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# Foreword

Cyber-physical laboratories were but a theoretical paradigm until they first became a reality around the turn of the century, when technological advances in the areas of hardware, software, networking, and control made the first rudimentary laboratories possible. Since then, the accelerated evolution of the technologies required by cyber-physical labs has substantially expanded their versatility and applicability to the degree that their use in the educational realm is expanding monumentally. Today, almost all definitions of cyber-physical laboratories, although some experts may disagree on some discreet points, involve either monitoring, controlling, or twinning an object in the physical world by means of software algorithms which permit the dynamic interaction between said object and the real world, maintained through either cabled or wireless communications to computer-based resources. Also, digital twins and simulations are widely used in the online laboratory field.

Of course, this implies that major advantages of cyber-physical laboratories are that they are scalable, often shared resources that are not constrained by spatial-temporal considerations.

Adequate laboratory experience at a time and place convenient for students has always been a major challenge for science, engineering, and technology educators. This applies to both traditional laboratory courses, where classes are scheduled only for a specified time period when students attend a laboratory class located within a laboratory of an academic institution, and distance learning programs which, in the great majority of existing Internet-based distance learning programs, lack any significant laboratory-based courses.

In the case of traditional laboratories, in many cases, they do not adequately compensate for the mixed ability level of students, and the allocated time for carrying out activities is many times insufficient for all students to complete their tasks satisfactorily to gain the sufficient experience they need to internalize often complex processes and internalize them. Also, in some cases, students want or feel a need to perform additional experiments beyond their assigned tasks. It is difficult to accommodate any extra experimentation because universities often lack resources to keep their laboratories open. Additionally, laboratory facilities are often inaccessible to the students of other departments within the same institution because of their geographical location. Ironically, too much laboratory equipment lies idle during most of their usable lifetime.

Although cyber-physical laboratories provide important advantages, they can be very difficult to implementbecause these facilities involve the areas of instrumentation, computer interfacing, health and safety, video streaming, data collection and management, web application development, database management, network security, learning management systems, pedagogical design, and course management. The cyber-physical remote or virtual laboratory, either as replacement of or supplement to traditional laboratories, must be able to address the above difficulties before they can be effectively integrated into learning environments.

Cyber-physical laboratories, however, offer valuable benefits in that properly managed, they can allow for their full integration into distance-learning or blended learning programs, which can potentially make them extremely scalable, affording easy access when integrated into online learning systems. Additionally, but equally important, cyber-physical laboratories provide the opportunity for greater collaboration at more affordable costs among universities and research centers by providing both researchers and students access to a wide collection of shared experimental resources by sharing costs and reducing the duplicity, which often occurs when institutions purchase the same, often expensive equipment individually.

Another very important consideration is that cyber-physical laboratories have been shown to be equally or more effective than some more direct forms of instruction and at least as effective as traditional physical laboratories. However, this has been shown to be true only when online guidance provides students resources as part of an integrated learning system. This guidance can be provided using a variety of forms ranging from providing students with tools for inquiry (such as a scratchpad for creating hypotheses), adding augmentations to the lab, or embedding it in background information. Research is now progressing to determine what kind of guidance is necessary for students to better learn from specific kinds of laboratories.

Recognizing the benefits cyber-physical laboratories can potentially offer, there has been an increased interest and effort toward applying or developing relevant technologies and how to most effectively implement them, as well as how to identify their effectivity insofar as student learning and educational outcomes are concerned. However, there are various factors that influence the development of remote laboratories, including the nature of the input(s) and output(s) of the experiments, the speed of operation, data collection restrictions, the need for video and audio feedback, data presentation, security safety requirements, scalability, and interfacing with other similar systems. In the case of virtual laboratories, a specific development aspect is the level of required fidelity, with at its extreme virtual reality laboratories that fully mimic the real laboratory (except for the olfactory aspects).

Considering the abovementioned factors, each of the current developments in this area is unique, and there is currently little room for further integration with other systems or for expanding different experiments for local, regional, and global collaboration. To address these factors, a number of issues need to be investigated to develop modular, effective, versatile, cost effective, user friendly, and sustainable remote and virtual laboratory systems that can deliver its true potential in the national and global arena, which will allow individual researchers develop their own modular system with a level of creativity and innovation, while at the same time ensuring continued growth by separating the responsibility for creating online labs from the responsibility for overseeing the students who use them. This feature is critical for scaling the number of users of a particular laboratory experiment and for expanding the development of new laboratories.

Part I of this volume, "State of the Art and Future Developments in Cyber-Physical Laboratory Architectures," introduces the reader to several system architectures that have proven successful in many online laboratory settings. The first online laboratory developments were reported in the late 1990s. Since then the emergence of new technologies has influenced the design structure of these developments and has allowed remote laboratories to have new features and capabilities.

This section will include chapters describing the state-of-the-art structure of remote laboratories as well as ongoing and potential future development. Authors are encouraged to include sufficient detail to enable an informed decision as to which approach best fits your needs. These chapters will describe the technologies used along with pedagogical issues to keep in mind while designing the architecture. The section will also provide a comparative picture of various technologies and developments. In addition, there will be an effort to report the standardization outcomes that are conducted by professional organizations to streamline online laboratory development.

Part II of this book, "Pedagogy of Cyber-Physical Experimentation," discusses the pedagogical questions that come along with the introduction of virtual and remote laboratories in the curriculum. Pedagogical questions concern, for example, the amount of freedom to hand over to students but also the type of guidance provided to students and the fading of this guidance over time, the differentiation of the lab experience for students with differing prior knowledge and/or inquiry skills, and how to shape students' collaboration when learning through an online lab, etc. This section offers a unique collection of chapters each describing one of the world's five most widely used ecosystems for online labs for science education. In these chapters, the latest developments of these ecosystems are presented, including the design and development of integrated student guidance, the online measuring and interpretation of student activities as a basis for providing students with adaptive feedback, (teacher) authoring facilities, accessibility of online labs for students, and the use of advanced learning scenarios such as collaborative learning and learning by modelling.

