Expanding the Boundaries of the Classroom

Implementation of Remote Laboratories for Industrial Electronics Disciplines

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It is apparent that implementation of practical sessions in engineering education paves the way for students to be familiar with instruments and, thus, with the industrial real world. In recent decades, the high cost and administration burdens of physical equipment have caused a significant decline in experimentation within engineering education. This situation has fostered the development and adoption of remote laboratories as a replacement. Recently, remote laboratories based on a large variety of technologies have been developed at multiple universities and adopted in industrial electronics engineering education. Furthermore, some of these laboratories are replicated at many universities. This was the commencement of a new mainstream that advocates a better remodeling of those laboratories to allow their allocation, sharing among universities, and their interoperable communication with other heterogeneous educational systems, e.g., learning management systems (LMSs). This article, on the one hand, reports on the design of the state-of-the-art remote laboratories for industrial electronics disciplines along with the cutting-edge technologies adopted. On the other hand, the article sheds light on the outstanding interoperable educational remote laboratories architectures, classifying them with regard to their exclusive features and provided services, and pointing out the limitations of each.

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Background

The extensive evolution of the global economy and worldwide competition in the industrial markets have demanded a further restructuring and enhancement of engineering education. Unfortunately, during the past 100 years, the educational paradigm has not witnessed a significant change [1]. In recent years, with the

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emergence and evolution of communication and Internet technologies, a dramatic shift from traditional learning to online-learning (e-learning) has started to occur [2]. This shift is more likely to rise, and the way is irreversible [3], [4] owing to the higher efficiency and the unlimited facilities that e-learning provides [5]. Remote laboratories are considered to be the most captivating aspect of e-learning due to the vital role of experimentation in consolidating the understanding of engineering concepts and in observing scientific phenomena [6]. In [7], it was reported that students retain 25% of what they hear, 45% of what they hear and see, and 70% if they use the "learning-by-doing" methodology. According to the 2012–2013 Criteria of Accrediting Engineering Programs of the Accreditation Board for Engineering and Technology (ABET) [8], the practice skills are essential in terms of learning program outcomes. A study was done on the first ten years of published articles of the *Journal of Engineering Education* (from 1993 to 2002). This study concluded that the keyword "laboratory" was only mentioned in 6.5% of the articles from 1993 to 1997 and 5.2% of the articles from 1998 to 2002. Remote laboratories have rendered the acquisition of practice skills more affordable by eradicating the geographic and temporal constraints. The first remote laboratories were robotic laboratories and were developed in the early 1990s [10], [11]. In the late 1990s, the release of the Internet server version (6i) [12] of Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) by National Instruments [13] ignited the increase in the development and adoption of remote laboratories among universities. A literature review of the recently published articles on remote laboratories [14] has concluded that the majority of remote laboratories deployed are in the industrial electronics field. They are deployed, however, in multidisciplinary fields. In the same literature review [14], a study of 42 different remote laboratories concluded that they use different software architectures without being reused or shared among universities. Interoperable remote laboratories' implementation and deployment is a novel field of science but has shown several leaps in the last few years. However, despite the widespread use of remote laboratories, their design and construction issues have not received too much attention; most of the published literature focuses only on the objective of a certain application within a conducted course showing their functional and operational aspects [15]. One noteable study [16] on the state-of-art remote laboratories gave an overview of solutions developed at several universities and classified them according to their application fields in engineering education. However, less attention has been paid to their integration with interoperable educational architectures and their design and construction. To fill these gaps and to complement the missing literature in this novel research field, this article presents a generic study on building and bringing laboratories online for industrial electronics applications, highlighting issues in all their design stages, and their emerging integration and implementation approaches, providing a wide literature review. This article classifies and analyzes the emerging approaches with a critical point of view in order to give an overview of the upcoming directions and challenges within this novel research field. The scope of the conducted study in this article is structured as follows: the section "Design and Common Architecture of Remote Laboratories" provides a broad overview of the subject. The section "Case Studies on Remote Laboratories Within Industrial Electronics Disciplines" presents relevant case studies. The section "Integration with Interoperable Educational Architecture Scenarios" discusses different scenarios for remote laboratories implementation and integration within interoperable educational architectures. The section "Future Trends" discusses the upcoming trends and challenges. And finally, the section "Conclusion" concludes the article.

