A Methodology to Obtain Learning Effective Laboratories with Learning Management System Integration

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Abstract—Online laboratories are useful and valuable resources in high education, especially in engineering studies. This work presents a methodology to create effective laboratories for learning that interact with a Learning Management System (LMS) to achieve advanced integration. It is based on pedagogical aspects and considers not only the laboratory application itself but also related resources that complement it. The methodology is flexible, covers all possible cases, and it is structured in stages that can be used with any system architecture, standards, or type of online laboratory (virtual, remote, or hybrid) because it abstracts technical aspects at a high level. This methodology facilitates the creation of new online labs so that any teacher, even those without specialized knowledge, can clarify many of the questions that may arise and gain understanding of how to implement an effective online laboratory with LMS integration to assist learning. As an example and validation of the methodology, this work describes a laboratory developed as a Shared Content Object Reference Model (SCORM) package which is hosted in the institutional LMS at the University of Jaen. The laboratory was presented to 338 students taking an Industrial Automation class, and student evaluations were quite positive.

Index Terms—Laboratories, education technology, control engineering education, students experiments

1 Introduction

Laboratories have a central role in engineering education. The technologies used to develop laboratories (labs) have advanced considerably over the past decades. One example is the creation of virtual and/or remote labs (VRLs) using web technology to facilitate student access to practical experiments [1], [2]. The application of Information and Communications Technologies (ICT) has enabled this amazing development; however, the most important ICT development in e-learning has been the Learning Management System (LMS) [3]. LMSs are essential tools for higher education today for both e-learning and blended learning (better known as b-learning)—or simply to support classroom teaching. After LMS authentication, students can access virtual spaces where they can find learning resources, tools to communicate with tutors and peers, assessment tools for evaluating their learning progress, and facilities to create and version learning contents.

Ideally, all resources related to student learning are provided in a learning scenario [4]—an environment where students can learn together in various combinations and interact with each other. Currently, many of these learning scenarios are implemented in LMSs. For this reason, engineering online laboratories should be integrated into the LMSs in the same way as other learning resources. Lab-LMS integration is an important issue that has been addressed by many studies [5], [6], [7], [8], [9] using different strategies. However, this subject can be both complicated and confusing for teachers with no experience in the field who want to create an online laboratory with LMS integration.

This work proposes a methodology that describes the actions that must be carried out to create an effective online learning laboratory with LMS integration. The methodology identifies the actors responsible for performing each action. It also includes an example of an online laboratory developed using this methodology that has been evaluated with 338 Industrial Automation students at the University of Jaén (UJA). The main objective of this paper is to help faculty understand the steps that must be performed to create an effective online lab integrated with an LMS and to know which actors are responsible for implementing each phase.

The rest of the paper is organized as follows: Section 2 briefly discusses Lab-LMS integrations and previous works. Section 3 presents the proposed methodology including phases, actors and deliverables. Section 4 shows a real-world example of the use of this methodology to create a laboratory including data collection concerning use of the laboratory and the results of an opinion survey. Section 5 describes a validation procedure, and Section 6 presents a conclusion and future research.

2 Laboratory-LMS Integration

There are many e-learning standards; Hilera [10] classified e-learning standards based on 12 categories related to different e-learning aspects: accessibility, architecture, quality, skills, content and evaluation, digital rights, student information, interoperability, metadata, learning process, repositories, and vocabulary and languages. By itself, no single category defines an online laboratory; online laboratories

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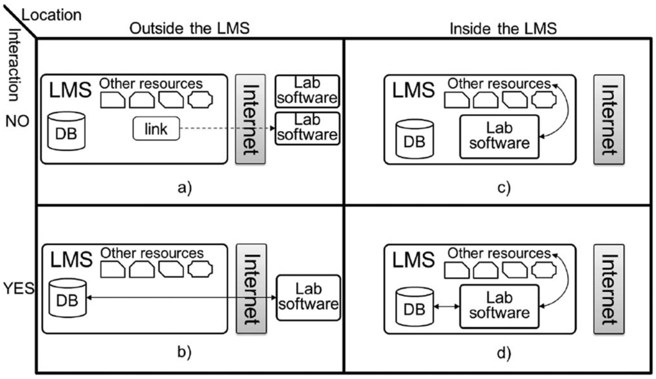

Fig. 1. LMS-Lab software scenarios based on location and interaction.

are multifaceted resources covering almost all the aspects defined in [10]; however, in relation to Lab-LMS integration, the most interesting standards are those related to content and evaluation, interoperability, and the learning process. From a technical point of view, online labs can be among the most complex types of learning resources that exist in an LMS. This complexity applies to the lab creation, use and maintenance. All online labs are presented to users as software applications that include a graphical user interface (GUI) through which students interact to work with real resources (remote laboratory (RL)), simulations (virtual laboratory (VL)) or both (hybrid laboratory).

Integrating a laboratory with an LMS can be implemented in different ways. There are two main aspects to consider in such an integration

- *Location*. Lab software can be located in the LMS as a learning resource or it can be located outside the LMS in some other location. Labs located in the LMS have some advantages. For example, the laboratory does not need to deal with authentication and authorization: only students with access permissions can run the lab software. Another important advantage is the establishment of relationships with other resources based on learning paths that nearly all LMS support. For example, the LMS can be configured to allow access to the lab only to learners who have satisfactorily completed prerequisite tasks.
- *Interaction*. Lab software can exchange information with the LMS. Labs obtain some benefit by establishing LMS-VRL communications such as exchanging learner credentials, allowing student identification through the LMS (if the laboratory is not already located there), learner customization—adjusting lab operations to learner preferences such as language, volume, speed, captioning, and so on, and allowing individualized practical experiments. Furthermore, student results can be stored in the LMS, which can use the information to control access to other resources in the LMS.