Finally, Part III is titled "Cyber-Physical Laboratories: Best Practices and Case Studies." This section highlights a number of remote laboratory case studies, covering a range of application areas that can be considered as representative best practices. There is a total of six chapters highlighting remote laboratories for life science experiments, automation engineering, hardware in the loop systems, integration of augmented reality and haptic devices, heat transfer experiments, additive manufacturing, and utilization of mobile devices for remote laboratories. The contributions provide an insight from a different perspective and each discussion leads the reader to understand the rationale behind the approaches taken and obtain further information of interest. Almost all the chapters in this section report the developments in engineering, technology, and physics topics.

It is our sincere hope that by reading the valuable contributions to this book, you will gain a greater insight as to the many considerations persons wishing to develop and implement cyber-physical laboratories must take into consideration, by reflecting upon the actual thoughts and experiences of some of the foremost developers and practitioners in this important and quickly evolving area. It is our further hope that any knowledge gained by our experiences serve to motivate you to become still more informed and motivated to join us in providing more valuable experimental and experiential tools to induce, motivate, and help students gain practical knowledge about real-world principles and phenomena.

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# Contents

# About the Editors

**Michael E. Auer** received his Ing. degree (1971) and his Ph.D. degree (1975) from the Dresden University of Technology. His working field was the analysis and design of high-speed integrated microelectronic circuits. From 1974 to 1991, he was an assistant professor at the faculties "Electrical Engineering" and "Informatics" of this university. His research at this time was related to high-speed digital circuit simulations, design systems and platforms for the design and simulation of microelectronic circuits, and real-time and network programming in UNIX environments.

From 1991 to 1995, he was head of the software department F+O Electronic Systems GmbH, Heidelberg. His research there was related to real-time and network programming, embedded control systems, programming in C, C++, PERL, as well as system and network administration of heterogeneous networks with UNIX, VMS, and Windows workstations.

In 1995, Michael Auer was appointed Professor of Electrical Engineering at the Carinthia University of Applied Sciences, Villach, Austria, and built up the teaching domain "Fundamentals of Electrical Engineering and Circuit Design."

Michael Auer has also a teaching position for "Microelectronics" at the University of Klagenfurt, Austria, and works as a visiting professor at some universities worldwide.

His current research is directed to technology-enhanced learning and remote working environments.

Besides being a co-chair or member of the program committees of several international conferences and workshops, he is especially involved as founder and general chair of the annual international conferences "Interactive Collaborative Learning" (ICL) and "Remote Engineering and Virtual Instrumentation" (REV).

In 2009, Michael Auer was appointed as a member of the Advisory Board of the European Learning Industry Group (ELIG). Furthermore, he is chair of the Advisory Board of the International E-Learning Association (IELA).

Michael Auer is Managing Editor of the OnlineJournals.ORG platform with a number of open access journals in the fields of "Online Engineering," "Emerging Technologies in Learning", Mobile Technologies," and "Engineering Pedagogy."

Michael Auer is Founder, President, and CEO of the “International Association of Online Engineering” (IAOE), a nongovernmental organization that promotes the vision of new engineering working environments worldwide. From 2009 to 2016, he was President of the “International Society for Engineering Education” (IGIP). In 2015, he was elected as President of the International federation of Engineering Education Societies (IFEES) for the term 2016–2018.

**Abul K.M. Azad** is a Professor in the Technology Department of Northern Illinois University, USA. He has a Ph.D. in Control and Systems Engineering and M.Sc. and B.Sc. in Electronics Engineering. He has been in academics for 25+ years, and his research interests include remote laboratories, mechatronic systems, mobile robotics, and educational research. In these areas, Dr. Azad has over 115 refereed journal and conference papers as well as 5 edited books. So far, he has attracted around $2.6 M of research and development grants from various national and international funding agencies. He is a member of the editorial board for a number of professional journals as well as an Editor-in-Chief of the International Journal of Online Engineering. Dr. Azad is active with remote laboratory field and is the President of the Global Online Laboratory Consortium (GOLC) as well as the Vice-President of the International Association of Online Engineering (IAOE). He is also active with few other professional organizations like IEEE, IET, ASEE, ISA, and CLAWAR Association, and served as Chair and Co-Chairs of numerous conferences and workshops. He was a program evaluator for the ABET and is active in evaluating research and development projects for various national and international funding agencies in the USA, Europe, and Australia.

**Arthur Edwards** holds a master’s degree in education from the University of Houston (1985). He has collaborated at the University of Colima, Mexico, for 29 years as lecturer/researcher, where he has been instrumental in the area of curricula and instruction. He is a co-founder of the College of Foreign Languages, the University English Program, and the Self Access Centers of this institution. As head of the Self Access Center, he developed an interest in Computer-Assisted Language Learning (CALL) and moved to the College of Telematics to follow up this line of research, where he is currently a senior tenured researcher. During this first period of his career, he authored two English textbooks published by the University of Colima Press.

In 1999, he was assigned to the College of Telematics full time, where he developed additional interests in eLearning and other related topics. He was awarded funding in 1999 to follow up his project of eLearning by the Ministry of Scientific Research of the Mexican government, being the first project approved for financing of the College of Telematics.

Over the last decade, Arthur Edwards has been integrated into the Mobile Computing workgroup, where he has collaborated on a series of nationally and internationally funded research programs in the area of ad hoc networking (primarily vehicular ad hoc networks) and remote mobile self-organizing robotics.

During this time, he has participated in the publication of approximately 50 scientific articles, 30 book chapters, and 6 books. He has also participated internationally as editor in four journals (two related to technology and two related to sustainability in education). Arthur Edwards has also participated in various national and international organizations, where he has evaluated research projects, publications, conferences, etc.

