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Virtualization of a Smart Home Lab: Design, Implementation and Evaluation

Abstract

Experimentation in the laboratory plays an important role in students' education in order to acquire the necessary practical knowledge. However, this laboratory experience cannot be offered to all students due to various reasons, such as expensive equipment, limited access, or insufficient capacity. For this reason, virtual labs have been gaining interest for several years to make lab work more accessible. This paper is dedicated to this topic, showing the possibilities and highlighting the important role of virtual labs in education. However, there is a lack of didactically and qualitatively sophisticated digital solutions in many areas. With a case study, this paper aims to extend the state of research around virtual labs and investigate the feasibility of virtualizing a smart home lab. In addition to the design phase, in which the requirements for the solution are elaborated, the implementation of the virtual lab with suitable technologies as well as the evaluation of the application with the help of user tests is presented. The results show that the virtual PUX lab is seen as a useful alternative to the real lab. The identified weaknesses from the user tests could be used to further improve the prototype for its integration into the DigiLab4U platform and its productive application in lectures and workshops.

Keywords

E-learning, virtual lab, OpenHAB

1 Introduction

With the constant development of internet technologies and increasing digitization in many different areas, education has also changed significantly in the past two decades (Schlenker, 2015). Digital and interactive media have rapidly spread as ways to enhance teaching and learning, replacing traditional teaching methods (Hoffmann et al., 2014 ; Unger, 2014). While

physical textbooks and traditional face-to-face lectures were mainly used in the past, nowadays various e-learning tools are used and new modern concepts such as blended learning and distance learning are implemented (Kamińska et al., 2019).

Developments in e-learning range from computer-based training (CBTs) and web-based training (WBTs) to extensive learning management systems (LMS) (Arnold et al., 2018 ; Sims, 2021). Moreover, with the availability of higher bandwidths, lower access costs and advances in computer graphics, another form of learning emerged using the new technology of virtual reality (VR), which marked the shift from conventional digital media to immersive learning environments (Huang et al., 2010). Oriented to scenarios from computer games, these platforms are also called serious games and make use of the visual-spatial dimension in which learners are immersed in a constructed 3D world and interact with modeled learning objects (Schlenker, 2015).

Meanwhile, digital technologies are an integral part of colleges and universities to improve the learning experience. By using modern multimedia and telecommunication technologies, e-learning offers some new possibilities. Most importantly, improved accessibility, flexibility, interactivity, increased motivation, various tools for organizing studies as well as collaboration across spatial boundaries are among the advantages. (Henderson et al., 2017 ; Seel and Ifenthaler, 2009)

The benefits are especially evident in times of a pandemic when face-to-face teaching is no longer possible (Glassey and Magalhães, 2020). Due to the pandemic, most colleges and universities had to adapt their teaching methods and switch to online teaching (Glassey and Magalhães, 2020). The transition to online lectures is relatively easy, but other areas face some challenges (Glassey and Magalhães, 2020). Due to the limitations of physical contact as well as logistical and security factors, developing a solution to effectively deliver the lab experience is a difficult task (Bhute et al., 2021). According to a McKinsey survey, teachers and learners are least satisfied with the digital form of lab work (McKinsey and Stifterverband für die Deutsche Wissenschaft, 2020). While the conversion of lectures was rated positively by students, the transition of teaching formats in smaller groups such as laboratory work with a high practical content was perceived rather negatively (Winde et al., 2020). Possible reasons are the higher demands regarding digital didactics and interactivity as well as the often longer development time that these e-learning formats require (Winde et al., 2020).

This shows that better and more effective methods still need to be found to achieve the required learning outcomes. Especially in STEM fields, hands-on experimentation in the laboratory is of high importance to apply

theory to practice and to gain the relevant experience and skills of practical laboratory work (Burghardt et al., 2021). Transferring this form of learning to a distance learning approach is challenging because it requires physical laboratory equipment and the laboratory environment (Gokhan and Saleem, 2008). However, research has already been conducted in this area for several years to find new approaches (Romagnoli et al., 2020). Virtual laboratories have been explored as solutions that enable laboratory practices over the network regardless of location and time (Romagnoli et al., 2020).