The following scenarios (Fig. 1) can be considered by taking lab location and interaction into account

1. *Outside and No Interaction* (Fig. 1a). Students execute the lab software, which is located outside the LMS, completely independently of the LMS, although the lab may have been launched by the student clicking a link in the LMS. There is no Lab-LMS integration. There are many examples of labs developed upon this model using ad hoc schemes [11], [12], [13] or web-based experimentation environments [14], [15].
2. *Outside and Interaction* (Fig. 1b). Students execute the lab software, which is located outside the LMS, outside the LMS environment, but the lab establishes communications with the LMS.
3. *Inside and No Interaction* (Fig. 1c). Students execute the lab software, which is located within the LMS, inside the LMS environment, thereby establishing relationships with other resources in the LMS based on the interactions between resources implemented by the LMS (e.g., prerequisites). This type of lab has minimal integration with the LMS.
4. *Inside and Interaction* (Fig. 1d). Students execute lab software located within the LMS. This type of lab can interact with the LMS and can be related to other resources located in the LMS. This scenario (fully integrated laboratory) has the most advanced integration with the LMS.

The approaches matching the scenarios shown in Figs. 1b and 1d can be implemented in the LMS using either ad hoc development [6], [16], [17], [18] or using one of the e-learning standards such as the Shared Content Object Reference Model (SCORM) [9], [19], [20], [21], eXperience API (xAPI, also known as the Tin Can API or TCAPI) [22], [23], Instructional Management System-Learning Design (IMS-LD) [7], [24], Learning Tool Interoperability (LTI) [25], [26], OpenSocial [27], [28], [29], Computer-Managed Instruction 5 (cmi5) [30], Inquiry Learning Spaces (ILS) [31], Massive Open Online Labs (MOOL) [32] or Laboratory as a Service (LaaS) [33].

3 Methodology

This methodology was developed based on the experience of the authors in designing and developing online laboratories and pedagogic/didactical concepts. The methodology is generic: it does not impose any standard or architecture and can be applied to create virtually any type of online laboratory. Therefore, the methodology can help faculty with no experience clarify their ideas and understand how to design and create online labs. The learning effectiveness of the laboratory is a key concept in this methodology. The online laboratory is just a tool at the service of the learning activities and should be designed from the syllabus and related to other learning resources [34]. An online laboratory is not an isolated element, it must be integrated with existing learning resources and become a component of a learning path. This process can be divided into three phases: Pre-VRL, VRL, and post-VRL [6]. In this sense, educational lab sessions should be guided by an integrated lesson plan [29] that defines an adaptive structure including all the resources necessary for students to achieve the objectives and skills. As shown in Fig. 2, the methodology is structured into 8 phases and indicates the actors and the deliverables generated by each phase. These phases are explained in more detail below.

3.1 Phase A: Objectives/Competencies

This phase is justified by the truism noted in [30]: "*If you don't know where you want to go, you won't know which road to*

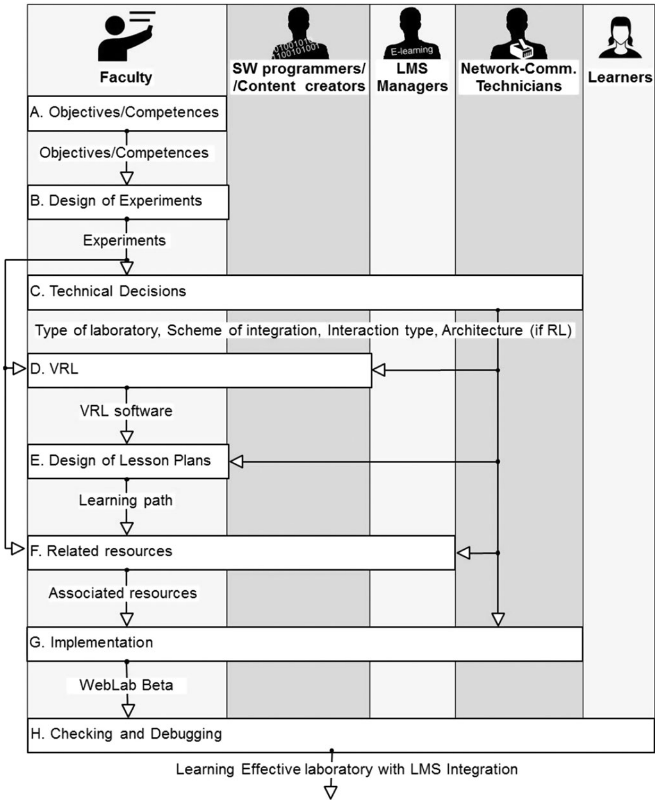

Fig. 2. Diagram of the methodology phases, actors, and deliverables.

take and you won't know if you have arrived". The existence of a learning lab is justified by the experiments that students can perform, while the experiments are justified by the objectives and competencies that they provide to learners. The objectives and competencies should be defined in the course syllabus; therefore, the starting point for the design of a learning laboratory is the course syllabus. This phase must be performed by the teachers responsible for the course in which the laboratory is going to be used. These teachers select the goals to be reached (related to practice content) from the course syllabus and specify the learning objectives, skills and competencies provided by the laboratory that learners should acquire.

3.2 Phase B: Design of Experiments

The teaching staff should design experiments that learners must complete to acquire the specified objectives and skills that were selected in Phase A. These are the experiments to include in the online laboratory.

3.3 Phase C: Technical Decisions

For each experiment or group of similar experiments, designed in Phase B, it is necessary to determine the most appropriate type of laboratory to implement the experiments (remote, virtual or hybrid) and the architecture/standards to use. This decision is heavily determined by the existing infrastructure and development experience of the institution. The following sentence given in [7] fits this topic perfectly: "*Nobody wants to reinvent the wheel each time a device goes online*". If the institution has used a certain architecture, LMS or ad hoc extension in the LMS to develop LMS-integrated online labs, it is best to use those, if possible.