**Ton de Jong** holds a chair in Instructional Technology at the University of Twente, the Netherlands. He has specialized in inquiry learning and collaborative learning (mainly in science domains) supported by technology. He was coordinator of several EU projects and several national projects, including the ZAP project in which interactive games/simulations for psychology were developed. ZAPs commercial licences now go over 80,000 in number. He was coordinator of the 7th framework Go-Lab project on learning with online laboratories in science and currently is coordinator of its H2020 follow-up project Next-Lab (see www.golabz.eu). He published over 200 journal articles and book chapters, was an associate editor for the *Journal of Engineering Education* and for *Instructional Science*, and currently is on the editorial board of eight journals. He has published papers in *Science* on inquiry learning with computer simulations (2006), design environments (2013), and virtual laboratories (2013). He is AERA fellow and was elected member of the Academia Europaea in 2014. He is dean of the master program Educational Science and Technology at the University of Twente. For more info see: http://users.edte.utwente.nl/jong/Index.htm

# Abbreviations

| | |
|---|---|
| AABB | Axis Aligned Bounding Boxes |
| AD | Automation Device |
| ADDIE | Analysis, Design, Development, Implementation, and Evaluation |
| ANN | Artificial Neural Network |
| API | Application Protocol Interface |
| AR | Augmented Reality |
| AWS | Amazon Web Services |
| BKT | Bayesian Knowledge Tracing |
| CAD | Computer-Aided Design |
| CGI | Common Gateway Interface |
| CMS | Content Management System |
| CPPS | Cyber-Physical Production System |
| CPS | Cyber-Physical System |
| CPU | Central Processing Unit |
| CSS | Cascading Style Sheets |
| CV | Computer Vision |
| DAQ | Data Acquisition |
| DMZ | Demilitarized Zone |
| DV | Dependent Variable |
| EA | Evolutionary Algorithm |
| FIFO | First In First Out |
| FREVO | Framework for Evolutionary Design |
| FSM | Finite State Machine |
| GBVL | Game-Based Virtual Learning |
| GCM | Gesture Control Module |
| Go-Lab | Global Online Science Labs for Inquiry Learning at School |
| GUI | Graphical User Interface |
| HMD | Head Mounted Display |
| HMI | Human Machine Interface |
| HTTP | Hypertext Transfer Protocol |
| ICT | Information and Communication Technologies |

| | |
|---|---|
| IIoT | Industrial Internet of Things |
| iLab | Interactive Lab |
| ILS | Inquiry Learning Space |
| IMS | Instructional Management System |
| IMS-CP | IMS Content Packing |
| Inq-ITS | Inquiry Intelligent Tutoring System |
| IoT | Internet of Things |
| ISA | iLab Shared Architecture |
| IV | Independent Variable |
| JSON | JavaScript Object Notation |
| LaaS | Laboratory as a Service |
| LiaaS | Lab Server Infrastructure as a Service |
| LiLa | Library of Labs |
| LMS | Learning Management System |
| LTI | Learning Tools Interoperability |
| MOOC | Massive Open Online Course |
| MOOL | Massive Open Online Lab |
| MQTT | Message Queue Telemetry Transport |
| NGSS | Next Generation Science Standards |
| NNGA | Neural Network Genetic Algorithm |
| NUI | Natural User Interface |
| OBBB | Object Oriented Bounding Boxes |
| OECD | Organisation for Economic Co-operation and Development |
| Olab | Online Labs |
| OTAP | Over-the-Air Programming |
| PDOM | Parallel Document Object Model |
| PhET | Physics Education Technology |
| PhET-iO | Interoperable PhET Simulations |
| PISA | Program for International Student Assessment |
| PLE | Personal Learning Environment |
| RAL | Remote Access Laboratory |
| RAMI | Reference Architectural Model Industry |
| RCE | Remote Code Editor |
| REST | REpresentational State Transfer |
| RFC | Request for Comment |
| RFID | Radio Frequency Identification |
| RL | Remote Laboratory |
| RLMS | Remote Laboratory Management System |
| RSDL | RESTful Service Description Language |
| RT Lab | Remote Lab |
| RT-WSN Lab | Remote Triggered Wireless Sensor Network Lab |
| SAR | Search and Rescue |
| SCADA | Supervisory Control and Data Acquisition |
| SCORM | Shareable Content Object Reference Model |
| SLAM | Simultaneous Localization and Mapping |

| | |
|---|---|
| SOAP | Simple Object Access Protocol |
| TCP | Transmission Control Protocol |
| UAV | Unmanned Aerial Vehicle |
| UI | User Interface |
| VD | Virtual Device |
| VE | Virtual Environment |
| VIS | Viewable Image System |
| VISIR | Virtual Instrument Systems in Reality |
| VL | Virtual Laboratory |
| VLCAP | Virtual Labs Collaborative Accessibility Platform |
| VNC | Virtual Network Computing |
| VR | Virtual Reality |
| W3C | World Wide Web Consortium |
| WDG | WOAS Device Gateway |
| WISE | Web-Based Inquiry Science Environment |
| WOAS | Web-Oriented Automation System |
| WPG | WOAS Protocol Gateway |
| WSDL | Web Services Description Language |
| WSN | Wireless Sensor Network |

# Part I
# State of the Art and Future Developments in Online Laboratory Architectures

## Introduction

Ian Grout

Today, we consider the use of the Internet as an everyday activity and routinely expect access to a rich set of resources which are presented to us in audio, visual and even tactile forms that suit our particular wishes or needs. Access to resources which are interesting, of a high technical quality, beneficial to the individual and easy to access, have a high quality of service (QoS) and are typically available continuously (on a "24/7" basis) is required. To reach the current situation that provides online services with these attributes, a great amount of work has been undertaken within higher education research and industry globally, led by individuals who have visions of what can be achieved and why they should be achieved. In higher education, one particular vision has been to widen access to engineering and scientific laboratory resources using online and remote access by embracing the positive power that the Internet can provide. Over the last number of years, the development of the online laboratory has evolved from an interesting engineering or computer science exercise where a primary question was "How can we use the Internet to remotely access our experiments and form an online laboratory?" to "How can we maximise the potential of our online laboratory?". The considerations and focus for practitioners in the field are evolving from a purely but interesting engineering, or computer science, technical challenge to a more end-user requirement challenge. This requires the laboratory developers to embrace new perspectives and challenges whilst maintaining or enhancing the technical foundations that underpin any laboratory infrastructure. Since the initial work undertaken in online laboratory design and development, a wealth of ideas, information and experiences have been collated. In addition, the number of laboratory providers and users has expanded so that now online experimentation is an integral part of many higher education programmes. Given that each laboratory resource developer has a particular set of aims and ideas of how the laboratory can be developed and used, each laboratory may have a different "look and feel", as well as different available resources from teaching materials through to the physical laboratory infrastructure itself. These would be based on a number of different developer requirements including availability of suitable electronic hardware and software, access to experiments, the ability to access the Internet for specific requirements and developer knowledge and experience, along with end-user requirements and needs. To provide a right balance between what set of outcomes would be desired, what would need to be created and what would be possible is a challenging task which is a problem to solve that has multiple dimensions.

