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***Abstract*—The flexibility and performance of digital laboratory elements such as remote labs, VR/AR or simulations summarized under the term cross-reality labs (CrossLabs), can be seen with the development in last and has been proven under the pandemic situation. Even though the potential of cross-reality labs is obvious referring to availability and flexibility for the students, these didactic solutions remain isolated at universities as well as for individual users. The implementations are mostly so rigid that the individual didactic objectives are not interchangeable between different universities and disciplines, hence there is a lack of interoperability. The CrossLab project seeks to design didactical, technical, and organizational solutions for open digital lab objects linking student-centered teaching and a cross-university learning environment. Of importance thereby is the fact that teaching is not adaptable to the digital laboratory, but the laboratories are adaptable to the requirements of the teaching-learning setting. The four project partners are working on a cross-type and cross-element mixture of diverse types of laboratories for cross-disciplinary use in a cross-universities settings. Thereby, the project leans on existing digital laboratories in various disciplines to create an open teaching and learning environment which can be adapted to the needs of students and to provide students with the skills necessary for future working scenarios.**

***Index Terms*—laboratories, cross-disciplinary, cross-university, competence oriented, student centered**

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I. Motivation

All over the world, laboratory courses are an integral part of scientific, engineering, and technical degree programs [1]. Laboratories are of crucial value in students' education [2] and are thus imperative both the application-oriented and research-oriented degree programs at all levels of study. During this phase of training, students acquire a more in-depth understanding of theoretical knowledge through hands-on experience [3] and gain a vivid perspective on the work environment in their chosen profession. However, providing the necessary infrastructure is an enormous challenge in terms of cost, especially with in parts declining student numbers in STEM subjects, due to the high maintenance and acquisition costs for the laboratory equipment.

In the area of educational laboratory design, the following two trajectories are observable: 1) traditional knowledge-based approaches to laboratory didactic are increasingly being extended, overlaid, or entirely replaced by competency-based approaches to student-centered, problem-based, and inquiry-based learning; and 2) with the digitalization of teaching-learning settings, alternative concepts are emerging, ranging from simulated laboratory environments the use of AR-VR techniques to remote laboratories [4]. These cross-reality concepts expand the spectrum of online-supported teaching-learning labs and aim at a variable didactic teaching-learning environment for the target audience-oriented presentation of thematic relevant contents for both learners and lecturers, always focusing on the learning objective.

Using digital labs enables lectures to make experiences tangible and bypass even physical boundaries to foster students' creativity and innovation skills [5]. The fundamental elements of Industry 4.0 [6] - technical assistance, information transparency, networking, and decentralized decision-making - can be integrated into existing or new experiments using cross-reality labs.

Since access to traditional laboratories was limited during the COVID19-pandemic [7], [8], the benefits of cross-reality labs became even more apparent. The preparation of the learning content in the form of digital, interactive simulations, video recordings or via remote access, with permanent availability, opens a flexible schedule that corresponds to the individual work rhythm and level of knowledge of each student. Even though both successful implementation and didactic evaluation have been documented for varying installations in several disciplines [9], [10], all remain locally isolated within the individual university. These mostly tailor made and fixed installations cannot easily be transferred to the context (prior knowledge of the students, individual focus, scope of the assignment) at another university and are usually only accessible to a limited group of own students, which is regrettable in view of the conceptual effort and the high financial commitment.

Hence, the project CrossLab [11] aims to define the technical, didactical, and organizational solutions for open digital laboratory objects, which enables lecturers to design demand-oriented, student-centered, and freely combinable teaching materials. The *cross* in the name reflects the following three major contributions of the project:

1) **cross-types** mixture of diverse types of laboratories,
2) **cross-elements** composition of individual laboratory objects,
3) **cross-disciplines** use of digital laboratories, and
4) **cross-universities** access to digital repositories.

In addition to the conception and technical realization of the modular integration and the development of new scenarios in various STEM disciplines, the didactic concepts and organizational strategies will simultaneously be refined to ensure the wide-ranging integration of CrossLab. This paper analysis the general vision related to challenges on the technical, didactical, and organizational level and describes the ongoing activities of CrossLab partners.

