

by the *Question and Test Interoperability Specification group* of the *Global IMS Learning Consortium* [21] and the group *Sharable Content Object Reference Model* [22].

Our VNLab uses an automatic assessment tool developed by *Cisco Systems*. The Web assessments are designed to provide information about student' knowledge of networking concepts and procedures [23].

E. Support Tools

In some virtual learning scenarios, there are other specific tools that support the learning process but cannot be homogeneously classified. These tools could be used for different purposes. Mainly, there are specific programs or applications that run in the local computer.

In the VNLab, students use three specific support tools.

1) *Wireshark* (previously known as *Ethereal*) is the most well-known network protocol analyzer. It allows students to analyze how traffic is sent across a network.
2) The *configuration register decoder* is a very simple but helpful application that allows students to know how changes in the configuration register of a Cisco router affect its capabilities (such as the boot process or console access).
3) *Hyperterminal PE* is a terminal emulation application that may be used to interact with the remote laboratory.

F. Learning Methodology

There are several proposals of learning methodology from a teacher-lecture-centered to a student-centered environment [24]. Practical activities require a specific learning methodology where the student is the central element of this educational model. Student-centered models must give students enough freedom to take advantage of the support offered, to plan their learning process, and to regulate their own working rate, guaranteeing a dynamic learning experience for each student.

The learning methodology applied in our VNLab is the general UOC methodology [25] adapted to carry out practical activities. It is based on the constructivist learning theory adapted to a VLE where asynchronous communication is allowed in space and in time between the students and the academic staff [26]. Such methodology allows students to have maximum flexibility, adapting their studies to their own rhythm and circumstances at any particular time [27]. The main features are as follows: the teacher facilitates and monitors the learning process of the students, students are encouraged to be responsible and autonomous, practical activities are divided into different parts to permit continuous evaluation, and communication between students themselves and between students and teachers improves. In short, the VNLab is student centered.

G. Support Documentation

Support documentation includes all information that will help students achieve the objectives of the practical activities.

Within the VNLab, students are provided with the following materials in electronic format.

1) *Ciscopedia*: A comprehensible router command reference document.
2) Practical assignments: Different practice activities that must be completed in order for the student to be evaluated. They are adapted to a fully virtual environment, taking advantage of the different resources available in the VNLab.
3) Virtual library: Links to different electronic media or resources that are deemed interesting to obtain some extra information about the different topics discussed in the curricula.

H. Evaluation

The evaluation is a pedagogical resource that allows the students to achieve their learning objectives. In a VLE, it is very important to offer students a flexible model of continuous evaluation, providing activities to be completed throughout the semester [28].

The system evaluation used in our VNLab follows a continuous evaluation model [25]. Students have to perform five activities. Four of them are optional and consist of short networking activities. There also is a mandatory activity with a higher difficulty level. Each activity is evaluated based on the results detailed in the report provided by the automatic assessment tool introduced in Section II-D.

I. Teacher

"Virtual teachers" of a virtual laboratory are members of the academic staff who help students reach their individual objectives, offering each student personalized attention. The teachers of a virtual laboratory should have specific skills. Among the most important skills are those related to the technological skills with regard to the tools that will be used in the laboratory [10]. Another aspect that impacts on the role of the teacher is the fact that the students are usually isolated in a VLE. They are at home alone. This isolation means that mentorship and guidance must be reinforced to guide, motivate, plan, and be more proactive.

On the other hand, virtual laboratories need a team of teachers composed of at least two members of staff, each with different skill sets: one of them will need in-depth knowledge of the content related to the subject, i.e., the "Theory Teacher," and the other will need more technical skills, i.e., the "Teacher Lab."

In the specific case of our VNLab, the "Teacher Lab" is an expert in networking configuration and installation who creates the installation instructions, the installation process, and the frequently asked questions (FAQs). The "Theory Teacher" prepares the practical activities and resolves possible questions related to networking contents.