This section, "State-of-the-Art and Future Developments in Online Laboratory Architectures", provides an insight into current developments in online laboratories. It is aimed to consider the current status in the field, end-user requirements and future directions in online laboratory development. The section consists of contributions from practitioners in the field and their insights into how these laboratories are designed, developed, deployed and can evolve. Each contribution provides an insight from a different perspective, and each discussion leads the reader to understand the rationale behind the approaches taken and obtain further information of interest.

In the contribution "Online Laboratory Architectures and Technical Considerations", developments in online laboratories are provided. A background into online laboratory development is initially provided along with examples of existing laboratory arrangements such as the "iLab Shared Architecture" from the Massachusetts Institute of Technology (MIT) and "WebLab-Deusto". Ad hoc solutions and Remote Laboratory Management Systems are introduced, along with frameworks and tools that are available and can be used to simplify the development and deployment of online laboratories. The contribution concludes with trends towards the creation of a common online laboratory architecture.

In the contribution "The WebLab-Deusto Remote Laboratory Management System Architecture: Achieving Scalability, Interoperability, and Federation of Remote Experimentation", WebLab-Deusto, an open-source Remote Laboratory Management System (RLMS), is introduced and discussed. It allows access to remote experiments and developers to share their own laboratories. This work is the result of collaborators, mainly from the University of Deusto in Portugal, working since 2004 in the field of remote/online engineering. The contribution provides a useful background history to the WebLab-Deusto project and the results obtained. The laboratory structure is shown, reasons why decisions in the laboratory development were made discussed, and its uses and the future directions such as the "LabsLand" spin-off activity provided.

In the contribution "Deploying Large-Scale Online Labs with Smart Devices", the upcoming challenges in moving remote experimentation from small-scale deployment to very large-scale deployment are considered. This is referred to as "Massive Open Online Labs (MOOLs)". Sharing resources whilst minimizing or even cancelling the waiting time to access a particular resource is a major challenge to support the end-user experience. This requires the resource provider to revisit both the pedagogical and technical methodologies of online laboratory implementation, sharing and deployment. The concept of the “Smart Device” model, which follows the “Laboratory as a Service (LaaS) scheme”, is introduced and attempts to describe the physical laboratory equipment, its digital components and interfaces as a unique entity.

In the contribution “Augmented Reality and Natural User Interface Applications for Remote Laboratories”, two key areas of focus to potentially enhance the end-user experience are considered. Firstly, augmented reality (AR), which the potential to create rich user interfaces, where users can view and interact with virtual objects, is considered. The discussion considers the use of AR and the use of virtual objects in remote laboratories as an alternative, immersive user interface. Secondly, natural user interfaces (NUIs), mechanisms to take input from users without using a fixed position or dimensionally restricted input, are considered. By using the natural movement of the user, a computer can be controlled without the use of objects such as the computer mouse and keyboard. Typically, a NUI incorporates some form of computer vision. By considering AR and NUIs, new and exciting ways in which a remote laboratory can be interacted with may be developed and deployed.

In the contribution “Designing Cyber-Physical Systems with Evolutionary Algorithms”, cyber-physical systems (CPSs) are considered, and the need for suitable design tools is discussed. As the degree of interaction among CPSs increases, this can lead to unpredictable and partially unexpected behaviour. Such potentially unwanted behaviour must be addressed in the design process. Hence, CPS design must be supported with suitable design methods and tools. Whilst a number of methods and tools that support CPS design already exist, there is no comprehensive toolset available. This chapter presents a proposal for a common CPS design toolset that combines existing and emerging tools to design, simulate, evaluate and deploy solutions for complex, real-world problems. A case study of swarms of unmanned aerial vehicles (UAVs) is presented as part of this discussion.

# Chapter 1
# Online Laboratory Architectures and Technical Considerations

**Danilo Garbi Zutin**

**Abstract** While a traditional, hands-on laboratory experience may be ideal, it is not always feasible. The costs associated with providing laboratory resources to students and the logistics of providing access can be prohibitive. This is particularly the case with laboratories that utilise limited resources or with students who may be performing their coursework remotely. In such cases, an Online Laboratory a laboratory that students can control remotely via the Internet can provide students with a valuable practical experience that is complementary to available hands-on laboratories. At the beginning, Online Laboratories were developed as ad hoc solutions and, as such, were designed for a very specific purpose and were not intended to be adapted or generalised. Ad hoc implementations of Online Laboratories are likely to neglect important aspects and requirements of an Online Laboratory system, such as scalability (ability to cope with a growing number of users and laboratories to manage). Furthermore, sharing Online Laboratories was also not a trivial issue. This chapter will present an overview of the main technical developments, software architecture models and access schemes used to deploy Online Laboratories.

**Keywords** Online Laboratories · Service-oriented architectures · Cloud computing · Web services · E-learning · Remote systems · Peer-to-peer networks

## 1.1 Introduction

The development of online laboratories has undergone major changes since the first systems were introduced almost 15 years ago. In the beginning, online laboratories were developed as ad hoc solutions, usually designed for a very specific purpose, and were not intended to be adapted or generalised, making online laboratories a

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closed, self-contained system. Fortunately the community soon realised that this strategy did not favour the large-scale use and scalability of online laboratory systems in formal education and research. The initial attempts to address some of these issues began with the development of the first Remote Laboratory Management Systems (RLMS), such as the iLab Shared Architecture (Harward et al. 2008) and WebLab-Deusto (Ordua et al. 2011), that took place mainly during the last decade. RLMSs grouped common functionalities around a single framework.

It is beyond the scope of this chapter to discuss the pedagogical setups that favour the use of Online Laboratories; however, one of its advantages, as pointed out by Cooper (2005), is the improved access for disabled students and the possibility to better combine experimentation with distance education programmes. In fact, the last one has been recognised by some authors as one of the driving forces that pushed the development of Online Laboratory systems (Feisel and Rosa 2005).