Virtual labs use simulation, animation and other technologies such as VR to replicate the real lab as closely as possible and to provide a similar lab experience (Rivera, 2014). Based on computer simulations, they enable conducting experiments without having to be physically present at the laboratory workstation (Esquembre, 2015 ; Ray et al., 2012). In some cases, simulation can even provide a better laboratory experience or any laboratory experience at all (Koskela et al., 2005). This is because virtual labs are not only useful during pandemic times, but also in situations where the real experiments pose a danger to learners or the equipment and materials are too expensive or poorly accessible (Koskela et al., 2005). Since virtualization requires only a computer device and an internet connection instead of the entire lab equipment, virtual labs allow for high scaling as well, so that in principle any number of instances can be created, and thus several students can be served in parallel (Seiler, 2012).

Although research around virtual labs already exists, there is still a lot of unexplored potentials, for example in the field of the internet of things (IoT) and industry 4.0 (I4.0), due to the lack of effective and high-quality solutions for digitized labs (Kokot, 2019). Accordingly, this paper will try to expand the state of the research with a selected case study.

2 Case Study: Virtual PUX-Lab

The application resulting from the technical implementation of the case study should be integrated into a central platform that is developed within the DigiLab4U research project. For this reason, an overview of the research project will be given first, in order to clarify the theoretical background and motivation behind the project. Afterwards, the PUX lab, which is to be virtualized, will be presented.

2.1 DigiLab4U

DigiLab4U stands for Open Digital Lab For You and is a research project managed by several educational institutions that have the goal to develop an open, digital platform for laboratories focusing on I4.0 and IoT (Pfeiffer and Uckelmann, 2019).

Real laboratory infrastructures are associated with high costs and are usually only accessible to a specific institution. DigiLab4U, therefore, aims to counteract this problem by providing an open, cross-institutional platform for I4.0 and IoT labs that allows lab infrastructures to be networked and used effectively and sustainably. The goals are to facilitate the exchange of research and teaching facilities through the lab network and to make the digitized, hands-on lab environments accessible to as many students, teachers, and researchers as possible. (Open Digital Lab for You, n. d.)

The platform is implemented with a client-server architecture and the core of the platform is the central LMS as the entry point for the users. Implemented with the open-source learning platform Moodle, this platform will offer general functionalities such as booking, payment, authentication and management of the labs. In addition, a framework software package called LabMS, short for Laboratory Management System is provided to facilitate the integration of the labs into the central platform. (Galli et al., n. d.)

A project that should be digitized and integrated into the central platform of the DigiLab4U research project is the PUX lab, which is presented in the next section.

2.2 PUX Lab

The research group Responsive Media Experience (REMEX) exists since 2013 at the Hochschule der Medien Stuttgart and has the goal to research and develop innovative solutions that address the user and his needs to achieve the best user experience. Research focuses, for example, on personalized and accessible user interfaces or smart homes & ambient assisted living (AAL). (Forschungsbericht 2020, 2021)

In order to implement and evaluate the solutions in practice, the PUX lab has been established. This is available to researchers and students for various projects. The lab houses devices such as smart Philips Hue lamp systems, smart sockets, and smart carpets, which can be used in personalized smart homes and AAL scenarios, for example. (Ein Netzwerk, das alles verbindet, 2021)

As smart homes and networked devices become increasingly relevant, students should accordingly be able to gain the necessary practical experience in their education. Therefore, a virtual environment is valuable to provide access to the lab and the devices to a higher number of students. A virtual version also represents a useful alternative considering the pandemic when equipment had to be borrowed by the students and was only available in limited quantities. For this reason, the case study of virtualizing the PUX lab will be presented in this paper.

