Facilitating Remote Laboratory Deployments Using a Relay Gateway Server Architecture

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***Abstract*—Hands-on experiments prepare students to deal with real-world problems and help to efficiently digest theoretical concepts and relate those to practical tasks. However, shortage of equipment, high costs, and the lack of human resources for laboratory maintenance and assistance decrease the implementation capacity of the hands-on training laboratories. At the same time, the Internet has become a common networking medium and is increasingly used to enhance education and training. In addition, experimental equipment at many sites is typically underutilized. Thus, remote laboratories accessible through the Internet can resolve cost and access constraints as they can be used at flexible times and from various locations. While many solutions have been proposed so far, this paper addresses an important issue of facilitating remote lab deployments by providing remote connectivity services to lab providers using a Relay Gateway Server architecture. A proof-of-concept solution is described which also includes other previously reported useful features. The system has been tested in engineering labs and student assessment is provided.**

***Index Terms*—Practical competences, real remote equipment access, remote desktop architecture, remote laboratory.**

I. Introduction

ALMOST all of the colleges offer engineering laboratories as an essential part of the educational experience and to meet requirements of accrediting organizations. Labs provide hands-on experience which relates real world observations with theories, concepts, and ideas. While many institutions cannot afford costly equipment and servicing costs, the lab equipment in some other institutions is often underutilized. Equipment might be also available in small quantities preventing conventional lab experience due to constrained access. Remote laboratory solutions over the Internet evolve for several recent years to address these bottlenecks [1]–[3]. Remote labs replace more challenging management of instructor time, class scheduling and equipment availability with significantly simplified and flexible management of individual remote access to experiments. Small number of equipment units can be shared within and between institutions. They provide new educational opportunities to underserved areas and to students with disabilities.

1) State-of-the-Art: Recent reviews of previously reported solutions on remote laboratories provide excellent systematic descriptions of the area [1]–[5]. State-of-the-art solutions provide sophisticated user, instructor, and lab management features for efficient access and sharing of remotely located equipment. They also support many features which provide for almost hands-on perception of remote labs. Examples include VISIR [6], iLab [7], WebLab-Deusto [8], Labshare Sahara [9], [10], ReLOAD [11], AIM-Lab [12], I-ATMUS [13], LiLa [14], NetLab [15], remote solutions for training in information technology (IT) [16], testing systems [17]–[19] and others. Several efforts successfully expanded to remote lab networks. For example, the pioneer iLab Shared Architecture currently provides advanced support for access booking and federation of remote labs for scalability which allowed sharing of experiments by several universities in US, Europe, Africa, and Australia [7]. In a similar way, WebLab-Deusto also supports a federation system to share remote laboratories [20], which additionally supports balancing users among multiple copies distributed in multiple institutions, as well as re-sharing laboratories to third institutions. Similarly VISIR has been deployed in several European universities, and Labshare project is focused on building a network of remote laboratories in Australia [10]. Labshare Sahara architecture supports access queues, equipment management, and arbitration to access multiple identical rigs. Labshare Sahara, LiLa, and NetLab also support teamwork labs [14], [15], [21], [22].

While reported remote laboratories have various system architectures and features, one of the classification criteria relates to two types of user-experimenter interactions with the experiment: a) controlling the experiment instrumentation through a computer interface, using virtual instrumentation or virtual-reality environments; and b) directly controlling the experiment instrumentation by remote access to control software [1].

The first category of remote labs exploits intermediate interfaces for the users to define lab configuration parameters which are then communicated to the lab servers controlling real equipment. For convenience, these intermediate panels can be designed to resemble real equipment for more authentic perception. Experiment results are communicated back to user-accessible panels in batched or interactive modes. Examples of such systems are iLab, VISIR, WebLab-Deusto-managed, ReLOAD, Emona net∗TIMS (http://tims.com.au/) and LabView Remote Panels from National Instruments (http://www.ni.com). Compared to other solutions these systems minimize

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data communication between users and laboratory servers and they are more suitable in bandwidth-limited networks. While being popular these solutions assume essential efforts to setup such environments and design virtual instrumentation panels for each experiment. Excessive data communication from experiments outputting signals at high sampling rates might be another limiting factor.

The second category of remote labs refers to direct control of experiments by exploiting, e.g., "remote desktop" type solutions [1]. Examples are Labshare Sahara [9], [10] and WebLab-Deusto-unmanaged [8]. Open source versions of Virtual Network Computing (VNC) remote desktop sharing utility are often used for implementations [23]. Different from the first category, VNC-based remote desktop software provides direct access to the lab servers. The users directly see GUIs of software controlling experimental equipment, so they can configure experiments using this software rather than intermediate Web-based or other client software panels. In VNC multiple users can concurrently access the same lab server which is convenient for supporting teamwork implementations.

The advantage of this approach is in lighter installation effort as there is no need in intermediate virtual instrumentation panels. The drawback of remote desktop solutions is in excessive bandwidth requirements to support continuous communication of screen updates. Typically, this is not a limiting factor in developed countries as evidenced by broad penetration of web conferencing tools exploiting similar concepts. Not surprisingly, one of these remote lab solutions exploits web teleconferencing software for easy deployment [23].

Optimized implementations of VNC such as TightVNC (www.tightvnc.com) communicate only updated screen fragments (not the whole screen) and support compression formats to minimize consumed bandwidths [23]. Remote desktop solutions might be also preferable for experiments plotting signals sampled at high rates, as communication of signals plots (screen images) may consume less bandwidth than communication of large data files of actual signal samples. At the same time, VNC-based remote desktop solutions are less secure in comparison with first category approaches as provide direct user access to lab servers.