## 1.2 Online Laboratories and Architectures

Online Laboratories are computer applications that allow students, teachers and researchers to conduct experimentation from a remote location. These experiments can be of any kind and from any domain (e.g. Physics, Chemistry, Electronics, etc.).

Access to an Online Laboratory is usually delivered via a client application that can run in a Web browser, standalone or even in an embedded system. If this client interacts with a remote server (in this work referred to as a Lab Server) and controls a piece of equipment where the experiment data is measured, the Online Laboratory is referred to as being a Remote Laboratory. If the Online Laboratory delivers data generated as the result of a simulation, it is classified as a Virtual Laboratory. In this sense, remote and virtual laboratories are subsets of Online Laboratories.

This section will provide an overview of the software architectures commonly used to deliver Online Laboratories.

### *1.2.1 Ad Hoc Online Laboratory Architectures*

In the beginning, these Online Laboratories were developed mainly following an ad hoc approach as depicted in Fig. 1.1. This means these solutions were designed for a very specific purpose and were not intended to be adapted or generalised. As a consequence, each Online Laboratory was a closed, self-contained system with no communication whatsoever with other entities, even if they implemented the same functionalities repeatedly. For example, in Fig. 1.1, both Laboratory 1 and Laboratory 2 implement user management, experiment data management and booking of laboratory sessions and their users cannot sign in with the same credentials to the other Online Laboratory.

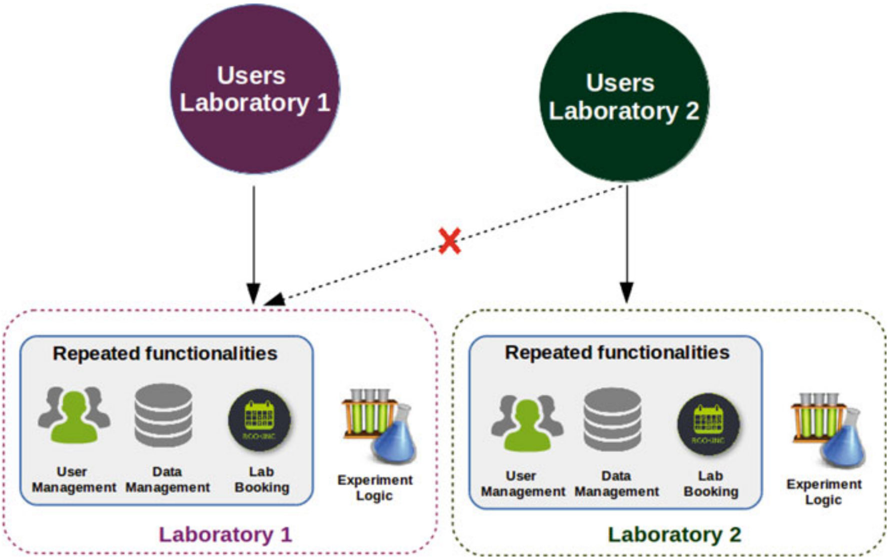


**Fig. 1.1** Ad hoc implementations of Online Laboratories

### *1.2.2 Remote Laboratory Management Systems*

When online laboratories began gaining uptake, a more structured approach was necessary to ensure the scalability of these Online Laboratory systems. The scalability of a system can be defined as its ability to efficiently handle a growing workload. In a network system, workload is mainly affected by an increasing number of users, instances and network nodes. Remote Laboratory Management Systems (RLMSs) were the first attempt to address this situation. An RLMS is a software that groups functionalities common to every online laboratory system around a single framework. Some of the initial functional requirements of these RLMSs were:

- User management, single sign-on with institution’s authentication systems
- Implementation of laboratory scheduling services
- Support for a scalable federation of online laboratories
- Support single sign-on in a cross-institutional federation of online laboratories
- Support for management of experiment data (data storage and retrieval)
- Integration with Learning Management Systems (LMS)

Remote Laboratory Management Systems contributed significantly for important advancements in the field of Online Laboratories, but their main contributions were the new possibilities created for sharing access to online experiments in an efficient and scalable manner, often across institutional boundaries. By grouping the functionalities described above around a common framework, the Online Laboratory system became a very specialised component, designed to process exclusively experiment-related requests. As a consequence of the decreased complexity of Online Laboratory systems, their development was also simplified to some extent. From this point of view, an RLMS could be considered a set of services available to laboratory servers that allowed for sharing of common functionalities among a cluster of Online Laboratories.

An example of an RLMS is the iLab Shared Architecture (ISA). ISA is a Web service infrastructure developed at the Massachusetts Institute of Technology (MIT) that provides a unifying software framework for online laboratory developers (Harward et al. 2008). ISA supports the access to a globally distributed network of Online Laboratories, and their users can access these laboratories by means of a single sign-on system. As opposed to most ad hoc implementations, ISA is not tailored to the requirements of a specific Online Laboratory, but rather to the requirements of how to provide support for the framing and maintenance of laboratory sessions and to share laboratories in a cross-institutional basis. The growing number and variety of Online Laboratories makes the use a common framework of generic services essential to ensure the systems scalability.

The use of Web services was favoured mainly due to its characteristics as a technology that allows the loose coupling of the different components of the ISA. Beyond that, the architecture should support the use of a diverse number of laboratory hardware and software and should not tie client and server platforms. It should also not make any assumptions on the network policies (firewalls, proxy servers) that a user might be under. These requirements favour the use of Web services for the implementation of this architecture due to their platform independence and standardisation. According to the World Wide Web Consortium (W3C 2002), Web services provide a standard means of interoperating between different software applications, running on a variety of platforms and/or frameworks. The iLab Shared Architecture is depicted in Fig. 1.2.