The use case is as follows: In the real PUX lab, an OpenHAB server exists which can be used to control smart devices from different manufacturers uniformly. In the case study, only the smart lamp systems are initially considered for the prototype. Students can therefore program their smart home applications and, by addressing the OpenHAB API, influence the lamps in the PUX Lab, e.g. switch them on and off, change the color or adjust the brightness. This scenario should also be possible in the virtual PUX Lab and should be mapped realistically. In the virtual PUX lab, students should learn how smart devices can be controlled with the help of OpenHAB, analogously to the real PUX Lab. In the future, the application is to be integrated into the DigiLab4U Moodle as a lab course and thus be available to a large number of students within workshops or lectures.

3 Requirements Analysis

In this section, requirements for the design of a possible solution for the virtual PUX lab are collected. These requirements are elaborated in three steps:

- Literature research
- Analysis of existing virtual labs
- Focus group discussion

A literature review is conducted to identify characteristics of virtual labs that have a positive impact on the learning experience and outcome. Moreover, existing virtual labs and learning environments are selected and analyzed to identify common features and frequently used elements. In the last step, a focus group discussion will be conducted to further complete the requirements and, if necessary, evaluate and prioritize them regarding their suitability for the virtual PUX lab.

3.1 Literature Research

From the literature, some requirements or possible elements for virtual learning environments can already be identified. A learning environment requires a well-thought-out combination of pedagogical, social and technological components to achieve the desired learning success (Wang, 2009). The overall didactic concept must be put together coherently, the learning objectives must be clear and the learning content should be prepared with the help of suitable media elements (Arnold et al., 2018). (Wendt, 2003) suggests diverse elements for a didactically meaningful concept. These include an intro sequence, the main menu for navigation, an introductory test for adaptive content, exercise and tutorial learning modules, an explorative practical learning environment, a learning success control, a learning management module and technical as well as content-related assistance (Wendt, 2003).

User-friendly design is also frequently recommended in the literature for learning environments (Arnold et al., 2018). The user interface must be clear and understandable so that learners can easily find their way around (Arnold et al., 2018). This includes, among other things, support for accessibility and multilingualism (Arnold et al., 2018). While (Gokhan and Saleem, 2008) list aesthetically pleasing and intuitive design, (Liu et al., 2009) mention four other critical features: accessibility of information, ease of navigation, interactivity of the system and system support. Moreover, (Mueller and Strohmeier, 2011) highlight further system-related criteria such as feedback, flexibility, adaptability, and reliability as well as information-related aspects like course quality, presentation format, and relevance.

(Romagnoli et al., 2020) formulate four criteria specifically related to the virtualization of laboratories: realistic user interface, realistic system replication, realistic graphical representation, and support for communication and collaboration. First, the user interface of a virtual laboratory must replicate the real device. Second, the behavior of the virtual system must match the behavior of the physical system. Furthermore, the virtual lab must be designed in a way that the learners feel as if they are performing the experiment in a real environment. In addition, the laboratory environment should include features to enable communication and collaboration. (Romagnoli et al., 2020)

3.2 Analysis of existing applications

To determine the characteristics and commonly used elements of virtual labs and learning environments, seven different applications of virtualized

labs were analyzed. The selection included, for example, a virtual microscopy lab, a virtual lab tour, and remote control of a robotics lab.

By investigating the applications, the following common elements and features could be identified: instructional videos, experiments, multi-language support, full-screen mode, and the possibility to contact supervisors. Furthermore, quiz questions, simulations, remote access, help resources, tutorials, 360-degree tour, 3D visualization and gamification in the form of an avatar, progress tracking, and sound/audio appear to some extent. Elements that all applications have in common are an explanation of how to use and operate the application, as well as a description of the learning objective or benefit of the application.

The suitability of the requirements identified so far for the virtualization of the smart home lab is determined in the next step with the help of a focus group discussion.