III. EVALUATION OF THE VNLAB: CASE OF A VNLAB

This section presents the results of the survey addressed to students who were enrolled in *Cisco Networking Academy*

TABLE I
VNLAB CLASSES AND NETLAB+ USAGE

Class Name	Students	Start date	End date	NETLAB+® Activities	NETLAB+® Hours
EO 05-06-2 Sem2	9	23 March 2006	23 July 2006	41,0	68,0
CCNA-0607	51	28 November 2006	31 July 2008	351,0	478,0
060918MONCCNA1-4	4	10 January 2007	28 June 2007	72,0	83,0
TSIE-CCNAII	16	8 March 2007	8 July 2007	23,0	23,0
Total	80			487,0	652,0

TABLE II
Q1–Q3: FREQUENCY RESULTS OF STUDENTS' PROFILE

QuestionID	Question description:	Answer	Frequency	Percentage
Q1	What is your Cisco course?			
		CCNA1-CCNA2	14	29,17%
		CCNA3-CCNA4	28	58,33%
		I have already graduated	6	12,50%
Q2	How many semesters have you been studying at UOC in a VLE?			
		1-2 semesters	13	27,08%
		3-6 semesters	20	41,67%
		More than 6 semesters	15	31,25%
Q3	How many years have you been working in a Networking area?			
		0	10	20,83%
		0-1 year	2	4,17%
		1-3 years	9	18,75%
		More than 3 years	27	56,25%

courses from Summer 2006 to Summer 2007 (see Table I). Students were enrolled in a full VLE at the UOC. The objectives of this study were as follows:

1) to evaluate the relevance of the VNLab structure presented in Section II;
2) to determine the most important benefits of the NETLAB+ resource presented in Section IV.

The survey was carried out using a Web questionnaire that was sent via the teacher board and via direct e-mail to the students. Specific criteria to design the Web questionnaire were taken into account [29], [30].

The Web questionnaire was available for four weeks to 80 students, of whom 49 participated. It was anonymous and voluntary. It was composed of 14 questions (Q1–Q14) divided into three parts: 1) the student profile part; 2) the VNLAB part; and 3) the NETLAB+ part. The NETLAB+ part results are presented in Section IV.

In the first part, questions 1–3 (Q1–Q3) were about the profile information of the respondents. The results are shown in Table II. The majority of the respondents had a wide level of experience in a VLE (73% of the students had more than one year of experience with the virtual campus), *Cisco Networking Academy* courses (71% of all respondents had finished the first and second *Cisco Networking Academy* semesters), and the networking area (56% of all respondents had worked in networking for three years).

To obtain information about the VNLab structure, students were asked to evaluate from 1 to 5 the relevance of each of the different resources of the VNLab.

1) It is not a necessary resource.
2) It is not an important resource.
3) It is an interesting resource.
4) It is an important resource.
5) It is an indispensable or vital resource.

TABLE III
Q4–Q12: RESOURCES RELATED TO EACH QUESTION

QuestionID	ResourceID	Resource description
Q5	**VCE**	Virtual Communication Environment
Q6	**SIM**	Simulators
Q7	**REM**	Remote Laboratory
Q8	**AAT**	Automatic assessment tool
Q9	**SUP**	Support tools
Q10	**MET**	Learning methodology
Q11	**DOC**	Support Documentation
Q12	**EVA**	Evaluation
Q13	**TCH**	Teacher of laboratory

The second part of the Web questionnaire on the VNLab structure had nine questions (Q4–Q12). The resource related to each question is given in Table III. The number of respondents, the frequency of each value, the percentage of 4 or 5 value, the mean value, the standard deviation, and the variance of the nine resources are summarized in Table IV.

A first analysis of the survey results shows the high relevance of all the VNLab resources. Between 69% and 83% of the students considered them to be important or indispensable resources. All the mean values were greater than 3.8.

Second, the results show a significant difference between some resources that can be classified into two groups: technological resources (i.e., VCE, SIM, and REM) and pedagogical resources (i.e., MET and AVA) are considered more indispensable than the other resources. Furthermore, the majority of students consider that the teacher's function is very important in a VLE. Similar results are found in [10], where students tend to depend more on the help of the teacher.

