Optical Engineering

RESEARCH PAPER

Remotely operated optical lab equipment for education: a DIY approach

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ABSTRACT. Digital and remote education is of growing interest for internationalized education programs that combine state-of-the-art training programs including hybrid and blended elements. Particularly, but not limited to optics and photonics, hands-on experiences in training laboratories are key ingredients of modern academic education programs that cannot easily be replaced adequately. We propose a versatile platform for remote-controllable experiments with a focus on a flexible implementation. We present a toolbox called Extended Reality Twin Lab, which enables teachers and lecturers in academia with a personal commitment to advance and innovate education methods and learning outcomes to build their own remotely controllable optics and photonics experiments. An open-source GitHub repository includes source codes for the server, the respective web applications, and the included microcontrollers. It also contains the 3D printable models used to create the attachments for optical components often used in scientific labs. All parts are modularly designed to enable individual adaptation to a variety of experiments. We exemplify our approach by presenting a fully remote-controllable Michelson interferometer that was readily implemented in an ongoing international master's degree curriculum. With this implementation, international students are now able to attend the course and acquire specific optical knowledge and lab training regardless of their actual physical location. Reviewing this running field experiment, we also discuss students' learning outcomes with respect to optical principles, experimentation, and instruments.

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1 Introduction

In the field of education, the integration of e-learning methods,[1] including streamed[2,3] or recorded lectures,[4] serious games,[5,6] virtual laboratories,[7–10] and remote labs[11–15] has been a subject of continuous exploration. Particularly in the area of optics and photonics, this approach offers great potential for free, seamless, and widely accessible training of young talent to foster the

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fascination for optical instrumentation, experimentation, and engineering. This trend has garnered substantial attention in recent years, as evidenced by the numerous studies and initiatives dedicated to advancing the field of remote labs,[2,16–22] underlining their meaning for free education. Especially for those with barriers to accessing education due to external circumstances such as local conflicts, natural disasters, or pandemics, but also personal circumstances, such as physical disabilities, social commitments, or financial restrictions, remote education solutions can drastically reduce those barriers.

The rise of maker culture,[23,24] facilitated by the growing accessibility of electronics such as microcontrollers, mini PCs, and smart devices, [25–28] as well as maker tools, has initiated a new era where constructing personalized remote labs is becoming increasingly popular.[19,20,22,29] However, despite the growing interest and a multitude of individual offers on the market, the widespread adoption of remote labs in educational settings is yet to be realized.[30] Recognizing the need for collaborative approaches, numerous gathering and sharing platforms have emerged from individual initiatives.[31,32]

In alignment with these trends and due to the lack of a suitable solution with a focus on education rather than research, we created an innovative remote-controllable experiment with real-time feedback to the learner. Although our approach of using actuators to remotely control each manipulable optical component is not entirely novel,[15,17,29] it is suitable for practical laboratory courses that focus on the physical phenomena of the experiment. We do not attempt to innovate in the area of simulations due to the inherent limitations to fully capturing the immersive and convincing nature of real experiments. Our commitment is to bridge the gap between physical hands-on experimentation and remote hands-on learning to ensure a comprehensive and lasting learning experience in the field of optics and photonics. When we began development, we aspired to create an open-source, versatile framework to enable others to replicate this approach and contribute to its development. That is why not only the remote-controllable experiment but also the necessary toolbox has been made accessible for teachers, lecturers, and instructors. This paper introduces our comprehensive framework, Extended Reality Twin Lab (XRTL), designed to empower remote learning through practical training within the field of optics and photonics and other disciplines. Herein, we detail the concept using the example of a fully remote-controllable Michelson interferometer, a standard experiment in photonics teaching, that has been integrated into current university curricula. We will use this particular experiment to illustrate the framework and to explain the reasoning for our design choices. However, it is emphasized that the concept and the implementation can be transferred to a multitude of optical and other experiments and are thus highly versatile.