3.3 Focus group discussion

Focus groups are moderated group discussions and belong to the qualitative methods. In a small group, usually consisting of six to ten people, a selected topic is discussed to obtain information about the thoughts and different perspectives of the individuals. The selection of participants is done deliberately by selecting individuals who have certain characteristics regarding the focus group topic. (Bär et al., 2020, Krueger and Casey, 2014)

In the case study, the focus group is used to gather requirements and ideas for a solution concept for the virtual PUX lab. A total of seven people participated in the focus group. Among the participants were staff members of the DigiLab4U research project and the REMEX research group as well as students as representatives of the future target group. Due to the contact restrictions of the pandemic, the focus group was conducted remotely within a 90-minute online meeting.

The participants were asked to collect possible elements and characteristics of virtual learning environments interactively in a mind map. On the one hand, some of the same characteristics as in the analysis of existing applications were identified, on the other hand, new points were also added to the mind map. These identified aspects were then prioritized and evaluated with regard to a solution for the virtual PUX lab.

The participants named interaction with the system that is as practical and realistic as possible as the highest-rated characteristic. In terms of user-friendliness, independence of place and time, support for different devices/operating systems/browsers, and accessibility are most important. FAQ, introduction/explanation, and links to help resources were favored

as support features. Regarding the use of media, participants voted for a 2D representation, and in the category of adaptability, they prioritized the support for multiple languages. For teaching elements, the participants see tutorial videos, quiz questions, and experiments as appropriate. Feedback should be provided in the form of a presentation of the result and an associated evaluation.

These features can be considered requirements for the virtual PUX lab and should be considered in the concept of the application.

4 Implementation

The application was implemented with a composition of several components according to the client-server model. These components and their communication with each other can be seen in Figure 1.
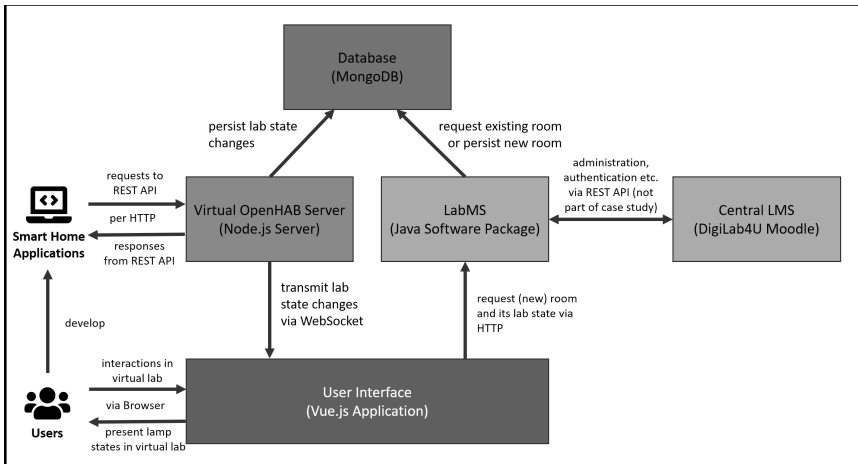

Figure 1. Architecture and components of the application

In the following, the individual components are described in more detail, which includes justifying the choice of technologies and the explanation of the implemented functionalities per component.

4.1 User Interface

The user interface represents the visual component, the so-called client, and is the entry point for users. Before starting with the development, a design concept was first created. Not only the layout and different components of the application were designed, but also the visualization of the virtual PUX lab. The real PUX lab is designed like a living room and consists, among other things, of shelves, an armchair, a small side table, a TV, and several lamps. This should also be reflected in the virtual version. For this, each element was created with the Figma program. Figma is a web-based vector graphics editor and serves as a prototyping and design tool. The program allowed us to quickly and easily create the elements as 2D representations using simple geometric shapes. All of the lamps in the PUX lab were modeled. These include four-floor lamps, four light strips, and a small table lamp. The lamps were arranged as in the real PUX Lab so that a third dimension can be guessed by the positioning, i.e. one-floor lamp in each corner of the room. The light strips could also be realistically placed behind the decorative elements such as the shelf or the TV. In addition, the lampshades and the glow of the light strips could be represented quite realistically with Figma by using effects such as color gradients and soft edges. The export of the models as SVG elements allows flexible adaptation so that dynamic and authentic animation, e.g. of the color change of a lamp, is possible.