However, the results show that the two resources, namely SUP and DOC, are less important in the learning process. These

TABLE IV
Q4–Q12: Descriptive and Frequency Analysis of VNLab Resources

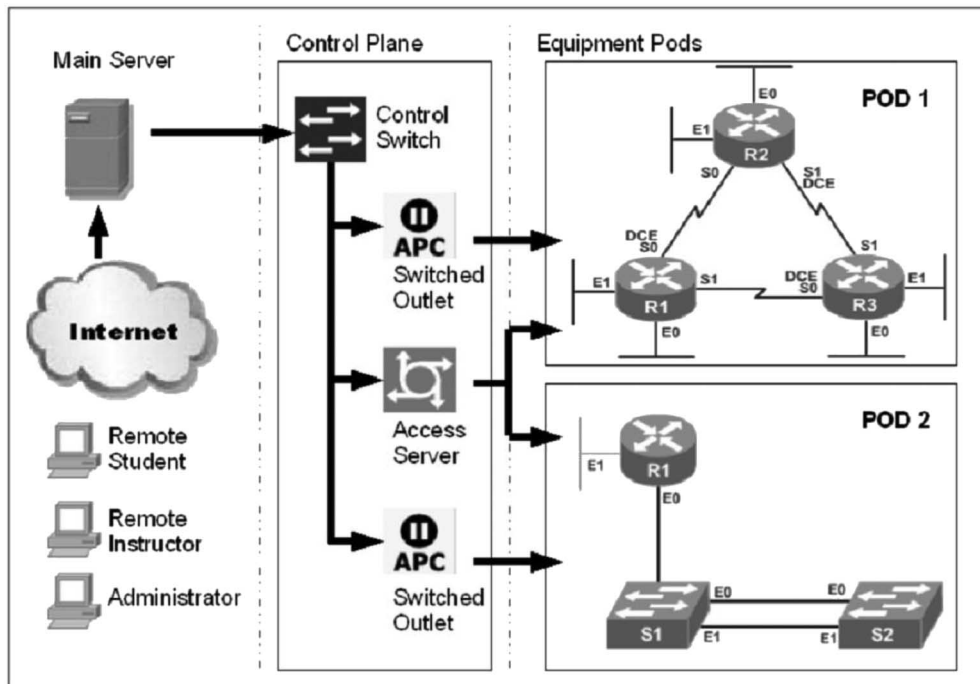|	N	1	2	3	4	5	4-5	Mean	Std. Dev.	Variance
VCE	48	0	4	5	19	20	81,3%	4,15	0,922	0,851
SIM	48	0	2	8	17	21	79,2%	4,19	0,867	0,751
REM	48	0	6	6	15	21	75,0%	4,06	1,040	1,081
AAT	47	0	4	8	17	18	74,5%	4,04	0,955	0,911
SUP	45	0	4	10	19	12	68,9%	3,87	0,919	0,845
DOC	46	0	5	9	18	14	69,6%	3,89	0,971	0,943
TCH	46	0	2	12	13	19	69,6%	4,07	0,929	0,862
MET	47	1	0	10	17	19	76,6%	4,13	0,900	0,809
EVA	48	0	1	7	20	20	83,3%	4,23	0,778	0,606

Fig. 1. NETLAB+ layout.

results are completely logical because these two resources are sometimes complementary.

The survey shows a high variance (greater than 1) in the rating of the remote laboratory resource (NETLAB+). A possible explanation of this value is that some students were not able to use it at its fullest capability for two reasons: 1) the high degree of use that the resource experienced in practice periods (scheduling problem) and 2) the crash of the server at weekends (24/7 service problem).

Therefore, we can conclude that to learn networking in a VLE, it is essential to have a VNLab composed of at least these nine resources. Another important conclusion is that the university must guarantee access to all the resources 24 hours a day, seven days a week. Finally, the NETLAB+ must be well time-dimensioned so that all the students can use it during peak hours.

IV. DESCRIPTION OF NETLAB+

As discussed in Section III, a remote laboratory is an important element in a VNLab. NETLAB+ is a remote laboratory that

provides a means of accessing physical networking devices, such as routers and switches, via an Internet connection. It is important to mention that this remote laboratory is not a remote networking device emulator: users are remotely accessing the console port of real networking devices. This greatly improves the virtual learning experience.

