Cyber-Physical Laboratories in Engineering and Science Education

Michael E. Auer • Abul K.M. Azad
Arthur Edwards • Ton de Jong
Editors

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Springer

Editors
Michael E. Auer
Carinthia University of Applied Sciences
Villach, Austria

Abul K.M. Azad
Northern Illinois University
DeKalb, IL, USA

Arthur Edwards
University of Colima
Colima, Mexico

Ton de Jong
University of Twente
Enschede, The Netherlands

ISBN 978-3-319-76934-9 ISBN 978-3-319-76935-6 (eBook)
https://doi.org/10.1007/978-3-319-76935-6

Library of Congress Control Number: 2018938392

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Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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.

Carinthia University of Applied Sciences, Villach, Austria	Michael E. Auer
Northern Illinois University, DeKalb, IL, USA	Abul K.M. Azad
University of Colima, Colima, Mexico	Arthur Edwards
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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