ISA supports asynchronous (or batched) and synchronous (or interactive) Online Laboratories. Asynchronous labs are special types of Online Laboratories whose experiments can have their entire execution course specified before it starts. The task of performing a batched experiment can be summarised in submitting an experiment specification, executing the experiment, retrieving, analysing and displaying the results to the user. Synchronous labs, in the other hand, are those Online Laboratories whose experiments require real-time control of the laboratory equipment. In fact the terms *batched* and *interactive* were coined by the ISA developers. The support for one or the other type of laboratories guided decisions on the framework development, described in the following sessions. The ISA batched architecture follows a typical three-tier model as depicted in Fig. 1.3. The role of Web services in this three-tier architecture is to provide the interfaces between the different components.

- The client application typically runs in the browser and is a domain-specific programme that communicates via the ISA API to carry out experiment-related tasks. It must be able to parse the batched parameters and experiment results and therefore understand the schemes used to encode these messages.

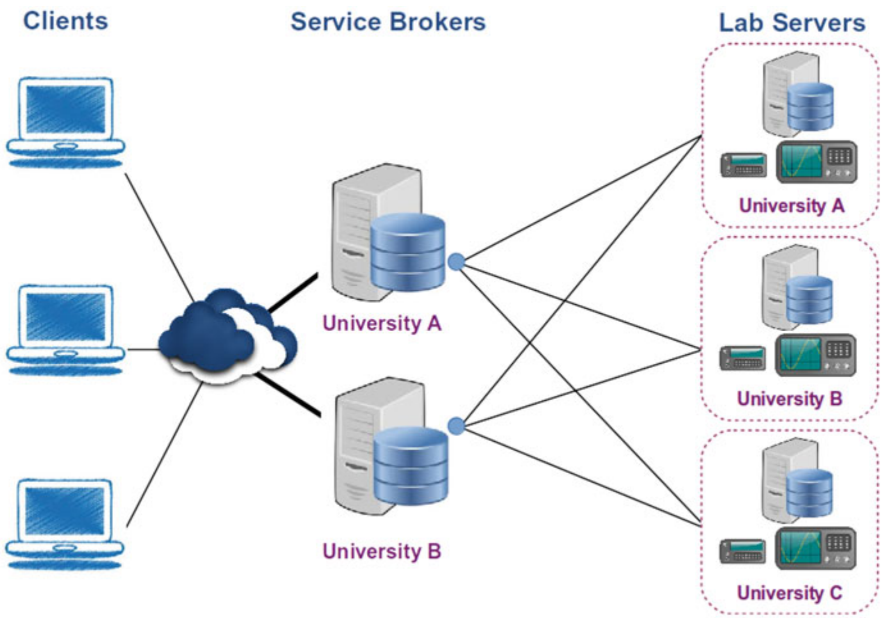


**Fig. 1.2** The iLab Shared Architecture

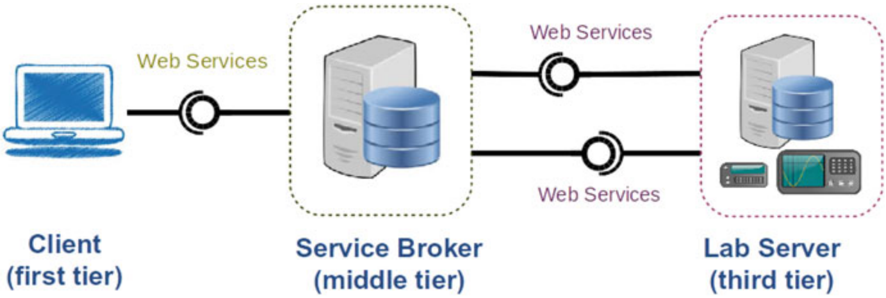


**Fig. 1.3** The iLab Shared Architecture – batched architecture

- The Service Broker mediates the communication between the client application and Lab Servers and provides user management functions, for example, to assign students. It normally resides on a server at the students' institution, where all accounts are managed.
- The Lab Server is the component of the architecture responsible to run experiments. Lab Servers serve the Service Broker with experiment results. They do not implement any lab user management and know nothing about the user running an experiment. The Lab Server exposes its functionalities to the Service Broker via its Web services API and never communicate directly with the client.

The ISA API allows the different components to be loosely coupled. The cardinality between Service Brokers and lab servers can be represented by a many-to-many relationship. This means that a Service Broker can request experiment execution to several different lab servers located anywhere in the globe, and a lab server can serve requests from several different Service Brokers located at different institutions. This relationship can be represented as shown in Fig. 1.2.

RLMSs have played a major role concerning the adoption of Online Laboratories. They contributed by providing common frameworks that laboratory developers could use to build their systems upon. RLMS aggregated several common functionalities of Online Laboratories and exposed them to developers via well-defined APIs. Although this section focused on the iLab Shared Architecture, this is not the only existing RLMS. Other examples of RLMSs are WebLab-Deusto (Ordua et al. 2011) and Labshare Sahara (Lowe et al. 2009).

## 1.3 Frameworks and Tools

This section will introduce the reader to some frameworks and tools created to simplify the development and deployment of Online Laboratories.

### *1.3.1 The Experiment Dispatcher: A Tool for Ubiquitous Deployment of Labs*

The Experiment Dispatcher is a software architecture used to provide ubiquitous deployment of Online Laboratories. It is a framework that provides Online Laboratory server infrastructure as a service (LIaaS) consumed by the laboratory developers to enable and/or facilitate the deployment and development of these systems (Zutin et al. 2016). This approach makes no assumption on how the access to the experiment will be delivered, since this is left for the discretion of the lab owner. For example, lab owners might decide to deliver remote experimentation using an RLMS and thereby take advantage of all benefits provided by these systems. Alternatively, the lab owner might decide not to use an RLMS, but rather interface their client application directly with the laboratory using the provided channels to relay messages between them. This new approach can complement the Smart Device specification (Salzmann et al. 2015) from the Go-Lab project (de Jong et al. 2014). The Go-Lab Smart Device paradigm aims to decouple client and server by defining interfaces between them and enabling thereby their easy integration with other third-party services. As pointed out by Salzmann et al. (2015), it originates from the RFID and sensor world, where information (metadata) is added to the device allowing user interface it to adapt itself based on the provided services. The specification makes no assumption on the inner working of the online laboratory, but rather defines the interfaces (message schema and protocol) for a client application to communicate with it.