In this section, NETLAB+ is described. First, technical details with regard to its infrastructure are shown in Section IV-A. Then, in Section IV-B, its usage and administration is outlined. In Section IV-C, its main features are described and compared to the desired features in a remote laboratory. Finally, in Section IV-E, its impact between students is evaluated.

A. Infrastructure

The logical layout of NETLAB+ is shown in Fig. 1. It is divided into three distinct layers: the equipment pods, the control plane, and the main server.

Equipment pods are the different deployed network device topologies that may be accessed by users. Each one is
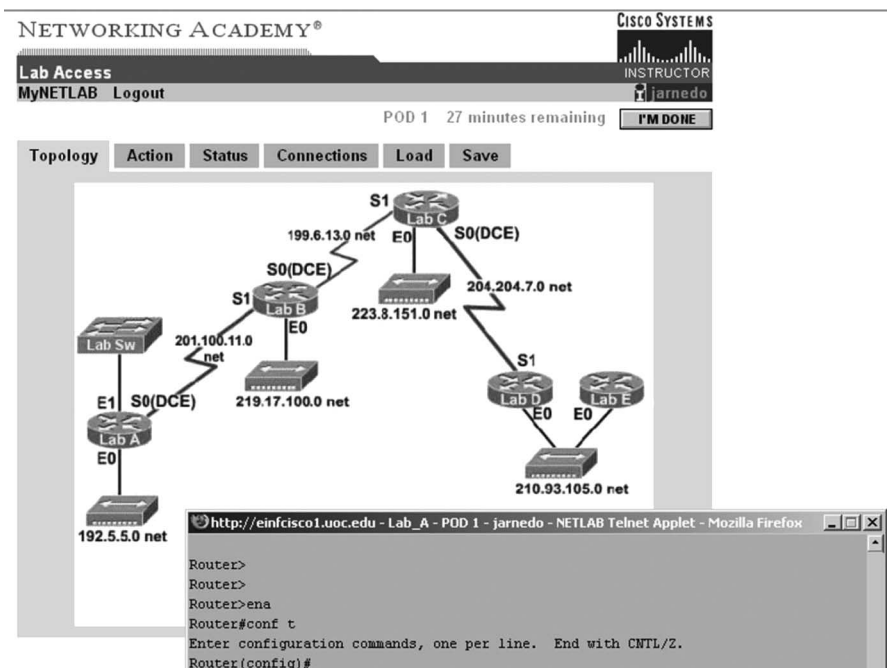
Fig. 2. NETLAB+ session: topology and console access.

composed of a fixed set of physical network devices and cabling. They are completely autonomous and isolated from each other, acting as self-contained laboratory environments. Pods may be added or modified in a modular way (by physically installing the devices and cabling in the facilities) to provide training in different network devices and topologies, according to the needs of the curricula, accepting custom-made configurations.

The control plane is formed by all the internal devices that govern pod operation. The most important components are the access server, which manages console connectivity to the different devices within a pod, and the switched outlets, which allow power to be remotely controlled on each individual device within each pod, providing users a way to access special device operations that need a hard reset.

The main server, which is the core element, provides the gateway to the control plane and equipment pods. Users only need a Web browser to connect to the server and control devices within a pod. Devices may also be accessed using a standard terminal emulator, such as the one provided in the VNLab (see Section II-E), but it is not essential. Access to the main server Web interface is integrated into the VNLab. Nevertheless, it currently operates as an autonomous system with its own user accounts.

The main server is a Linux-based IBM xSeries 305 rack-mounted computer with two Ethernet interfaces, one for the external connection to the Internet and another one for the internal connection to the control plane switch.

B. Usage and Administration

Three kinds of users exist: students, instructors, and administrators. Students may only schedule access to available equipment pods and interact with the devices within each one.

Via a Web interface, they make personal or team reservations. The latter provide a means for collaborative learning and teamwork. Pods may not be accessed without a previous reservation.