Embracing the do-it-yourself (DIY) spirit,[33–36] our XRTL leverages self-made attachments and a modular software toolset to convert existing experiments into remotely controllable setups (see Fig. 1). Our extensions are designed to be budget-friendly, using affordable electronic components and our in-house three-dimensional (3D) printers. Since the effectiveness of a remote lab

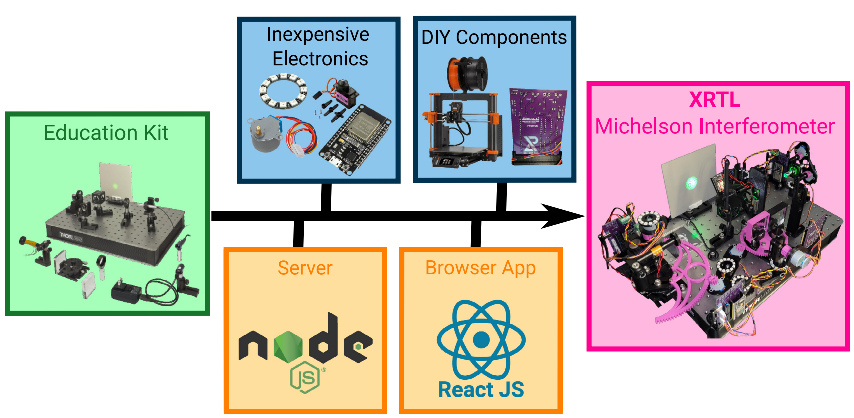

Fig. 1 Outlined transition of a standard experimental setup to an XRTL fully remote-controllable experiment as applied to a Michelson interferometer.

in enhancing the learning experience hinges on the degree of the learner's involvement,[9] we try to maximize this engagement by providing software modules (JavaScript) to create an enhanced graphical user interface (GUI) suitable for the different parts that an experimental setup can consist of.

Via XRTL, we want to simplify the steps to enable and thus strengthen the use of remote laboratories in educational institutions. Although we demonstrate XRTL based on an already implemented setup, it can be straightforwardly extended or adapted to experiments in other disciplines. Our XRTL is not only an innovative approach, but also an evolving open-source project with continuous development and updates accessible on GitHub.[37,38]

2 Learning Objectives

Delivering higher education and making it accessible for as many individuals as possible is one of the leitmotifs of many higher education institutions all over the world. Ideally, accessibility of education should overcome external barriers such as the recent pandemic. At the same time, it must maintain its high teaching standards and learning objectives. Here, the implementation of the XRTL concept aims to find exactly this balance by delivering ambitious optics laboratory training to international Master's degree students regardless of their physical location. After the transition of a standard Michelson interferometer experiment to a remote-controllable experiment, distant learners can perform a highly interactive experiment similar to their fellow students on-site. This strongly increased online student engagement compared to former solutions for lab courses.[3] Specifically, the main criteria we defined for a successful lab course can be categorized into two areas with different levels of adaptability to digitalization: fundamental and secondary learning objectives.

Fundamental learning objectives of a lab course: in the curriculum of our master's degree courses, the focus of the optics lab course is to convey both basic concepts and effects in physics as well as to train the students' documentation and data presentation skills to successfully analyze and communicate scientific topics. With XRTL, it is possible to fully transfer these fundamental objectives to a digital environment. The necessary actions to adapt these skills are primarily nonphysical in nature, so an on-site presence is not necessary. However, the persuasive power of an experiment carried out by the learners themselves is retained, as it becomes clear that an analog experiment is carried out synchronously to all actions taken in the virtual environment, as discussed specifically in Sec. 5 by example (see Fig. 9). The aspects of optical physics that can be specifically investigated with our XRTL Michelson interferometer described here are: checking the two outputs of a Michelson interferometer, determining the laser wavelength, measuring the spectral spacing of the laser emission peaks, measuring the coherence length of different light sources, determining the refractive index of two acrylic glass plates, measuring the thermal expansion coefficient of an aluminum rod.

Secondary learning objectives: besides the fundamental goals, a lab course also plays an important role in conveying data acquisition and error handling competencies as well as raising awareness for safety issues in a scientific laboratory. The latter is hard to achieve, as the physical absence of the operating person offers the highest possible level of protection. Hence, common safety measures such as proper eye protection are obsolete. In contrast, it is possible to raise awareness for thoughtful parameter settings, either by limiting the parameter space on the smart components to a meaningful interval or by displaying a warning on the user interface when improper values are entered.

