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A review of contemporary virtual and remote laboratory implementations: observations and findings

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Abstract Many studies have shown that laboratory activities increase students' achievements and interest in the subject matters and further help their learning, especially in disciplines such as sciences, engineering, computing and others. Advances in technologies and communication networks have created the possibility to develop virtual and remote labs providing new opportunities for both on-campus and remote students circumventing certain limitations of physical laboratories. In this paper, we review contemporary remote and virtual laboratory implementations in different disciplines. Our review and analysis uncover a number of interesting observations, findings and insights into virtual and remote laboratory implementations. Virtual and remote laboratories provide a number of advantages such as remote 24 × 7 access, flexibility and freedom to learn at one's own pace and reset/retrial experiments without wasting resources in a safe environment and provide new opportunities for learning. We observe that these labs when incorporated with sound pedagogical framework, learner support, content and tutor interaction result in higher learning outcomes and richer learning experience. Future work will evolve to implement innovative labs in different education contexts taking advantage of technological advances. Collaboration, catering to different learner personalities, impact of learning outcomes, pedagogical frameworks for virtual and remote labs are areas for further investigation.

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Introduction

Laboratory work is fundamental to learning in scientific and applied fields such as computer science, engineering, natural sciences and others (Lustigova and Novotna 2013; Ma and Nickerson 2006; De Jong et al. 2013). Tuysuz (2010) noted that laboratory activities increase students' achievements and interest in the subject matter covered in the class and help their learning. Web-based learning environments and technologies provide many opportunities to education. These systems bring several advantages to enhance learning experience for both on-campus and distance learning students (Mason 2013). In addition, they allow universities and other higher learning institutions to develop new teaching methodologies and increase collaboration among students and instructors. Online learning tools are now implemented in various universities, schools and classrooms (Elawady and Tolba 2009; Paechter et al. 2010). There has been significant interest and research on developing technologies for laboratories. Many different types of laboratories—virtual and remote labs—have been implemented. With the growth of online and distance learning, these laboratories offer unique opportunities for students (Alam et al. 2014; Tuysuz 2010). For example, distance students are able to apply the knowledge they gained and carry out experiments in a similar fashion to on-campus students, without the need to be physically located in the laboratory. As a result, these students are able to achieve a higher level of learning than otherwise possible. We also find that these laboratories not only cater to distance learning, but also provide new opportunities and flexibility for teachers and learners on-campus.

Virtual and remote laboratories have recently gained momentum in research due to the advances in technology and network communications. In the literature, we find many terms used to describe virtual and remote laboratories such as web-based labs, online labs, remote labs, cloud labs and many others. In general, we can classify three categories of labs:

- *Physical Lab* This is the traditional lab environment where students are physically in the laboratory to conduct experiments. This type of lab is also termed hands-on lab in the literature.
- *Remote Lab* A remote lab is defined when the experiment(s) are located physically away from the experimenter. The experiment is conducted in a physical lab, which is connected to the learner(s) remotely via the network. For example, students may connect remotely to move robots in a laboratory to conduct an experiment.
- *Virtual Lab* In a virtual lab, programs simulate laboratory environments whereby students can access and conduct experiments in a virtual space. This lab is also termed simulated lab.

A number of research initiatives have been undertaken in various disciplines demonstrating how these laboratories could work in their respective disciplinary area. Research work also has also focused on evaluating the effectiveness of physical laboratories compared to virtual laboratories. Certain empirical studies report no differences in student performance between physical and virtual laboratories [e.g., (Wiesner and Lan 2004; Klahr et al. 2007; Zacharia and Constantinou 2008)]. In other studies [e.g., (Finkelstein et al. 2005; Olympiou and Zacharia 2012)], virtual laboratories are shown to be advantageous than physical laboratories in acquiring conceptual knowledge. In Zacharia et al. (2012), young children (ages 5–6) who had incorrect prior knowledge of balancing beam are advantaged by learning in a physical lab environment. Further studies have shown that students who have exposure to both physical and virtual laboratories outperform students who only conduct experiments in physical labs (Zacharia et al. 2008; Kollöffel and Jong 2013). With the advent of technological advances and network communications, virtual and remote laboratories are implemented in many different disciplines. This necessitates further research into these contemporary implementations and draws on lessons learned. Thus, we pose the following research questions which we aim to address in this review: (a) What are the contemporary remote and virtual laboratory implementations in different disciplines? (b) What are the observations, findings and lessons learned through such laboratory implementations? In this paper, we review a number of contemporary virtual and remote laboratory implementations in different disciplines. Furthermore, our analysis draws observations, findings as well as challenges and potential areas for future research in this burgeoning field.

This paper is organized as follows: The methodology used in reviewing the literature is described in "Methodology used for review" section. "Virtual and remote laboratories in different disciplines" section presents the contemporary work on virtual and remote laboratory implementations in different disciplinary areas. "Other related work in virtual and remote laboratories" section discusses other related work in virtual laboratories, in particular its impact on various issues such as the collaboration and sharing, and learning management system. "Observations and findings" section discusses our observations and findings from the review. "Conclusion" section concludes the paper with a discussion of future research directions.

Methodology used for review

The objective of this paper is to review a number of contemporary virtual and remote laboratory implementations. Research databases such as IEEE Xplore (http://ieeexplore.ieee.org/Xplore/home.jsp), ACM Digital Library (http://dl.acm.org/) and ScienceDirect (http://www.sciencedirect.com/) were used as the main sources in obtaining relevant articles.