Before a student (or team of students) accesses a pod, all devices within that pod are cleared from previous configurations from other students' sessions and become available. The Web browser presents a graphical representation of the equipment pod physical topology, both installed devices and cabling. By clicking on each device, direct console access is achieved, as shown in Fig. 2. Furthermore, the interface also provides access to control plane power outlet operations, providing a means to perform actions that would usually only be possible with physical access to the device: power on/off, power recycle, or special boot modes only available with direct access, such as password recovery.

In the case of a student team making a reservation, concurrent access is granted to the whole pod. All students in that group may access all devices within a pod at the same time. In the case of console access, shells are shared, which means that students will see what others in the same device are writing.

Instructors have the same access rights as students. Furthermore, instructors are able to create and group accounts for students under their responsibility. For each group, each instructor specifies which pods may be accessed and under which circumstances (time, day, how many hours must pass between reservations, etc.). Each instructor may also review his students' pod reservations and cancel or modify them if deemed necessary.

The administrator's main responsibilities are both server and pod setup and maintenance, log review, and instructor enrollment. All of these may be remotely achieved via the server Web interface (except, obviously, the installation and cabling of new pods).

C. Services

The desired features [31] of a remote laboratory are given in the list that follows.

1) *Reservation:* A key aspect of NETLAB+ is its ability to autonomously provide scheduled access to the different laboratory pods and enable instructors to review current reservations. This is of prime importance in trying to provide a genuinely 24/7 service, which is a key requisite for a remote laboratory.

2) *Collaboration:* Providing means for student collaboration and teamwork is also very important in a remote laboratory. By using group reservations, it is possible for groups of students to access a single equipment pod, and all its devices, at once. This capability is akin to several students working together in an in-person laboratory (looking at each other's screen, sharing the keyboard, exchanging places on each device console port, etc.).

3) *Classroom lectures:* Instructor-led sessions may also be scheduled as a group reservation where the instructor joins the group. Both instructor and students may interact within the laboratory in a synchronous way.

4) *Recovery to known status:* After a session ends, all the devices in a laboratory pod are automatically set to a clean state configuration; thus, the next user will not find the pod in an unknown state. No time is wasted by students or instructors in restoring devices to a clean state.

5) *State saving and loading:* It is possible for students to save or load the state of the current configuration for any devices within a pod. This service allows students to continue previous sessions without the need to start from scratch, even in those cases where other students use the same devices in between sessions.

6) *Accessibility:* The combination of a 24/7 connection to the Internet with all the aforementioned automated features truly enables a fully autonomous system that may be fully accessed at any time.

7) *Security:* NETLAB+ is not deployed as a general-purpose server with some extra features. The operating system configuration has been adapted to the server's very specific task. The server is also automatically regularly updated. The server may also be easily integrated into any security policy within the organization.

Apart from the basic list of desired features, methods for student assessment are also provided. For each student session, the final configuration, each issued command, and its output on all devices are recorded in a report that instructors may access. In the case of a group session, who issued each command is also recorded. It is also possible to configure the server to send the report via e-mail. This allows the teacher to monitor the students during their learning process.

D. Use Statistics

A summary of NETLAB+ usage at the UOC is shown in Table II. Each row represents a different virtual class that is held between specific dates. The total number of laboratory activities solved using NETLAB+ is 487, amounting to 652 h of usage.

TABLE V
Q14: NETLAB+ BENEFITS

Students' Answers	N	% Students
I can use NETLAB+® anywhere	29	63,27%
I can use NETLAB+® anytime	31	69,39%
NETLAB+® does not need previous installation	23	51,02%
NETLAB+® is always ready at the session start	9	20,41%
NETLAB+® lets me save and load my activities	25	55,10%
NETLAB+® enables teamwork	5	10,20%
NETLAB+® is easy to use	12	28,57%
NETLAB+® is for my exclusive use	11	24,49%
Other answers	6	12,24%
Total Students (maximum 4 options by student)	49	

Apart from specific laboratory activities, students may activate open-ended sessions. It is important to note that on some days, there were 14 student laboratory activities using NETLAB+.

E. Evaluation

To assess its impact between students, the survey discussed in Section III also included two questions with regard to NETLAB+ (Q13–Q14).

