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Hybrid Take-Home Labs Empower Future STEM Education

Abstract

The acceptance of digitally supported teaching has increased enormously in recent years, not only because of the coronavirus crisis. Online labs are increasingly being used in STEM subjects to meet the availability, usability, and granularity of what they offer. This ensures the connection of theoretically taught basics to their application and deepening in practical courses in the basic subjects. However, hands-on experimentation and the haptic learning associated with it are being somewhat lost.

The *Hybrid Take-Home Labs* project aims to develop and test the foundations for practical support of learning processes in STEM subjects, enabling students to conduct even complex virtual and remotely controlled laboratory experiments from home using their own resources, combined as needed for student-centered teaching that meets the requirements of future-oriented competency-based learning.

Keywords

Control education engineering, distance learning, virtual and remote labs.

1 Introduction

Since the beginning of the coronavirus pandemic, e-learning has primarily been able to alleviate the loss of face-to-face teaching at Ilmenau University of Technology—except work in laboratories, which is mostly only possible in person. Soon, however, real experiments will be increasingly feasible from home. To this end, TU Ilmenau is developing a portable online laboratory infrastructure that will enable students of STEM subjects to conduct their own complex "tactile" laboratory experiments remotely using their own control units via the Internet. The Thuringian Ministry of Science is funding the project. It was initiated together with the Association for the Promotion of Science and Humanities in Germany as part of the "Fellowship Program for Innovations in Digital University Teaching" [1].

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In recent years, digitally supported teaching has found its way into universities, not just since the coronavirus pandemic. So-called online remote labs are just as powerful as on-site technical facilities, but they are also more flexible, as students can access them virtually from anywhere. Since their subject matter is permanently available remotely in the form of digital, interactive simulations, and video recordings, students can decide when to access it according to their individual work rhythm, schedule, and level of knowledge. Online labs enable remotely controlled experiments through web-based access to real controls and physical systems. This ensures the connection of theoretically taught basics to their application and deepening in practical courses. However, practical experimentation and the "haptic learning" associated with it are being lost, i.e., many problems dealing with real hardware are being "abstracted away". E-learning environments are predominantly based on visual and auditory components. With the advent of haptic technology, we can now simulate/create forces and thus also the sense of touch. This practical side of the learning process will be enabled by the *Hybrid Take-Home Labs* currently being developed at TU Ilmenau.

TU Ilmenau has been using digital laboratory solutions in its STEM students' online and hybrid education for more than ten years. For example, the interactive hybrid online lab GOLDi ("Grid of Online Lab Devices Ilmenau") has been used for courses, practical work, and online demonstrations on a national and international scale [2, 3]. It was not only through the pandemic situation of 2020 and 2021 that the advantages of digital laboratory solutions became clear in terms of performance and flexibility. The preparation of subject matter in digital, interactive simulations, video recordings, or remote access opens up a flexible time allocation corresponding to individual work rhythm and level of knowledge with permanent availability.

Meanwhile, many interested learners have their own hardware at home—be it an Arduino or a Raspberry Pi for software enthusiasts, or now affordable FPGA demo boards and digital logic experiment kits for hardware enthusiasts to independently control interactive objects or interact with software applications. Thus, while they have their own control units, they lack direct access to the complex experimental environment of a professional laboratory. The *Hybrid Take-Home Labs* will allow students to perform complex experiments in an online lab with their hardware flexibly used as their own control unit. For this purpose, they will be provided with a *Take-Home Lab* interface unit. On the one hand, this interface unit connects them to the GOLDi online lab via the Internet. On the other hand, it serves as an interface with all the inputs and outputs of a real technical system, such as an elevator, a 3-axis gantry, or a high-bay warehouse located remotely in the

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university's remote lab. Students design the control algorithm and program their own control unit in their residential schoolroom. We believe that "haptic" feedback will increase the immersion of the learners in a distance learning environment and their interaction with other learners using a variety of sensory inputs in addition to text, video, and audio. The opportunity to have richer tactile experiences can improve the way students explore content at a distance. This principle could also be extended to other learning areas, for example, teaching the control of complex chemical plants remotely.