Design and Common Architecture of Remote Laboratories

Remote laboratories are those that can be controlled and administrated online. They differ from virtually simulated laboratories in that they interact with physical instruments. The common generic architecture design of today's remote laboratory is shown in Figure 1. Next, a comprehensive definition of the main components of this architecture is presented, pointing out the available technologies they mostly rely on.

User Interface

The user interface is a virtual end-user workbench that handles all the laboratory administration processes. It is a Web site that runs on the user's Web browser and usually requires a server-side programming language to retrieve the user's data from a database such as PHP, ASP, and JSP, along with a GUI embedded in the HTML code. The code is built by a Rich Internet Application or a plug-ins-based technology to resemble a real laboratory workbench and add rich dynamic contents, such as Adobe Flash, ActiveX, and Java Applets. Other scripting languages commonly used are JavaScript, which adds interactive elements to the Web page without relying on the server, and AJAX, which retrieves information from the server in an efficient way and without the need to refresh the Web page. The Web site could be supplanted by a software application installed on the user PC and connected to a database server (application server).

Web Server

The Web server is a server PC that hosts the Web site and the database files. Apache and Microsoft IIS are the most commonly used servers, and MySQL, Microsoft SQL, and Oracle are the most commonly used databases. The Web server sends the user requests to the laboratory server in the form of XML messages through TCP/IP model over HTTP layer. Other attempts have been made to use non-HTTP-based protocols such as Common Objective Request Broker Architecture, Java Remote Method Invocation, Virtual Network Computing, Remote Desktop Protocol,

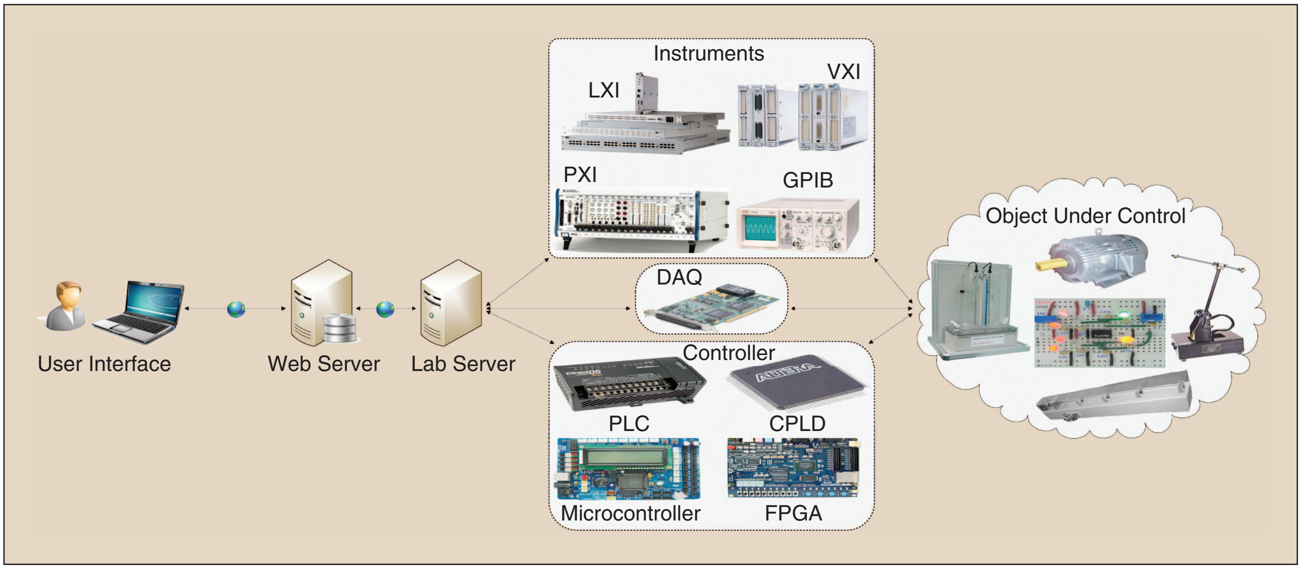

FIGURE 1 – Common generic remote laboratory architecture.

and TCP/IP sockets. Some of these technologies, however, are restricted to local networks only [17].