The first question in the third part of the Web questionnaire (Q13) asked whether NETLAB+ let students fulfill their needs for a VLE in the field of networking. A high number of students agreed that it did (68% of them answered *yes*).

A second multiple-choice question (Q14) was available to obtain the major benefits of the NETLAB+ resource. Table V shows the most important benefits that students found in NETLAB+. Students could select up to four different options. The features of *accessibility* (*anytime*: 69% and *anywhere*: 63%) are the most important options selected by the students. The results also show that the ability to save/load the current session state (52%) and that they do not need previous installation (51%) are highly valued by students.

V. MAPPING OUR VIRTUAL LABORATORY STRUCTURE INTO OTHER VIRTUAL INDUSTRIAL ELECTRONICS LABORATORIES

The integrated VNLab structure described in Section II, with its nine resources, is suitable to be applied to any general virtual laboratory and, in particular, to the field of industrial electronics. Therefore, different proposals in the literature on virtual industrial electronics laboratories have been reviewed in this section. The objectives of conducting the review are as follows:

1) to identify the different resources that every author describes in its particular structure;
2) to map the nine resources proposed in Section II into the previous industrial electronics resources identity.

From the review of the literature, the *WebLAB* described in [32] is best suited to our model because it includes almost all the nine resources presented in Section II. WebLAB uses LMS Moodle as a *virtual communication environment* and Matalab/Simulink as a *simulator* resource-specific application

to manipulate a real plant *remote laboratory* (the core element and the most well described in this paper). Some self-evaluation tests can be considered as a kind of an *automatic assessment tool*. The proposal also points out the use of some Flash and Java programs in the WebLAB as *support tools*. Pedagogical and strategic resources are also addressed in the proposal. Huba and Simunek point out that *laboratory methodology* applies a "learning-by-doing" style following the constructivist paradigm of a student-centered environment. On the other hand, *support documentation* includes e-books, manuals, and conference papers. However, they do not provide the *evaluation model* details in their paper nor do they define the exact *role of the teacher* in their WebLAB.

The rest of the reviewed papers do not allow for such a complete mapping with all of our resources, although some of them can be identified.

Technological resources are the resources used most often in the different proposals for virtual laboratories.

1) The *virtual communication environment* is detailed in [33]–[35]. More precisely, they use LMS Moodle (i.e., forum and wiki) as a communication platform between virtual laboratory users (teachers and students).

2) On the other hand, the majority of the reviewed papers [33]–[40] extensively describe a *simulator* or a *remote laboratory*. In fact, such a resource is the core element of all proposals.

3) *Automatic assessment tools* for evaluating the learning progress do not receive the attention that they deserve in the reviewed papers; only [32] and [38] take them into account.

4) Other authors [33], [35] also include *support tools* and *documentation*. For instance, [35] provides tutorials, manuals, examples, FAQs, and software in the virtual communication environment.

However, pedagogical resources are not frequently described in the virtual laboratory proposals.

1) The authors of [34] have introduced a very interesting *pedagogical methodology* in their remote laboratories, which is based on "problem-based learning." They adopt the constructivist philosophy.

2) On the other hand, the *documentation resource* only explicitly appears in [33], although it is assumed that all proposals for virtual laboratories provide specific documentation despite not being mentioned in the paper that describes each laboratory.

Finally, less information with regard to the human resources is provided in the reviewed papers, although, as we pointed out in Section II, the *role of the teacher* is very important in the general structure of a virtual laboratory. Only some authors, e.g., Donzellini and Ponta [34], present the integration of the Deeds simulator with the "virtual teacher" and the students via the virtual communication environment (LMS Moodle). Teachers keep track of the students' activity and provide news and guidance.

To sum up, many of the nine resources proposed in Section II have already been taken into account in the design of the existing virtual industrial electronics laboratory proposals, and the ones that are not explicitly described could be added. Such revision allows us to conclude that the resource systematization and classification proposed in this paper is valid for a significant number of the existing proposals.

VI. CONCLUSION

In a virtual university, networking courses cannot be held face-to-face; therefore, providing students with real practice skills becomes a big challenge. New virtual spaces are necessary in a VLE to find a solution to carry out practical activities. Such virtual spaces are called VNLabs, which are used for the specific field of networking. In addition, this VNLab model can be applied to several laboratories in the industrial electronics field.