2 Planned Innovations in the Teaching Process

Online labs can be divided into remote, virtual, and hybrid labs (see Figure 1).

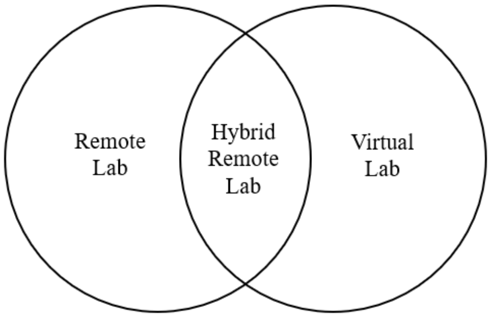

Figure 1: Overview of experiment types in online labs

Remote labs allow experiments to be performed remotely via web-based access to real controls and physical systems (electromechanical hardware models). Virtual labs work exclusively in virtual artificial worlds. In addition to enabling remotely controlled experiments via simulation, hybrid labs combine both approaches by allowing students to work with virtual devices that correspond to real devices in their essential characteristics. This approach follows the idea of digital twins, which is likely to be of great importance for developing Industry 4.0 work environments in the future. The GOLDi online lab implements all variants flexibly. Thus, it is possible to perform all experiments either entirely virtually or on real devices or using a combination of both.

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The many different online labs that have been successfully used for many years all have the disadvantage of "abstracting away" many of the problems associated with dealing with real hardware. This fellowship application aims to extend the existing lab concept with the idea of ***Hybrid Take-Home Labs*** (Figure 2).

The approach of *Take-Home Labs* (or Pocket Labs or Mobile Labs) is not new. It stands for portable mobile labs that can be borrowed by students and, in our discipline, often used in conjunction with a laptop or tablet PC—for example, in lectures, in a seminar, at home, or on the go [4].

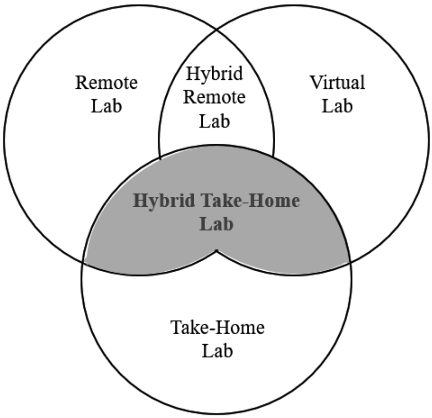

Figure 2: Overview of experiment types in online labs

By now, many interested learners have their own hardware at home—whether it is an Arduino or a Raspberry Pi for software enthusiasts or now affordable FPGA demo boards and digital logic experiment kits for hardware enthusiasts. So, they have their own control devices but no direct access to complex experimental environments. Within the *Hybrid Take-Home Lab*, they can flexibly use their hardware as their own control device to perform complex experiments in conjunction with the GOLDi online lab. Learners can easily connect to this interface with their own control devices and thus can control these complex hardware models (from home).

In the future, the *Take-Home Lab* modules will also be used in the pre-university sector, especially for student recruitment (initial contacts have been made in the STEM Excellence Cluster—an association of high schools

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in Germany). But also, in the post-university sector for training and further education.

3 Usage of the GOLDi online lab in basic computer science education

In the following, the usage of the GOLDi online lab in fundamental computer science education for students in technical fields will be presented first. Then, how the *Hybrid Take-Home Lab* concept extends these with diverse applications will be shown.

The GOLDi online lab currently supports topics in computer engineering and digital technology as offered in the basic studies of TU Ilmenau for all engineering courses, in which the foundations for the understanding, systematic design, and formal verification of digital systems are laid.

The courses "Computer Engineering" and "Design of Digital Systems" are intended to enable students to design and build digital control systems independently and verify their correctness. Students will acquire the ability to use digital circuits to acquire sensor values and process them so that actuators respond in a manner specified in the assignment, such as controlling an elevator or a simple 3-axis portal.

