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***Abstract*—Remote laboratories play an important role in modern education. Because of this, a multitude of different protocols and systems for building and integrating remote laboratories have been developed over the last years. This Paper analyses these different protocols and systems (SCORM / xAPI, IMS-LTI, IEEE 1876-2019, IVI / VISA, OPC-UA, Weblab-Deusto / LabsLand, GOLDi-Labs) and sorts them into different layers to build a protocol stack for implementing remote laboratories, accompanied by some examples of what is currently possible to implement. A gap in the protocol stack was identified between *Controller* and the whole *Laboratory* where no standardised protocol exists. Suggestions for the requirements of such a protocol are laid out. The new possibilities with such a protocol are presented by showing examples of new types of remote laboratories, followed by a short discussion of problems not yet solved by such a new protocol.**

***Index Terms*—Laboratories, remote laboratories, student experiments**

I. Introduction

In their studies, engineering and natural sciences students are expected to not only learn the theoretical background of the topics in their curriculum, but also to gain a lot of hands-on expertise [1]. Traditionally, these skills have been taught in real, physical laboratories with physical access to the students, but lately the research shifted to non-traditional laboratories such as virtual and remote laboratories [2].

Depending on the discipline, traditional laboratories include real machinery such as milling machines for mechanical engineers [3], to-scale models of machinery such as model conveyor systems [4] or building automation setups for automation engineers [5], chemistry labs with a distillation apparatus for students of chemistry [6], experiments using gaussian laser beams for physicists [7], micro-controller systems for computer scientists [8], and many more.

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Within a pandemic situation such as COVID-19, it is hard for universities to provide physical access to real laboratories in order to obey the hygienic rules set by the government [9], [10]. To solve this problem, the idea is to give access to laboratories remotely. Because the student is not on site, the experimental setup must therefore be visible as well as controllable from the outside. Such remote laboratories allow the acquisition of skills traditionally associated with real laboratories at the same or even a higher rate [2]. This follows a larger trend of building remote laboratories due to the efforts of digitisation in German higher education [11].

In this Paper, the current stack of technologies for remote laboratories is analysed. The goal is to see which problems might exist in implementing remote laboratories and where potential gaps for remote laboratories can be found. In the second Section, current protocols used for remote laboratories are presented. Those protocols are then compared, together with some examples of how these protocols can be used for remote laboratories. The fourth Section analyses gaps in the current protocol stack. The paper ends with a conclusion and outlook.

II. Current Protocols and Systems

This Section aims to give an overview over current standards and protocols used for remote laboratories. The focus is on higher level protocols and neither the wiring of the hardware nor the low-level communication to the hardware (like I2C or low-level TCP).

A. SCORM / xAPI

The *SCORM (Sharable Content Object Reference Model)* [12] is a file format which allows using the same learning objects in multiple learning management systems. It defines metadata for describing the learning data, how to pack the learning content (organised as *Shareable Content Objects* or SCO for short) into a single file as well as how the learning content can communicate to the learning management system. SCORM is widely supported by many systems [12]. However, there is some criticism about SCORM [13]: Since each SCO is a complete unit and SCO should be independent of each other, combining multiple of those SCO to a consistent course is often difficult (especially if those SCO were developed by different authors).

The *xAPI* (also referred as the *Tin Can API*) [14] was developed by the same group as SCORM. The standard allows learning activities to send so called *activity statements* to learning management systems, with each activity statement consisting of an *actor* (e.g. a student), a *verb* (e.g. measure) and an *object* (e.g. temperature). Additional properties (both predefined and new ones) can be used. However, since the standard is quite flexible, it is hard to define a unified vocabulary across multiple learning resources [15].

It is important to note that both, SCORM and xAPI, are developed as general purpose standards. While both allow to use remote laboratories in learning management systems, they are not specifically designed for remote laboratories and most likely need an other protocol for the actual communication to a remote laboratory (for an example, see [16]).

B. IMS-LTI

Learning Tools Interoperability (LTI) [17] is a specification for integrating tools and other content in learning management systems developed by the *IMS Global Learning Consortium*. The basic idea of LTI is to view learning resources as services, which can be called from learning management systems through a HTTP / REST API [18] and authentication through *OAuth* [19]. IMS-LTI has proven to be flexible enough to integrate different learning activities into different learning management systems such as serious games [20] or laboratories [21] without needing any adaption to different learning management systems.