The JavaScript framework Vue.js in combination with TypeScript was chosen for the implementation of the frontend. Vue.js belongs to the best-known and most widely used JavaScript frameworks to build reactive web applications relatively easily and quickly (Vue.js, 2021). In addition, Tailwind was used as a CSS framework. With Tailwind, the desired styling of a page can be efficiently implemented using utility classes (Tailwind, n. d.). Figure 2 shows the main user interface implemented in the case study. The most important components are briefly explained:

Language Selection Possibility to switch between English and German.
Introduction Short introduction to the virtual PUX lab, briefly explains what the virtualPUX lab is and how it can be used.
OpenHAB Information & Interaction Options Presenting important OpenHAB information likeserver address of the virtual OpenHAB server and the current room ID. Possibility to enter orcreate a new room.
Visualization of virtual lab state Main area showing the virtual depiction of the PUX lab as aninteractive SVG image. Colour and brightness as well as the on/off state of the lamps aredisplayed.

List of Things and Items Textual information about the OpenHAB Things and the associatedItems and Item Groups.

Action Log Log of requests that change the state of the Items.

Help Section Important resources that might help to use the virtual PUX lab, e.g. explanatoryvideo, FAQ, and external resources.

Further features implemented throughout the application are tooltips, toast messages, buttons to quickly copy relevant text to the clipboard like server address or Item names, responsive design for different screen sizes, as well as accessibility aspects such as support for keyboard navigation and screen readers.

4.2 LabMS

The LabMS is a framework software package that includes all necessary software and logic components and is already designed to communicate with the central LMS. Each lab, that should become part of the DigiLab4U platform, can be set up with the help of its own LabMS instance, so that the integration is facilitated by the already existing interface to the central platform, which is responsible for e.g. authentication, booking, and the collection of learning analytics data. In this respect, the technology for the backend is already given: The LabMS is based on Java and uses the Spring-boot framework, which simplifies the programming of web applications, e.g. the construction and use of REST interfaces.

The LabMS also represents the server or the backend to the frontend application and is responsible for processing the requests from the frontend. On the one hand, the user interface offers the possibility to create a new room. For this, the LabMS generates a new token consisting of 84 characters, which uniquely identifies the new room, and the new lab instance is stored in the database with the initial default state including the newly generated room ID.

On the other hand, users can enter different rooms via the user interface using room IDs. For this purpose, the LabMS loads the state of the respective lab instance from the database using the room ID sent by the frontend and sends the requested state back to the Vue.js application.

All further interactions from the user, such as changing a lab state, are done via the virtual OpenHAB server.

4.3 Database

In order to be able to persist the lab state of the respective rooms, the application also includes a database. MongoDB was selected as the technolo-

gy for this. MongoDB belongs to the document-based NoSQL databases, which have been developed for modern applications with scalability and flexibility in mind. MongoDB stores data in a JSON-like document format. This form is very close to the structure of object-oriented programming, which leads to efficient work with data. In addition, MongoDB allows for flexible customization of the data structure, powerful and flexible queries, and can also handle a large amount of data (Was ist MongoDB?, 2021).

The virtual PUX lab data is stored in a specific document structure. However, since MongoDB does not enforce a schema, this can be flexibly adapted in the future, e.g. if additional smart devices are to be simulated. There is one document per lab instance and the data is stored in the form of nested objects and arrays. At the top level, the room ID or API token is stored, which uniquely identifies the lab instance. Two timestamps are also recorded. Both the time of creation and of the last modification to the lab instance are stored. Furthermore, the Things and the associated Items as well as the Item Groups persisted, which as a whole, form the lab state.