To achieve this goal, the mathematical basics of Boolean algebra are first taught. This is followed by the systematic, formally verifiable functional description of digital controls, such as the formulation of the dependencies of sensor values in the form of Boolean equations. Another theoretical concept, which is especially important for constructing sequential circuits, is finite state machines (FSM). Based on this, it is shown how these descriptions can be implemented in digital circuits. In order to illustrate the correctness of their behavior, a practical construction through the interconnection of basic elementary circuits, which correspond in their function to the essential elements of Boolean algebra, is necessary, in which haptic learning types are addressed at the same time. This is usually done in a laboratory experiment. This teaching concept can be accompanied by and supported by the help of our hybrid online lab GOLDi and the *Take-Home Lab* extension.

As already mentioned, the GOLDi online lab flexibly supports all variants of remote labs: remote, virtual, and hybrid labs. Thus, it is possible to perform all experiments either entirely virtually or on real devices, or in a combination of both.

The task in an experiment is to control a physical system with a self-designed algorithm to execute a given sequence of movements. The digital-twin concept enables the exploration of side effects that can occur in faulty designs as early as the design phase. In this process, partial concepts of the

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control algorithm can be tested on a virtual emulation of a physical system, independently of its later implementation. Once the algorithm works on the digital twin, it will also work in a real environment.

4 Expansion of the lab concept to include Hybrid Take-Home Labs

The beneficial introduction of digital labs from a student perspective is still a technically, didactically, and organizationally complex topic. It is about much more than simply digitizing lab equipment. Instead, it is about the goal-oriented digital transformation and implementation of agile, self-directed, creative, and collaborative research-based learning that promotes competence. The entire GOLDi lab is thus not a "hard-coded" installation, with a firmly defined model of possible learner interaction patterns, but rather the subject of a continuous process of adaptation and evaluation.

For this purpose, the term ***Hybrid Take-Home Labs*** defines open digital lab objects (interface units) combined in a demand-oriented and interoperable way for student-centered teaching to effectively meet the requirements of future-oriented competence-based learning and working 4.0.

An Application scenario: *The following task is given: "The trolley of a gantry crane is to move back and forth between the left and right limit switches. The movement can be stopped and released again with a push button. For this purpose, the two motors for left and right travel are to be controlled."*

The student will first derive and simulate his/her automaton graph using the Interactive Learning Object GIFT. Then, he/she can derive the equations, which are the starting point for a digital sequential circuit.

As regards practical implementation, the student uses his/her private "collection" of essential digital components (AND, OR, NAND, NOR, flip-flops, ...) and his/her plug-in board. After the circuit is built, the student wants to test his/her design on the real hardware model in the Remote Lab and connects his/her circuit to the inputs and outputs of the Take-Home-Lab interface.

When starting the experiment, the student notices that the trolley does not stop at the left limit switch, and thus a GOLDi protection mechanism aborted the experiment. He/She gets the error message that the trolley still wants to move to the left when reaching the end position. After a short troubleshooting test, he/she realizes that he/she had misconnected a cable. As a learning experience, he/she understands that meticulous work is advantageous in the construction of digital circuits.

During further testing, he/she notices that some signals are set to zero by chance. After some consideration, he/she realizes that he/she has not yet connected the reset pins of the flip-flops. A quick look at the data sheet tells him/her that they

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have to be switched to zero to prevent a reset, and he/she adds that to his circuit. The student has had his/her first experience with incompletely wired components.

Nevertheless, his/her circuit does not reliably trigger the desired stop in the movement when the push button is pressed. In the electrical engineering course, he/she once heard that you have to debounce switches to switch in a defined way. Using a capacitor and resistor as a low-pass circuit, he/she can fix the problem. In this case, the student once experienced live effects as they are theoretically presented in the courses and practically applied the techniques described to fix his/her problems.