C. IEEE 1876-2019 / IEEE 1484.12.1-2002

The IEEE standard 1484.12.1-2002 [22] (including correction [23]) enables developers of learning resources to describe them based on various metadata. These include general information (e.g. title, language, structure), technical information (e.g. format, size), educational information (e.g. interactivity level, typical age range) and many more. A new, updated release of this standard was published in 2020 [24].

Based on 1484.12.1-2002, an extended IEEE standard IEEE 1876-2019 [25] was created. This standard focuses on laboratories and how those could be viewed as interactable smart objects. In this standard, the metadata structure of the laboratory itself as well as its APIs is defined. In addition, vocabulary for *xAPI* (see above) is defined.

The standard 1876-2019 allows the implementation of many different laboratories. However, this also means that every lab owner could write the API in a different way. There are a few predefined services, but they only allow access to basic meta information (e.g. a sensor service allows getting meta data of all services). It is important to note that the laboratory is seen as a single unit.

D. IVI / VISA

The *IVI (Interchangeable Virtual Instrument)* specification [26] is a standard for developing drivers for instruments and accessing them through a unified API. Originally, instruments can be accessed through *ANSI-C* or *Component Object Model (COM)* [27], although newer versions of the standard also allow the access through the *.NET framework* [28] or TCP [29]. This allows the replacement of instruments of the same class without changing the software using those instruments, i.e. changing one oscilloscope with another oscilloscope. The IVI standard includes API definitions for a number of instrument classes, new classes might be added to the specification [30]. Generally, an IVI driver can be used for direct communication to the device only, except for TCP/IP devices it can not be used for remote access to devices.

In a similar vein, the *VISA (Virtual Instrument Software Architecture)* specification [26] (developed by the same foundation as the IVI standard) gives a unified API for devices connected through various bus systems like *VXI*, *GPIB*, or *IP/TCP*. It is possible to use IVI devices with VISA [31]. Again, the focus of VISA is the direct device communication.

E. OPC-UA

The *OPC Unified Architecture (OPC-UA)* [32] is an *International Electrotechnical Commission (IEC)* standard that allows network access to data in an object oriented way. There are different, more specific standards which provide models for specific technologies (e.g. for *BACnet* or programmable logic controller) [33]. For remote laboratories, OPC-UA can be used to build virtual representations of hardware models, so called digital twins, and thus make the state of hardware digitally available [34].

F. WebLab-Deusto / LabsLand

WebLab-Deusto [35] is a remote laboratory management system developed as open source software by the *University of Deusto*, Spain. It is open-source and aims to provide a set of APIs for developing new remote laboratories. Furthermore it includes user and experiment management in the form of permissions, user-tracking, scheduling, and more. It also allows to share and use remote laboratories developed on top of its set of APIs, which are flexible enough to even integrate systems like computer games [36] or existing systems such as *VISIR* [37] into WebLab-Deusto. The system supports a wide range of different experiments, ranging from setups comprised of entirely real hardware to completely virtual laboratories. In general, it seems like WebLab-Deusto is perceived well by students [38]. *LabsLand*[1] [39] is a commercial version of WebLab-Deusto which allows the sharing of laboratories across different institutions.

G. GOLDi-Labs

GOLDi-Labs [40], [41] is a hybrid online laboratory developed at the *Technical University Ilmenau*, Germany. It focuses on experiments around computer science and embedded systems. The system allows the execution of experiments comprised of one control unit (e.g., a micro controller) and one electromechanical model (e.g., a 3-axis-portal). This provides

[1] https://labsland.com/en

a broad range of possible combinations as any control unit can be mixed with any electromechanical model. The architecture aims to make any model or control unit replaceable by a simulation forming a hybrid remote lab or just a simulation.

GOLDi is a monolithic architecture integrating its own lab management system. The system can be set up at multiple locations and institutions and allows for a basic sharing of experiments between them. However the system can not be used outside of the original application, because all components are tightly coupled. Apart from the experimentation aspect of the system, GOLDi also includes interactive learning objects [42], [43], which are purposely built to help the students prepare an experiment.