Error handling can be taught similarly to on-site lab work, as the main sources of errors such as statistical fluctuations and measurement inaccuracies remain. There are additional challenges to address, too. On the one hand, some systematic error sources (e.g., disturbance due to ventilation) might not easily be accessible via the web application. On the other hand, digital data transfer and possible hysteretic behavior of the actuators and attachments may introduce new error sources that are not native parts of the performed experiment if done manually (see Sec. 5). Therefore, when conducting an XRTL experiment, students are faced with errors that may differ slightly from the experience in an on-site laboratory. Finally, data acquisition processes are usually simplified in a digital lab experiment, as all relevant parameters need to be processed by the application anyway. To counteract this, we deliberately refrained from

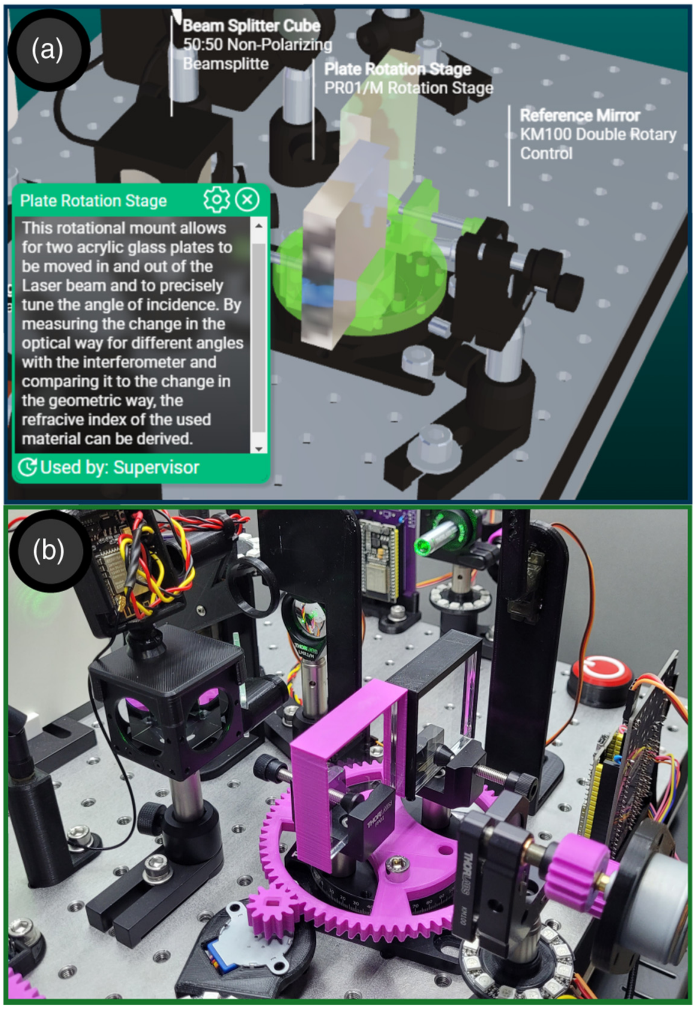

Fig. 2 Comparison of the app visualization with a real view. (a) Screenshot of the app with the option for labels turned on and a selected info window. (b) Photo of the real experimental setup showing the same part.

converting stepper motor steps into length or angle units and left this to the students as part of the tasks. This aspect is based on the idea that even a screw turned by hand does not provide a direct reference to the physical quantity that was actually intended to be changed.

Since the effectiveness of a remote lab in enhancing the learning experience hinges on the degree of student involvement,[9] the GUI for the XRTL remote-controllable experiment was created to provide a visual overview of the experiment and its components rather than simply providing controls and input fields (see Fig. 6). Ultimately, the GUI creates an opportunity to realize aspects that cannot easily be implemented in the on-site laboratory. Additional elements can be displayed to improve the experimentation experience, for example by adding a label to the virtual component that describes its functionality (see Fig. 2), or by visualizing otherwise invisible physical phenomena such as force fields or optical beam paths.