When these limitations do not exist, then the following decisions must be made:

1. Type of laboratory: virtual and/or remote.
2. Architecture (in case of remote laboratories): ad hoc or based on specific systems such as web services, Matlab, or LabView.
3. LMS integration scheme (Fig. 1).
4. Interaction type: ad hoc or based on e-learning standards.

In the most general case this decision should be made by consensus of the teaching staff, software programmers, network and communications technicians, and LMS administrators for the organization that will implement the laboratory. In many cases several of these roles may be played by the same person.

3.4 Phase D: VRL

The main element in an online laboratory is the Lab software (VRL). The experiments are supported by the VRL where the students carry out the experiments. There are some differences between different types of VRLs:

- *VL*—the software includes simulations of the experiments and offers a graphic user interface that allows learners to interact.
- *RL*—the software includes connections to remote real equipment and offers a graphic user interface that allows learners to interact with that equipment. Note that such remote connections can lead to security problems that should be taken into account.
- *Hybrid lab*—the software includes both connections to remote real equipment and simulations of the experiments and offers a graphic user interface that allows learners to interact.

All the software for the various types of VRLs must be programmed using a web-compatible technology such as JavaScript or any other technology that can be embedded in a web page. Technologies that require the use of a plugin in the web browser such as Java applets or Flash are not appropriate since the web browser vendors have eliminated or announced timelines for the removal of these standards. The following features of a laboratory are both desirable and convenient for attaining effective learning. This methodology advises prospective lab creators to implement the following features

1. *Assistance*. Popup help for all elements of the laboratory software GUI is useful to help learners manipulate the lab equipment or simulations.
2. *Customization*. Individualized lab operations based on learner preferences (language, speed, captioning, and volume) that can be stored for future use help students master the content.
3. *Individualized experiments*. Experiments are personalized; each student runs a different personal experiment.
4. *Automatic assessment*. The work performed by each learner is automatically evaluated by the software.
5. *Learning Progress Tracking*. The results of student monitoring and the learning outcome for each student is stored.

Advanced laboratory-LMS integration can facilitate the implementation of some of these characteristics. Lab-LMS communications allow learner authentication, thus connecting learners with customization, individualized experiments, auto assessment and records of their learning progress. This interaction is determined by the decisions made during Phase C and can be based on ad hoc implementations or the e-learning standards cited in the previous section. In addition, if the laboratory is located within the LMS (recommended) it can establish relationships with other resources in the LMS to create learning paths and facilitate the lesson plan configuration presented in the next phase. The VRL should be developed by software programmers in close collaboration with the responsible faculty.

3.5 Phase E: Design of Lesson Plan

The VRL software that results from Phase D is not the only resource that students should use. Other resources should be included, created and presented in conjunction with the VRL software to maximize laboratory effectiveness. In this phase the responsible faculty should determine and design the resources and the lesson plan to form a learning path consisting of the learning sequence, the relationships between the resources included with the VRL and the navigation between them. This phase is limited by the decisions taken in the Phase C because the system architecture and the LMS control many of these decisions. Ideally, the VRL is located in the LMS along with its related resources and the learning path can be established by configuring the availability, time schedule, and prerequisite properties that are usually implemented by the LMS. From here forward in this paper, the term WebLab will be used to refer to the assembly formed by the VRL software and all its associated resources.

3.6 Phase F: Related Resources

The related resources designed in Phase E must be created in a compatible environment and format. Ideally, these resources are created by specialized content creators with the advice of the responsible faculty and other personnel; however, in most real-world cases, this work is performed by the teaching staff. Below are some resources directly related to VRLs that should be found in a WebLab:

General Information (Pre-Lab). Students work better and less stressfully when they can answer these questions before starting the laboratory itself: What am I going to do? How does this relate to my studies? What type of laboratory am I going to use? Am I able to work and understand this lab? What purpose will it serve? What will I learn? What skills/competencies will I acquire? How are these contents presented? The teacher must answer these questions prior to presenting the VRL by framing the WebLab in the course syllabus, demonstrating the type of WebLab, and providing a description of the WebLab structure and navigation as well as any prior knowledge needed to understand the WebLab, its objectives, and the skills/competencies that the learner will acquire by completing the lab.

Prior Theoretical Knowledge (Pre-Lab). Lab presented to students usually have related theoretical content that is explained in traditional classes. As explained in [36], "*A common goal is to relate theory and practice or to bring the 'real world' into an otherwise theoretical education*". When this type of content is included in the course theory, it is not necessary to provide it in the lab itself. However, very often there are VRL-specific theoretical contents that students need to understand and carry out the experimental practices that are not included in the course theory. In this case, these contents should be included in the WebLab model. This information should extend the theoretical lesson of the course that the VRL is enriching. It particularizes the more general ideas given in the theoretical course lessons to the specific case of the experiments included in the VRL.

Pre-VRL Evaluation Tool (Pre-Lab). Students will better understand the laboratory experiments and be more likely to complete the WebLab if they have acquired the prior knowledge required for this purpose. It is necessary to ensure that learners have the VRL-specific knowledge required to use the VRL. Tutors should design a resource to evaluate the learners' knowledge and this element should be included in the WebLab (e.g., a test).

VRL Execution Requirements (Pre-VRL). In some cases, it is also necessary to explain the software requirements needed to execute the VRL such as the operating system required and any browser configuration changes or extra software that must be installed. This resource should be created by the software programmers.