III. Comparison

In this Section, the different protocols are compared in order to see whether they are enough for remote laboratories or if there is still a gap in need to be filled.

A. Ordering Protocol Layers

For comparison, all protocols can be ordered in different layers for which they are designed for. This means that there is a need to define the layers needed for remote laboratories. Based on [25], five layers were identified:

1) The lowest level is the **hardware** itself. This mainly includes the hardware found in laboratories as well as any peripheral devices needed.
2) The next layer is the **controller** (often built through software) which communicates with the hardware devices. On this layer, it is assumed that each device is still separated from each other.
3) Since a single piece of hardware is often not useful for experimentation, there is a need to combine multiple hardware controllers to get a usable *laboratory*.
4) On this layer, the laboratory is wrapped into a meaningful task for learners. This way, we get **learning objects**. This layer is only relevant in a learning scenario.
5) At the last stage, learning objects are then incorporated into a **learning management system**, which allows to include them into full courses, if desired. This layer is only relevant in a learning scenario.

In comparison to [25], we added a new layer *controller* as well as the communication between *controller* and *laboratory*. Our reason for this is as follows: We have seen (cf. [44] Section 2.1: Online Laboratories) that many remote laboratories are used for similar tasks, i.e. controlling a system by user defined algorithms and programs or taking measurements in accordance to varying input parameters. However, even if the task is the same, most remote laboratories differ widely in their used hardware. By introducing another layer between the laboratory and the actual hardware these differences can be abstracted and the overall experiment setup can be reused in the laboratory layer.

At the same time, as the hardware is abstracted in what is essentially an hardware abstraction layer, it gets easier to share remote laboratory hardware either virtually or physically and embed it in other remote labs, which is not possible when there is a tight coupling between the laboratory layer and the hardware itself.

Furthermore, as seen in the aforementioned *GOLDi* remote laboratory, an experiment might not be directly coupled to a single hardware component. For example, each experiment can contain different hardware modules, that are configured and coupled by the user in advance of an experiment. A similar but tighter integrated variant of this modularised hardware is *VISIR* [45], where the electronic hardware gets connected by a switching matrix on site.

In all cases, the introduction of a controller layer facilitates the decoupling of the experiment logic from the hardware control. It therefore enables a more flexible configuration as well as allows the usage of spatially separated hardware modules in the same experiment. This is key to the new class of remotely coupled experiments which enable new ways of remote and local experimenting in the form of hybrid take home labs [46].

Based on these layers, the different protocols / systems can now be matched to the different layers. The result, as can be seen in figure 1, is as follows:

A. **SCORM / xAPI:** Since SCORM / xAPI is used to communicate between learning objects and learning management systems, it can been seen between 4) and 5).
B. **IMS-LTI**: Similar to SCORM / xAPI, IMS-LTI allows the integration of artifacts into learning management systems and thus must be sorted between 4) and 5).
C. **IEEE 1876-2019:** The IEEE 1876-2019 allows the usage of laboratories as learning objects and is thus between 3) and 4).
D. **IVI / VISA:** Those two standards describe the low-level communication to hardware and is thus in most cases (even if remote communication is possible) between 1) and 2).
E. **OPC-UA**: Since OPC-UA can be used to expose the state of physical hardware devices through network, it should be placed between 1) and 2).
F. **WebLab-Deusto / LabsLand:** Both systems allow the usage of pre-configured laboratories for teaching while not providing a full learning management system and as such should be placed between 3) and 4).
G. **GOLDi-Labs:** For GOLDi-Labs, the situation is a bit more complicated. Mainly, it allows the communication to a laboratory and is thus between 3) and 4). Although the laboratory always consists of two devices (one control unit, one model), we should not put GOLDi between layer 2) and 3) since it uses no defined protocol and is limited to a setup of exactly one contol unit / model.