4.4 Virtual OpenHAB Server

The virtual OpenHAB server simulates the functionalities of the real Open-HAB server in the PUX Lab. For this purpose, a part of the REST API of OpenHAB is replicated in the virtual variant to realize the same behavior. The use case is supposed to be the following: Instead of students sending the HTTP requests of their smart home applications to the real OpenHAB server to control the real lamps in the PUX Lab, they should send the HTTP request to the virtual OpenHAB server and accordingly see the effect in the virtual PUX lab.

For the implementation, the first step was to analyze the REST API and the OpenHAB ecosystem. OpenHAB stands for Open Home Automation Bus and is an open-source home automation platform, which means it allows the building of a customized smart home system. OpenHAB supports more than 200 technologies and integrates about 2000 devices using add-ons. Thus, a flexibly configurable platform with a uniform user interface for the management and control of smart home devices is provided. This means that, for example, the smart Philips Hue and Ikea Trådfri lamps can both be controlled in exactly the same way via OpenHAB, regardless of the interfaces of the different manufacturers. (OpenHAB, 2021)

For the use case, the specific entities Things and Items are relevant, and are used to build the OpenHAB model of the PUX Lab. In short, Things represent the physical layer, i.e. the physical devices like the different lamps in the case study, and Items describe the virtual layer, i.e. the information

about the devices. Each Item can be changed with an appropriate request and the Things respond to these events sent for an associated Item. There are specific Item types that decide which commands are allowed to change the state in a certain way. (Things, 2021)

To replace the real OpenHAB server for the virtual PUX lab, a Node.js server was developed using the Fastify framework. Fastify is one of the fastest web frameworks, which can be used to implement performant servers efficiently with low overhead and a powerful plugin architecture (Fastify, 2021). For the simulation, three relevant REST endpoints of the OpenHAB API were replicated. For the previously described Things and Items entities, the respective GET endpoints were implemented. By taking the JSON response of the real OpenHAB server as a template for both endpoints and adapting it if necessary, realistic behavior can be ensured.

As the third and most important endpoint, the POST endpoint of the Items was implemented, with which the state of a lamp can be changed. For this, the behavior of the real OpenHAB server was analyzed in detail. On the one hand, the same validation was implemented, so that only the commands and numerical values allowed per Item type are permitted in the defined range. On the other hand, the same reaction to incorrect input was implemented, i.e. the same HTTP error codes and responses are returned if, for example, an unknown Item name, an invalid command, or a missing or unknown API token is sent. For a valid request, the state is updated according to the command and written to the database for the respective lab instance. In addition to regular Items, there are special Items, called Item Groups, that comprise other Items. When a request goes to an Item group, in addition to the Item Group state, the states of all affected Items must be updated accordingly.

The state changes must also be reflected in the user interface. For this purpose, the WebSocket protocol is used to enable communication from the virtual OpenHAB server to the frontend. In case of a state change, all required information, i.e. timestamp of the request, affected Item, and new state, is communicated to the frontend. Errors are also communicated so that they can be presented in a user-friendly manner in the action log of the Vue.js application. The Socket.io library was used to implement the WebSocket protocol, which greatly simplifies the establishment of connections between the backend and frontend (Socket.IO, 2021). In addition, Socket.io enables the creation of so-called rooms (Socket.IO, 2021). A room is a channel that multiple sockets can enter or leave (Socket.IO, 2021). This fits perfectly with the case study where users can enter a room or a lab instance. As soon as a user enters a room via the user interface, the client establishes a socket connection to the backend and joins the respective Socket.io room, which
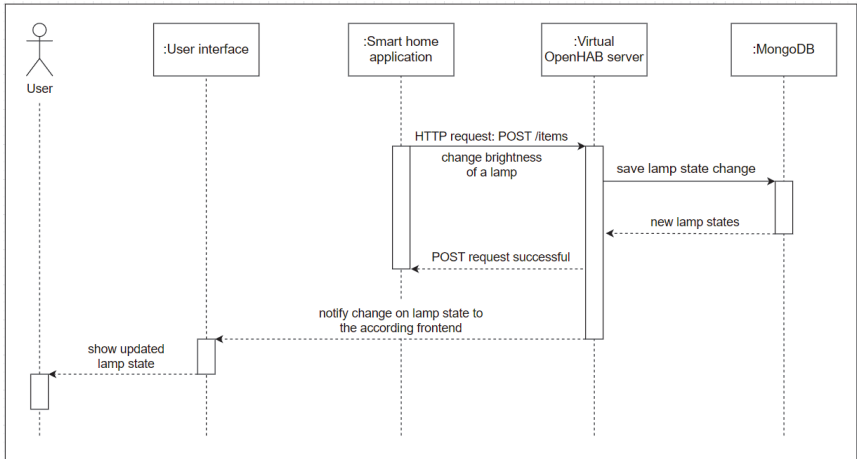
Figure 3.   Sequence diagram of a typical scenario