2) Facilitating Lab Deployments: When deployment easiness is a major factor, the advantage of remote desktop solutions is recognized [9], [10]. The iLab developers also admit that deployment complexity is a major limiting factor for broad adoption of first category systems in US [7]. For the same reason, the WebLab-Deusto [3], [4], [8] maintains two solutions, named "managed" for the first category, and "unmanaged" for the second for various needs.

While the transition to remote desktop solutions potentially eliminates the task of Web-based virtual instrumentation panel design, deploying remote labs still involves server installations for access and scheduling, and lab server connections.

For this reason, in this paper, a remote laboratory design is approached with a goal of facilitating remote lab deployments for third party lab providers. Relay-Gateway-Server (RGS) architecture is proposed that to certain extent considers both lab users and lab providers as clients. Students, instructors, and labs connect to each other using a centralized broker service. Similar to web-conferencing philosophy, all parties (including labs) connect to RGS servers at designated times, and then student and instructor users are relayed to the lab computers. Even though most of known solutions utilize certain type of gateway servers for various tasks, the goal of the proposed solution is to simplify lab connectivity for providers by offering them RGS broker services as well, and minimize professional IT workload for broader adoption. The student and instructor users may connect from any location having Web-browsers and network connectivity, and similarly the remote laboratory connection simplifies. To reflect this specific aspect, the approach is referred to as RGS architecture. The RGS connects all parties involved, supports access and scheduling, provides administrative functions for convenient experimenting, but it is relieved from specific lab design tasks. Lab designs are delegated to lab providers. The approach is conceptually close to a web-conferencing based solution [24], but it replaces the concept of a semi-manual adaptation of a web-conferencing service by dedicated remote lab architecture. To some extent, it also correlates with Service-Oriented Architecture (SOA) mentioned in [25]. Provided a third party support of RGS services, connecting labs remotely may become a broadly adopted routine culture similar to web-conferencing. Even though many design and security aspects should be still addressed, the exploration of this alternative approach may provide further insights to remote lab developer community.

This paper presents a proof-of-concept solution which supports RGS architecture. For testing purposes it has been deployed and offered to students to conduct labs in radio-communication electronics and is named eComLab. So far two other remote radio-communication experiments are also reported, Emona net∗TIMS (http://tims.com.au/), and a setup based on Emona-DATEx equipment [26]. [26] does not report any details on remote architecture, and Emona net∗TIMS is a proprietary costly solution intended for remote-only deployment. Typically, lab providers would prefer to have equipment, which also allows hands-on modality. None of them provided systematic assessment of remote user experience. The remote labs based on RGS architecture are offered to undergraduate and graduate electrical engineering students and surveys are collected to assess the efficiency.

Table I summarizes all the features of the current eComLab deployment, which continuously evolves and incorporates more state-of-the-art concepts. The RGS architecture is a novel feature, while conventional features such as video, chat, teamwork capability and others are also adopted. State-of-the-art systems support other functionalities as well [1]–[5].

The rest of the article is organized as follows. The state-of-the-art VNC-based remote desktop laboratory architectures including proposed RGS are summarized in Section II. The eComLab's system features are introduced in Section III. The user experiences and are summarized in Section IV. Conclusions are provided in Section V.

II. Relay-Gateway-Server Architecture

The biggest design challenge in the remote laboratory development is to create an architecture that can support

TABLE I
CURRENT FEATURES OF eCOMLAB REMOTE LABORATORY, RGS, AND ENHANCEMENTS

System Features	Examples of other systems having or mentioning similar features	Comments
1. System as a service. Relay-Gateway-Server (RGS) architecture enables connectivity and logistics. Labs providers and users are RGS service clients.	Advanced feature, enhancing [23]	The main goal is to facilitate software development effort for Lab providers. [23] addresses this issue exploiting online meeting software. [21] mentions Service Oriented Architecture (SOA), which is also potentially related.
2. Virtual Network Computing (VNC) based implementation	[26]	Open source VNC implementations are available.
3. Group policy with the experiment control passing function	[14],[15],[21],[26],[27]	Useful feature for teamwork labs
4. Remote desktop transmission quality control	[8],[26]	[26] mentions VNC usage for remote access. Many VNC implementations support compression. [8] also mentions VNC as one of possible options
5. Real-Time Web camera	[26],[8],[11],[13]	Many systems support this feature
6. Experiment chat room/discussion board	[26],[27]	Various configurations are reported
7. Lab access statistics, graphical		Useful feature for instructors to track student activity.
8. Integration with online assessment sites	[26] and [28] mention it among desirable features	One can design surveys using SurveyMonkey (http://www.surveymonkey.com/) from within the system.
9. Radio-communication experiments, undergraduate and graduate class experience	Case study and assessment, [25]	It is not clear if [25] was deployed and offered to students, but in available literature that fact was not reported. High cost and vendor-modules-only equipment constraints are limiting factors for net*TIMS (http://tims.com.au/).

appropriate access to remote hardware. In the previous section two broad types of remote systems are discussed. This paper adopts remote desktop type architecture as it is more convenient for facilitating connectivity of third party lab providers and minimizing professional IT deployment workload. For this reason only remote desktop type architectures are discussed next. Even though many issues should be still addressed, the proposed approach may potentially boost broad adoption of remote labs as explained in the previous section. To present the deployed remote laboratory system, two conventional remote desktop based architectures are briefly described next.