By sorting the protocols / systems this way, it can be seen that there are protocols for each layer except between the controller and the laboratory. To be more precise, there is no standardised way how different instruments in a laboratory can communicate to each other without seeing each one as a seperate laboratory. GOLDi-Labs only partially allows this,

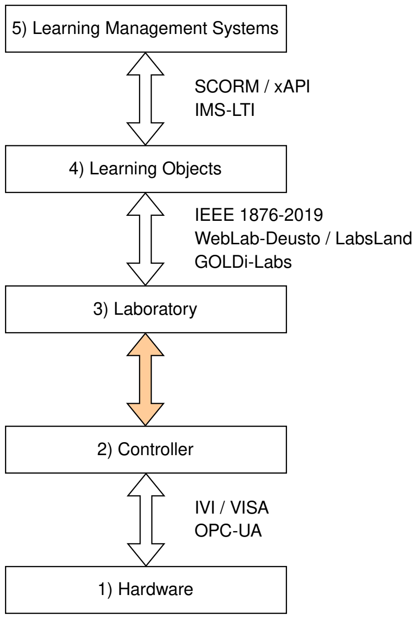

Fig. 1. Ordering protocols/standard on different communication layers for remote laboratories. Highlighted layer connection has no standardised protocols. Inspired by [25] with added layers.

but it is limited to only two devices (exactly one control unit and one model).

B. Currently Possible Use Cases

In the current status, some use cases—or scenarios—can be realized already. Others that need a new protocol like proposed in this paper are then described in Section IV-A.

Among the currently possible scenarios are the following:

- Purely virtual experiments. They can be executed as simulations that run on a university server or even the user's machine. An example for this is *LogicCircuits* [47], [48], a simulator for teaching and designing digital circuits.
- Laboratories with remote access, where the inner workings of a laboratory is usually proprietary. Only specifically designed experimental setups are accessible this way. The configurability and adaptability are limited. An example for this is *GOLDi*, described in Section II-G.
- A combination of virtual and real laboratories, but still only on proprietary systems and with very limited extendability.

IV. Open Gaps in Protocols

If we look at the aforementioned Figure 1, it can be seen that currently, there is no standard for the communication between the controller of a device and the laboratory as a whole. This is most likely due to the fact that most laboratories, according to [44], are built from the ground up. Thus, it can be speculated that these laboratories are built as a whole and do not differentiate between the different devices used in the laboratory. There are some more flexible laboratories like the *GOLDi* system (see Section II-G) which allows the combination between a control unit and a model, but still are limited to only two devices at a time.

Therefore, we suggest the development of standardised protocols for inter-device communication in laboratories. Such a protocol should have enough flexibility to allow connecting device controllers in different constellations and thus enable the re-usage of hardware devices for many different protocols. This would allow the creation of a multitude of different experiments while reducing costs due to device re-use. Optimally, such a protocol would be able to communicate between different physical locations to increase the number of devices even more.

Currently, such a protocol is developed by the authors in the context of the project CrossLab [49]. CrossLab is a joint project of four German universities building flexible laboratories across different disciplines. Part of the project is the development of an inter-device, inter-institution protocol for experiments, which is intended to close the discovered gap. The project is still in an early state as of the publication of this paper.

A. Suitable Scenarios for New Protocol

This Section highlights some new scenarios which could be implemented using a new protocol between *controller* and *laboratory* which are not (easily) possible without such a protocol.

1) Controller for a Chemical Experiment: Imagine two institutes want to build an experiment together: One institute experiment provides a chemical model, the other provides some kind of micro controller to control the device. With the current situation, both institutes need to agree on a (proprietary) protocol. If a third institute then wants to join the experiment, it has to manually program an interface to that specific (proprietary) protocol.

If we have a protocol as suggested, each of the institutes would instead only need to implement this standard. The communication would work automatically without first defining an own protocol. This is especially important if you want to add many more institutes as potential participants.

2) IT-Security Laboratory: An IT-security laboratory is another interesting example, where the new protocol could enable more rewarding learning experiences. The students would be assigned to a virtual machine equipped with the necessary tools to hack into another system. After successfully entering the target system, the students could be granted access to another physical device. This device can either be used as a simple reward for the student's accomplishment of successfully infiltrating the target system (e.g. a robot arm which can then be controlled to grab a flag) or it could be used as a further challenge (e.g. a physical hardware like a router which must be hacked by the students). In this case, the new protocol allows for greater flexibility when creating unique exercises for the students, while also simplifying the process of including physical devices by providing clear interfaces for the participating devices.