A. References to the state of the art

Cross-reality labs have gone through various stages of development over the past decades. While early digital lab solutions focused on the actual application based on an individually developed web infrastructure, the trend towards a generic framework can be documented over the last 20 years. This second generation of remote labs aims to develop a generic architectural design for the infrastructure that can be used independently of the actual implementation [12]. To this end, Thames [13] has designed, among other things, a requirements catalog that evaluates aspects of scalability, security, maintainability, etc. from the point of view of modularization and standardization.

The specification of generic frameworks and interfaces laid the foundation for the third generation of remote labs, the shared labs [14]. Here, the idea of permanent availability was continued and transferred to cross-university labs. Thus, the students at partner universities were to use each other's infrastructure, which required extensions to the frameworks, especially at the administrative and organizational level, to ensure data protection, coordination of access and evaluation of the results.

All previous implementations do not achieve the CrossLab desired flexibility, as concrete learning content was usually defined once at the design stage and adjustments on the side of the configuration of the lab object as well as the user interface was/is only possible with a profound understanding of web technologies at the programming level. CrossLab aims to close this gap and thus creates a basis for more intensive use of learning goal-oriented configurable digital labs in inter-university use.

II. Requirements and Challenges

In this section, we first classify the Cross-X requirements to derive specific challenges. Based on this, the approaches to solve these challenges are described in the next section from the perspective of the partner universities.

A. Cross-Types

Considering publications on laboratory-based education, most practicals are based exclusively on a single type of setting, i.e., classical laboratories, simulations, or e.g., remote labs. CrossLab partners are convinced that a finely tuned combination of classical laboratory courses, simulations, remote labs, and VR-AR setups are essential when it comes to providing teaching content, ensuring broad accessibility, and making more effective use of labs.

In this way, students first learn the basics of a topic using simulations and then switch to a remote laboratory with their expanded knowledge. While the influencing variables are clearly definable in the simulation environment, the remote lab brings with it increasing complexity. Conversely, the student can assess the limits of a setup in the simulation, which is avoided in the real system by safety mechanisms. Final, students can perform extended experiments in the real lab. The advantage in this multi-stage chain is the systematic preparation of the students for the real laboratory. Time-consuming introductions to the basics can thus be omitted and the team can concentrate on the actual experiments - the efficiency of the learning process increases.

B. Cross-Elementes

Orthogonal to the combination of different digital lab types, the CrossLab project envisages a modularization of the individual installations. The decomposition of an experiment into individual elements creates the possibility of reproducing them in different hardware or as a simulation. For example, in a control loop, the sensors, the actual algorithm and the actuators

TABLE I
IDENTIFIED SPECIFIC CHALLENGES WHILE IMPLEMENTING THE CROSS-X GOALS

	technical	didactical	organizational
types	individual interfaces, different features	adjustment of system configuration and intended didactical learning outcomes	digital skills of lecturers
elements	seamless data exchange, real-time behavior		
disciplines	remote configurability of lab objects	specific learning perspectives	access planning, physical reconfiguration privacy, maintance and monitoring
universities	student access	different didactical profiles and formalisms	

can then be exchanged similarly to the hardware/software-in-the-loop [15] approaches. The focus of the setup can be shifted variably between fault-tolerant environmental detection or embedded programming. This allows the experiments to be tailored more closely to the specific learning objectives.

Consequently, the modules can then also be distributed to different locations. While the sensor and actuator technology is available at one location, another institution takes on the task of providing various controller architectures - which can then also be included in completely different experiments.

C. Cross-Disciplines

The third claim aims at the use of cross-X laboratories across faculty and subject boundaries. For example, laboratory installations from process engineering can be used to additionally introduce students of natural sciences, chemistry, biology to specific challenges of the system. The significant shift of didactic goals requires an adaptive laboratory configuration, student interfaces and monitoring / safety mechanisms.

Besides these advantages, clearly the expansion will enable an exchange with other disciplines and institutions. For the implementation, several things are particularly important, for one, the CrossLab labs shall be thought of in a student-centered way - didactically and technically - to strengthen the guidance towards an interdisciplinary education/understanding and, two, technical innovations concerning the configuration interface are needed (Lab-Bus).