1) Conventional Remote Desktop Architectures: It allows users to access the host computer directly over the Internet using remote desktop software such as Remote Desktop for Windows (http://windows.microsoft.com/) or GoToMyPC (http://www.gotomypc.com/). In this case, the user is actually controls experimentation software on the host computer. The user connects to the host over the Internet using some specific information, typically the host computer's IP address and a preset password. Although this architecture is simple for implementation, it lacks multiple user support. Typically, remote desktop software is designed as one-to-one communication architecture. When many users want to access the same experiment, the first-in-first-out sequencing method is used. This basic configuration does not provide user access management (e.g., scheduling, timing control, teamwork capability with control delegation, chat rooms).

2) Experiment-Server-Centric (ESC) Architecture: More sophisticated remote laboratory system architectures deal with multiple experiments and users at the same time. Typically, advanced remote laboratories have user management mechanisms to support and regulate user access.

In ESC architecture, the server functions as a software support for all of the experiments. In other words, all of the experiments are connected to the central server. Several virtual machines can be installed in the server. Each virtual machine is connected to the experimentation hardware and contains all the necessary software to control the hardware. A user management program, which is installed on the ESC acts as an experiment access manager, which directs and connects the user to the requested experiment (virtual machine).

LabShare Sahara, as reported in [10], [21] is an example employing server-centric system concept. It provides for multiuser access. Several virtual machines are installed on the central server and connected to experiments. Users can access all the experiments through the regular Web browser from any remote computer without any additional software. The LabShare Sahara Web-interface includes real-time audio/visual monitoring tools to provide the users more realistic perception of experiments. This architecture is shown in Fig. 1(a).

3) Relay-Gateway-Server (RGS) Architecture: In this system [Fig. 1(b)], the server's two main functions are experiment management and relay services. Both users and labs are clients in some sense that connect to the RGS. The users may connect from any location having Web-browsers and network connectivity, and similarly the remote laboratory connection simplifies.

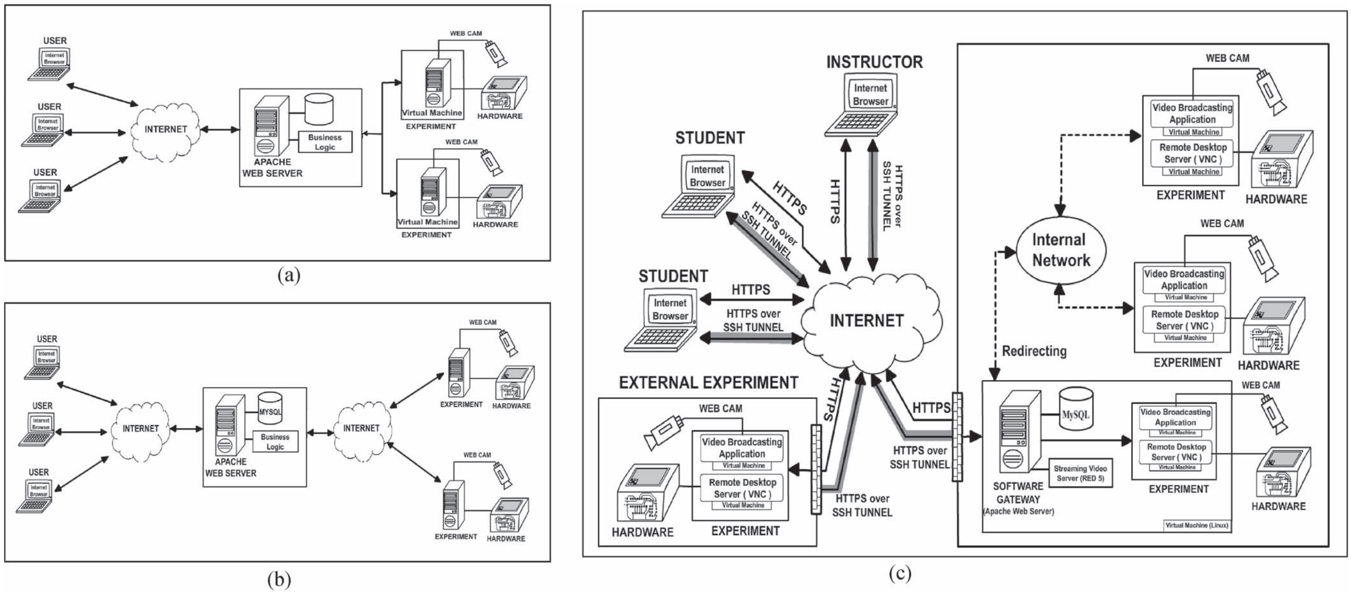


Fig. 1. (a) ESC architecture. (b) RGS architecture. (c) eComLab system architecture.

The RGS provides all the management functionality of the ESC server, i.e., user authentication and authorization. Additionally, the RGS functions as a relay to connect user and experiment clients.

Relay functionality is necessary to help connect clients in separate networks. For example, imagine the case where both the user and the lab are in separate networks behind NAT (Network Address Translation). In a standard setup, the NAT will prevent any direct connections between the clients. The publicly accessible RGS will function as an intermediary and relay communication between the user and the lab, thus allowing a remote connection.

While IT administrators may setup NAT and similar technologies to explicitly allow direct connections to protected computers, this requires potentially significant effort on the part of the administrators (e.g., managing all labs in the network) and authorization by the organization. The RGS facilitates and automates this process as much as possible.

4) Deployed RGS-Based eComLab System for Testing: The eComLab is a hybrid of Experiment-Server-Centric (ESC) [10] and Relay-Gateway-Server (RGS) architectures to leverage the advantages of both concepts. It provides the users, instructors, and developers flexibility to access the system from various locations [Fig. 1(c)]. It evolved from remote desktop solution [29] to server centric system [30], and then to a hybrid ESC and RGS solution as described next.