Firstly, our focus was to select contemporary implementations of virtual and remote laboratories. Thus, we constrained our search to publications since 2005. Searches based on the following keywords were considered "virtual lab," "remote lab," "cloud lab," "simulation lab" and "online lab" resulting in (IEEE Xplore = 485; ACM = 73; ScienceDirect = 326) articles. Secondly, we scanned through the abstract and title to select relevant articles for further analysis. Specifically, we focused on innovative virtual and remote lab implementations in different disciplines to explore current trends and evaluate how these studies contribute to answer the research questions posed. Articles were shortlisted for further consideration if: (a) The articles discussed design of contemporary virtual or remote lab implementations in different disciplines; (b) the articles considered issues related to virtual and remote lab implementations; and/or (c) the articles focus on evaluations of virtual and remote lab implementations. Studies that did not directly contribute to the review were excluded. This analysis narrowed down to 11 ($n = 11$) articles to review. Table 1 outlines the selected articles listed according to subject, purpose, lab technology, data collection method and results.

Virtual and remote laboratories in different disciplines

In the literature, we can find innovative virtual and remote laboratory implementations in diverse disciplines. Below, we outline contemporary implementations from robotics to biology, chemistry, physics and computing. These studies provide a cross section of contemporary virtual and remote laboratory implementations in diverse disciplines.

Virtual and remote laboratories for programming robots

In Chaos et al. (2013), the authors describe both virtual and remote laboratories developed for the Autonomous Robots subject in the Master of Systems Engineering and Automatic Control program at the Spanish National University for Distance Education (UNED) and at the Complutense University of Madrid (UCM). These laboratories were set up for distant and online education. Students are given access to control the robot both manually and/or through programmed interfaces. The difference is students interact using a simulated environment in the virtual laboratory, while they interact with a real robot in the remote laboratory. A number of sensors are incorporated to the robot that allows students to program based on the sensor readings. Students are first given access to the virtual laboratory environment to attempt their tasks, and once a mastery of the interface and programming is achieved, access is given to the real robot environment through the remote laboratory. Although the interface is the same in terms of manipulating the robot in a simulated environment, manipulating the robot in the real world has additional complexities. For example, the motor may suffer from nonlinear effects, such as saturation on acceleration and dead zones; sensors may be affected by noise and outliers in measurements, delays and failures in communication. Students are given a time slot to test their solutions in the remote laboratory, and it is moderated by lab assistants who are able to solve issues (such as collisions, mechanical failures) that cannot be remotely addressed by the students. The hands-on real-world experience

Table 1 Virtual and remote lab implementations in different disciplines

Subject	Papers	Sample size	Lab technology	Description
Engineering	Chaos et al. (2013)	$N = 30$	LabVIEW MATLAB Easy Java Simulations	Both virtual and remote laboratories are effectively used to provide a flexible, safe and easily accessible environment for students to develop their skills prior to applying them in a real robot via remote laboratories
	Marques et al. (2014)	$N = 1272$	VISIR	VISIR remote labs are popularly used in engineering. This study aims to find out what factors impact integration of VISIR labs to courses. It found out that instructional support for VISIR is crucial
Sciences	Hossain et al. (2015)—biology	$N = 4$	BPU	This is a remote biology laboratory providing convenience by allowing students to remain engaged with their experiments from any place at any time. Also, a log provides data that can be used in learning analytics to provide useful insights
	Ding and Fang (2009)—physics	$N = 64$	C++ Builder	Students are provided with a simulation environment to explore topics in diffraction and reflection of light. Both research skills and exploratory learning are encouraged
	Woodfield et al. (2005)—chemistry	$N = 1400$	Java	A virtual chemistry lab (ChemLab) provides students the freedom to conduct chemistry experiments in an exploratory manner that is not practical possible in a physical lab. The authors observed that creative learners are more likely to explore and experiment in ChemLab simulations than structured learners because of their individual learning preferences
Information Technology (IT)	Joseph Prieto-Blazquez et al. (2009)—VPLab	$N = 284$	VCE, SIM, VM, AAT	VPLab proposes a general structure on virtual labs for undergraduate courses in computer programming language. It identifies several critical components required and evaluates students' views on different resources. An interesting finding is that teacher interactions are highly rated by distance learners along with technology artifacts

Table 1 continued

Subject	Papers	Sample size	Lab technology	Description
	Hwang et al. (2014)—NVBLab_	$N = 35$	Network virtualization-based lab	The paper in a networking class works on a number of network-based assignments from basic and advanced labs with individually as well as group based. Group-based advanced labs with communication between tutors and peers have statistically significant impact on learning outcomes
	Razvan et al. (2012)	$N = 260$	VMWare/NetLab+	Using cloud computing in network course labs to implement and test complex networking and security scenarios. The students believe that they have had their study experience enhanced by the proposed virtual infrastructure
	Alharbie et al. (2012)	$N = 33$	VMWare	Using a private cloud and a VMware virtualization platform to design virtual machines that can emulate computer labs which are accessible from anywhere. The aim of the experiments is to analyze students' satisfaction with virtual computing labs
STEM	Achuthan et al. (2011)	Not stated	Web technologies	The aim of this project is provide lab experience to experiment in virtual and remote labs settings provided through a web interface for students who are unable to access physical labs. Each experiment is developed with Theory, Procedure, Self-Evaluation, Simulator, Assignment, Reference and Feedback to provide pedagogical framework and context for each experiment. Faculty of many institutions in India showed high satisfaction with the proposed labs
	De Jong et al. (2014)	$N = 0$	Web technologies	The Go-Lab project aims to provide an engaging and motivating environment for students to experiment through online labs using inquiry-based learning pedagogical approach. Go-Lab aims to trial in over 1000 schools across Europe in the near future

provides a rich source of knowledge to enhance the learning process of students that must deal with practical problems usually neglected in theory.

The virtual and remote laboratories have been operating in the program for 2 years. They are proven to be extremely useful for teaching the role that sensors play on robotics. Student satisfaction survey has shown that they either agree or completely agree with the fact that these laboratories are necessary for a complete understanding of robotic sensors.