VRL Software Manual (Pre-VRL). The VRL software GUI allows students to interact with the remote or virtual elements of the laboratory to realize the experiments. Software programmers should create tutorials to guide students using the lab.

Experiment Guide (Practice scripts) (VRL). The experiment guide helps students carry out the experiments; it is an essential element that explains the steps the learner must take to perform the experiments. It consists of specific instructions that unambiguously describe the work learners must perform. The number of practical experiences included must be determined by the teaching staff, taking into account the feasibility of including them in the VRL.

Communication and Cooperation Tool (VRL). Teacher-student and student-student communications are a positive factor in any educational experience. The teacher should assuage any doubts students have about using the WebLab. Student-student cooperation requires a communication resource. An LMS resource could be used for both these purposes.

Post-VRL Evaluation Tool (Post-VRL). It is necessary to verify that the student has mastered the concepts and obtained the desired skills. This final verification is an important element that can help to ensure the effectiveness of the entire WebLab—the VRL and all the related resources. There are many ways to perform this evaluation, including personal interviews, surveys, or tests.

3.7 Phase G: Implementation

All the VRL-related resources and the VRL itself must be situated and installed according to the architecture and standards selected earlier. In addition, relationships between all the resources must be established to implement the learning path designed in the lesson plan. This phase relies heavily on the choices made in Phases C and E.

3.8 Phase H: Checking and Debugging

In this phase, the operation of all the elements is tested as a whole. Teachers should act as students and use (test) all the

$$U_a(s) \longrightarrow \boxed{G(s)} \longrightarrow \Omega(s) \qquad G(s) = \frac{\Omega(s)}{U_a(s)} = \frac{K}{1+Ts}$$

Fig. 3. Transfer function of the DC motor system.

resources included in the WebLab, ensuring that they all behave perfectly. Additionally, learners can participate in checking later versions of the WebLab (beta versions).

4 Use-Case Example

The WebLab called "Modelling Dynamic Systems: DC Motor" is a virtual laboratory developed using the proposed methodology. It is used in the Industrial Automation course included as part of several Industrial Engineering degrees at the UJA. Industrial Automation is taught in the second semester of the second year of the Industrial, Mechanical, Electrical, Industrial Management and Electronic Engineering programmes. The course provides an overview of the applicability of automatic controls in industrial environments and applies basic knowledge of control technologies to continuous and discrete processes. Below, the methodology explained earlier is discussed in the context of the implementation process used to create this laboratory:

4.1 Objectives/Competencies

A specific competency in the course syllabus [37], CEX6, states that one of the competencies learners should acquire is "Knowledge and ability for modelling and simulation knowledge of automatic regulation and control techniques and their application to industrial automation". This competency is associated with the "Industrial Automation" course whose faculty decided to create an online lab to partially support CEX6. The lab has the following objectives:

- *Global:* "Knowledge and capability for modelling and system simulation" and "Basic knowledge of automatic control and its application to industrial automation".
- *Specific:* "Study of the dynamic behaviour of a DC motor" and "Identification of the parameters that define the dynamic model of the system (DC motor)".

4.2 Design of Experiments

The faculty designed one experiment: "Identification of the K (static gain) and T (time constant) parameters that define the dynamic behaviour of a motor modelled as a first order system". It is based on the transfer function shown in Fig. 3.

4.3 Technical Decisions

The faculty determined the following technical decisions: The type of laboratory would be VL and the integration scheme would be the advanced integration e-type (Fig. 1d), with the VL located in ILIAS [38], the institutional LMS of the UJA. The interaction types would be based on SCORM sub-specifications and relationships with other resources in the LMS. In this case, the participation of communications and networks technicians was not necessary because all the needed communications are created through the LMS as normal web transactions.

4.4 VRL

In this case the programmer, who was a faculty member, chose Java as the programming language in conjunction with Easy Java Simulations (EJS) [39], [40] and the scormRTE Java package [41] to develop the VRL software and communicate with the LMS. The VRL retrieves the learner's identification from the LMS to customize the application's interface and provide customized practice experiments (based on customized constants for each student, so each learner works with a different first order system). The lab also performs an automated evaluation of the student's work and stores the evaluation results in the LMS. Elements of the software interface include a mouseover popup window that shows help text. In addition to the experiment designed in Phase B, the programmer included a pre-experiment practice tutorial to help learners use the software GUI.

4.5 Design of Lesson Plan

The faculty designed the following resources to maximize the learning effectiveness of the VRL:

1. a-item. General information about the WebLab that frames the WebLab from the learner's perspective, a basic description of the WebLab, and instructions on how to complete it.
2. b-item. Theoretical information about modelling, the dynamic model of a DC motor, the first order dynamic model of the system, and instructions about how to obtain the parameters of the first order dynamic model (static gain of the system, K, and time constant, T).
3. c-item. Pre-VRL test concerning the theoretical information required to complete the lab.
4. d-item. VRL requirements documentation explaining the setup options needed to execute a Java applet in a browser.
5. e-item. Practice scripts for the two experiments that guide learners step by step: a software GUI (experiment 1) and identification of a DC motor (K and T parameters of the first order system, experiment 2).
6. f-item. Post-VRL test covering the experimental work and the desired objectives.
7. g-item. A forum about the WebLab.
8. h-item. A survey to acquire the opinions of learners who worked with the WebLab.

The faculty designed a SCORM structure based on four web pages that included most of these resources. Pages 2, 3, and 4 contain valuable resources (c-item, VRL and f-item, respectively) and store student results in the LMS. Fig. 4 shows the learning path design including the structure of the SCORM package. There is a path that goes from the d-item to the h-item through the SCORM package and all the included resources. The g-item can be used at any time.