For *internal* labs, eComLab employs ESC architecture as a proven solution. For external labs, eComLab provides RGS services. Relay functionality is implemented by an SSH tunnel established between the experimentation station and the RGS.

Currently, all of the components in the central server and experiment computers are set up as virtual machines. This simplifies the setup, maintenance, and security of the system. For example, several experiments can be set up by cloning and distributing an initial virtual machine image. Snapshots of the virtual machines can be used as fast system backups. Finally, virtual machines better separate different experiments and their user interfaces from each other, providing a sandbox environment for students so that the host machine is protected from tampering. In the following, virtual machines are often referred to as machines.

The central server runs Ubuntu Linux and combines several service servers such as an Apache HTTP server for the Web interface, a MySQL database for storage, and a Red 5 streaming video server. This centralized virtual machine server will serve as RGS if needed. It is responsible for managing all of the user access procedures. In ESC mode, aside from administrating the machines in computers serving remote physical experiments, the central server has the ability to host and administrate several virtual machines directly connected to experimentation equipment.

It is recommended that each experimentation computer contains a set of two virtual machines. The first one contains a video broadcasting application, which is connected to a webcam and is responsible for real-time experiment video transmission. The second virtual machine contains a remote desktop server. In the current implementation, TightVNC (www.tightvnc.com/) is used as it provides bandwidth efficient communication when only updated screen fragments are sent to the user, and these fragments can be additionally compressed. As an example, for a case scenario of a signal modulation experiment, measured traffic for the remote desktop updates was 83 Kbits/s in the current installation, and the system has an ability to scale the resolution based on available bandwidths.

To achieve better security, all transmissions in the eComLab system are encrypted. In Fig. 1(c), lab users exchange HTTPS messages with the central server, dotted arrows represent internal messages exchanged among the virtual machine servers.

The VNC is not very secure protocol by default, and it might be blocked by firewalls or NAT routers. In RGS, a single connection to the RGS server can be used to transport all data from the experimentation system. The current prototype uses an SSH tunnel for this. Since SSH is considered secure, outgoing connections to SSH servers are usually allowed, and an experiment system may thus connect to the RGS. However, even when this port is blocked, one can still create an SSH tunneling by selecting another port that is not being blocked by the firewall (e.g., HTTP port). The SSH tunneling has the drawback of decreasing the performance of the system. This is because the system wastes some bandwidth to wrap the communication for bypassing the firewall blocking. Different strategies are used to mitigate this problem, namely, SSH tunneling is only used if necessary, SSH tunneling is not used inside Intranets, the TightVNC implementation only sends modified screen fragments, finally, and the user has an option of setting up the transmitted screen resolution.

Fig. 2(a) is an example of a lab installation including an experiment computer with radio-communication circuit board attached. More basic configurations are also possible (e.g., no monitor, no webcam, and a simple experiment computer).

eComLab has passed several development and modification stages. The chosen tools and software (Java, Flash, and MySQL) provided operation envisioned at current stage. The reader is referred to [31] for in-depth analysis of software selection options for remote lab designs. Future versions eComLab may exploit other emerging development tools and environments such as HTML5 (http://www.w3.org/TR/html5/). It is necessitated by limited portability of Flash and Java, which can be addressed by HTML5. This is despite HTML5 is in fact a work in progress as some parts of its specification are drafts, some performance problems are reported, its encoding is browser specific and one can expect unknown security threats. Nevertheless, HTML5 will allow developers to ensure portability across many devices. Current version of eComLab is not available for mobile devices. Until known HTML5 issues will be addressed, support for mobile devices can be implemented using Object C for iOS and Android Java for Android devices.

The nature of shared VNC sessions allows for a simplified form of load balancing. Several VNC repeaters "duplicate" the VNC stream from the RGS, relieving some of the stress on the RGS itself. Instead of a direct connection to the RGS, clients connect to one of the repeaters for their VNC streams, as instructed by the RGS. Similarly, the read-only nature of the camera video stream allows it to be duplicated and distributed as well. Load balancing practices of Labview Sahara and WebLab-Deusto will be studied in future to improve scalability.

Even though eComLab does not support federated sharing of labs similar to iLab, WebLab-Deusto, and Labshare Sahara, it facilitates adoption of remote lab ecology by providing brokering services for lab providers for easier connectivity with reduced IT workload.

III. eComLab FUNCTIONALITY

A. General Description

The eComLab is a remote educational laboratory, which is specifically designed for electrical engineering students to perform hands-on experiments remotely over the Internet in radio communications. The main objective of eComLab is to provide students and instructors with a user friendly and multifunction remote interface to a state of the art educational lab environment. The following main features are supported.

1) Students and instructors access the remote labs using regular Web browsers. The only requirement is that the browser needs to have Flash and Java plug-ins.
2) The system can concurrently support multiple experiments and users.
3) New experiments can be connected directly to the central server, or the server can function as a Relay Gateway for remote experimentation centers (i.e., an experiment and controlling computer).
4) Third party remote experiments can be integrated with the eComLab with reduced efforts.
5) If more than one user wants to access the same experiment, the system will queue them.
6) Students can work in teams; the first user will have full control over the experiment, while the others will have an opportunity to watch the experiment without interfering with the main user. The users may pass experiment control to each other, communicate using the chat function, and monitor the hardware through real-time video during each experiment session.
7) The instructors can remotely manage the system through the Web browser and join or monitor experiments at any time.
8) The system gives the instructor the opportunity to modify the experiment specifications such as the experiment duration and maximum user number.