Lab Server

The lab server is a server PC that hosts the instrumentation control software and is connected directly to the equipment by standards such as USB, RS-232, Ethernet, IEEE-488.2, and serial and parallel ports. The instrumentation control software sends commands to the equipment regarding the received requests or the programmed code from the user. The instrumentation control software could be built from scratch with a multipurpose programming language such as Java, C#, or C/C++, or with a graphical programming environment such as LabVIEW and MATLAB/Simulink [18]. LabVIEW and MATLAB possess rich and powerful features to ease remote laboratories construction, including:

- data exchange with other GUI applications such as Component Object Model, ActiveX, Common Gateway Interface, Java and .Net applications, and Web services
- support for standard application programming interface (API) such as Interchangeable Virtual Instruments and Virtual Instrument Software Architecture to provide interface-independent communication with different platforms
- connection with Open Database Connectivity or Object Linking and Embedding Database compliance database; compilation as Dynamic Link Library files to be called from the Lab server software as a driver to execute the experiments on the hardware
- support for OLE for Process Control servers to enable developing Human–Machine Interface and Supervisory Control and Data Acquisition.

The instrumentation control software could also be a proprietary software that comes with the equipment.

Equipment

Equipment encompasses the instruments, the Data Acquisition Card (DAQ), and the controller. There are several modular types of instrumentation platforms such as PCI eXtensions for Instrumentation, LAN eXtensions for Instrumentation, IEEE-488.2, and VME eXtensions for Instrumentation. The DAQ is used to retrieve and convert digital and analog data signals. The controller is a programmable device that directly controls the objects and it is suited for all types of applications. In the literature, the controllers typically used in remote laboratories are programmable logic controllers (PLCs) [19], [20], programmable logic devices (PLDs), field-programmable gate array [21], [22] and complex programmable logic devices [23], and microcontrollers [24]. The equipment is connected to the object under control using connectors, converters (e.g., A/D, D/A), inter-integrated circuit (I^2C)-based electronic boards, etc. In some applications, a relay-switching matrix is used to switch and route the connection between instruments and experiment elements [25], [26].

Case Studies on Remote Laboratories Within Industrial Electronics Disciplines

Electronic Circuits Measurement and Wiring

Measurement and wiring of electronic circuits' practices have an essential role in all industrial electronics education disciplines in teaching students the principles of electronics. Among the most remarkable remote laboratories for this purpose are NetLab [27], [28] and Virtual Instrument Systems in Reality (VISIR) [25]. In addition, it is important to address the commercial versatile design and prototyping educational platform, NI ELVIS II [29]. However, NI ELVIS II itself is not a remote laboratory but embeds 12 of the most commonly used laboratory instruments and is totally controlled by LabVIEW and, thus, can be easily controlled remotely. For instance, in [30], a remote laboratory is developed for measuring noninverting, inverting, and differential amplifier circuits. A similar approach for operational amplifier circuits experiments is found in [31]. Circuits must be manually mounted on the plug-in boards of NI ELVIS II. However, in RemotElectLab [26], a relay-switching matrix has been developed for NI ELVIS (the older version) to allow instruments to measure voltage or currents at different nodes of the circuit remotely. In [32], a LabVIEW API and a simple cross-platform interface have been created to facilitate publishing NI ELVIS II laboratories. Other approaches have been realized for electronic circuits measurement as in [33]; a remote laboratory is developed for measuring circuits with an operational amplifier, recording the amplitude characteristics of a T-notch filter, and measuring the I/O characteristics of diodes, PNP and NPN transistors, and resistor–capacitor filters; in [34], a remote laboratory is developed for running experiments on a normal bipolar junction transistor common emitter amplifier circuit.