4.6 Related Resources

All resources listed in Phase E were created by the faculty and the programmer following the advice of a content creation specialist. The d-item was designed as a learning module in ILIAS, the g-item as an ILIAS forum, and the h-item as an ILIAS survey. The SCORM package was developed

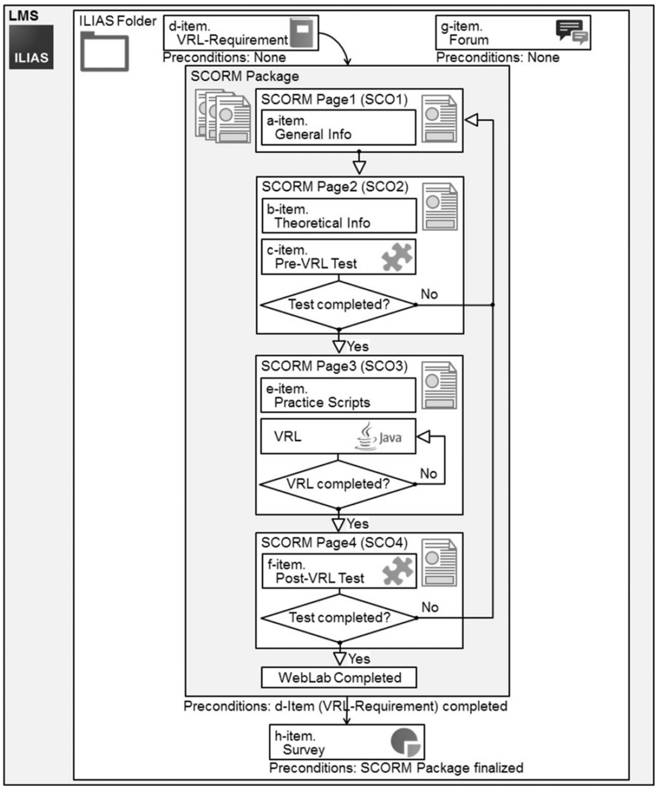

Fig. 4. Learning path, sequencing, and navigation between resources.

from a template. The resources contained in the SCORM package were created by formatting the files included in the SCORM template as HTML5 pages. The VRL created in Phase D was embedded in page 3 as an applet.

4.7 Implementation

The resources created in Phase F were located in an LMS folder to facilitate the learning path design. Sequencing and navigation (SN) within the SCORM package was implemented using SCORM. The SN between the resources in the LMS folder was implemented using the resource availability properties in the LMS—specifically, the survey could not be taken until the student had completed the SCORM package (LMS prerequisite).

4.8 Checking and Debugging

The WebLab was tested by the faculty and advanced students to verify the behaviour of all resources and check for errors. Detected errors were corrected, and a working version of the WebLab was obtained.

Of the 369 students enrolled in the course, 338 were assigned to practice groups. Each practice group had a private virtual space in the ILIAS LMS, and each private virtual space included a folder for the WebLab containing the resources shown in Fig. 4. One of the most important goals of a VRL intended for education—probably the most important—is to increase students' understanding of the nature of experimentation [42]. Two methods were used to evaluate and validate this laboratory:

1. Results. Final results were obtained from 273 learners based on assessments of the work they performed in the WebLab.

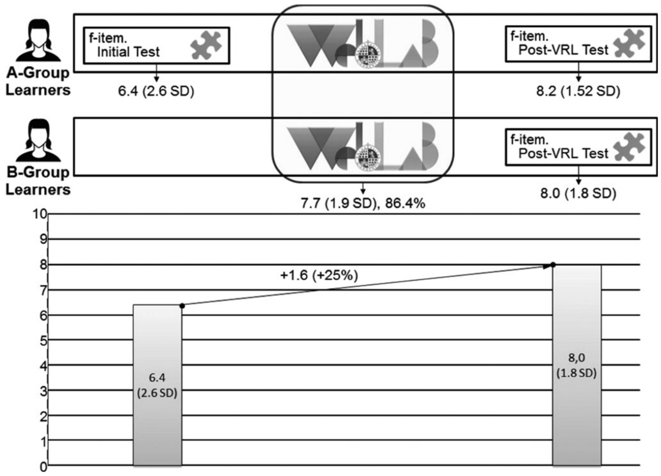

Fig. 5. Results obtained by students who participated in the WebLab.

Of the students who accessed the WebLab, 86.4 percent passed it, and most of these also obtained good grades (average score per student was 7.7 with a standard deviation (SD) of 1.9). These results demonstrate that the WebLab was a rather positive experience for the majority of students who completed it. A copy of the f-item (the post-VRL Test) was added, formatted as an ILIAS test in the folders of half of the groups as a pretest, to assess how well the WebLab functioned. The learners who were members of the group who took this pretest are called Group A or control group, while the learners belonging to other groups, which did not take the pretest, will be called Group B from now on. It can be assumed that Groups A and B had similar initial knowledge because they were created randomly. The average score obtained by the A group students in the pretest (executed prior to the WebLab) was 6.4 (2.6 SD) while the average score obtained by the B group students in the same test executed in Page 4 after using the VRL (posttest) was 8.0 (1.8 SD). These scores confirm that students who have executed and completed the WebLab gain extra knowledge (+25 percent). Fig. 5 shows these results graphically, demonstrating that using the WebLab was positive for the participating students.

2. Survey. This survey measures learner satisfaction based on their responses to survey questions (h-item) about the WebLab. The survey was completed by 128 students after they completed the WebLab. The survey was voluntary, and not all students who completed the WebLab participated.