B. GUI Description

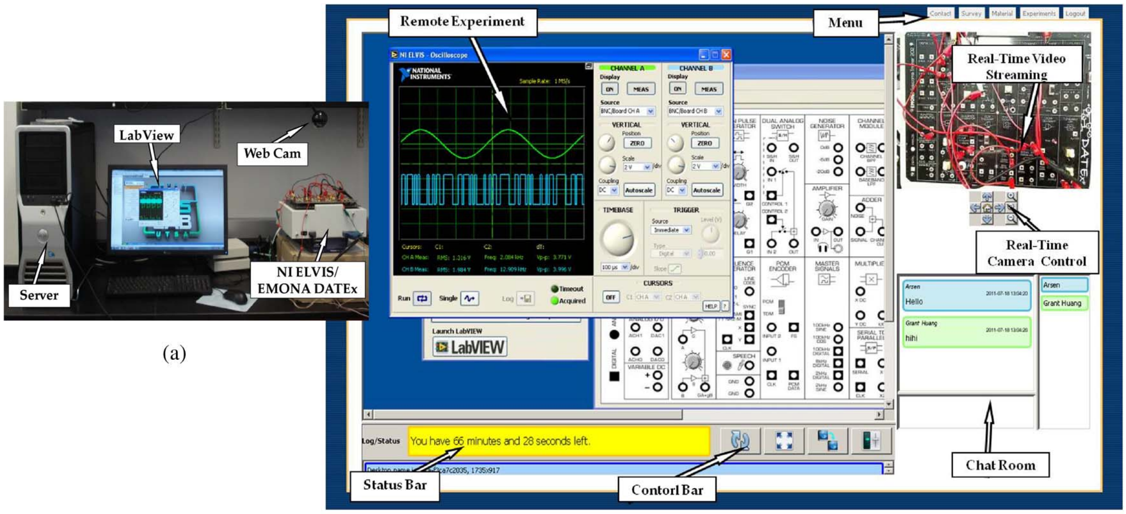
Instructors and students have different roles in the system and see different GUIs. Their work areas are coded in PHP with a MySQL database.

In eComLab the remote desktop applet uses a modified version of the open source Tight VNC (www.tightvnc.com/), and the video streaming client is based on a modified Red 5 client player version written in Flash (http://osflash.org/red5/).

Once a student logs into the eComLab system, he/she accesses a page having three areas. The main area is the experiment list and flags indicating available and reserved experiments. With this, students can see the available experiments. Another useful area is a discussion board called the "wall", where students can post their questions or comments.

Once the user selects the preferred experiment, he/she accesses the experiment screen shown in Fig. 2(b). It is composed of four parts: the remote desktop application, the real time video, the chat room, and the menu bar.

The remote desktop application is an applet that allows students remotely to control the experiment. This applet periodically communicates with the main central server to check which student has the right to control the experiment, how many users there are, and to update the user queue automatically. Note that the system allows only one student to have control over an experiment at a time; however, other students in the virtual experimentation room can observe. The status bar under the remote desktop application shows the remaining experiment time



(a) (b)

Fig. 2. (a) An example of eComLab system installation, (b) Student area, experiment screen.

for the main user, and the user position in the queue with the remaining time to gain experiment control for the other users. The control bar next to the status bar gives several additional useful functions to the user such as remote desktop transmission rate control and refresh, remote desktop full screen mode, and experiment control passing to another user. The control bar functions are the following.

- As for any remote laboratory, the fast access of the eComLab to the network is important to avoid delays impairing perception. As reported in literature [32], [33] the slow Internet connections may cause long delays. In our system, an approach to overcome bandwidth constraints is by using a resolution control function on control bar which varieties frame transmission rate, screen resolution and color map to suit users' needs. This is in addition to a compression implemented by TightVNC.
- As shown in Fig. 2(b), the experiment Web page contains several blocks such as a chat and video area, which limits the remote desktop operating area. The small remote desktop confines the user operating area, which was reported by users to be sometimes inconvenient. The full screen function button was designed for enhanced visibility if needed.
- The experiment control passing function provides students teamwork capability if it is authorized by the instructor. Each group is also assigned by the instructor. Two modes are implemented. In the first mode one student is the main user and the other students watch, all from the same group. Another mode is based on passing control between the user within the group. The main user is in charge of the experiment, and during the session, he/she can pass the experiment control to one of the users by selecting a user name from the group member list. After passing the control, the main user becomes an observer.

The significance of perceived "reality" affects students' willingness to accept the experimental results [10], [34]. That is why the real time video area in the experiment screen is a flash video allowing real-time observation of the experimentation hardware. Users can change the camera angle, zoom in, or zoom out, which helps them to change the transmitted video source and obtain detailed image information from a specific part of the hardware. Live stream video is optional, which can be turned Off/On by administrator or instructor. For eComLab the video is used to show the connections on the boards. In addition, there might be other experiments in future which will involve moving components such as wirelessly controlled moving mechanisms. The camera is also used for special training sessions, when instructors explain board wire connectivity for experiments during live broadcasts. Feedbacks from participating students indicate that the cameras indeed provide richer sense of reality.

Finally, the chat room area in the experiment screen is an applet that allows all users in the virtual experimentation room to communicate with each other in real-time through comments or suggestions.

The instructor also accesses the system through a Web browser. The instructor's GUI has been designed to manage the eComLab remotely. The instructor can manage the student list, experiments, academic materials, surveys, and monitor usage statistics. Additionally, the instructor can join any experimentation group when needed and assist group members or monitor the experiment process.