In Chaos et al. (2013), it is shown that both virtual laboratories and remote laboratories are effective and useful. Virtual laboratories provide a safe, easily accessible environment for students to master their skills prior to applying them in a real-world environment via remote laboratories. Also, by applying in a real-world environment, students are exposed to complexities of real-life situations which are hard to emulate in virtual environments and typically ignored in theory. The following statement by the authors states this fact: "Using the virtual laboratory like the remote one has been a success: students can get confidence in their work before testing in the real robot and they can make a first debug of the code before testing it in the real robot; 74 % of the students feel more comfortable if they can use the virtual laboratory before connecting with the real robot." Overall, this paper has successfully integrated both virtual and remote laboratories in a robotics subject providing a rich learning experience for students.

A remote lab in biology

Hossain et al. (2015) present an architecture and implementation for a remote laboratory in biology. A specific set of experiments based on *P. polycephalum* which is a single-celled, multi-nuclei and cytoplasmic organism were conducted. Initially, a system administrator would start an experimental session by preparing Petri dishes that are inoculated by *P. polycephalum* at the center unless a special initial condition was specified by a student ahead of time. Students are notified with access keys once all experiments are loaded. A student then accesses experiments remotely using a web interface. This experimental session would last 2–3 days in which time there would be no further manual intervention. During this time, students are able to manipulate and investigate the states of their experiments through a web-based UI at any time and place without having to book a time slot. All experimental data are archived when the session expires and students are able to investigate these later at any time using the same UI. Students also can share their experiments and data with others.

The remote laboratory is used in a graduate biophysics course. Four students conducted 11 online experimentation sessions. Students' activities are logged as well as three one-on-one interviews were conducted in weeks 2, 5 and 10. Both student activity and feedback were analyzed. Student feedback indicated this platform lowered the threshold of entry to biology experimentation in three ways: It empowered non-biologists to perform real experiments without concerns about wet-lab training and safety. The system abstracted away all of the wet-lab details and allowed the students to concentrate on experimental strategies and data analysis. The system provided convenience by allowing students to remain engaged with their experiments from any place at any time. Also, the log provides data that can be used in learning analytics to provide useful insights.

This proposed platform considers development of innovative biotic processing unit (BPU) to handle specific types of experiments and automation in biology. The current implementation is proof of concept for a particular type of experiments in biology. This paper demonstrates the benefits of such a remote laboratory.

The virtual chemistry lab (ChemLab)

In this study, Woodfield et al. (2004, 2005) discuss the Virtual ChemLab project, which is a simulated lab that allows students to simulate chemistry experiments in a number of ways. Virtual ChemLab simulation does not replace physical wet labs where students learn the "how" in conducting a chemistry experiment (such as cleaning test tubes, setting up experiments). Rather, the goals of each Virtual ChemLab simulation are to provide students with an intuitive, safe, open-ended unrestricted simulation environment similar to a hands-on experiment, where they can create experiments, test and view their results. The general features of a ChemLab simulation include 26 cations that can be added to test tubes in any combination; 11 reagents that can be added to the test tubes in any sequence and any number of times; necessary laboratory manipulations including centrifugation, flame tests, decanting, heating, pH measurements and stirring; a lab book for recording results and observations; and a stockroom window for creating test tubes with known mixtures, generating practice unknowns or retrieving instructor-assigned unknowns. The simulation uses over 2500 actual pictures to show the results of reactions and over 220 videos to show the different flame tests. ChemLab provides a truly exploratory open-ended experiment framework with 26 cations that can be combined in any order or combination and 11 reagents that can be added in any order, creating in excess of 10^{16} possible outcomes in the simulation.

A team evaluated the ChemLab's Inorganic Qualitative Analysis simulation using online surveys sent to over 1400 students enrolled in freshmen-level chemistry courses between January 2001 and April 2002 at Brigham Young University (BYU). Surveys consisted of Likert-type questions and free response questions. Additionally, interviews and observations of students were conducted. Data were analyzed through descriptive statistics and several analyses of variance (ANOVAs) and linear regressions. The most interesting observations and findings occurred when student opinion and performances are correlated with each student's personality profile. The personality profile of each student is determined by Herrmann Brain Dominance Instrument (HBDI).

The authors found that creative learners (higher cerebral score) are more likely to explore and experiment ChemLab simulations compared to structured learners (higher limbic score) not necessarily because they are incapable, but because of their individual learning preferences. The study also found out that students who are structured in their thinking and precise (left-brained preferences) are more satisfied with the simulation than the students who are intuitive, nonlinear and experientially oriented (right-brained preferences). Perhaps the largest educational benefit of the inorganic simulation is that students can focus on the principles of general chemistry, rather than focusing on troubleshooting aspects in a wet-laboratory setting. This does not mean that wet labs are un-important as skills on “how” to conduct a real experiment are important and use of ChemLab simulation in conjunction with wet labs provides the best learning experience. Students like the fact that they can repeat, trial and error, in a safe, convenient and flexible manner that was not practical in a wet lab.

A virtual laboratory for physics

In this paper, Ding and Fang (2009) investigate the effectiveness of a simulation laboratory on teaching and learning of physics concepts. Students usually have a set of opinions about physical phenomena derived from their everyday experience. However, these assumptions are normally incorrect and create misconceptions. To address these misconceptions, the authors aimed to produce an alternative constructivist teaching approach that could facilitate active engagement in learning and effectively allow students to apply physics concepts and principles in various situations. The authors created a simulation laboratory using C++ Builder. The laboratory was able to simulate the diffraction and reflection of light and allow students to configure parameters for experiments and observe the rules of physics. In addition, its powerful displaying environment allows an understanding of physical concepts and an analysis of scientific knowledge. Hence, it promotes a better understanding of physical models.

In this study, 64 college students at Hubei University were selected to undertake the experiment. Data were collected through interviews with six students of the experimental group and 32 anonymous written testimonies of this same group. The result of the study shows that this method indeed improves research skill and capacity for exploration by the experimental group. The findings suggest that simulation laboratories have potential to improve teaching and learning physical processes and encourage students in physics to engage in exploratory learning.