3) Hybrid-Take-Home Labs: In hybrid-take-home labs [46] students are allowed to take a subset of the hardware required for the experiment home with them. One example would be a simple microcontroller-board with the necessary interfaces to connect to a remote model. This, when compared to traditional remote labs, enables a more immersive learning experience for the students since they can now physically interact with parts of the system. Furthermore it also keeps some of the benefits of remote labs since the controlled models do not necessarily need to be located at the university but could also be located at a partnering institution.

B. Physical and Organisational Limits

When thinking about remotely coupled experiments where parts of the experiment are spatially distributed, we naturally have to think about latency in information transmission. Lets take for example a remote experiment comprised of a control unit in Germany and a quadrocopter in Australia. The theoretical lower limit of latency is calculated by the distance and the speed of light: $\Delta t_{\min} = \frac{\Delta s}{c} = \frac{14\,500\,\mathrm{km}}{299\,792\,458\,\mathrm{m\,s^{-1}}} \approx 48\,\mathrm{ms}$. The packet based internet infrastructure will only add to this delay. The loop time, which is the time in-between two updates of the motor speed is usually below $1\,\mathrm{ms}$ [50]. It becomes obvious that such a system can not be controlled over this distance, which is a physical limit and can therefore not be covered by any architecture.

There might be also problems resulting from restrictive network policies either by individual entities or even whole countries. E.g. China aggressively filters network packets and drops all SSL packets using encrypted server name indications [51]. Similar problems might arise when institutions such as schools or universities deploy firewalls [52], [53] or similar network security technology. When a remote laboratory is affected by such policies / technologies, there is a chance that remote laboratories do not work. The addition of the new controller layer does not help in that case and, depending on how it is implemented, might increase the risk of blocking, because the network communication might get more complicated.

Another problem that is not solved by the new controller layer is that it is still cumbersome to create good laboratory tasks, which should be embedded in a didactic context. Ideally, this would be at least a semi-automated process that can map existing laboratory equipment to viable laboratory tasks, which should be in *constructive alignment* [54] to the respective learning goals. On the contrary the new layer allowing for a more flexible approach to combine laboratory equipment increases the complexity in finding a good task. However, a more flexible ecosystem might result in a better alignment of learning goals and remote laboratory.

V. Conclusion & Outlook

In this Paper, current protocols and systems were presented which can be used to build remote laboratories (namely SCORM / xAPI, IMS-LTI, IEEE 1876-2019, IVI / VISA, OPC-UA, Weblab-Deusto / LabsLand and GOLDi-Labs). These protocols were sorted on a five-layer protocol stack (hardware, controller, laboratory, learning objects and learning management system). Through this, a gap was identified between *controller* and *laboratory*.

Based on this, we suggest the development of a new protocol. Such a protocol should focus on inter-device communication or even allow communication between different physical locations. One contender for such a protocol is currently developed by the CrossLab project [49].

In addition, other, non-technical problems were discovered. Remote protocols might suffer from physical limitations (e.g. latency), network policies or didactic challenges. We suggest that future research should also be focused on these non-technical problems.

References

[1] D. Satterthwait, "Why are 'hands-on' science activities so effective for student learning?" *Teaching Science*, vol. 56, no. 2, p. 7–10, 2010. [Online]. Available: https://search.informit.org/doi/10.3316/aeipt.182048

[2] J. R. Brinson, "Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research," *Computers & Education*, vol. 87, pp. 218–237, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360131515300087

[3] R. F. Schkoda, T. A. Schweisinger, and J. R. Wagner, "An improved undergraduate mechanical engineering laboratory structure and curriculum: Design and assessment," *International Journal of Mechanical Engineering Education*, vol. 40, no. 3, pp. 182–196, 2012. [Online]. Available: https://doi.org/10.7227/IJMEE.40.3.3

[4] H. Bassily, R. Sekhon, D. E. Butts, and J. Wagner, "A mechatronics educational laboratory – programmable logic controllers and material handling experiments," *Mechatronics*, vol. 17, no. 9, pp. 480–488, 2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957415807000670

[5] M. d. C. Currás-Francos, J. Diz-Bugarín, J. R. García-Vila, and A. Orte-Caballero, "Cooperative development of an arduino-compatible building automation system for the practical teaching of electronics," *IEEE Revista Iberoamericana de Tecnologias del Aprendizaje*, vol. 9, no. 3, pp. 91–97, 2014.