Conclusively, the virtual layer of the XRTL web application allows the integration of animations or video sequences to illustrate processes, which are too fast, too small, or otherwise imperceptible to naked-eye observation. In the future, it could offer the possibility of integrating learning analytics, which can also lead to redesigns based on the results achieved.[39,40]

3 Requirements for Implementing Remote Experiments

To create a fully remote-controllable lab experiment for educational purposes, it is crucial to consider certain prerequisites[15,17,29,41] as described in the following. In general, working in a scientific lab requires spontaneous adaptation to unforeseeable circumstances. For educational purposes in a state-of-the-art scientific environment, the following approaches are to be considered:

First, reduction of the possible input values of control parameters to the minimum amount needed for operation to achieve the educational goal. This can be achieved by limiting the input to pre-defined states that can be selected by the operating person, for example. Following this approach, the state of the experimental setup is always easily predictable and the need for spontaneous interaction for error correction is drastically reduced.[42,43] However, this also limits the operating person to a narrowly guided way of experimenting and does not encourage exploration and free experimentation. As this may be desirable in some settings such as elementary education of experimental skills, especially in a higher education context more freedom in the experimentation usually increases student engagement and learning success.[44,45]

Second, remote access to every single controllable aspect of an experimental setup. This approach delivers a high level of experimental freedom and usually best represents the circumstances of a real laboratory. However, this also comes with high efforts regarding the establishment, maintenance, and operation of the remote setup. In the worst case, this can lead not only to damage to the experimental equipment, as in the case of manual operation, but also to damage to the remote infrastructure itself. In addition, a large number of control options can distract from the educational content of the experiment, which can lead to a reduction in learning success. When designing a remote experiment, it is of great importance to keep a good balance between the two aforementioned scenarios to ensure both a high level of experimental freedom as well as sufficient security and manageable, remotely controllable resources.

In the following, we will present the requirements for the successful implementation of a remote-controllable educational experiment with the help of the XRTL toolbox. To start the design of a remote experiment, it is essential to consider the adaptability of the desired learning objectives to a digital environment. If, for example, the focus of the corresponding learning module is the delivery of haptic skills, it is very hard to convey this remotely. However, in certain areas, it has proven very useful to use virtual training prior to the operation of the real setup.[10,46,47] In contrast, fundamental concepts, experimentation routines, and data collection can be taught with close to no limitations in a remote lab scenario. Furthermore, with the help of remote-controllable experiments, learning objectives can be addressed that are not easily implemented in a classical lab course.[48,49] Finally, it is possible to construct analogies between real-world and remote aspects to raise the operator's awareness. For example, an optical setup usually needs adjustment before performing measurement tasks. This can be translated into a remote experiment by not setting default values for certain experimental parameters and including an adjustment step to find adequate values.

Usually, remote-controllable experiments are considered when access to the on-site experimental setup is restricted. Prominently, during the COVID pandemic, it was not always possible to bring students and instructors together in the lab. In this regard, a remote experiment can be considered even more useful, as it offers the possibility to experiment in a self-learning or blended-learning scenario, respectively. The restrictions of a remote-controllable experiment can be actively utilized to reduce the instructor's tasks concerning safety and operational issues so they can focus on teaching aspects or even to a level where the operating person does not need personal instruction at all. After the design process of the remote-controllable experiment, the technical requirements for the establishment of a remote-controllable setup need to be checked. In the case of the XRTL toolbox, the following prerequisites need to be fulfilled:

1. **Trivialities to consider**: In addition to the physical experimental setup, the location for the setup needs to be accessible for maintenance and to enable a stable Wi-Fi connection of the components with the network. The pitfall of the latter is striking in its simplicity: a stable internet connection via a suitable device is needed for both the student and the supervisor.
2. **Rapid prototyping and 3D design**: This is the key enabler of our approach. To connect actuators to movable parts of the experimental setup, attachments of some kind are usually needed. The ability to design and manufacture custom parts to bridge the gap between actuators and setups drastically saves financial and time resources compared to third-party assignments. However, specifically for optical experiments, we offer a growing

open-source library of 3D printable attachments for standard optical components such as kinetic mounts, iris apertures, etc., which are available in our GitHub hardware repository.[38]