The main contribution of this paper is the conception and definition of a general structure for a VNLab that allows students to perform practical networking activities. The proposed structure, which is based on the experience gained during the past 11 years at the UOC, identifies the most important resources that a VNLab should have, from pedagogical or human factors to specific technological resources.

However, the survey conducted in Summer 2007 has allowed us to identify the most important resources within a VNLab based on the importance given to them by students. These results confirm that in a VNLab, all the nine resources introduced in this paper are very important. The survey also concludes that the remote laboratory is one of the most important resources for developing networking activities. It is the only way for VLE students to work with real devices from anywhere and at anytime. The VNLab described in this paper uses Cisco NETLAB+ as the remote laboratory.

Furthermore, the results show that the most important benefits of the remote laboratory are its great availability (anytime, anywhere), its ability to operate in a fully autonomous manner, and the possibility to automatically save and reload all devices to a previously known state.

Finally, the integrated structure proposed in this paper has been examined in the industrial electronics field. Such a study leads us to the conclusion that the resource systematization and classification is valid for a significant number of the existing proposals.

REFERENCES

[1] *The CISCO Website*. [Online]. Available: http://www.cisco.com

[2] *The Universitat Oberta de Catalunya Website*. [Online]. Available: http://www.uoc.edu/web/eng/

[3] K. Chiu, "What are the benefits of a virtual laboratory for student learning?" in *Proc. HERDSA Annu. Int. Conf.*, Melbourne, Australia, Jul. 1999, pp. 12–15.

[4] U. Harms, "Virtual and remote labs in physics education," presented at the 2nd European Conf. Physics Teaching Engineering Education, Budapest, Hungary, Jun. 2000.

[5] L. J. Leitner and J. W. Cane, "A virtual laboratory environment for online it education," in *Proc. 6th Conf. Inf. Technol. Educ. (SIGITE)*, 2005, pp. 283–289.

[6] A. K. Noor and T. M. Wasfy, "Simulation of physical experiments in immersive virtual environments," *Eng. Comput.: Int. J. Comput.-Aided Eng. Softw.*, vol. 18, no. 3/4, pp. 515–538, 2001.

[7] C. Levert and S. Pierre, "Designing distributed virtual laboratories: Methodological and telecommunications aspects," *Int. J. E-Learn.*, vol. 2, no. 3, pp. 18–28, 2003. [Online]. Available: http://dl.aace.org/13504

[8] A. M. Remigiusz, J. Rak, and M. Godziemba-Maliszewski, "A proposal of virtual laboratory structure," in *Proc. 23rd IEEE Instrum. Meas. Technol. Conf.*, Apr. 2006, pp. 847–850.

[9] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, no. 3, p. 7, 2006. [Online]. Available: http://doi.acm.org/10.1145/1132960.1132961

[10] D. C. Sicker, T. Lookabaugh, J. Santos, and F. Barnes, "Assessing the effectiveness of remote networking laboratories," in *Proc. 35th Annu. Conf. Frontiers Educ.*, Oct. 2005, pp. S3F-7–S3F-12.

[11] J. E. Corter, J. V. Nickerson, S. K. Esche, and C. Chassapis, "Remote versus hands-on labs: A comparative study," in *Proc. 34th Annu. Conf. FIE*, Oct. 2004, vol. 2, pp. F1G:17–F1G:21.

[12] D. Z. Deniz, A. Bulancak, and G. Ozcan, "A novel approach to remote laboratories," in *Proc. 33rd Annu. Conf. FIE*, Nov. 2003, vol. 1, pp. T3E:8–T3E:12.

[13] L. Toderick, T. Mohammed, and M. H. N. Tabrizi, "A reservation and equipment management system for secure hands-on remote labs for information technology students," in *Proc. 35th Annu. Conf. FIE*, Oct. 2005, pp. S3F:13–S3F:18.

[14] M. Vallim, J. Farines, and J. Cury, "Practicing engineering in a freshman introductory course," *IEEE Electron Device Lett.*, vol. 49, no. 1, pp. 74–79, Feb. 2006.