Electrical Machines and Control

Remote laboratories are widely adopted to teach the students the principals of electrical ac and dc machines and their performance, fault detection, and speed control. In [35], a developed remote laboratory setup of an ac machine for fault detection of incipient rotor bar and three-broken-rotor-bar is described. A similar approach is found in [36] for fault detection in induction motors. In [37], a remote laboratory is developed to introduce to the students the principles of proportional integral derivative (PID) controls on a speed-controlled dc motor. In [38], a remote laboratory is developed for controlling the speed of a DSP-controlled induction motor using a vector-controlled strategy. In [39], a remote laboratory is developed for a separately excited dc motor and generator. It allows speed control of the dc motor using armature and field voltage, generator no load, and terminal voltage characteristics.

Automation and System

PLC-based remote laboratories [19], [20] for controlling devices, such as motors, are commonly used in automation and system courses. The students program the PLC device by uploading their code written in a PLC programming language (e.g., ladder-style logic or instruction list) in order to define an adequate control strategy, such as PID control, and then monitor the feedback through a Web cam or an HMI software that allows control and real-time handling of the system. Thereby, the remote laboratory acts as a SCADA system, which is widely used in the real industrial world.

Embedded Systems

Laboratories based on PLDs [22], [23], [40] and microcontrollers [24] are commonly used in embedded systems courses. Each controller usually comes integrated in a board with additional peripherals such as light-emitting diodes, push buttons, LCD display, speaker, keyboard, switches, sensors, etc. The students write their program codes in an assembly language (in case of microcontroller) or in hardware description languages (in case of PLD) and upload them through the user interface to be compiled and debugged to the controller board. Then, they monitor the peripherals' behaviors through a connected Web cam.

Integration with Interoperable Educational Architecture Scenarios

Federated Laboratory Repository and Metadata

Today, the remote laboratory of a university is rarely used by other universities due to the lack of information about the laboratory. The Lab2go project [41], [42] was launched to fill this gap. It is a Web portal, inspired by the semantic Web feature of Web 3.0, that acts as a repository and provides a common framework for online laboratory providers all over the world. The laboratory with all their related information are added with metadata using semantic Web technologies, which allows them to express a piece of data about some entity in a way that it can be combined with information from other sources to facilitate their allocation and precisely define the search criteria rather than the traditional available searching tools that are oriented to keywords. Lab2go created a generic model ontology consisting of various properties to add to laboratories such as remote laboratories, virtual laboratories, hybrid laboratories, experiments, access URL, status, cost, release date, languages, description, administrator, etc. Likewise, the ontology consists of properties to add to experiments such as description, scientific field, documentation, and duration. Basic terminologies from Dublin Core [43] and other standards are adapted from learning object metadata (LOM) [44] as well. However, Lab2go does not provide access to experiments. Another approach was realized within the Library of Labs (LiLa) project [45], which has created a repository portal that includes online laboratories from distinct universities. LiLa uses a metadata set based on Dublin Core and LOM to allow annotation of the experiment by the scientific community and its target audience. Metadata also defines license terms, usage conditions, and a contact to negotiate the software cost if applicable.