A 23-question survey consisting of 10 web pages was created to facilitate participation and improve usability. The first questions captured respondent characteristics and the environments in which they worked with the WebLab. The responses showed that most of the learners were 20–24 years old (73 percent), male (84 percent) and were studying for a mechanical engineering degree (52 percent). All the respondents accessed and passed the WebLab (100 percent). The vast majority of respondents (97.7 percent) read Theme 6 (the theory on which the WebLab is based), and most of them attended all the classes

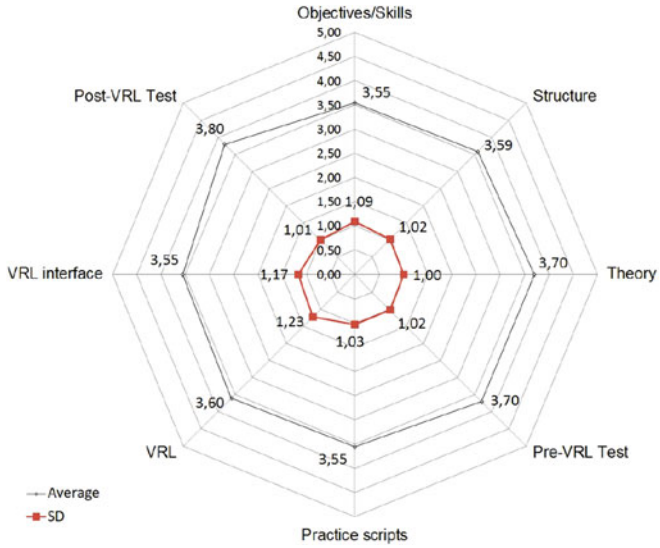

Fig. 6. Students' opinions about WebLab contents.

where this theory was explained (62 percent). Most executed the WebLab more than once (70 percent).

Some questions that showed screenshots of the WebLab contents were used for two purposes: to determine whether the contents of each page of the laboratory fulfilled their intended functions and to see if students thought the content items were appropriate. The available responses used a 1–5 Likert scale (Fig. 6).

One question obtained student feedback about various general aspects of the WebLab using a 1–5 Likert scale. The aspects considered were the WebLab's purpose, system reliability, clear and precise instructions, time taken, sensation of immersion, easy use, navigation, structure, web design and easy access. Fig. 7 shows the results to these questions. All the aspects obtained quite good results and scored above 3.3 out of a possible 5. The highest-scoring items were for "time taken" and "web design". The last survey question asked students to make a final assessment of the WebLab from 1 to 5. Fig. 8 shows that the assessment of the WebLab made by the students was quite

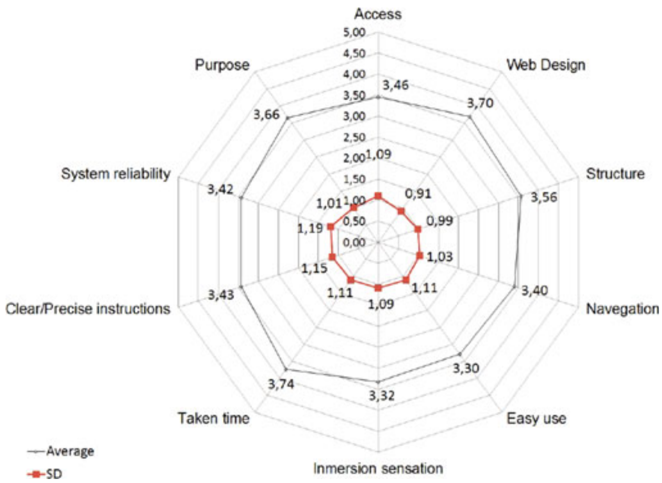

Fig. 7. Students' opinions about diverse aspects of the WebLab.

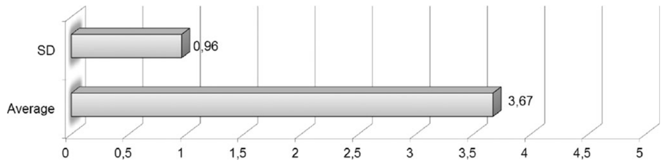

Fig. 8. Students' final rating opinions about the WebLab.

positive, scoring a 3.67 out of 5 (7.34 out of 10) which was a fairly satisfactory outcome.

5 Validation

Validation of the methodology described in this paper is a complicated process because it depends on the implementation performed for any particular WebLab. The method used in this work is based on some desirable properties that WebLab should have. Some of these properties were analysed to ensure that a WebLab developed using this methodology would meet them:

1. *Multi-type Labs*. The methodology can be applied to any type of online laboratory: remote, virtual or hybrid.
2. *Universal Remote Access*. The proposed methodology allows the development of laboratories accessible from any location through the Internet—in this sense, there is no physical limit.
3. *Learning Effectiveness*. The principles of the methodology are based on factors that help achieve lab learning effectiveness. The various phases ensure that the laboratory experiments are designed with one main goal: students should achieve the objectives and/or reach specific competencies. The VRL is presented to learners embedded in a comprehensive pedagogic structure that includes important pedagogical resources related to the experiments in the lab.
4. *VRL-LMS Integration*. The methodology requires advanced VRL-LMS integration based on the exchange of information such as student identification and scores.
5. *Known Environment*. This methodology recommends locating WebLabs within an LMS. By doing this, both learners and tutors will operate in a known environment that facilitates their work.
6. *Standardization*. The methodology does not impose any standard but recommends using e-learning standards for the VRL-LMS integration and that systems and standards should be consolidated to implement online laboratories.
7. *Customization*. The behaviour of the contents of the WebLab can be customized based on user identification. For example, customized practice data can provide different work tailored to each learner. VRL-LMS integration facilitates this property.
8. *Automatic Evaluation*. The methodology recommends that lab software evaluate the work performed by learners in the experiments.
9. *Automatic Learning Progress Tracking*. Automated monitoring of students' work is desirable for tutors—not only in laboratory experiments but also for associated resources, e. g. tests. This property is closely related to

the properties D, E, G, and H; when a laboratory satisfies all these properties, the learning progress can be tracked easily and automatically by LMSs.