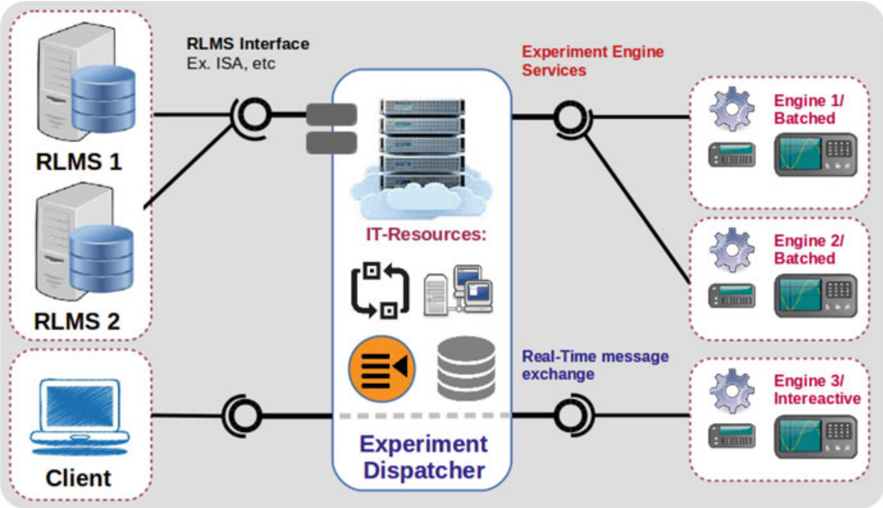


**Fig. 1.4** The Experiment Dispatcher

The Experiment Dispatcher centralises functionalities commonly provided by Online Laboratory servers and allows its seamless reuse by heterogeneous Online Laboratories. Additionally, it abstracts the development of the software necessary to deliver remote experimentation. It supports experiments that run according to the batched execution model. The term batched experiment, alternatively also called *asynchronous experiment*, concerns the scheduling schema employed. Batched experiments should have their entire execution course specified before it begins. The task of performing a batched experiment can be summarised in submitting an experiment specification, executing the experiment, retrieving, analysing and displaying the results to the user. Batched laboratories are designed to run relatively fast, therefore scheduling of lab session by means of a calendar-based booking is not necessary. Batched experiments are usually queued prior to processing by the Lab Server. Examples of batched Online Laboratories are the MIT Microelectronic Device Characterization (del Alamo et al. 2003) and the University of Queensland Radioactivity Laboratory (Jona and Vondracek 2013). Batched Online Laboratories are very reliable, since the user interaction with the lab equipment is limited and highly controlled by the RLMS framework. Interactive experiments are also supported, but with limited functionalities at the present moment. The Experiment Dispatcher is depicted in Fig. 1.4.

The relaying service of the Experiment Dispatcher is an essential functionality to transfer messages to the laboratory equipment and support an ubiquitous deployment of remote experimentation. This approach allows a laboratory equipment to reside at any network, even behind NATs, as long as Internet connectivity is provided. In that sense, it shares some characteristics of a peer-to-peer network.

There exist platforms that provide message routing in real time to devices connected via intermittent Internet connections. These are the so-called Internet of things platforms or middleware. An example of a commercial solution is Amazon IoT platform (https://aws.amazon.com/iot/) that also employs a publish-subscribe mechanism and supports HTTP, WebSockets and the Message Queue Telemetry Transport (MQTT) protocol, a machine-to-machine lightweight publish/subscribe messaging transport (MQTT 2014). However, the Online Laboratory field of application is a very specialised one, and these commercial platforms are not tailored to comply with the functional requirements of most systems, such as integration with RLMSs.

### *1.3.2 The Gateway4Labs System*

The Gateway4Labs is an initiative led by the University of Deusto, Spain, to facilitate the integration of Online Laboratories in different learning tools such as LMSs, PLEs and CMSs (Ordua et al. 2015). It attempts to provide a unifying centralised software framework to a level of interoperability between the lab management and learning management layers. As pointed out (Sancristobal Ruiz et al. 2014), there are different ways to integrate Online Laboratories with learning tools; however, most implementations are ad hoc and tailored to a specific system. The main motivation for that is the fact that several functionalities implemented by RLMSs and LMSs are duplicated (Ordua et al. 2015), such as user management and user tracking.

The Gateway4Labs system is a middleware that provides a centralised component for the integration of Online Laboratories and learning tools such as LMSs (Ordua et al. 2015). Support for different RLMSs is achieved by means of a plug-in-based architecture. A plug-in wraps the authentication mechanism with a particular system (e.g. Online Laboratories, RLMSs). Consumer tools can interact with Gateway4Labs via three different interfaces, namely, via a HTTP RESTful interface, via IMS-LTI or via OpenSocial. In the case of LTI, the Gateway4Labs middleware handles the LTI launch request and calls the Online Laboratory system requesting the launch of a client application. To launch an application, it might have to authenticate against the Online Laboratory system, if the last one requires so. According to the LTI security model, tool providers and consumers must exchange out-of-band a permanent launch link and a credentials necessary to launch the application on the remote system. LTI compatibility ensures that Gateway4Labs can be used by adopters of a large range of LMS users, assuming they implement the LTI interface.

In the context of the Go-Lab project (de Jong et al. 2014), Gateway4Labs offers the software framework that allows for the integration of third-party Online Laboratories into the Go-Lab ecosystem. The Go-Lab system uses the OpenSocial API, a specification originally developed by Google to allow third-party trusted applications to run in a container hosted by other Web applications. Gateway4Labs became an essential tool to ensure a more lightweight integration of external online laboratory systems with Go-Lab.

### *1.3.3 The Go-Lab Smart Device Paradigm*

Go-Lab (Global Online Science Labs for Inquiry Learning at School) is a European Commission co-funded project that aims at creating a European-wide federation of Online Laboratories and the pedagogical framework to allow for their effective use by secondary school teachers to enrich classroom experience as well as the learning activities out-of-class. Go-Lab is a European collaborative project co-funded by the European Commission in the context of the Seventh Framework Programme with 18 partner organisations from 12 countries.