Integration with LMS

LMS is a software application that facilitates the provision of theoretical online classrooms by means of integrated features and tools such as administrative tools, synchronous and asynchronous communication tools, assessment and tracking tools, multimedia sharing tools, and standard compatibility. However, most of the features provided by LMS are of crucial importance to practical sessions; LMSs, however, are confined to theoretical resources and don't support their practical counterparts. The goal is to make use of all the services provided by open-source LMSs, such as Moodle [46], DotLRN [47], and Sakai [48], and apply them in the remote practical laboratory sessions as shown in Figure 2. Thus, several initiatives have been launched to integrate remote laboratories into LMS. The MARVEL project [49] has created a booking module for the most popular open source LMS, Moodle, which is based on hour slots. A further modification to such booking system has been made [50] to facilitate the integration of remote laboratories based on LabVIEW publishing tools. In [51], a similar approach to integrate a remote laboratory into Moodle via plug-ins is described. In the LiLa project [52], the experiments are provided in the form of shareable content object reference model (SCORM) [53] objects and can be downloaded as shareable content objects (SCOs) to be reused in other SCORM-complaint LMS. LiLa provides access control and booking systems as an inherent part of SCO to have the same effect if the SCO is deployed out of the LiLa portal (in an LMS). The access to the experiment, either in the LiLa portal or in the LMS, is provided by a URL. A user authenticated by the LMS will be automatically authenticated to the experiment. Nonetheless, the user must have reserved a time slot to access the experiment. A middleware architecture based on Web services for integrating remote laboratories with open-source LMSs such as Moodle and DotLRN is described in [54]. The architecture would allow the communication of remote laboratories by means of Web services with created modules designed for adding experiments within the LMS. Moreover, it would support the access of experiments within iLab shared architecture (ISA) [55]–[57] through the LMS [58]. In the previously mentioned integration approaches within LMS, in general, the relation between the course activity and the practical session is not evident. Moreover, it is not clear whether the collaborative tools of the LMS are supported or whether it is only created to allow sequential access to the experiment [59]. One of the factors that have slowed down the integration of remote laboratories into LMSs is that LMSs were usually closed proprietary software systems and were not customizable [60] until open-source solutions became prevalent. Other approaches attempt to integrate remote laboratories into standards compatibles with most of LMSs such as SCORM [52] and IMS Learning Design [61].

Integration with Shareable Architectures

Recently, as discussed earlier in the article, diverse projects and types of remote laboratories devoted to industrial electronics disciplines have proliferated among universities. However, these laboratories are not affordable and are confined to the private usage of their owner university due to the complexity of their interoperation. This was a breeding ground for new researchers to attempt to establish a seamless, interoperable, and shareable integrated architecture that encompasses several remote laboratories from several universities in order to span their dissemination and interinstitutional operation as shown in Figure 3. Consequently, this will reduce cost and increase availability. The most innovative shareable integrated architectures are ISA, iLab, Sahara (developed within the Labshare project [62]–[64]), and WebLab Deusto [17], [65]–[67].

The iLab project provides a middleware infrastructure based on Web services and is developed by .NET technology known as ISA. ISA is an efficient management framework that can support administration and access to a wide variety of platform-independent developed online laboratories. The architecture started with a three-tiered model consisting of laboratory clients, service broker middleware, and laboratory servers. The service broker (SB) is responsible for providing generic functionalities such as authorization, scheduling, data storage, etc. Typically located at the client side campus, it can be connected to

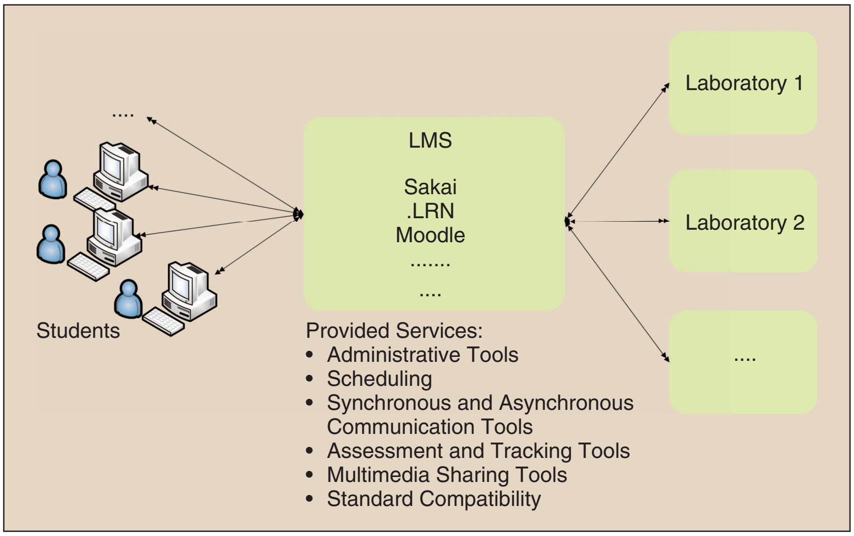

FIGURE 2 – Remote laboratories integration with open-source LMSs.