A virtual computing lab

In this paper Alharbie et al. (2012), the authors provide a virtual computer lab for students in an IT undergraduate course. The virtual computer is provided to each student as a pre-configured virtual machine that is hosted on a private cloud environment. Students access a virtualized desktop that has a look and feel of accessing a local machine. A pilot study was conducted to evaluate the feedback of students about the virtual computing lab in a course consisting of laboratory-based individual tutorials and assignments, which include group work. The authors conducted a survey of 33 students to evaluate their satisfaction and experience. The survey was divided into four sections: (1) the assistance in learning; (2) accessibility and ease of use; (3) virtual lab versus physical labs; and (4) overall experience. Students were highly positive with the flexibility, accessibility and ease of use of virtual computing labs from any location and at any time without needing to install and configure software for use in their tutorials and assignments. It was clear that students when working individually preferred to use the virtual computing labs;

however, when they needed to meet group members, tutor interactions and social purposes, they preferred to come to physical labs. Giving access to virtual computing labs while also having regular physical labs for tutor and group interaction provided the best learning experience in this study. Other large-scale virtual computing lab deployments mentioned in the paper include (Schaffer et al. 2009).

VISIR remote labs in engineering

Marques et al. (2014) present a study on the implementation of Virtual Instrument Systems In Reality (VISIR) remote labs in a range of engineering courses; in particular, they focus on the impact of such labs in achieving learning outcomes. VISIR (Tawfik et al. 2013) developed by Blekinge Institute of Technology, Sweden, provides a flexible environment to construct and test different electrical and electronic circuits. It is been widely used to create remote laboratories. The authors examine VISIR implementation against various aspects, such as achievements of learning objectives, its implementation and user access, student academic results and teachers and students perceptions. The authors use a multi-case research study methodology, with each case representing a different course where VISIR was integrated. The study was carried out during two successive semesters in 2010 and 2011 covering seven courses, i.e., with one course in the first semester and the rest six courses in the second semester. These courses were drawn from various engineering degrees representing various student educational backgrounds. Two dimensions were used to analyze the results: didactical approach and results obtained. The former looks into learning outcomes, integration design, teacher supervision and implementation problems, while the latter looks into the actual use of VISIR, teachers' and students' perceptions of usefulness and student learning achievements. The paper answers the research question—"Is VISIR always useful, no matter how it is integrated into a course? Or are there certain conditions/characteristics that maximize student learning?" through analysis in a multi-case research study. The authors found that instructional support for VISIR is crucial. VISIR can always be useful to some students (those more motivated or with a learning style more adequate to this kind of tool), but it can be reinforced when particular conditions are put in place: (1) Students have a hands-on practice session before they start to use VISIR; (2) VISIR is more useful in introductory courses; (3) in terms of learning outcomes, VISIR labs increase student confidence in labs, with students who used VISIR generally having improved lab reports, improved lab examination results, higher grade distributions, statistically significant correlations between VISIR accesses and the lab grade, and higher learning gains. VISIR is a good choice when combined with a hands-on lab since it diversifies students' ways of learning and enables them to practice freely, increasing their confidence in the lab and enhancing their lab skills.

VPLab: a virtual programming laboratory

Prieto-Blazquez et al. (2009) mainly focuses on designing the virtual programming laboratory, termed as VPLab. It identifies several critical components required to ensure the success of VPLab in enhancing students' knowledge and skills in computer programming language. These critical components are further categorized into three resources: technological resources, pedagogic and strategic resources and academic staff resources. The technological resources focus on the technology artifacts that can be used to simulate virtual laboratories and to assess student knowledge and understanding. These technology artifacts are virtual communication environment (VCE), simulator (SIM), remote laboratory (REM), virtual machine (VM) and automatic assessment tool (AET). The pedagogic and strategic resources focus on the theory, pedagogical approach and methodology that allow the understanding and/or creation of knowledge. The pedagogic and strategic resources used in VPLab are learning methodology, support documentation and other materials, and evaluation. The academic staff resources focus on the teachers or members of academic staff who help students to reach their individual objectives and who personalize learning and attention to each student. The authors also conducted a questionnaire-type survey to 284 participants who are distance learning students to evaluate the relevance of the proposed structure and their critical components. The survey is divided into two parts where the first part obtains the profile of survey respondents and the second part analyses the significance of each critical component. Several components that score highly in the survey are:

- The teacher component of academic staff resources.
- The evaluation and learning methodology of pedagogic and strategic resources.
- The virtual communication environment (VCE), simulator (SIM), virtual machine (VM) and automatic assessment tool (AAT) of technological resources.

An interesting finding in the study was that although technological resources were rated highly by the students, the distance learning students appeared to place more importance on pedagogical and human factors.

NVBLab: the virtual collaborative networking lab

Hwang et al. (2014) discuss an experiment whereby students in a networking class work on a number of ICT network-based assignments from basic to advanced labs using two platforms. The control group uses virtual machines (VMs) installed in their PC to do the assignments, while the experimental group students are given access to guest OSs with a web-based GUI interface featuring a web terminal, a command search window, laboratory materials and chat windows—group and individual. This platform is termed network virtualization-based laboratory (NVBLab).

The experiment was conducted during the summer semester (2013) at Kasetsart University with a total of 35 students with the control group having 15 students and 20 students in the experimental group. The experiment had four steps: (1) lab orientation and pretest 1; (2) experimental treatment and posttest 1 for basic labs; (3) pretest 2 and experimental treatment for advanced labs; and (4) posttest 2 and a questionnaire. The basic labs are conducted individually for experimental and control groups, while the advanced labs are conducted individually for the control group while it is in groups of 5 for the experimental group with access to chat windows for collaborations which allows communication between group members, teaching assistants and lecturer when doing assignments.