D. Cross-Universities

The intended exchange between universities aims at a better utilization of installations, a greater variety of setups and cost savings for the individual partners. In this case, twins of remote or digital experiments could also be set up at various locations, thus ensuring an improved failure protection. To ensure cross-university use, the development of a digital infrastructure and knowledge about the technical design of individual laboratories is required. Organizational formats for rights management and a reservation system must be established for the exchange between universities. Another level that should not be forgotten is data protection and securing the provision of services and how to provide certificates of achievement for the participants.

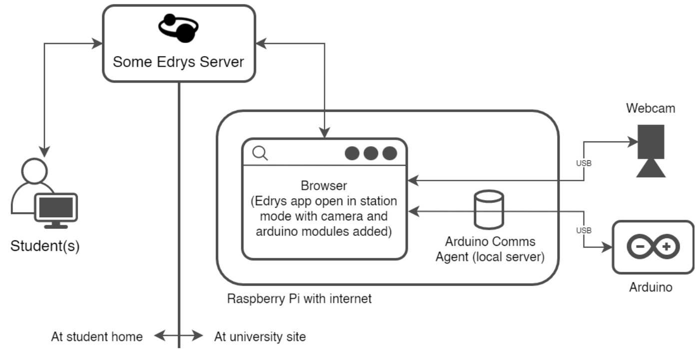

Fig. 1. Example of an Edrys installation, with one Browser running in station mode that is connected to the local hardware, and another browser in student mode (used to interact with hardware).

Tab. I summarizes the challenges arising from requirements A-D. For this purpose, we grouped them in the columns on the technical, didactic and organizational level. We have focused on the challenges that are addressed in the framework of the project.

III. CROSSLAB-IMPLEMENTATIONS AND SOLUTIONS

A. Remote Microcontroller Lab at TU Bergakademie Freiberg

One aspect of particular interest is the shareability of embedded systems without the need for complex infrastructure, server installations, and so forth. Using the Remote Microcontroller Lab, we are currently exploring the possibilities of different RemoteLab frameworks in this sense as well as ways in which micro-labs can be integrated into the idea of a larger CrossLab infrastructure. Serving as a starting point is an open-source distance learning platform – Edrys[1] – that facilitates the development and sharing of distance learning devices. What makes Edrys special is that it allows sharing a local set up only using a web browser.

A central server is still required as a starting and meeting point, but a logged in member can share their local setup/hardware just by opening a special Edrys-website that operates in ”station” mode. This website operates as a relay between the local hardware, which must be accessed/controlled by a `localhost` server, and the remote Edrys-server. A publish-subscribe system is then used to send/mirror all messages between the station and all students operating on that particular station, as depicted in figure 1.

The easy configuration and development of plugins allows us to create basic labs, which consist of an editor-[2], a terminal-[3], and webcam-module.

While this configuration is static, we can deliver different forms of didactic/educational content with our LiaScript-

[1] Website: https://edrys.org
[2] Editor: https://github.com/Cross-Lab-Project/edrys_module-editor
[3] PyXTermJS: https://github.com/Cross-Lab-Project/edrys_module-pyxtermjs

module[4]. LiaScript is a system for creating online-courses with extended Markdown-syntax (cf. [16]). Courses are treated as Open-Source projects and can be hosted and published in a distributed manner, without the need for a centralized server. Additionally, we provide plugins for LiaScript, which enable the programming of simulated Arduino-platforms directly within the browser, or to learn programming in different languages. This way, users do not have to occupy the station-hardware, but instead can run simple experiments and training in this simplified environment. Doing so, one course can contain different simulated labs and training instances programming, courses can be created and adapted for students from different disciplines and with diverse backgrounds. Beyond that, LiaScript allows translating its courses automatically into different languages (with fine-tune settings to protect course parts from translation), whereby it takes care of which parts can be translated and protects the other parts, such as code.

B. GOLDi at TU Ilmenau

The goal of the newly developed GOLDi 2.0 remote lab is to design a new generation of RemoteLab in which multiple laboratory devices can be combined in a remote lab management system. This will enable the exchange of single devices or entire experiments between institutions across university boundaries (see Figure 2). It is a generalization of the previous GOLDi RemoteLab concept (GOLDi – Grid of Online Lab Devices Ilmenau [9], [17]).