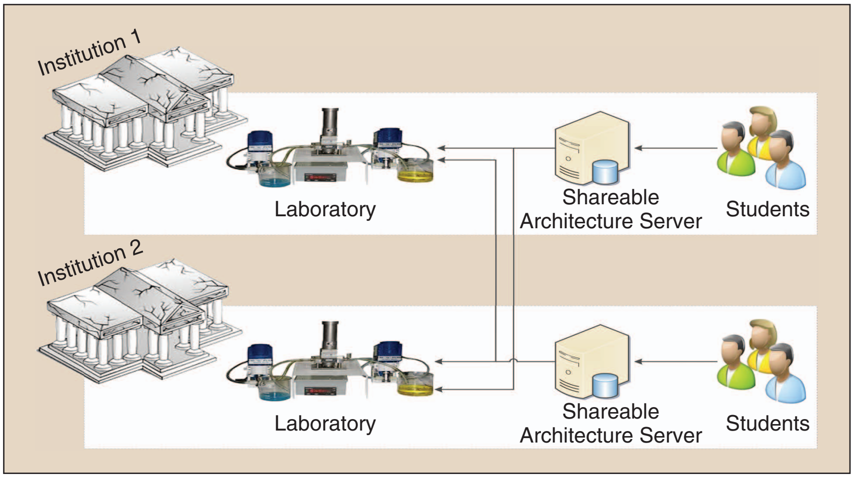

FIGURE 3 – The role of implementing remote laboratories within a shareable architecture. Students from "institution 1" could access their institution's laboratory and the laboratory of "institution 2" as well, and vice versa.

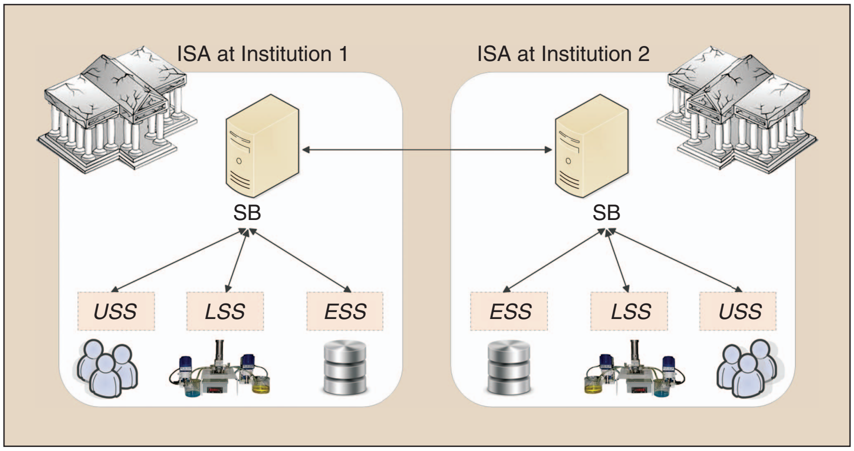

FIGURE 4 – The topology of ISA for interactive experiments.

multiple laboratory servers at distinct institutions with Web services. Conversely, a given laboratory server can receive experiments from an arbitrary number of SBs. This architecture is only valid for batched experiments for which the student query is queued and the results are returned after being executed. The students don't have to be connected while their experiments are being executed as they are not directly connected to the laboratory server. Interactive experiments differ from their batched counterparts in the sense that they require control of laboratory hardware while the user sets parameters and observes results, thus requiring a greater bandwidth between the laboratory client and the laboratory server. In order to accommodate these requirements, ISA has been extended to include lab side scheduling service (LSS), user side scheduling service (USS), experiment storage service (ESS), ticketing, and support for high-bandwidth communication between the laboratory client and server. LSS, USS, ESS, and ticketing are based on Web services. USS and LSS set the policy of the student institution and the laboratory, respectively, but both are designed to work together. The SB only vouches for the user to the laboratory server and then retires and permits the student to directly control the laboratory server, leaving the storage task of experiment data to ESS. The SB is still responsible for authentication and authorization. It issues a ticket stub (coupon) to the users when they log in, which is redeemed by the laboratory server and the ESS before execution. The topology of ISA for interactive experiments is shown in Figure 4. LabVIEW Integrated Interactive Lab Server is developed to integrate laboratories based on LabVIEW GUI by a standard and easy way to the iLab interactive architecture. In the case where LabVIEW is not the chosen technology, the laboratory client and server must implement the Web