The new experiments are easily connected to eComLab RGS system through an "Add New Experiment" five-step wizard from the administrator web page.

Step 1) The wizard guides the instructor through the necessary software (VNC server, Java, and Camera control) installation process.

Step 2) The instructor adds new experiment name, maximum users number per experiment session, experiment session duration, and group type, which defines the users' collaboration level.

Step 3) This step handles the network issues such as IP and available port number for VNC server detection and configuration.

Step 4) This step helps instructor to configure and add real time web camera to the experiment if needed.

Step 5) In this final step instructor confirms all the settings and connects the new experiment to eComLab RGS architecture.

IV. User Experiences

The eComLab has been used in radio communication courses at the ECE Department of the University of Texas at San Antonio since 2008. From then on, remote laboratory units have been offered to both undergraduate and graduate students. Students had to complete two conventional hands-on labs to get familiar with experimentation units then conduct two remote experiments through the eComLab. Students can work in a group or alone.

Experiments are conducted using three identical bundled NI ELVIS (http://www.ni.com/) and EMONA DATEx boards. Different from net∗TIMS DATEx (http://tims.com.au/) can be used for both hands-on and remote experimentation needs. Students spent, on average, 45 minutes to complete each experiment. They were divided into groups to share the limited number of hardware and for testing group-work feature. During the remote experimentation phase, all three units were connected to the eComLab's experimentation computers. All the connections on the EMONA DATEx board were connected to the Agilent (http://www.home.agilent.com/) U2751A 4 × 8 USB Modular Switch Matrix [26], which provides an opportunity to remotely change the physical connectivity on the DATEx board as required by a selected experiment. The control software for the EMONA DATEx, NI ELVIS, and Agilent switch are installed on each experimentation computer.

Undergraduate and graduate students were surveyed to assess their perception of remote labs. Additionally, 12 high school lecturers also were offered remote labs and have been asked to provide feedback. The trustworthy surveys with reliability coefficients (Cronbach's Alpha > 0.7) based on Likert scale have been used to assess acceptance, usability, and usefulness of the eComLab following similar practice in [6], [35]–[38]. The survey questions were divided into three category sets; acceptance, usability, and usefulness. Assessment metrics are based on five-level Likert grading scale, from "Strongly Disagree" to "Strongly Agree" answer options.

Table II shows survey results. Notation refers to undergraduate (U), graduates (G) students, and lecturers (L). The minimum score is one (1) and the maximum score is five (5). While Likert scale based methodology is common, the authors of [39] question statistical applicability of Likert scales in such scenarios. That is why, in addition to Likert scale data, Tables III–V characterize user perceptions in question-answer format for selected questions.

The mean scores (on Likert scale) of the questions in "Acceptance" category for three different type of users are $M = 4.83$ (L), $M = 3.86$(U), and $M = 3.91$(G) (Table II). As Table III shows, almost all the users enjoyed working with the eComLab experiments (91%). They found that the eComLab provides acceptable user experience. Most of the users thought that they were in control of the experiment (67%), and the eComLab provides an acceptable sense of reality (68%).

TABLE II
Summarized Survey Results

Categories	Questions	User Type	N	Alpha	M	SD
	4	U	17	0.88	3.86	1.17
Acceptance	4	G	24	0.92	3.91	1.09
	5	L	12	0.99	4.83	0.37
	4	U	17	0.72	3.83	0.96
Usability	4	G	24	0.91	3.81	1.07
	5	L	12	0.98	4.68	0.58
	5	U	17	0.94	3.82	1.01
Usefulness	5	G	24	0.94	3.82	0.97
	5	L	12	0.98	4.71	0.61

Questions: Number of questions in survey categories.
U: Undergraduate students.
G: Graduate students.
L: Lecturers.
N: Number of users.
Alpha: Cronbach's Alpha reliability parameter.
M: Mean value, Min=1 and Max=5.
SD: Standard deviation.

TABLE III
Selected Survey Questions and Results From Acceptance Category

Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
Q1. I enjoyed using remote eComLab.				
4%	0%	5%	37%	54%
Q2. Even though I worked remotely, I have felt myself to be in control of the experiment.				
8%	4%	21%	50%	17%
Q3. The eComLab potentially conveys an impression of conducting physical experiment.				
4%	12%	16%	46%	22%

The positive feedbacks are also observed in the "Usability" category (Likert scale: $M = 4.68$(L), $M = 3.83$(U) and $M = 3.81$(G)). In addition, Table IV shows that almost all the users strongly agreed that the eComLab provides flexibility, in the sense of time and location, to perform experiments (90%). The eComLab provides a friendly and easy to use interface (88%) with several handy tools, which enable group work during experiments (80%). Finally, almost all the users found that the functionality of the eComLab was satisfactory.

In "Usefulness" category (Likert scale) $M = 4.71$(L), $M = 3.82$(U) and $M = 3.82$(G). As Table V further elaborates, the eComLab helped students to better understand the topics in communication (86%). It motivated the students to learn more and helped them to better understand the subject (59%).

TABLE IV
SELECTED SURVEY QUESTIONS AND RESULTS FROM USABILITY CATEGORY

Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
Q1. The eComLab provides flexibility (Time and Location) to perform experiments.				
4%	4%	2%	34%	56%
Q2. The eComLab has a proper interface (Chat and Control Passing Function) to enable group work.				
8%	0%	4%	58%	30%
Q3. The remote lab user interface is friendly and easy to use.				
0%	8%	12%	54%	26%

TABLE V
SELECTED SURVEY QUESTIONS AND RESULTS FROM USEFULNESS CATEGORY

Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
Q1. The eComLab experiments helped me to understand the subject.				
8%	0%	6%	67%	19%
Q2. The eComLab generally motivates to learn more about the subject.				
4%	8%	29%	50%	9%

One can see that overall perception assessments are positive. The eComLab can also record longitudinal student activity, i.e., intensity of student accesses can be assessed during the day. In fact, quite uniform access time distribution confirms the advantage of remote experimentation; students were able to conduct the labs at suitable times for them as evidenced by continuous access.