10. *Shareable & Reusable*. Developing and deploying online laboratories is costly; therefore, shareability and reusability are important properties. Laboratories created using this methodology that follow the recommendations are easier to share and reuse.

The use of the proposed methodology ensures that developed laboratories will meet many of the properties described above and facilitates the achievement of all the other properties.

6 Conclusion

This paper presented a new methodology for developing effective WebLabs with LMS integration. This methodology specifies a sequence of 8 phases including the steps, actors and deliverables for each phase. This methodology can be used to develop any type of laboratory and provide universal remote access to experiments while ensuring that the labs contain several positive features (learning effectiveness and VRL-LMS integration) and facilitating the attainment of some other properties (running in a known environment, standardization, customization, automatic assessment, monitoring of the learning progress, and shareability and reusability). The methodology is a useful resource for teachers without lab design and development experience who want develop an LMS-integrated online laboratory. It is also valuable for those with prior experience because it clarifies and provides detailed explanations of the most important aspects to consider when designing and developing an online laboratory. An example WebLab called "Modelling Dynamic Systems: DC Motor" was developed using the proposed methodology. This example WebLab is fully LMS-integrated and presents several desirable features: it runs in a known environment, includes automatic evaluation, is standardized, customized, tracks learning progress in the LMS, and is shareable and reusable in any SCORM-conformant LMS. It was used by 273 students in the "Automática Industrial" course in the UJA, and the results, as well as student opinions, indicate that the WebLab is a valid tool that helps to increase students' understanding (by approximately 25 percent) and helps them attain the desired objectives and skills. For all these reasons, the laboratory has been effective in helping students learn.

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References

[1] Y. Amigud, G. Archer, J. Smith, M. Szymanski, and B. Servatius, "Assessing the quality of web-enabled laboratories in undergraduate education," in *Proc. 32nd Annu. Frontiers Edu.*, 2002, vol. 2, pp. F3E-12–F3E-16.

[2] S. Dormido, "Control learning: Present and future," *Annu. Rev. Control,* vol. 28, no 1, pp. 115–136, 2004.

[3] S. Lonn, S. D. Teasley, and A. E. Krumm, "Who needs to do what where?: Using learning management systems on residential versus commuter campuses," *Comput. Edu.*, vol. 56, no. 3, pp. 642–649, 2011.

[4] M. Klebl, "Educational interoperability standards: IMS learning design and DIN didactical object model," in *Handbook on Quality and Standardisation in E-Learning*. Berlin, Germany: Springer, 2006, pp. 225–250.

[5] N. Abdellaoui, C. Gravier, B. Belmekki, and J. Fayolle, "Towards the loose coupling between LMS and Remote Laboratories in online engineering education," in *Proc. IEEE EDUCON Conf.*, 2010, pp. 1935–1940.

[6] G. Donzellini and D. Ponta, "The electronic laboratory: Traditional, simulated or remote?," in *Advances on Remote Laboratories and e-Learning Experiences*. Bilbao, Spain: Universidad de Deusto, 2007, pp. 223–245.

[7] C. Gravier, J. Fayolle, G. Noyel, A. Leleve, and H. Benmohamed, "Distance learning: Closing the gap between remote labs and learning management systems," in *Proc. 1st IEEE Int. Conf. E-Learn. Ind. Electron.*, 2006, pp. 130–134.

[8] L. de la Torre, "New generation virtual and remote laboratories: Integration into web environments 2.0 with learning management systems," Ph.D. dissertation, Dept. Informatica y Automatica, UNED, Madrid, Spain, 2013.

[9] I. Ruano-Ruano, J. Gómez-Ortega, J. Gámez-García, and E. Estévez-Estévez, "Integration of online laboratories – LMS via SCORM," in *Proc. IEEE Int. Conf. Syst. Man Cybernetics*, 2013, pp. 3163–3167.

[10] J. R. Hilera and R. Hoya, "Estándares de e-learning: Guía de consulta," Universidad de Alcalá, 2010. [Online]. Available: http://www.cc.uah.es/hilera/GuiaEstandares.pdf

[11] B. Aktan, C. A. Bohus, L. A. Crowl, and M. H. Shor, "Distance learning applied to control engineering laboratories," *IEEE Trans. Edu.*, vol. 39, no. 3, pp. 320–326, 1996.

[12] E. Guimaraes, et al., "REAL: A virtual laboratory for mobile robot experiments," *IEEE Trans. Edu.*, vol. 46, no. 1, pp. 37–42, Feb. 2003.

[13] J. Sanchez, S. Dormido, R. Pastor, and F. Morilla, "A java/matlab-based environment for remote control system laboratories: Illustrated with an inverted pendulum," *IEEE Trans. Edu.*, vol. 47, no. 3, pp. 321–329, Aug. 2004, doi: 10.1109/TE.2004.825525

[14] R. Dormido, et al., "Development of a web-based control laboratory for automation technicians: The three-tank system," *IEEE Trans. Edu.*, vol. 51, no. 1, pp. 35–44, Feb. 2008.

[15] H. Vargas, J. Sanchez Moreno, C. A. Jara, F. A. Candelas, F. Torres, and S. Dormido, "A network of automatic control web-based laboratories," *IEEE Trans. Learn. Technol*., vol. 4, no. 3, pp. 197–208, Jul.-Sep. 2011, doi: 10.1109/TLT.2010.35

[16] M. A. Trenas, J. Ramos, E. D. Gutierrez, S. Romero, and F. Corbera, "Use of a new moodle module for improving the teaching of a basic course on computer architecture," *IEEE Trans. Edu.*, vol. 54, no. 2, pp. 222–228, May 2011, doi: 10.1109/TE.2010.2048570

[17] L. de la Torre, R. Heradio, J. Sanchez, and S. Dormido, "UNEDLABS: An example of EJS labs integration into moodle," presented at the *World Conf. Phys. Edu.*, Istambul, Turkey, 2012.