TABLE 1–A COMPARATIVE STUDY ON iLAB (ISA), LABSHARE (SAHARA), AND WEBLAB DEUSTO.

	iLAB (ISA)	LABSHARE (SAHARA)	WEBLAB DEUSTO
DEVELOPER	Massachusetts Institute of Technology (MIT)	University of Technology of Sydney	University of Deusto
WEB TECHNOLOGIES	Microsoft (ASP.NET, MS SQL, and IIS)	PHP, Java, PostgreSQL, and Apache	Python, Java, MySQL, and Apache
COMPATIBILITY	Only runs on Microsoft Windows Server	Cross-platform	Cross-platform
AUTHENTICATION	Simple database authentication and ticketing	Simple database authentication and interface to an institution's local such as Lightweight Directory Access Protocol (LDAP)	Simple database authentication, OpenID, trusted IP address, Facebook, and LDAP
CLIENT-SERVER COMMUNICATION	HTTP-based protocols	HTTP-based protocols, AJAX, and virtual machines	HTTP-based protocols, AJAX and virtual machines
PROVIDED SERVICES	• User accounts and administrative tools • Scheduling • Interactive experiments • User tracking • Batched experiments • Strong support to distributed and federated user account management owing to its genius distributive architecture and the functionality of SB, LSS, USS, and ESS	• User accounts and administrative tools • Scheduling • Interactive experiments • Queuing • Arbitration of access to multiple identical experiment workbench	• User accounts and administrative tools • Scheduling • Interactive experiments • Queuing • User tracking • Mobile access
MULTIUSER COLLABORATION AND COMMUNICATION	Not supported	Not supported	Not supported
ADDING EXPERIMENTS	Complex, owing to the Web services API design for the communication with service broker, LSS, USS, and ESS. However, it integrates LabVIEW GUI in a standard and easy way	Simple, due to its simple protocol and configuration and it is based on virtual machine, which provides direct access to the local laboratory server	Simple, it provides libraries for Java Applets, Adobe Flash, Java, .NET, LabVIEW, C\C++, and Python to ease integration of new experiments based on different technologies
NUMBER OF UNIVERSITIES	3 (Africa), 3 (Australia), 2 (Asia), 3 (Europe), 2 (North America) [57]	4 (Australia) [62]	1 (Spain) [67]
NUMBER OF LABORATORIES ADDED	21 [57]	13 [62]	6 [67]

service interfaces according to the client to SB API as defined by ISA in order to access its generic functionality.

Sahara and WebLab Deusto offer similar functionalities, but their architectures are different; the core of their architectures depends only on a scheduling server, and they are only installed at one domain through which other universities can access. Thus, the main singularity of ISA is its genius-distributed architecture. A comparative study on the actual versions of the aforementioned architectures is presented in Table 1.

Future Trends

The main upcoming challenge in remote laboratories implementation is to have a single architecture that encompasses the discussed features such as interoperability, compatibility, metadata, standardization, and integration of educational contents. For these reasons, the founders of the above-mentioned projects (Lab2go, LiLa, WebLab Deusto, iLab, and Labshare), together with other partners, have formed the Global Online Laboratory Consortium (GOLC) [68] to research and promote the development of a common infrastructure for a unified and interoperable architecture that is able to share online laboratories efficiently around the world. A major research field within GOLC is to create LabConnectors [64], based on an interoperable cross-system protocol, to allow interchangeability of remote laboratories between ISA, Sahara, and other architectures such as WebLab Deusto, Internet Shared Instrumentation Laboratory [69], and Distributed Control Lab [70]. LabConnectors is a common API that establishes common nomenclatures of Web services-calls, valid for several architectures, to allow calling experiments integrated in an architecture from another architecture as shown in Figure 5. Web services have a significant role in creating an interoperable architecture. Web services are a programming language–independent design solution that allows communication between heterogeneous software applications over a network by means of ad-hoc standard protocols. Despite the high interoperability of Web services, they have an intrinsic weakness of latency, interoperability, and performance due to the high number of transport layers used to wrap instruments into Web services and the overhead of using simple object access protocol (SOAP) [71]. Thus, although Web services are not adequate for real-time control of instruments [15], their advantages outweigh their disadvantages. Recently, many approaches are moving from SOAP to representational state transfer [17], [72]–[74], which uses as a data format JavaScript Object Notation rather than XML [75], due to its simplicity and high transfer speed, avoiding the heavy weight of XML libraries in APIs of client and laboratory server sides.