[6] C. J. Donahue, "Fractional distillation and gc analysis of hydrocarbon mixtures," *Journal of Chemical Education*, vol. 79, no. 6, p. 721, 2002. [Online]. Available: https://doi.org/10.1021/ed079p721

[7] B. M. Zwickl, N. Finkelstein, and H. J. Lewandowski, "The process of transforming an advanced lab course: Goals, curriculum, and assessments," *American Journal of Physics*, vol. 81, no. 1, pp. 63–70, 2013. [Online]. Available: https://doi.org/10.1119/1.4768890

[8] R. B. Reese and B. A. Jones, "Improving the effectiveness of microcontroller education," in *Proceedings of the IEEE SoutheastCon 2010 (SoutheastCon)*, 2010, pp. 172–175.

[9] M. P. A. Murphy, "Covid-19 and emergency elearning: Consequences of the securitization of higher education for post-pandemic pedagogy," *Contemporary Security Policy*, vol. 41, no. 3, pp. 492–505, 2020. [Online]. Available: https://doi.org/10.1080/13523260.2020.1761749

[10] K. A. A. Gamage, D. I. Wijesuriya, S. Y. Ekanayake, A. E. W. Rennie, C. G. Lambert, and N. Gunawardhana, "Online delivery of teaching and laboratory practices: Continuity of university programmes during covid-19 pandemic," *Education Sciences*, vol. 10, no. 10, 2020. [Online]. Available: https://www.mdpi.com/2227-7102/10/10/291

[11] T. R. Ortelt, C. Terkowsky, A. Schwandt, M. Winzker, A. Pfeiffer, D. Uckelmann, A. Hawlitschek, S. Zug, K. Henke, J. Nau, and D. May, *Die digitale Zukunft des Lernens und Lehrens mit Remote-Laboren*. Wiesbaden: Springer Fachmedien Wiesbaden, 2021, pp. 553–575. [Online]. Available: https://doi.org/10.1007/978-3-658-32849-8_31

[12] E. R. Jones, "Implications of scorm and emerging e-learning standards on engineering education," in *2002 GSW*, no. 10.18260/1-2-620-38744. ASEE Conferences, 2002, https://strategy.asee.org/38744.

[13] O. Bohl, J. Scheuhase, R. Sengler, and U. Winand, "The sharable content object reference model (scorm) - a critical review," in *International Conference on Computers in Education, 2002. Proceedings.*, 2002, pp. 950–951.

[14] J. M. Kevan and P. R. Ryan, "Experience api: Flexible, decentralized and activity-centric data collection," *Technology, Knowledge and Learning*, vol. 21, no. 1, p. 143–149, 2016. [Online]. Available: http://link.springer.com/10.1007/s10758-015-9260-x

[15] A. Berg, M. Scheffel, H. Drachsler, S. Ternier, and M. Specht, "The dutch xapi experience," in *Proceedings of the Sixth International Conference on Learning Analytics & Knowledge*, ser. LAK '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 544–545. [Online]. Available: https://doi.org/10.1145/2883851.2883968

[16] J. P. Schardosim Simão, L. Mellos Carlos, H. Saliah-Hassane, J. B. da Silva, and J. B. da Mota Alves, "Model for recording learning experience data from remote laboratories using xapi," in *2018 XIII Latin American Conference on Learning Technologies (LACLO)*, 2018, pp. 450–457.

[17] I. G. L. Consortium, "Learning tools interoperability core specification." [Online]. Available: http://www.imsglobal.org/spec/lti/v1p3/x

[18] B. Costa, P. F. Pires, F. C. Delicato, and P. Merson, "Evaluating a representational state transfer (rest) architecture: What is the impact of rest in my architecture?" in *2014 IEEE/IFIP Conference on Software Architecture*, 2014, pp. 105–114.

[19] C. Severance, T. Hanss, and J. Hardin, "Ims learning tools interoperability: Enabling a mash up approach to teaching and learning tools," *Technology, Instruction, Cognition & Learning*, vol. 7, no. 3–4, p. 245–262, 2010.

[20] I. Perez-Colado, I. S. W. B. Prasetya, B. F. Manjón, I. Martinez-Ortiz, and M. Freire, "Simplifying serious games and analytics deployment in a virtual campus using lti and xapi," in *2020 X International Conference on Virtual Campus (JICV)*, 2020, pp. 1–4.