3. **Electronics**: To enable communication with the actuators, basic electronic skills such as soldering and microcontroller configuration are required. In our hardware repository, detailed documentation for custom ESP32 microcontroller firmware is available, including printed circuit board (PCB) layout suggestions for easier electronic connections. Standard actuators and sensors such as stepper motors, servos, and cameras have existing presets for fast setup (see Secs. 4.1 and 4.2).
4. **Programming**: The operation of a remote-controlled experiment requires a user interface for data input and readout. XRTL offers a browser-based modular GUI that can be adapted to a variety of experiments assuming that basic programming skills in JavaScript and React.js are provided. The modular architecture reduces the effort to a minimum. In general, any event-based application can be used for communication with an XRTL server. Implementations for the Python programming language and LabView VIs are subject to future development (see Secs. 4.2, 4.3, and 4.4).[50]

Taking into consideration these key aspects, we show how to transform an existing experiment into a remotely controllable experiment in the following section using the XRTL toolbox as shown in Fig. 1.

4 Implementation of the Concept Using the Example of a Michelson Interferometer

The XRTL toolbox relies heavily on the internet of things (IoT) approach. To create a digital framework for remotely controllable experiments, different platform solutions are possible. One alternative solution is remote, desktop-based control units. After a careful consideration of these approaches and full awareness of their advantages and disadvantages, the authors decided against a monolithic client-server solution for the network connection, that is, a desktop-based solution. It is a technical goal of our approach to support a modular implementation of the experiment. Thus, creating separate server backends for each experiment would be costly and complex to maintain. Instead, we have implemented controls at the component level and utilize an IoT-based approach. While this increases communication and complexity within the experiment, it offers quick implementation, customization options, and easier maintenance. In our approach, a server acts as a central message broker following the modern IoT standard for designing adaptable networks of controllable components. This kind of approach is the contemporary standard under the term IoT in designing complex yet modular open networks of controllable and communicating components.

Hence, in our XRTL framework, all app users and the experiment components are connected as clients to an XRTL server over the Internet. To increase the modularity of the toolbox, every component autonomously communicates with the server. This approach defines the general communication structure as shown in Fig. 3.

The server acts as a central element by first authenticating the communication between the clients and then coordinating it after successful authentication. This is implemented on an event-driven basis. In the following, the process of setting up an XRTL experiment is exemplified with the Michelson interferometer described in Sec. 5. The base of the setup is the Thorlabs Michelson interferometer Educational Kit,[51] but clearly almost any other commercially available or home-built interferometric setup can be adapted for this purpose. It resembles a comprehensive experiment, including detailed documentation and task suggestions for students of various qualification levels.

The first step is to carefully plan which parts of the experiment need to be operated, which and how many actuators and cameras are needed, and where they can be placed to allow for an efficient and functional arrangement. For example, the laser mount held by a Thorlabs KM100 Kinetic Mount (KM100) [Fig. 4(a)] with two adjusting screws [Fig. 4(b)] for slight tilting and rotation was going to be augmented to become the Laser Alignment as listed in Sec. 5 in Table 1 Nr. 11.