The pretest results show that there is no statistically significant difference between the experimental and control groups indicating similar background skills in both basic and advanced Labs. Also, the posttest 1 shows no statistically significant difference between the control and experimental groups. However, there is a statistically significant difference in posttest 2 between experimental and control groups showing improved students' learning achievements for the experimental group. The paper also evaluates the command count and chat message count in the experimental group. It is concluded that the group interaction and immediate feedback and support from other group members have provided an increase in student interest resulting in students in the experimental group completing more assignments and achieving higher learning outcomes (scores).

A virtual laboratory project in science and engineering

The Virtual and Accessible Laboratories Universalizing Education (VALUE) project (Achuthan et al. 2011) was initiated by Amrita University in support of National Mission on Education through Information and Communication Technology (NME-ICT) scheme in India. Amrita University's goal is to provide college and university students throughout India with access to virtual laboratories, allowing them to experiment, discover and have learning experiences similar to their colleagues who have access to physical laboratories. The virtual experiments have all been developed using the same coordinated processes. Firstly, an experiment is selected based on All India Council for Technical Education (AICTE) or the University Grants Commission (UGC) model curricula. Next, virtual labs research assistants reacquaint themselves with the experiment. They then work with one of the Amrita University e-learning teams to create storyboards, provide suggestions for the experiment design, test and evaluate interim versions. The virtual labs research assistants also collect reference materials and assist subject matter faculty with the development of the theory and procedure discussions, assignments and self-evaluation quizzes. Amrita University's e-learning team, the Center for Research in Advanced Technologies for Education (CREATE @ Amrita), is responsible for creating the virtual lab interactive animations and simulations. After the experiments are completed, they undergo extensive beta testing in the hands of the virtual labs research assistants and by faculty review. Each experiment has a standard format with seven components: Theory, Procedure, Self-Evaluation, Simulator, Assignment, Reference and Feedback. By 2011, 98 experiments have been completed in physical sciences, chemical sciences and biotechnology and are available online (http://vlab.amrita.edu/). A workshop was conducted to disseminate the use of these virtual labs among faculty across a number of higher education institutions. At the end of each workshop, exit surveys were given. The survey contained several questions regarding the perceived effectiveness of the virtual labs. The survey results indicate that faculty felt virtual labs could be an effective tool with more than 94 % of the responses to be either Good, Very Good or Excellent, with over half of those respondents responding with Excellent or Very Good. In response to the questions, “Do you feel such virtual labs site aids/assists you in your job as a teacher?” 97 % of the respondents answered yes.

In summary, VALUE virtual labs have incorporated guided labs with theory, procedure, static and dynamic simulations as well as in some cases remote labs, self-assessment, assignment, references and feedback in a single portal that is easy for students and faculty to use and allow self-directed experimentation.

Online labs for STEM education

In de Jong et al. (2014), the authors present Go-Lab project. The main aim of Go-Labs project is to provide school children with a motivating environment to acquire scientific inquiry skills and undertake guided engaging science experimentation. To meet this objective, Go-Labs provide a platform that incorporates remote and virtual labs as well as data-set analysis tools (which are collectively termed online labs). In Go-Labs, the central pedagogical approach is inquiry learning. In inquiry learning, students are not directly offered information, rather a guided investigation process, whereby research questions/hypothesis is derived, investigations are conducted via experimentation, results are observed, and conclusions are made. This approach is proven to be more effective than other lab approaches using “cookbook” procedures or discovery approaches. Teachers are a main stakeholder in the project. Go-Lab provides teachers with authoring facilities to create and share their own “Inquiry Learning Spaces (ILS).” The Go-Lab portal (www.golabz.eu) provides many tools and facilities for creating and sharing inquiry-based labs in science and technology fields. This project has developed a number of labs and expects to pilot across 1000 schools within Europe in the near future. We expect to see future work evaluating the results of this project.

A virtual networking lab

Razvan et al. (2012) propose and implement architecture for a cloud-based virtual networking lab. Networking lab experiments require students to configure and test complex network scenarios using network hardware and software. Typically, these network labs are constrained by the hardware resources in a lab. However, by creating a virtual networking lab, students are able to configure complex network scenarios using virtual networking hardware and resources. A virtual networking lab, unlike a virtual computing lab, requires students to configure multiple VMs and other virtual hardware such as virtual routers and virtual switches. The authors in the paper present an architecture for a virtual networking lab and implement it by employing virtualizing technologies such as VMWare and NetLab+. The networking lab is successfully deployed with over 900 labs and over 1700 h of lab work put into testing the described NetLab+ solution by over 260 students. The survey evaluations surpassed expectations as almost all students believe that they have had their study experience enhanced by the proposed virtual infrastructure. Some suggestions for improvement include providing better mobile access to the virtual labs as well as access to physical networking hardware. As all labs are conducted in a virtual environment, students lack the experience of working with real physical hardware devices.

Other related work in virtual and remote laboratories

In the previous section, we reviewed virtual and remote laboratory implementations in different disciplines. In this section, we discussed an overview of related work in virtual and remote laboratories such as technologies used, sharing remote labs, group work and integration with learning management systems (LMS).

Technologies for virtual and remote labs

There have been many technologies used and tools developed for remote and virtual labs. For instance, in the above review, we came across Easy Java Simulations (EJB) and LabView in Chaos et al. (2013), virtualization technologies such as VMWare in Alharbie et al. (2012), VISIR in Marques et al. (2014), biotic processing units—BPUs in Hossain et al. (2015) and many others. We also find literature that focuses on technology that can be used to develop virtual and remote laboratories. For instance, Abdul-Kader (2009) proposes the use of X3D (extensible 3D) to develop and design immersive virtual reality learning environments. X3D is a high-level object oriented programming language that allows the creation of 3D (three-dimensional) scenes and mimic the behavior of objects. To demonstrate X3D features and capabilities, the author implements two virtual labs—a virtual chemistry lab and a English language lab using X3D. The paper demonstrates the possibility to use such technologies to develop immersive virtual labs which can motivate learner and provide new possibilities for learning.