[21] P. Orduña, S. Botero Uribe, N. Hock Isaza, E. Sancristobal, M. Emaldi, A. Pesquera Martin, K. DeLong, P. Bailey, D. Lopez-de Ipiña, M. Castro, and J. Garcia-Zubia, "Generic integration of remote laboratories in learning and content management systems through federation protocols," in *2013 IEEE Frontiers in Education Conference (FIE)*, 2013, pp. 1372–1378.

[22] "IEEE Standard for Learning Object Metadata," *IEEE Std 1484.12.1-2002*, pp. 1–40, 2002.

[23] "IEEE Standard for Learning Object Metadata - Corrigendum 1: Corrigenda for 1484.12.1 LOM (Learning Object Metadata)," *IEEE Std 1484.12.1-2002/Cor 1-2011 (Corrigendum to IEEE Std 1484.12.1-2002)*, pp. 1–24, 2011.

[24] "IEEE Standard for Learning Object Metadata," *IEEE Std 1484.12.1-2020*, pp. 1–50, 2020.

[25] "IEEE Standard for Networked Smart Learning Objects for Online Laboratories," *IEEE Std 1876-2019*, pp. 1–57, 2019.

[26] IVI Foundation, "IVI Specifications," last accessed: 27.05.2022. [Online]. Available: https://www.ivifoundation.org/specifications/default.aspx

[27] D. Cheij, "Using interchangeable virtual instrument (IVI) drivers to increase test system performance," *IEEE Aerospace and Electronic Systems Magazine*, vol. 16, no. 7, pp. 8–11, 2001.

[28] IVI Foundation, "IVI-3.4: API Style Guide."

[29] ——, "IVI-6.1: IVI High-Speed LAN Instrument Protocol (HiSLIP)."

[30] C. Kennedy, "Development of a new interchangeable virtual instrument class specification," in *IEEE Autotestcon, 2005.*, 2005, pp. 812–819.

[31] IVI Foundation, "IVI-6.3: IVI VISA PXI Plug-in."

[32] M. H. Schwarz and J. Börcsök, "A survey on opc and opc-ua: About the standard, developments and investigations," in *2013 XXIV International Conference on Information, Communication and Automation Technologies (ICAT)*, 2013, pp. 1–6.

[33] P. Drahoš, E. Kučera, O. Haffner, and I. Klimo, "Trends in industrial communication and opc ua," in *2018 Cybernetics & Informatics (K&I)*, 2018, pp. 1–5.

[34] M. Jacoby and T. Usländer, "Digital twin and internet of things—current standards landscape," *Applied Sciences*, vol. 10, no. 18, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/18/6519

[35] P. Orduña, J. Garcia-Zubia, L. Rodriguez-Gil, I. Angulo, U. Hernandez-Jayo, O. Dziabenko, and D. López-de Ipiña, *The WebLab-Deusto Remote Laboratory Management System Architecture: Achieving Scalability, Interoperability, and Federation of Remote Experimentation*. Cham: Springer International Publishing, 2018, pp. 17–42. [Online]. Available: https://doi.org/10.1007/978-3-319-76935-6_2

[36] J. García-Zubia, J. Irurzun, I. Angulo, P. Orduña, J. Ruiz-de Garibay, U. Hernández, and M. Castro, "Developing a second-life-based remote lab over the weblab-deusto architecture," in *REV2010 International Conference on Remote Engineering & Virtual Instrumentation*, Stockholm, 2010, p. 171–176.

[37] L. Rodriguez-Gil, P. Orduña, J. García-Zubia, and D. López-de Ipiña, "Advanced integration of OpenLabs VISIR (Virtual Instrument Systems in Reality) with Weblab-Deusto," in *2012 9th International Conference on Remote Engineering and Virtual Instrumentation (REV)*, 2012, pp. 1–7.

[38] J. Garcia-Zubia, D. Lopez-de Ipina, P. Orduna, U. Hernandez, I. Angulo, and J. Irurzun, "Acceptance, usability and usefulness of weblab-deusto from students point of view," in *2008 Third International Conference on Digital Information Management*, 2008, pp. 899–904.