In GOLDi 2.0 the online lab will no longer be seen as a collection of monolithically constructed experiments but as a collection of laboratory devices that communicate with each other. Of course, all previous hands-on and online lab variants can still be realized with this novel approach. But it also opens completely new possibilities for experimentation [18]

- It will be possible to control a hardware model on one location with a control unit from another location within one experiment.
- It will be possible to control lab devices with hard real-time requirements remotely in an experiment via the internet by attaching a lab device responsible for the time-critical part directly to the model (e.g., a quadcopter), while the not time-critical control can be done via a remote lab element.

[4]LiaScript: https://github.com/LiaScript/module-liascript

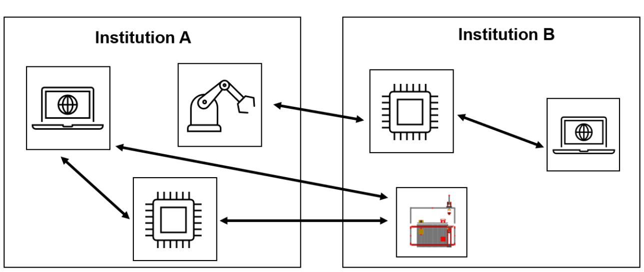

Fig. 2. GOLDi 2.0 – Sharing lab devices across institutional boarders

- For large electromechanical hardware models with a huge number of inputs and outputs can be controlled from many different locations. Thus, parallelization of experiments is possible.

Another interesting application is hybrid take-home labs. These days, interested students have private hardware at home – like an Arduino, a Raspberry Pi, a FPGA demo board, or experimentation kits for digital logic. Therefore, GOLDi 2.0 provides learners with an interface unit, which they can use to easily connect their own control units to complex hardware models at the university (from home), forming a Hybrid Take-Home Lab.

GOLDi 2.0 enables simulations, the creation of virtual lab environments, and remote labs. It will combine new application areas for online labs in a demand-oriented and interoperable way, e.g., automation technology, optics, mechanical engineering, or chemistry, in a single learning environment, to effectively meet the requirements of future-oriented competence-based learning.

For example, regularities of Boolean algebra can be explored interactively using the tool *"SANE"* (Switching Systems Worksheets on the Web). For sequential circuits and control algorithms that are systematically designed on the theoretical basis of finite state machines, the tool *"GIFT"* (Graphical Interactive FSM-Tool) is available. The connection between Boolean algebra, circuit algebraic expressions and their circuit engineering implementation is provided by the online tool *"BEAST"* (Block Diagram Editing and Simulation Tool).

The above-mentioned CrossLab goals are addressed by the GOLDi 2.0, developed by the Ilmenau University:

- The **cross-type** goal is addressed by our existing experiments in the embedded programming and the control algorithm domains, as well as the hybrid take-home labs. In addition, five new experiments will be enhanced and integrated using the CrossLab platform. A PLC controlled filling station will be further automated towards fully remote access. The control of an electric motor as remote lab and take-home lab enables students a life programming experience, although the motor is remote.
- The **cross-disciplines** aspect is covered by the fact that new fields of application are currently being developed in addition to STEAM applications, for example in the fields of optics or chemistry.
- The collaborative and distributed usage of laboratory devices in a single learning environment across university boundaries reflects the **cross-university** target.

C. Virtual Security Laboratory at NORDAKADEMIE

The NORDAKADEMIE gAG Hochschule der Wirtschaft is currently building multiple laboratories which hopefully capitalize on CrossLab. One such laboratory is the virtual security laboratory:

The danger of cyber-crime is increasing for all parts of economy. Cyber-attacks create massive damage to different industry areas [19]. Companies are getting more aware of the importance of IT security. Looking at the current trend of Industry 4.0 [20] and the growing number of industrial devices connected through the Internet [21], IT security will only grow in importance over the next decade. Therefore, there is an increasing demand for a deep understanding of IT security mechanisms.

To meet the demand, the NORDAKADEMIE gAG Hochschule der Wirtschaft is building a new IT security laboratory. Here, students can learn and practice the use of IT security tools such as Metasploit [22] or Wireshark [23] by solving exercises in simulated realistic network environments consisting of servers, sub-nets and regarding network devices.