V. CONCLUSION

This paper presented a novel remote laboratory Relay Gateway Server (RGS) architecture, which further facilitates the connectivity of remote students, instructors, and experiments. The proposed eComLab system employs a hybrid architecture integrating RGS and known experiment-server-centric concept. Several state-of-the-art features are included such as teamwork capability, bandwidth control, secure access, multiple user support, queues, real-time video observation, chatting, and writing wall windows. Users conveniently access remote labs using Web browsers exploiting widely used Java and Flash software. Current version of the system does not support mobile clients. But the system continuously evolves to improve user experience, and more features and software support will be included following best reported practices. It has been deployed and offered to undergraduate and graduate students. Their feedback confirms acceptance of remote experimentation as an alternative to conventional hands-on labs.

REFERENCES

[1] L. Gomes and S. Bogosyan, "Current trends in remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4744–4756, Dec. 2009.

[2] J. Ma and J. V. Nickerson, "Hands-on, simulated, remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, no. 3, art. no. 7, pp. 1–24, 2006.

[3] L. Gomes and J. Garcia-Zubia, *Advances on Remote Laboratories and E-Learning Experience*. Bilbao, Spain: Univ. Deusto, 2007.

[4] J. Garcia-Zubia and G. R. Alves, Eds., *Using Remote Labs in Education*. Bilbao, Spain: Univ. Deusto, 2011.

[5] A. K. M. Azad, M. E. Auer, and V. J. Harward, *Internet Accessible Remote Laboratories: Scalable E-Learning Tools for Engineering and Science Disciplines*. Hershey, PA, USA: IGI Global, Nov. 4, 2012.

[6] I. Gustavsson, K. Nilsson, J. Zackrisson, J. G. Zubia, U. H. Jayo, A. Nafalski, Z. Nedic, Ö. Föl, J. Machotka, M. I. Pettersson, T. Lagö, and L. Håkansson, "On objectives of instructional laboratories, individual assessment, use of collaborative remote laboratories," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 263–274, Oct.–Dec. 2009.

[7] V. J. Harward, J. A. DelAlamo, S. R. Lerman, P. H. Bailey, J. Carpenter, K. DeLong, C. Felknor, J. Hardison, B. Harrison, I. Jabbur, P. D. Long, T. Mao, L. Naamani, J. Northridge, M. Schulz, D. Talavera, C. Varadharajan, S. Wang, K. Yehia, R. Zbib, and D. Zych, "The iLab shared architecture: A web services infrastructure to build communities of internet accessible laboratories," *Proc. IEEE*, vol. 96, no. 6, pp. 931–950, Jun. 2008.

[8] P. Orduna, J. Irurzun, L. Rodriguez-Gil, J. Garcia-Zubia, F. Gazzola, and D. Lopez-de-Ipina, "Adding new features to new and existing remote experiments through their integration in WebLab-Deusto," *Int. J. Online Eng.*, vol. 7, no. S2, pp. 33–39, 2011.

[9] D. Lowe, T. Machet, and T. Kostulski, "UTS remote labs, labshare, Sahara architecture," in *Using Remote Labs in Education*, J. Garcia-Zubia and G. R. Alves, Eds. Bilbao, Spain: Univ. Deusto, 2011, pp. 403–424.

[10] D. Lowe, S. Murray, E. Lindsay, and D. Liu, "Evolving remote laboratory architectures to leverage emerging internet technologies," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 289–294, Oct.–Dec. 2009.

[11] B. Hanson, P. Cumer, J. Gallagher, K. Page, E. Read, A. Weightnam, and M. Levesley, "ReLOAD: Real laboratories operated at a distance," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 331–341, Oct.–Dec. 2009.

[12] H. Shen, Z. Xu, B. Balager, V. Kritiansen, O. Stream, M. S. Shur, T. A. Fjeldly, J. Q. Lu, and T. Ytterdal, "Conducting laboratory experiments over the internet," *IEEE Trans. Educ.*, vol. 45, no. 3, pp. 180–185, Aug. 1999.

[13] N. Lehlou, N. Buyurgan, and J. R. Chimka, "An online RFID laboratory learning environment," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 295–303, Oct.–Dec. 2009.

[14] V. Mateos, A. Gallardo, T. Richter, L. Bellido, P. Debicki, and V. Villagra, "LiLa booking system: Architecture and conceptual model of a rig booking system for on-line laboratories," *Int. J. Online Eng.*, vol. 7, no. 4, pp. 26–35, 2012.

[15] J. Machotka, Z. Nedic, and Ö. Göl, "Collaborative learning in the remote laboratory NetLab," *J. Syst. Cybern. Inf.*, vol. 6, no. 3, pp. 22–27, 2008.

[16] V. Y. Tagawa, "Network training system with a remote, shared classroom laboratory," U.S. Patent 7 016 949, Mar. 21, 2006.

[17] C. A. Price, K. Stover, T. Suplica, C. Bray, M. Rygaard, and B. Tsao, "System and method for remotely configuring testing laboratories," U.S. Patent 2002/0 032 762, Nov. 7, 2006.