[39] P. Orduña, L. Rodriguez-Gil, J. Garcia-Zubia, I. Angulo, U. Hernandez, and E. Azcuenaga, "LabsLand: A sharing economy platform to promote educational remote laboratories maintainability, sustainability and adoption," in *2016 IEEE Frontiers in Education Conference (FIE)*, 2016, pp. 1–6.

[40] K. Henke, T. Vietzke, H.-D. Wuttke, and S. Ostendorff, "GOLDi – Grid of Online Lab Devices Ilmenau," *International Journal of Online and Biomedical Engineering (iJOE)*, vol. 12, no. 04, p. 11–13, 2016. [Online]. Available: https://online-journals.org/index.php/i-joe/article/view/5005

[41] K. Henke, T. Vietzke, R. Hutschenreuter, and H.-D. Wuttke, "The remote lab cloud "goldi-labs.net"," in *2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REV)*, 2016, pp. 37–42.

[42] K. Henke, T. Fäth, R. Hutschenreuter, and H.-D. Wuttke, "GIFT - an integrated development and training system for finite state machine based approaches," in *Online Engineering & Internet of Things*, M. E. Auer and D. G. Zutin, Eds. Cham: Springer International Publishing, 2018, pp. 743–757.

[43] K. Henke, J. Nau, R. Hutschenreuter, R.-N. Bock, and H.-D. Wuttke, ""hidden" integration of industrial design-tools in e-learning environments," in *Cross Reality and Data Science in Engineering*, M. E. Auer and D. May, Eds. Cham: Springer International Publishing, 2021, pp. 437–455.

[44] J. Nau, J. Richter, D. Streitferdt, K. Henke, R. N. Bock, and A. Mitschele-Thiel, "On the development of a unified online laboratory framework," in *Online Engineering and Society 4.0*, M. E. Auer, K. R. Bhimavaram, and X.-G. Yue, Eds. Cham: Springer International Publishing, 2022, pp. 10–22. [Online]. Available: https://doi.org/10.1007/978-3-030-82529-4_2

[45] I. Gustavsson, J. Zackrisson, L. Håkansson, I. Claesson, and T. Lagö, "The VISIR project – an Open Source Software Initiative for Distributed Online Laboratories," in *2007 International Conference on Remote Engineering and Virtual Instrumentation (REV)*, 2007, pp. 1–6.

[46] J. Nau, K. Henke, and D. Streitferdt, "New ways for distributed remote web experiments," in *Learning with Technologies and Technologies in Learning*, M. E. Auer, A. Pester, and D. May, Eds. Cham: Springer International Publishing, 2022, unpublished.

[47] J. Haase, "Flipped Classroom with Digital Circuits: An HTML5-based Interactive Simulation Tool," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 307–312.

[48] ——, "An HTML5-based Interactive Simulation Tool for Teaching and Self-Study of Electronic Circuits," in *2018 12th European Workshop on Microelectronics Education (EWME)*, 2018, pp. 41–44.

[49] Crosslab consortium, "Crosslab project, home page." [Online]. Available: https://cross-lab.org/

[50] R. I. Marasigan, Y. D. Austria, J. B. Enriquez, L. Lolong Lacatan, and R. M. Dellosa, "Unmanned Aerial Vehicle Indoor Navigation using Wi-Fi Trilateration," in *2020 11th IEEE Control and System Graduate Research Colloquium (ICSGRC)*, 2020, pp. 346–351.

[51] D. L. K. Bock, "Exposing and Circumventing China's Censorship of ESNI," 2020.

[52] A. Hramiak and H. Boulton, "Escalating the use of web 2.0 technology in secondary schools in the united kingdom: Barriers and enablers beyond teacher training," *The Electronic Journal of e-Learning*, vol. 11, no. 2, p. 91–100, 2013.

[53] M. Huang, W. Luo, and X. Wan, "Research on network security of campus network," *Journal of Physics: Conference Series*, vol. 1187, no. 4, p. 042113, 2019. [Online]. Available: https://doi.org/10.1088/1742-6596/1187/4/042113

[54] J. Biggs, "Enhancing teaching through constructive alignment," *Higher Education*, vol. 32, no. 3, p. 347–364, 1996. [Online]. Available: https://doi.org/10.1007/BF00138871