Sharing remote labs

One of the positive advantages of remote labs is that typically expensive equipment from a single laboratory can be shared between on-campus, distance learners and even among different institutions. We see a number of initiatives that aim to improve access by sharing remote labs across many different institutions and learners. MIT's iLab project (Harward et al. 2008) which has developed the iLab Shared Architecture (ISA) middleware platform allows remote labs to be integrated by institutions and used by learners worldwide. LabShare Lowe et al. (2011) is an initiative that aims to provide shared remote labs across higher educational institutions in Australia. The Library of Labs (LiLa) (Richter et al. 2011) and Go-Lab (de Jong et al. 2014) are European initiatives that share remote and virtual labs.

Integration with learning management systems (LMS)

Learning management systems (LMS) are popularly used by institutions for managing learning content. Popular LMSs include Moodle (https://moodle.org), Blackboard (http://www.blackboard.com) and others. LMSs provide many features such as posting learning content, discussion forums and tools for collaboration that have become integral part of blended and distance learning students in many learning-centered institutions. Integrating remote and virtual labs to LMSs has advantages of providing a singular portal to all academic resources including laboratories. We find many efforts in the literature that develops technologies to integrate virtual and remote labs to content and learning management Systems (Sancristobal et al. 2010; Orduna et al. 2013) and others.

Groups in virtual and remote labs

Group work has been considered important in learning contexts. Forming groups and group work in virtual and remote labs have caught the attention of certain researchers. In Hwang et al. (2014), it was shown that group laboratory assignment in the NVBLab where students collaborated had higher achievements in learning outcomes compared to the control group. Also, in Alharbie et al. (2012), some students articulated that they preferred to come to on-campus labs to meet group members and interact with them. Mujkanovic et al. (2011) and Mujkanovic et al. (2012) investigate ways to effectively form groups in remote labs settings.

Next, we will discuss the observations and findings from the review.

Observations and findings

We observe a number of benefits with the use of virtual and remote laboratories. These benefits are summarized below:

- *Accessibility and availability* A major advantage of both remote and virtual laboratories over hands-on lab is its accessibility from remote locations and its availability anytime. Remote labs provide learners with remote access to physical laboratories. For instance in Hossain et al. (2015), students are able to login 24 × 7 from any device and observe their experiment. Students using virtual ChemLab (Woodfield et al. 2005) can work on simulations any time from any device connected to the browser. Also virtual laboratories and remote laboratories may be the only option for laboratory experience available for distance learning students. The virtual and remote robotic laboratories in Chaos et al. (2013) are used by distance learning students at UNED and Complutense University. Also, remote laboratories allow sharing valuable lab resources among institutions [e.g., iLab (Harward et al. 2008), LabShare project (Mujkanovic et al. 2011; Seiler 2013)].
- *Flexibility* Learners in virtual laboratories have the freedom to explore, repeat experiments and learn at their own pace which is not practically possible in a physical lab or even in a remote lab. Students are able to access and experiment in the virtual lab at their own convenience at any time from any location without the need to schedule or be restricted to a timetable slot. The freedom to explore without restrictions or consequences is rarely afforded in physical labs. For instance, in ChemLab (Woodfield et al. 2005), students have the freedom to

explore a vast possibility of experiment simulations with 26 cations that can be combined in any order or combination and 11 reagents that can be added in any order. Students can reset and repeat experiments as they wish and learn at their own pace.

- *Cost-effectiveness* Virtual and remote labs are cost-effective when compared with physical labs. This is one of the greatest advantages for developing remote labs as expensive equipment can be shared by many learners remotely (Harward et al. 2008). For some types of laboratory, the running cost for virtual labs is much lower as simulations are conducted in virtual environments. For example, the chemistry virtual lab does not waste actual chemical resources.
- *Safety* Virtual and remote laboratories provide a safe environment for learners to conduct an experiment. For instance, in a chemistry simulation environment such as ChemLab (Woodfield et al. 2005), learners are able to create experiments without the worry about chemical explosions or hazardous materials. Another example, students conducting biology experiments in a remote biology lab did not need to concern about the safety issues (Hossain et al. 2015).
- *Newer opportunities for learning* Virtual environments enable newer possibilities to perform simulations and experimentations that sometimes are not possible to be performed in physical or even remote labs. For instance, in the virtual network lab Razvan et al. (2012), students have the opportunity to configure complex network scenarios and hardware devices which are difficult to source in a physical lab environment. In Ding and Fang (2009) and Woodfield et al. (2005), it is clearly stated that exploratory investigation which is not practical in a physical lab is available to students in the virtual labs.

Another observation is that virtual labs have the possibility to create experiment environments focusing on the topic or pedagogical objective of the experiment while abstracting away complexities that may occur in a real-world experiment. This is clearly shown in the remote laboratory for robotics in (Chaos et al. 2013). In this situation, students are first given a virtual environment whereby they manually operate a robot in a virtual environment. The objective is to introduce students to the control interface of a robot and to build their interests by interacting with it. In the next phase, students write a program to control the robot based on sensor inputs and mapping goals in order to develop their knowledge and skills in developing algorithms manipulating the robot. Finally, when expertise and confidence are developed, students are exposed to a remote laboratory which has real robots in action. By this time, students have already gained the expertise, knowledge and skill to face the intricacies and complexities of the real-world situation. Had students been first exposed to a remote/hands-on lab, these complexities would have been distracting, complicating and even overwhelming students which potentially lead to a failure in achieving the learning outcomes. Thus, we observe that virtual and remote laboratory environments provide new opportunities for learning. In this instance, by effectively incorporating virtual and remote laboratories using appropriate pedagogical structure, it allowed students to perform experiments with a focus on the learning objective at hand while abstracting the real-world complexities. This is also observed in the remote biology lab in Hossain et al. (2015) and virtual chemistry lab discussed in Woodfield et al. (2005). Hossain et al. (2015) discuss how a non-biology student with no wet-lab training was able to conduct an experiment in biology using the remote lab. Thus, it allows the student to focus on the *P. polycephalum* experiment by abstracting away from the wet-lab training which is not the objective of the lab experiment. This sentiment is also reiterated in Woodfield et al. (2005): "…the largest educational benefit of the inorganic simulation is that students can focus on the principles of general chemistry, rather than focusing on troubleshooting aspects in a laboratory setting. These troubleshooting aspects imply more than just laboratory technique. Laboratory technique focuses on how to do something, whereas the troubleshooting aspects focus more on why something does not happen the way it should. One of the reasons beginning chemistry students feel overwhelmed in their first laboratory class is because, we believe, they are consumed by the details of lab technique and the troubleshooting aspects in the laboratory."