is uniquely identified by the room ID. Socket.io rooms can thus be used to send state changes to a subset of clients, namely only those clients that belong to the respective Socket.io room at that time.

The possibility of sending an API token along with OpenHAB requests was exploited to uniquely identify lab instances. Therefore, in the Open-HAB virtual server, all three implemented endpoints expect an API token in the Authentication Header in the Basic Auth format to perform the actions for the correct lab instance. The API token from the request is thus used to identify from which lab instance the state needs to be returned or updated. If the API token is missing, the same error code and response will be returned as for the real OpenHAB server.

In order to better understand the communication of the described components, an exemplary scenario is visualized in Figure 3. The sequence diagram shows the process in which, for example, the brightness of a lamp is changed. It starts with an HTTP request from the smart home application to the virtual OpenHAB server. The server validates and evaluates the request and saves the change of the lab state in the database. The smart home application is then informed that the HTTP request was successful. In addition, the virtual OpenHAB server notifies the user interface about the change to the lab state, but only the accordingly affected clients. The user can then see the updated lamp state in the user interface.

5 Evaluation

The evaluation phase of the implemented virtual PUX lab application was conducted with the help of user tests as well as in consideration of the previously defined requirements. The results will be examined to check whether and to what extent the requirements could be met.

5.1 User Tests

In user testing, participants who represent the relevant target group of the application are observed during a specific task related to the use of a product in order to discover both strengths and weaknesses and the corresponding opportunities for improvement (Niegemann et al., 2004).
A total of six user tests were conducted. All participants are students with a technical focus representing the future target group of the application under investigation. Each user test lasted about one hour and was conducted as an online meeting with the help of remote access on a computer where all required programs were already set up. In the beginning, all participants were given the same three tasks to solve by using the application and the OpenHAB interface of the virtual PUX lab:

1. Turn on and off all the lamps.
2. Change the brightness of the HueLampLittleTable to 70 %.
3. Change the color of the HueLampBackLeft to red.

The think-aloud method was used during the user tests. In this method, participants are asked to say out loud everything that is going through their minds without interpretation or analysis while completing a specific task (Güss, 2018).

After completing the tasks, participants were asked open-ended questions about their experience with the application in order to obtain feedback. In addition, a questionnaire with seven questions on a 5-point Likert scale was answered by each participant in order to check the various aspects of user-friendliness such as satisfaction, usability, comprehensibility, learnability, and efficiency.

The overall result of the users' tests is generally positive as all questions were answered either with 'Strongly agree' or 'Somewhat agree'. When asked about their first impression of the application, all respondents mainly emphasize the nicely designed user interface and the visualization of the virtual lab and refer to the general clarity and logical structure. The participants also rate the user-friendly operating aids such as the copy buttons

and the tooltips positively and see components such as the FAQ and the examples in the help section as well as the action log as useful and helpful.

All participants have successfully mastered the three given tasks. Since there was little to no knowledge of OpenHAB among all participants at the time of the user tests, a clear learning success can be observed. All of the participants describe a similar experience in that they first had to learn and get familiar with the OpenHAB system in the beginning, but with some help and time, as well as the first successful request, working with OpenHAB is relatively easy after that.