[18] C. I. Chen, "Design of measurement system based on signal reconstruction for analysis and protection of distributed generations," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1652–1658, Apr. 2013.

[19] A. Yazidi, H. Henao, G. A. Capolino, F. Betin, and F. Filippetti, "A web-based remote laboratory for monitoring and diagnosis of AC electrical machines," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4950–4959, Oct. 2011.

[20] P. Orduna, E. Sancristobal, M. Emaldi, M. Castro, D. Lopez-de-Ipina, and J. Garcia-Zubia, "Sharing the remote laboratories among different institutions: A practical case," in *Proc. 9th Remote Eng. Virtual Instrum. Int. Conf.*, Bilbao, Spain, Jul. 2012, pp. 1–4.

[21] D. Lowe, C. Berry, and S. Murray, "Adapting a remote laboratory architecture to support collaboration and supervision," *Int. J. Online Eng.*, vol. 5, no. S1, pp. 51–56, 2009.

[22] D. Lowe, C. Berry, and S. Murray, "Adapting a remote laboratory architecture to support collaboration and supervision," in *Proc. REV*, 2009, pp. 103–108.

[23] L. Yong and O. J. Anshus, "Improving the performance of VNC for high-resolution display walls," in *Proc. CTS*, 2009, pp. 376–383.

[24] N. Swamy, O. Kuljaca, and F. L. Lewis, "Internet-based educational control systems lab using NetMeeting," *IEEE Trans. Educ.*, vol. 45, no. 2, pp. 145–151, May 2002.

[25] M. Tawfik, E. Sancristobal, S. Martin, C. Gil, A. Pesquera, S. Ros, R. Pastor, R. Hernandez, G. Diaz, J. Peire, and M. Castro, "Towards a better deployment of remote laboratories in undergraduate engineering education," in *Advances on Remote Laboratories and E-Learning Experiences*. Bilbao, Spain: Univ. Deusto, 2007, pp. 388–402.

[26] R. Oros, V. Jinga, M. Alexandru, and D. Ursutiu, New Technologies in Telecommunication Laboratories, (Accessed Jan 10, 2013). [Online]. Available: https://decibel.ni.com/content/docs/DOC-3739

[27] K. E. Holbert and M. M. Albu, "A signal processing laboratory employing on-line teaming for remote experiments," in *Proc. ASEE Annu. Conf. Expo.*, Nashville, TN, USA, 2003, Session 2359.

[28] M. Cooper and J. M. M. Ferreira, "Remote laboratories extending access to science and engineering curricular," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 342–353, Oct.–Dec. 2009.

[29] A. Melkonyan, D. Akopian, and C. L. Chen, "Real-time remote internet-based communication laboratory," in *Proc. 39th ASEE/IEEE Front. Edu. Conf.*, San Antonio, TX, USA, Oct. 2009, pp. 1–6.

[30] A. Melkonyan, M. Pontual, G. Huang, A. Gampe, and D. Akopian, "eComLab: Remote laboratory architecture for radio-communication," in *Proc. ASEE Gulf-Southwest Annu. Conf.*, Houston, TX, USA, Mar. 2011.

[31] J. Garcia-Zubia, "Addressing software impact in the design of remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4757–4767, Dec. 2009.

[32] M. A. Bochicchio and A. Longo, "Hands-on remote labs: Collaborative web laboratories as a case study for IT engineering classes," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 320–330, Oct.–Dec. 2009.

[33] A. Mittal, C. Gupta, and A. Gupta, "Addressing the bandwidth efficiency, control, evaluation issues in software remote laboratory," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2326–2333, Jun. 2008.

[34] J. E. Corter, J. V. Nickerson, S. K. Esche, and C. Chassapis, "Remote versus hands-on labs: A comparative study," in *Proc. 34th ASEE/IEEE FIE Conf.*, Savannah, GA, USA, Oct. 20–23, 2004, pp. 17–21, Session F1G.

[35] G. R. Alves, M. A. Marques, M. C. Viegas, M. C. Costa-Lobo, R. G. Barral, R. J. Couto, F. L. Jacob, C. A. Ramos, G. M. Vilao, D. S. Covita, J. A. Alves, P. S. Guimaraes, and I. Gustavsson, "Using VISIR in a large undergraduate course: Preliminary assessment results," *Int. J. Eng. Pedag.*, vol. 1, no. 1, pp. 12–19, 2011.

[36] D. Lang, C. Mengelkamp, R. S. Jäger, D. Geoffroy, M. Billaud, and T. Zimmer, "Pedagogical evaluation of remote laboratories in eMerge project," *Eur. J. Eng. Edu.*, vol. 32, no. 1, pp. 57–72, Mar. 2007.

[37] N. Lewis, M. Billaud, D. Geoffroy, P. Cazenave, O. Stream, and T. Zimmer, "A distance measurement platform dedicated to electrical engineering," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 312–319, Oct.–Dec. 2009.

[38] J. Garcia-Zurba, P. Orduna, I. Angulo, U. Hernandez O. Dziabenko, D. Lopez-de-Ipina, and L. Rodriguez-Gil, "Application and user perceptions of using the WebLab-Deusto-PLD in technical education," in *Proc. 41th ASEE/IEEE Front. Edu. Conf.*, Rapid City, SD, USA, Oct. 2011, pp. 1–6.

[39] S. Jamieson (2004, Dec.). Likert scales: How to (Ab)use them. *Med. Educ.* [Online]. *38(12)*, pp. 1217–1218. Available: http://mahenry.sumnermckenzie.com/pdf/1LikertScales.pdf

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