The effects described here are typically not observable with an online experiment, as they cannot occur there. Students who do not have their own control unit assemblies can also borrow them in addition to the *Take-Home Lab* interface units.

The difficulty level of the tasks can be adapted to the respective knowledge level in the semester. For example, at the beginning of the semester, only simple tasks such as working with Boolean constants and variables are possible. However, these can be immediately tested independently in the *Take-Home Lab* with their own simple control units (e.g. switches or push buttons) by setting variables (actuators) to constant values and triggering an immediate reaction to the hardware model GOLDi online lab. In the next training step, tasks on Boolean expressions follow, with the help of which more complex dependencies of sensor signals can be considered when controlling actuators. Finally, to control sequential processes, skills for the design of sequential circuits or digital automata (FSM) are required, which can also be developed with the Interactive Learning Objects described above and exported to the GOLDi Online Lab from home via the *Take-Home Lab* modules.

In higher semesters, microcontrollers or programmable circuits (FPGAs) can then be used as the students' own control devices. As required for programming FPGAs, the necessary knowledge for programming in higher programming languages (e.g., C++) or hardware description languages (e.g., VHDL) is acquired in separate courses. Challenging tasks that can be solved with this knowledge are, for example, parallel control algorithms for elevator control. Also, a comparison between a software solution and a hardware solution via a microcontroller or an FPGA is interesting for higher-semester education. For the editing of source code in the browser and its compilation, the Interactive Learning Object WIDE (Web-Integrated Design Environment) is available, which can be accessed via the Web interface of the GOLDi Online Lab, thus providing a uniform user interface for all programming languages.

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The further development of the *Hybrid Take-Home Lab* will always take place with the involvement of students of higher semesters in the context of software projects and annual student research projects and bachelor's and master's theses. In particular, this is intended to develop skills for the challenges that the concept of Industry 4.0 poses to future graduates.

With the individualized use of heterogeneous digital laboratory installations of other GOLDi-Cloud partner institutions with other hardware models, the bandwidth, and the proportion of practical training components in STEM subjects can be significantly increased. This allows universities to balance the heterogeneity of students concerning practical skills in the lab context.

In addition to the benefits for the learners, the applicant also expects a leap in innovation on the part of the teachers through the networking of the respective disciplines at the participating university locations and beyond. While individual staff members design conventional laboratory implementations and didactic concepts, the overarching use of the respective infrastructures increases interaction and reflection. This direct exchange entails an explicit didactic evaluation and thus continuous quality development.

5 Conclusion

The *Take-Home Lab* project presented here is an integral part of the new project CrossLab (in German: "Flexibel kombinierbare Cross-Reality Labore in der Hochschullehre: zukunftsfähige Kompetenzentwicklung für ein Lernen und Arbeiten 4.0" [5]—which stands for: flexibly combinable cross-reality laboratories in university teaching: future-proof competence development for learning and working 4.0), which has been running since summer 2021. The partners want to combine the concepts for digitizing the laboratory education that they have developed at their various locations into a cross-university, interdisciplinary network. Thus, the individual CrossLabs, which enable simulations, the creation of virtual lab environments, and remote labs, will be combined into a single learning environment. Currently, new areas of application for online labs are being explored, e.g., automation technology, optics, mechanical engineering, or chemistry.

In addition to the conception and implementation of their technical realization (configuration and linking of the individual *Take-Home Lab* objects) and new use cases in various STEM disciplines, didactic concepts and organizational strategies are to be further developed in parallel to ensure broad integration capability. In the future, the *Take-Home Lab* modules will

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also be used in the pre-university sector, especially for student recruitment, but also in the post-university sector e.g., for training and further education.

The Vice President for Studies and Teaching at TU Ilmenau, Professor Anja Geigenmüller, expects the current research activities in this area to provide a boost not only to digital laboratory technology developments but also to innovative didactic concepts: "The further joint development of innovative formats across disciplines and even locations will help to continue to make STEM courses attractive and also to incorporate ubiquitous digitalization into teaching content and teaching methods." [6]

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