The laboratory will be built using modern cloud computing technologies. By using cloud computing, we will be able to build complex scenarios spanning over multiple network segments while also having a relatively low-cost solution compared to other types of laboratories [24]. In addition, it will be possible to scale capacities if the demand for such a laboratory increases [24].

The laboratory will address the following goals of CrossLab: by integrating different real devices into the scenarios, students will be able to access more realistic environments (**cross-type** as well as **cross-elements**). At the same time, those devices can be at different institutions, as well as access to the laboratory can be granted to different universities (**cross-university**).

Additional laboratories are currently planned who should tackle the area of building automation [25] and CoBotic [26]. Furthermore, the integration of the interactive digital circuit simulator *LogicCircuits* [27], [28] into the remote laboratory environment is ongoing work.

D. Industry 4.0-Labs at TU Dortmund

TU Dortmund (TUDO) has years of experience in the field of instructional design and formative evaluation of laboratories in higher engineering education. Further, systematic consulting experience as well as in-house workshops for laboratory teaching enrich the CrossLab project [29]–[31].

TUDOs Center for Higher Education has one of 18 instances of a remote laboratory called VISIR. The abbreviation VISIR stands for Virtual Instrumentation Systems in Reality [32]. VISIR allows for planning and conducting remote experiments on electronics such as Ohm's Law, Kirchhoff, maximum potency transmission, components characterization, etc. Using a computer mouse or touchpad, circuits can be virtually built on a graphical user interface (GUI) that replicates a typical breadboard for realizing electronic circuits. Due to comparable installations at the 18 locations from nearly all over the world, VISIR already fulfills the cross-university approach within CrossLab [10].

In addition, TUDO collaborates for years with LabsLand, a provider of digital practicals. These practicals can be remotely accessible laboratories around the world or ultra-concurrent practicals uploaded to the LabsLand website [33]. Thereby, TU Dortmund has first-hand experiences in cross-type practical implementations as remote experiments, simulations, and ultra-concurrent remote laboratories are part of LabsLand [34]. Based on the existing experience and installation at TUDO, the CrossLab team at TUDO is developing new digital practicals, which follow the concept of cross-types, cross-elements, cross-disciplines and cross-universities. Hence, an exchange and engagement with LabsLand will be evaluated within the project as well.

The main goal of TUDO is the development of new cross-reality practicals considering industry 4.0, e.g., at the Faculty of Biochemical and Chemical Engineering, where an immersive VRs are created. These are within the field of fluid mechanics and visualize barely measurable scalar and vector variables [35] as well as theoretical constructs such differential balancing [36]. Information design principles of Industry 4.0 are thereby used [37]. The cross-disciplines character is addressed in the simultaneous consideration of fluid and solid mechanical differential balancing. An example of such a digital practical can be found at the Chair of Fluid Mechanics in the Faculty of Bio- and Chemical Engineering.

Next to the technical implementation new didactical approaches are followed where students are set-up with a real-life situation as they get a work order via email from a bad-tempered supervisor. In the open and incomplete work order, a jet pump must be developed and models for flow, performance curve and efficiency must be established. Students must identify the problem, create work packages, and communicate them to the experimental supervisor. One person in the group is assigned as the group leader for the project. By dealing with initially unclear tasks and approaches, the overarching learning outcome is the independent development of solutions in unclear and unknown situations and thus the working of the working world 4.0 is addressed.

This laboratory experiment with a digital twin in virtual reality uses technology of Industry 4.0. The digital twin is based on the Unreal Engine and the file containing it is provided for download, which also serves the idea of cross-university. On the digital twin, measurements can be taken on measuring devices and flow variables as well as particle movements can be visualized. The onset of cavitation limits the suction height and thus sets physical limits to the models.

IV. Conclusion

The diversity of the digital laboratory instances described above underlines the necessity of implementing the Cross-X ambitions of the project. The cross-cutting laboratories from individual disciplines (computer science at the project partners in Ilmenau, Elmshorn and Freiberg) but also the broader projects in the field of sciences and engineering (project partners Freiberg and Dortmund) open the possibility of implementing the technical and didactical concepts as well as evaluating them across disciplines and universities.

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