Go-Lab proposes a new paradigm to facilitate the reuse and sharing of laboratory equipment and user interface components (widgets) by defining laboratory equipment as smart devices. The smart device paradigm aims to decouple client and server by defining interfaces between them and enabling thereby their easy integration with other third-party services. As pointed out by Salzmann et al. (2015), it originates from the RFID and sensor world, where information (metadata) is added to the device (therefore smart device). This information can be the data range of the sensor, the measured unit, etc. This metadata contains the information necessary for a hypothetical client application to adapt itself to interact with the sensor or actuator in question.

Instead of providing a monolithic interface, smart device paradigm decomposes the functionalities of the Online Laboratory and specifies its interfaces in terms of sensors and actuators, each one with well-defined interfaces (Salzmann et al. 2015). Although not a requirement, Web browsers are the typical environment to render the user interface of the smart device, preferably with HTML5 and JavaScript, due to their cross-platform support. The Go-lab Smart Device specification is divided into different parts that define the behaviour of the smart device and how to interact with it. The specification defines the transport protocols used by the client applications to interact with the smart device, the message schema used, the schema of the metadata that carries the description of the smart device sensors and actuators and a description chosen to describe the sensors and actuator services. This is depicted in Fig. 1.5.

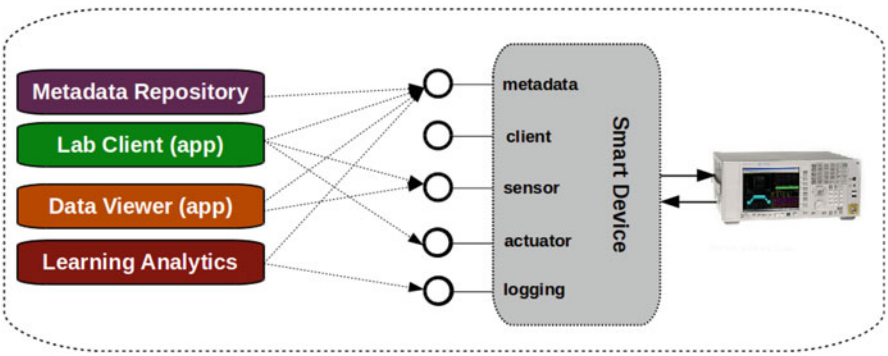


**Fig. 1.5** Different clients consuming a smart device service (Salzmann et al. 2015)

The specification defines WebSocket (Fette and Melnikov 2011) as the transport protocol for the messages sent to and received from the smart device sensors and actuators. According to Salzmann et al. (2015), the decision towards WebSockets is justified by its asynchronous nature. The protocol allows for a bidirectional full-duplex communication channel. Clients can send messages to a smart device server, which can also send data to the client application asynchronously. This eliminates the need for the client application to perform long polling when the clients wants to check on the status of an asynchronous request.

The Go-Lab Smart Device specification for Online Laboratories has served as a draft for the IEEE P1876 (IEEE Networked Smart Learning Objects for Online Laboratories) working group (IEEE-SA 2015). The IEEE P1876 focuses additionally in other aspects of Online Laboratories and learning objects in general, such as defining methods for linking learning objects to design and implement smart learning environments (IEEE-SA 2015).

## 1.4 Conclusions and Trends Towards a Common Architecture

The advancements brought by the development of RLMSs fostered numerous cooperation initiatives between different Online Laboratory developer groups. As the community around RLMSs grew, we observed the development of segmented clusters, of adopters of a specific RLMS. If on one side it was becoming easier to share Online Laboratories among systems within the same RLMS, on the other side, sharing these systems across different RLMS was not a trivial issue, as the APIs and interfaces used to communicate different components (e.g. laboratory clients and servers, booking services, experiment data retrieval) were not compatible. Furthermore, this incompatibility was not limited to the APIs, but spanned from lower level communication layers (e.g. hardware interfaces) to higher layers of abstraction, such as the metadata schemes and the terminologies used. For example, even terms that in a first glance appear to be of trivial understanding, such as “experiment”, had different interpretations among different RLMSs. As a consequence, several opportunities for collaboration and sharing of remote experimentation were left unexplored due to technical constraints. When this problem became more apparent, some initiatives, like the Global Online Laboratory Consortium (GOLC 2012), were started aiming to address the incompatibility between different systems. The work carried out by GOLC members was mainly concentrated in two different pillars, namely, technical and educational. As a result, an interoperability API (Lowe et al. 2015) and a metadata schema were proposed. The interoperability API aimed at defining an API for data exchange between different RLMSs that would enable these systems to share Online Laboratories. The GOLC metadata schema was a joint effort of GOLCs technical and education committees and aimed at creating different metadata profiles and defining the semantics between different resources in a Remote Laboratory system (Richter et al. 2012).

The numerous initiatives and frameworks presented in the previous sections are a testimonial for the great efforts spent with the development, deployment and usage of Online Laboratories. All these initiatives, such as the Global Online Laboratory Consortium, the standardisation efforts and the numerous research groups, contributed to many advancements in the field of Online Laboratories and software architectures for their deployment and federation. However, until the present moment, no trend towards a convergent software architecture is observed. Instead, RLMSs continue to follow independent paths. Current trends show that the role of RLMSs is changing. This change is mainly driven by the necessity to seamlessly include Online Laboratories into a learning activity, which is not in the scope of RLMSs. As pointed out by Sancristobal Ruiz et al. (2014), a possible solution is packing the virtual and Remote Laboratories within content packages that comply with e-learning standards such as IMS content packaging (IMS-CP) or Sharable Content Object Reference Model (SCORM), since these standards are supported by the majority of LMSs.

The IMS Global Learning Consortium also provides since 2010 the LTI (Learning Tools Interoperability) specification to integrate third-party tools (usually remotely hosted by a tool provider) into a tool consumer such as a LMS. This is the approach used with the Gateway4Labs initiative (Sect. 1.3.2). These different initiatives and projects show that RLMSs are being reduced to a set of services, instead of a Web application rendering user interfaces. For example, Colbran and Schulz (2015) pointed out with a new implementation of the iLab Shared Architecture that when the RLMS is reduced to a set of services, lab clients can reside anywhere on the Internet such as in Learning Management Systems. In this way, the developer can modify the behaviour of the RLMS in a programmatically way.

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