[18] F. Lerro, et al., "Integration of an e-learning platform and a remote laboratory for the experimental training at distance in engineering education," in *Proc. 9th Int. Conf. Remote Engineering and Virtual Instrumentation*, 2012, pp. 1–5.

[19] Advanced Distributed Learning (ADL), *SCORM 2004*, 4th Run-Time Environment [EB/OL]. (2009). [Online]. Available: http://wwww.adlnet.org

[20] I. Ruano, J. Gámez, and J. Gómez, "Laboratorio Web SCORM de Control PID con Integración Avanzada" *RIAI*, unpublished.

[21] E. Sancristobal, M. Castro, J. Harward, P. Baley, K. DeLong, and J. Hardison, "Integration view of web labs and learning management systems" in *Proc. IEEE EDUCON Conf.*, 2010, pp. 1409–1417

[22] Rustici Software, Experience API, 2016. [Online]. Available: http://experienceapi.com/

[23] H. D. Wuttke, M. Hamann, and K. Henke, "Integration of remote and virtual laboratories in the educational process" in *Proc. 12th Int. Conf. Remote Eng. Virtual Instrum.*, 2015, pp. 157–162, doi: 10.1109/REV.2015.7087283

[24] IMS Global Learning Consortium, Learning Design Specification, 2001. [Online]. Available: http://www.imsglobal.org/learningdesign/index.html

[25] IMS Global Learning Consortium, Learning Tools Interoperability (LTI). (2015, Jan.). [Online]. Available: https://www.imsglobal.org/activity/learning-tools-interoperability

[26] P. Orduna, et al., "An extensible architecture for the integration of remote and virtual laboratories in public learning tools," *IEEE Revista Iberoamericana de Tecnologias del Aprendizaje*, vol. 10, no. 4, pp. 223–233, Nov. 2015.
[27] M. Häsel, "Opensocial: An enabler for social applications on the web," *Commun. ACM*, vol. 54, no. 1, pp. 139–144, 2011.
[28] L. Tobarra, et al., "Creation of customized remote laboratories using deconstruction," *IEEE Revista Iberoamericana de Tecnologias del Aprendizaje*, vol. 10, no. 2, pp. 69–76, May 2015.
[29] P. Orduna, et al., "Generic integration of remote laboratories in public learning tools: Organizational and technical challenges," in *Proc. 2014 IEEE Frontiers Edu. Conf.*, 2014, pp. 1–7.
[30] Advanced Distributed Learning Initiative (ADL), cmi5 (Computer-Managed Instruction 5). (2015). [Online]. Available: https://adlnet.gov/adl-research/performance-tracking-analysis/cmi5/
[31] M. J. Rodriguez-Triana, et al., "Rich open educational resources for personal and inquiry learning: Agile creation, sharing and reuse in educational social media platforms," in *Proc. Int. Conf. Web Open Access Learn.*, 2014, pp. 1–6, doi: 10.1109/ICWOAL.2014.7009219.
[32] C. Salzmann, D. Gillet, and Y. Piguet, "MOOLs for MOOCs: A first edX scalable implementation," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 246–251, doi: 10.1109/REV.2016.7444473.
[33] M. Tawfik, et al., "Laboratory as a service (LaaS): A model for developing and implementing remote laboratories as modular components," in *Proc. 11th Int. Conf. Remote Eng. Virtual Instrum.*, 2014, pp. 11–20, doi: 10.1109/REV.2014.6784238.
[34] F. Lerro, S. Marchisio, E. Perretta, M. Plano, and M. Protano, "Using the remote lab of electronics physics ("laboratorio remoto de física electrónica") to support teaching and learning processes in engineering courses," in *Using Remote Labs in Education*. J. G. Zubía and G. R. Alves, Eds. Deusto (Spain): Deusto Digital, 2011, pp. 211–230.
[35] D. Lowe, G. Bharathy, B. Stumpers, and H. Yeung, "Laboratory lesson plans: Opportunities created by remote laboratories," in *Proc. 9th Int. Conf. Remote Eng. Virtual Instrum.*, 2012, pp. 1–6, doi: 10.1109/REV.2012.6293111
[36] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education," *J. Eng. Educ.*, vol. 94 no. 1, pp. 121–130, 2005
[37] E. P. S. Jaén, "Memoria de grado de Ingeniería Electrónica Industrial," Art. no. 6. (2013). [Online]. Available: http://www10.ujaen.es/sites/default/files/users/secgrados/memorias_grados/memorias_verificadas/memorias/EPSJ_Ingenieria%20Electronica%20In-dustrial.pdf
[38] ILIAS e.v., Open source e-learning. (2013). [Online]. Available: http://www.ilias.de
[39] F. Esquembre, "Using easy java simulations to create scientific simulations in java," in *Proc. EUROCON*, 2003. vol. 1, pp. 20–23.
[40] F. Esquembre, "Facilitating the creation of virtual and remote laboratories for science and engineering education," *IFAC-PapersOnLine*, vol. 48, no. 29, pp. 49–58, 2015.
[41] I. Ruano, J. Gámez, and J. Gómez, "Building SCORM embedded WebLabs with LMS interaction," in *Proc. IEEE Frontiers Edu. Conf.*, 2014, pp. 1–4.
[42] J. E. Corter, S. K. Esche, C. Chassapis, J. Ma, and J. V. Nickerson, "Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories," *Comp. Educ.*, vol. 57, no. 3, pp. 2054–2067, 2011.

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