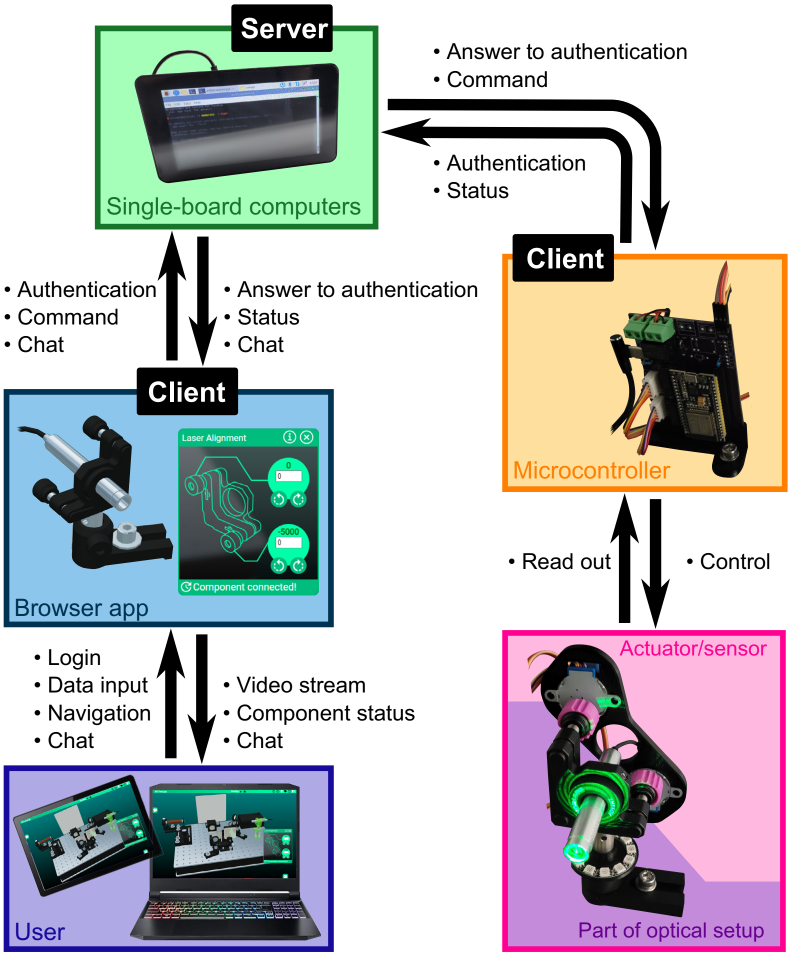

Fig. 3 Overview of the communication structure of a remote-controllable experiment created with the XRTL toolbox. Both the operating person and the components of the experiment act as clients and communicate with each other via the server.

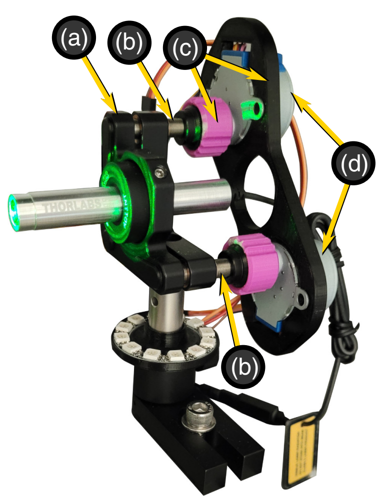

Fig. 4 Laser alignment component of the XRTL Michelson interferometer. (a) Thorlabs KM100 Kinetic Mount, (b) fine adjusting screws for tilting and rotation, (c) 3D-printed attachments, and (d) stepper motors.

After building the whole setup in a way that a good result can be obtained within the fine adjustment range of all components and here especially the KM100, a suitable attachment had to be designed [Fig. 4(c)] and the proper actuators had to be chosen [Fig. 4(d)]. For more details about the design process, refer to Sec. 4.1. For the KM100 as well as for several other widely used Thorlabs components, the blueprints for the 3D printable attachments as well as a list of the used actuators can be found on our GitHub hardware repository.[38]

After choosing the desired hardware, a suitable microcontroller and optionally an accordingly equipped PCB needs to be configured with the matching modules to control, in this example, two stepper motors and one info light-emitting diode (LED) ring. The necessary firmware alongside detailed instructions on how to configure the microcontroller for a variety of different modules is available on the aforementioned repository. Details on the functionality of the microcontrollers can be found in Sec. 4.2.

This describes the basic physical actions that need to be performed to equip an experimental setup with the XRTL toolbox. From that point onwards, dedicated programming tasks have to be done for a successful implementation of a remote-controllable experiment. Our GitHub software repository[37] includes detailed instructions for configuring an XRTL server on devices such as single-board computers. In addition, the repository includes a suggested browser-based single page application (SPA) endpoint. This SPA is designed with modularity in mind, allowing instructors to effortlessly modify and adapt it to their specific requirements by forking the repository. For details about the software, refer to Secs. 4.3 and 4.4.

4.1 Attachments, Actuators, and Sensors

When creating the hardware for the attachments to the optical components, we focused on continuous enhancements and optimizations while adhering to six fundamental design principles that underpinned our approach.