Many studies present evidence that virtual and remote labs can be effective in students learning when they are incorporated through well-considered pedagogical reasoning (Abdulwahed and Nagy 2009). For instance, Chaos et al. (2013), it is clearly shown that virtual and remote labs assisted students' learning through the integration of simulations to create relevant expertise before experimenting with real robots in a remote lab. In Hwang et al. (2014), students who collaborated in NVBLab had achieved higher learning outcomes in comparison with the control group. In Marques et al. (2014), the authors present how VISIR labs allowed students to gain confidence, let them practice their lab experiences outside of the physical laboratory, achieve higher scores and increase students' engagement. In summary, we observe that virtual and remote labs provide new opportunities for learning and a careful consideration and integration to classrooms (both distance and on-campus) through sound pedagogical reasoning can lead to higher learning outcomes.

We also observe a number of other interesting findings in our review as follows:

- *Complementary nature to physical labs* With all the advantages that remote and virtual labs provide, we observe that they do not still replace physical/hands-on labs. In many disciplines, such as chemistry and biology, "wet-lab" training is an essential part of learning to conduct experiments which cannot be obtained by virtual and remote labs alone. However, these different types of labs are complementary in nature and may be combined in ways that provide a rich and engaging learning experience for the learners. For instance, in robotics lab (Chaos et al. 2013), the authors have cleverly integrated both virtual and remote laboratories to achieve different learning outcomes and goals. In virtual laboratory, students gain expertise in developing algorithms to control a robot by abstracting away from the complexities of real-world scenario. Next, once the expertise is gained, students are exposed to manipulate real robots through the remote laboratory allowing students to experience issues/complexities in a real-world setting. This fact is also stated in the other literature. For instance, in the virtual chemistry lab (Woodfield et al. 2005), the authors clearly state the importance of using wet labs: “We believe that learning the how is vitally important, which is why we believe Virtual ChemLab is best used with a ‘wet’ laboratory.” In Marques et al. (2014), the authors concluded in their multi-case study VISIR lab is a good choice when combined with a hands-on lab. In Razvan et al. (2012), authors state that in virtual networking lab, lack of experience in real hardware is one of the suggestions for improvement. An exception to the above statement, where there is no clear advantage of using a hands-on lab compared to virtual laboratory, is in virtual computing labs. It is interesting to note that virtual computing labs, which provide access to a remote desktop, have little distinction between remote lab and virtual lab as discussed in the definitions section. We can classify virtual computing lab as both a remote lab or a virtual lab as per the definition. The actual virtual machine is hosted on a remote server and thus can be classified as a remote lab. We can also classify it as a virtual lab, as the virtual machine is actually running on a simulated hardware layer so in essence a virtual simulated environment. Also, it can be configured so that the users of virtual computer lab may look and feel exactly as if the VM is run as a local machine so that there is little distinction between a physical computer lab machine and a virtual machine. Thus, virtual computing labs combine the advantages of remote/virtual labs (i.e., access to the computing lab from anywhere at any time while also having the look and feel of a local machine). Thus, we expect to see many institutions taking advantage of virtualization technologies to centralize management computing resources, to provide virtual computing labs in future.

- *Different types of labs and technologies developed for different contexts* We also observe that there are different types of labs developed for different contexts (i.e., discipline, learning outcome, lab experiment objective, type of experiment). For instance in Chaos et al. (2013), the authors develop both virtual and remote laboratories to teach students controlling robots in virtual and remote settings. In Hossain et al. (2015), the authors develop a remote laboratory in biology to create experiments on *P. polycephalum*. The authors in Woodfield et al. (2005) provide a virtual environment allowing students to simulate chemistry experiments. In Prieto-Blazquez et al. (2009), students are provided with a set of tools and environment to learn programming. Razvan et al. (2012) provide students a virtual network lab that allows students to configure and test networks. It is evident that we cannot generalize the remote and virtual robotics lab developed in Chaos et al. (2013) for students to do biology experiments on *P. polycephalum*. Additionally, even if we consider a single discipline such as biology, the remote lab for P. Polycephalum discussed in Hossain et al. (2015) may not be relevant to other types of biology experiments. Thus, we can safely conclude from our observations that each type of labs (remote or virtual) focuses on different contexts—learning outcomes, disciplines requirement, experimental objectives, etc., and creating a single framework or implementation environment that encompasses all types of labs suitable for all contexts is practically infeasible. We expect heterogeneity in future research and developments in virtual and remote labs. Similarly, we also observe different types of technologies and tools used to develop various types of labs (e.g., VISIR, NetLab+, BPUs and others). We expect that heterogeneous technologies and tools will be used in future for developing both virtual and remote laboratories. However, heterogeneity does not imply that students will face difficulties in accessing these labs. We expect students to access these different labs seamlessly using the web portals. We observe initiatives such as iLabs (Harward et al. 2008), LabShare (Lowe et al. 2011), Go-Labs (de Jong et al. 2014) and integration to existing learning and content management systems (Sancristobal et al. 2010; Orduna et al. 2013) where learners access different lab implementations seamlessly using a single portal.