[15] *The Blackboard Website*. [Online]. Available: http://www.blackboard.com/

[16] *The BSCW Website*. [Online]. Available: http://bscw.fit.fraunhofer.de/

[17] *The WebCT Website*. [Online]. Available: http://www.WebCT.com

[18] *The Moodle Website*. [Online]. Available: http://moodle.org/

[19] A. Repenning and J. Ioannidou, "Collaborative use & design of interactive simulations," in *Proc. CSCL*, Stanford, CA, 1999, p. 59.

[20] *The CISCO NetAcad Website*. [Online]. Available: http://www.cisco.com/web/learning/netacad/index.html

[21] *The IMS Global Learning Consortium Website*. [Online]. Available: http://www.imsproject.org/

[22] *The Sharable Content Object Reference Mode Website*. [Online]. Available:http://www.adlnet.gov/scorm/index.cfm

[23] *The Cisco CCIE Assessor Lab Website*. [Online]. Available: http://www.cisco.com/ccie/assessor

[24] T. Brush and J. Soye, "Implementation and evaluation of a student-centered learning unit: A case study," *J. Educ. Technol. Res. Develop.*, vol. 48, no. 3, pp. 79–100, Sep. 2000.

[25] A. Sangra, "A new learning model for the information and knowledge society: The case of the Universitat Oberta de Catalunya (UOC)," *Int. Rev. Res. Open Distance Learn.*, vol. 2, no. 2, pp. 1–19, Jan. 2002.

[26] B. Gros, "Constructivism and designing virtual learning environments," in *Proc. Soc. Inf. Technol. Teacher Educ. Int. Conf.*, 2002, pp. 950–954. [Online]. Available: http://go.editlib.org/p/10638

[27] M. R. Simonson, *Teaching and Learning at a Distance*. Upper Saddle River, NJ: Merrill Prentice Hall, 2000.

[28] L. C. Kaczmarczyk, "Accreditation and student assessment in distance education: Why we all need to pay attention," in *Proc. 6th Annu. Conf. ITiCSE*, 2001, pp. 113–116.

[29] D. Dillman, R. Tortora, and D. Bowker, "Principles for constructing Web surveys," Digital Equipment Corp., Maynard, MA, Tech. Rep. SESRC-TR-98-50, Aug. 1998.

[30] D. Solomon, "Conducting Web-based surveys," *Pract. Assess., Res. Eval.*, vol. 7, no. 19, 2001. [Online]. Available: http://pareonline.net/getvn.asp?v=7&n=19

[31] *The NDG NETLAB+ Website*. [Online]. Available: http://www.netdevgroup.com/

[32] M. Huba and M. Simunek, "Modular approach to teaching PID control," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3112–3121, Dec. 2007.

[33] D. Hercog, B. Gergic, S. Uran, and K. Jezernik, "A DSP-based remote control laboratory," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3057–3068, Dec. 2007.

[34] G. Donzellini and D. Ponta, "A simulation environment for e-learning in digital design," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3078–3085, Dec. 2007.

[35] J. Fernandez, R. Marin, and R. Wirz, "Online competitions: An open space to improve the learning process," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3086–3093, Dec. 2007.

[36] M. Casini, D. Prattichizzo, and A. Vicino, "Operating remote laboratories through a bootable device," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3134–3140, Dec. 2007.

[37] U. Munz, P. Schumm, A. Wiesebrock, and F. Allgower, "Motivation and learning progress through educational games," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3141–3144, Dec. 2007.

[38] L. S. Indrusiak, M. Glesner, and R. Reis, "On the evolution of remote laboratories for prototyping digital electronic systems," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3069–3077, Dec. 2007.

[39] H. Hassan, C. Dominguez, J. M. Martinez, A. Perles, and J. Albaladejo, "Remote laboratory architecture for the validation of industrial control applications," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3094–3102, Dec. 2007.

[40] L. L. Bello, O. Mirabella, and A. Raucea, "Design and implementation of an educational testbed for experiencing with industrial communication networks," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3122–3133, Dec. 2007.

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