- **Ease of 3D printability**: acknowledging the prevalence of fused deposition modeling printers within the DIY community, we ensured the designs were aligned with their accessibility, recognizing their wider usage compared to stereolithography printers.
- **Reducing material usage while upholding robustness**.
- **Modular parts**: the reuse of design parts facilitates adaptation to similar optical components and effectively reduces waste.
- **Optical feedback function**: the integration of a thoroughly planned color scheme and indicator LEDs was intended to offer immediate optical feedback to learners, substituting the tactile feedback commonly encountered in lab settings.
- **Compact footprint**: this enables closer integration with other components and attachments, maintaining a uniform appearance and providing a comprehensive system overview.
- **Non-invasive attachment design**: the optical components do not need any permanent modification and can be reused in any other setup after their usage within the XRTL remote experiment (details provided in our GitHub hardware repository[38]).

These six guiding principles were instrumental in shaping our design methodology, ensuring a blend of functionality, sustainability, and user-friendly integration within laboratory environments. The bulk of the designing effort was realized with FreeCAD 3D design software to further emphasize the open-source approach of the XRTL toolbox.

4.2 Microcontrollers

Our goal for the microcontrollers within the XRTL environment was to keep them mostly autonomous, leaving as many hardware-related control options as possible up to the individual controller. Such decisions are, for example, to keep track of motor positions and boundary conditions, when and how to drive a motor, or when to send a status update to the server.

If, for example, a web application user wants to move a stepper motor by a certain number of steps, an event containing the motor *controlId* and the desired number of steps (*key value*) will be sent to all microcontrollers. The microcontroller the motor is attached to recognizes the motor *controlId* and extracts the action to be carried out (*control key*) and the number of steps as indicated by the *key value*, and ensures this will not cause the motor to leave its predefined parameter space.

To assist instructors in setting up microcontrollers for an XRTL experiment, we provide precompiled binaries that are ready to be flashed onto ESP32 microcontrollers, eliminating common causes of errors. Within these binaries, instructions for common control tasks, such as servo or stepper motors, are defined and can be utilized. We decided to organize our firmware in a modular manner, encapsulating specific functions in modules that can be added during runtime. To do so, the person setting up the remote-controllable experiment just needs to run a setup script to select the desired modules and conduct parameter settings. After the microcontrollers are supplied with power, the previously defined modules are automatically instantiated and are ready for use.

As for the concrete example of a remote-controllable Michelson interferometer, the implemented modules are:

- **wifi** and **socket**: establishing connection to the wireless network and the Socket.IO server
- **camera**: providing camera stream and control over camera settings
- **infoLED**: displaying information, such as actuator movement or connection status
- **servo** and **stepper**: managing of speed, position, boundaries, and initialization of motors
- **input**: monitoring and converting a voltage on an input pin
- **output**: controlling an output voltage on an output pin

To allow the automation of more complex tasks that may include more than one actuator, we also provide a macro module. Within this module, several sets of instructions to other modules are present as activatable states. If such a state is activated, all associated instructions are consecutively executed, leaving the experiment in this predefined state.

4.3 Server

The basic principle of XRTL is the connection of experiment components with each other and (multiple) user endpoints. Here too, the IoT approach offers the opportunity to freely choose a possible user endpoint. In our case, we created a browser-based SPA as described in Sec. 4.4. To ensure the easy implementation, adaption, and reintegration of experiments and their components, we chose a lightweight broadcasting protocol based on MQ Telemetry Transport, which is widely established in the IoT application field. In this type of protocol, there are two network entities: a message broker and some clients. The broker receives messages (events) from clients and distributes them accordingly. Figure 5 provides an overview of this topic and used libraries