Everyone agrees that the virtual PUX lab requires significantly less effort. On the one hand, there is no need for the hardware set-up process, and on the other hand, physical devices are no longer necessary. The participants see a great added value in the virtual lab, as it enables them to work in the PUX lab without being on-site. Respondents also describe the application as a practical, real-world environment in which students can try out, experiment, and test on their own in projects regardless of location. All respondents would use the virtual PUX lab to gain hands-on experience with OpenHAB and smart devices, and see the benefit, especially in online courses. The possibility of collaboration in the same lab instance using the room ID is also mentioned as a positive aspect. Furthermore, the respondents envision the use of the virtual PUX lab in many different use cases and projects in the future and show interest in the possibility of flexible further development of the application to support even more smart devices.

Further potential for improvement is discovered in the area of user-friendliness and comprehensibility. The user tests proved to be very helpful in this regard in identifying usability weaknesses that only become apparent when tested with real users. The deficits identified regarding the layout or the presentation of the state, the group membership or the current room, could therefore be eliminated for a better user experience. With the incorporated suggestions for improvement, the prototype of the virtual PUX lab is now in a mature state and can be productively tested in lectures and workshops.

5.2 Review of Requirements

Furthermore, the requirements elaborated in Requirements Analysis3 could also be met to a great extent. Most importantly, the following features and functionalities were successfully implemented:

- Introduction text and help section with explanation video, FAQ and help resources

- Further user-friendly auxiliary functions like toast notifications, tooltips and copy buttons
- Realistic representation of state changes through animation in the SVG
- Interaction possibilities like entering or creating a room and controlling lamps by OpenHAB requests
- Feedback for requests in form of an action log and for other actions with toast notifications
- Collaboration with others in the same room through room ID
- Support for different device types and operating systems, as long as a current browser is available and JavaScript execution has not been disabled by the user
- Responsive web design for mobile devices, i.e. adapting the layout to different screen sizes
- Support for multiple languages as well as accessibility features such as keyboard navigation and screen reader support

6 Conclusion and Future Work

The paper has shown that laboratory experience is of high importance in the education of students. Hands-on learning and experimentation on real-world problems are necessary to acquire important skills and to transfer theoretical concepts into practice. Technological advancements in e-learning have led to increased exploration of virtual labs as an alternative to making these experiences more flexible and accessible to a larger number of students. This area of research holds great potential, which is why this paper has looked at the virtualization of a smart home lab within a case study.

The PUX lab was chosen as a case study to explore the feasibility of virtualizing a smart home lab. To design a potential solution, requirements were drawn from the literature and an analysis of existing applications and narrowed down to the case study in more detail using a focus group discussion. Subsequently, the first prototype was implemented as a web application. The evaluation phase, which included user tests, confirmed the feasibility of virtualizing a smart home lab. The previously defined requirements were largely met and the concept of the application with the implemented functionalities left an overall positive impression on the target group. The virtual PUX lab is accepted as a useful alternative to the real lab. In particular, the time- and location-independent access without the need for physical laboratory equipment is considered valuable for efficient work, especially with regard to an extraordinary situation such as a pandemic. Exploiting economies of scale and location-independent collaboration on

projects were also cited as additional benefits of the virtual version, allowing for a real-world hands-on laboratory experience for a wide range of students.

It has been shown that the virtualization of a smart home lab is possible. The suggestions regarding usability, layout, and other forms of assistance that emerged from the user tests in the evaluation phase could be incorporated into the prototype to allow for an improved user experience. The application is now in a mature state so that the virtual PUX lab can be integrated into the DigiLab4U platform and tested in productive settings as in lectures and workshops.

Currently, the virtual PUX lab is designed as an open environment, which allows a variety of creative use cases in projects. In future work or further developments, an expansion of the didactic concept would be conceivable. For this purpose, tasks and predefined experiments with specific learning objectives as well as automatic evaluation could be integrated to verify the desired learning success. In addition, further smart devices could be supported and simulated in the virtual PUX lab.

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