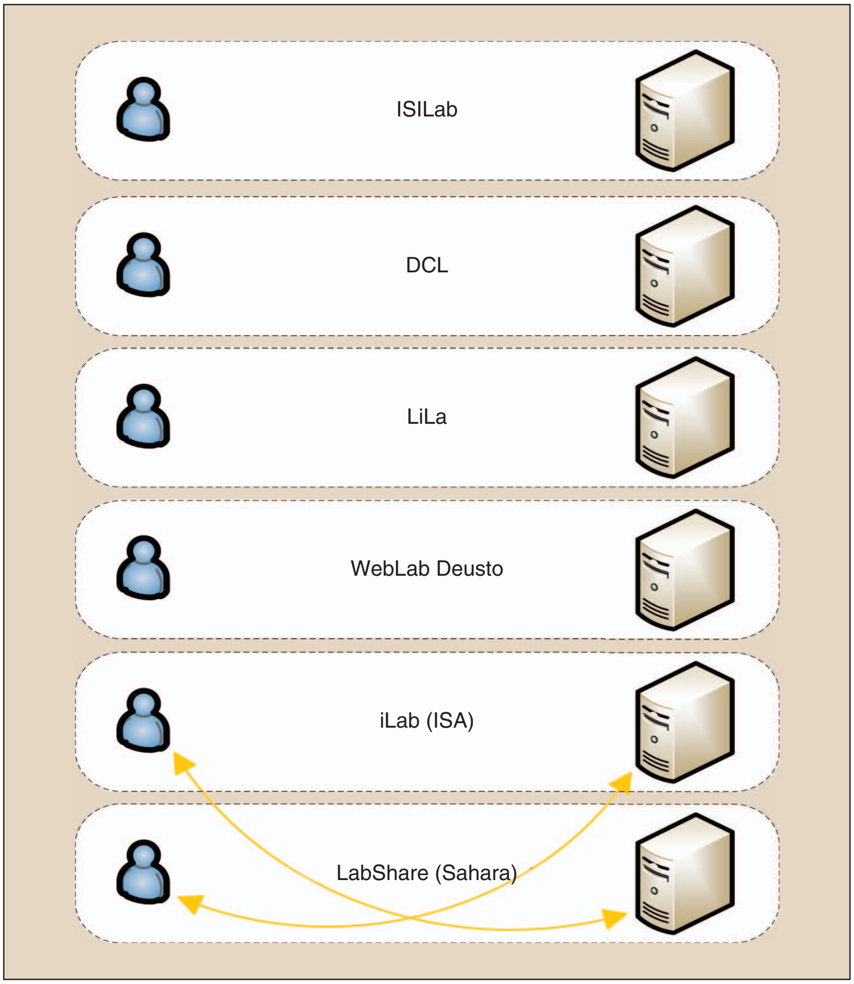

FIGURE 5 – Interoperability between various shareable remote laboratories architectures. For instance, users of ISA could access experiments integrated in Sahara or any other architecture, and vice versa.

Conclusion

The evolution of Internet and communication technologies has facilitated the development of remote laboratories at many universities for use in multidisciplinary fields of engineering education. This has paved the way for a new research field into the proper implementation of these types of laboratories in the engineering curricula. Such implementation requires the interoperability of remote laboratories to be integrated with other heterogeneous architectures in order to provide online laboratory sessions along with other educational services and tools such as administration, communication, assessment, tracking, etc. However, this implementation contemplates an efficient sharing of remote laboratories among universities in order to reduce the physical equipment cost and optimize their utilization. This research field is one of the major challenges in the future path of engineering education.

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