- *Innovative labs taking advantage of technological advancements* With the advances in technologies, we expect further work that aims to take advantage of such technologies in education including the design and development of innovative laboratories: for instance, advances in virtual reality environments—Microsoft HoloLens (https://www.microsoft.com/microsoft-hololens/en-us), etc.—and haptics (Bivall et al. 2011) and others. Also, we observe in Razvan et al. (2012) and Alharbie et al. (2012), making use of cloud computing technologies to provide innovative computing and networking laboratories.
- *Different types of labs may cater to different learner personality and preferences* An interesting finding from Woodfield et al. (2005) was that personality profiles and learning preferences have impact on opinion, performance and exploratory use of Virtual ChemLab. Woodfield et al. (2005) found that within a 99.9 % CI, the higher someone's cerebral score (creative learner), the less help they feel they need in using the inorganic simulation, and the higher someone's limbic score (structured learner), the more help they need. Also, structured learners, with a confidence interval of 95 %, report that they spend smaller percentage of time exploring or conducting "what if" experiments in Virtual ChemLab. Woodfield et al. (2005) show that structured learners have a much harder time experimenting in Virtual ChemLab and also believe that these students will have difficulty learning in any loosely structured learning environment, not because they are incapable, but because of their individual learning preferences. This raises interesting questions as to whether different types of labs (hands-on, remote and virtual) and experimental formats cater to different personality traits and learning preferences. If so, "what factors cater to what types of learners?" and "how can we develop labs catering to different learning preferences?" are areas for future research and exploration.
- *Virtual and remote labs are more prevalent in higher education settings* We observe that many virtual and remote laboratory implementations discussed in the literature pertain to higher education settings. This may be because many distant education learners are prevalent in higher education and benefit the most from such labs. However, the Go-Lab project (de Jong et al. 2014) aims to cater to school children. We feel that as more evidence becomes prevalent on the benefits and complementary nature of virtual and remote labs with physical labs, there will be more developments catering to school learners and uptake of these types of labs in school education environments.

In summary, virtual and remote labs and related technologies provide enormous opportunities to learning for both on-campus and distant learners. However, we need to be aware that these tools by themselves do not provide higher learning outcomes; rather, the combination of a good pedagogical framework, learner support, good content and tutor interaction, etc., is all essential to form a rich learning environment whereby learners can excel. We find evidence to support this claim in our review. In de Jong et al. (2014), this point is stated as follows: "… just providing a lab does not suffice for an effective learning process. Research shows that in order for inquiry to be successful it needs to be combined with guidance; when guidance is available, an inquiry learning process leads to better conceptual knowledge than traditional instruction." In our review, we observe attempts whereby a combination of many factors is incorporated to create rich learning environments. For instance in the VALUE project (Achuthan et al. 2011), rather than providing a simulation or virtual experiment environment by itself, each experiment is presented with Theory, Procedure, Self-Evaluation, Simulator, Assignment and Reference. This approach combines each experiment with its background context and learning materials. In (de Jong et al. 2014), the inquiry-based labs have a number of phases such as orientation, conceptualization, investigation, conclusion and discussion. In VPLab (Prieto-Blazquez et al. 2009), rather than providing a virtual lab, a number of critical components including technological resources, pedagogic and strategic resources and academic staff resources were developed to enhance student knowledge and skills in programming. Another interesting finding in this paper was that students rated pedagogical and human factors highly in addition to technological resources, providing further evidence to our claim above.

In future, we expect to see further innovative remote and virtual lab implementations taking advantage of the possibilities provided by advances in technology. Also, as our understanding of pedagogy and how students learn increases, we will further experiment innovative ways to integrate these technologies in physical, virtual and remote settings to provide higher learning outcomes. There is still few research that investigates collaboration in virtual/remote labs and their potential for learning: An interesting finding by Hwang et al. (2014) is that when students had an opportunity to collaborate in the virtual laboratory, there was a statically significant improvement in learning outcomes. In a slightly opposing view, Alharbie et al. (2012) argued that students prefer to use virtual computing labs when working individually from home due to flexibility, convenience and improved access, while they prefer to use on-campus, hands-on labs for group work and collaboration. Is this due to a lack of collaboration tools available in virtual computing labs? Can we encompass collaboration tools in remote and virtual settings for better learning outcomes? How will this impact learning? etc., have much scope for future research and investigation. Also, in Woodfield et al. (2005), it was clearly stated that certain types of learners needed less help in exploring Virtual ChemLab, while others needed more help. Do virtual labs cater to certain personality profiles and preferences of learners than others? How can we create learning environments catering to different learner needs? These are all potential areas for future research.

Conclusion

In this paper, we review contemporary implementations in remote and virtual laboratories in different disciplines. From our review, we make a number of observations and findings. Virtual and remote laboratories bring in new opportunities and possibilities to learning in many different disciplines. Benefits include accessibility and flexibility where students can conduct experiments from any location, accessing remote equipment 24×7, and have the flexibility to reset and redo experiments at their own pace. The remote and virtual labs also provide cost-effective ways for institutions to provide lab experience for students, while students also have a safer environment to conduct experiments without wasting resources. In a more interesting finding, many new opportunities for learning have been possible due to virtual and remote labs that would not have been practically possible otherwise. It is interesting to note that although remote and virtual labs have many benefits, they do not necessarily replace hands-on labs in some instances. Integrating physical labs with virtual and remote labs in innovative ways using a sound pedagogical framework to support learning can create rich learning environments and ability to achieve higher learning outcomes.

In future, we expect to see further innovative virtual and remote laboratory implementations taking advantage of advances in technology and incorporating well-founded pedagogy in different education contexts providing new opportunities for learning and higher education outcomes. Integration of such labs and seamless access through portals and learning/content management systems will certainly evolve. Using technology to cater to group collaboration, different personality profiles and preferences of learners and developing pedagogical frameworks to integrate innovative labs effectively to achieve learning outcomes are areas for further research.

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