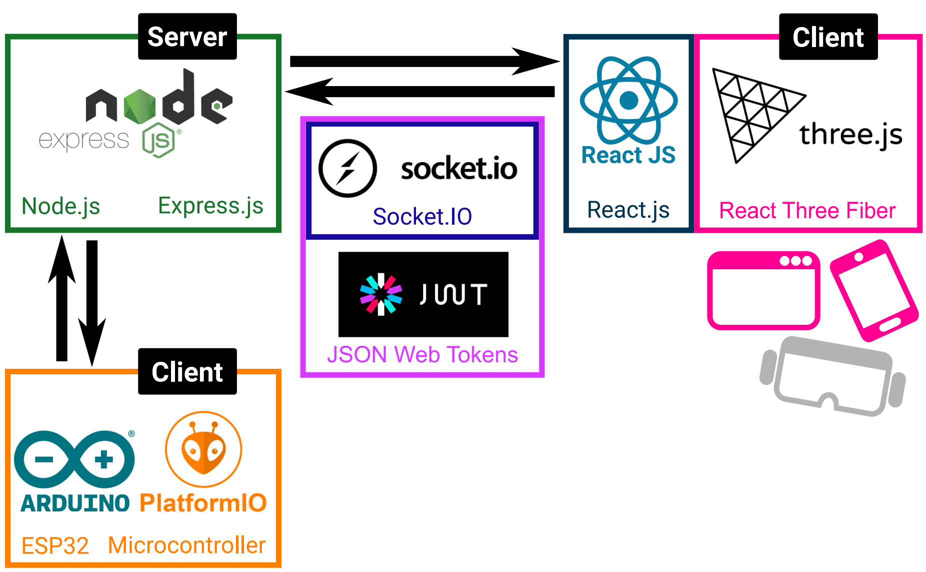

Fig. 5 Overview of the libraries and platforms used to develop and run XRTL. More details can be found on our GitHub software repository.[37]

Algorithm 1 Representation of the functional structure of the server event command. A JSON Object is sent to be filtered by the component with controlId "km100_bottom" to move the stepper motor a specific amount of steps.

```
socketCtx.socket.emit("command",{
userId: "test_user",
controlId: "km100_bottom",
move: 42,
}
```

and platforms. To minimize the initial hurdles for developers and contributors, a uniform code base was required within the XRTL project, which was chosen to be JavaScript. To ensure access only for verified components and clients, a security layer based on JSON Web Tokens was implemented.

For controlling experiment components, a command event is defined as shown in Algorithm 1. Each event holds a *controlId*, which allows the corresponding component to filter and react to the payload contained within the received event. The payload consists of a set of key-value-pairs encoding the command (control key) and its parameters (key value).

The overall open-source and well-documented JavaScript technology stack allows the server to be implemented easily on most common operating systems and platforms. For the XRTL use cases, we usually implemented a Raspberry Pi 4 single-board computer running a version of Raspbian Linux.

4.4 Single Page Application

The open-accessible network with the IoT-oriented WebSocket protocol as mentioned in Sec. 4.3 allows the integration of multiple endpoints. Any technology is possible as long as it supports WebSockets, including Python scripts, LabVIEW programs, Unity games, and web applications. The basic idea for our developed endpoint was to offer platform- and device-independent access. Furthermore, an SPA using React.js was chosen as a software environment for its comparably easy implementation and user-friendliness.

As shown in Fig. 6, the SPA consists of both experiment-specific parts like the aforementioned digital twin setup and its virtual components as well as universal parts [Figs. 6(c), 6(e), and 6(f)] such as navigation bar, chat, console, and the all-embracing context environments. We chose a 3D model representation as default digital twin in all our experiment implementations. The goal here was to establish an immersive lab environment like a student would experience by working on a real experiment. The 3D models of experiments were designed with Blender, a free and open-source 3D computer graphics software toolset, where we can create a ready-to-use model for our React.js SPA.

The component-based paradigm of React.js has proven to be very handy in the development of XRTL. It allows a separate development of data (context), integration layers, core functionalities, connectivity (context) as well as experiment components, and the 3D model (see Fig. 7). While the experiment-independent React.js components are integrated by default, the universal components must be selected and implemented when building or customizing an XRTL SPA. These are the only components that determine what the experiment looks like and how it is controlled. These universal components with their related control windows can be re-used for XRTL implementations in further experiments. With more and more XRTL experiments, the open source project will provide a growing set of ready-to-implement React.js components for commonly used optical setup components in the project GitHub.[37] The entire app is embedded in context environments that are responsible for providing app-wide data objects and connectivity functions concerning the WebSocket connection.

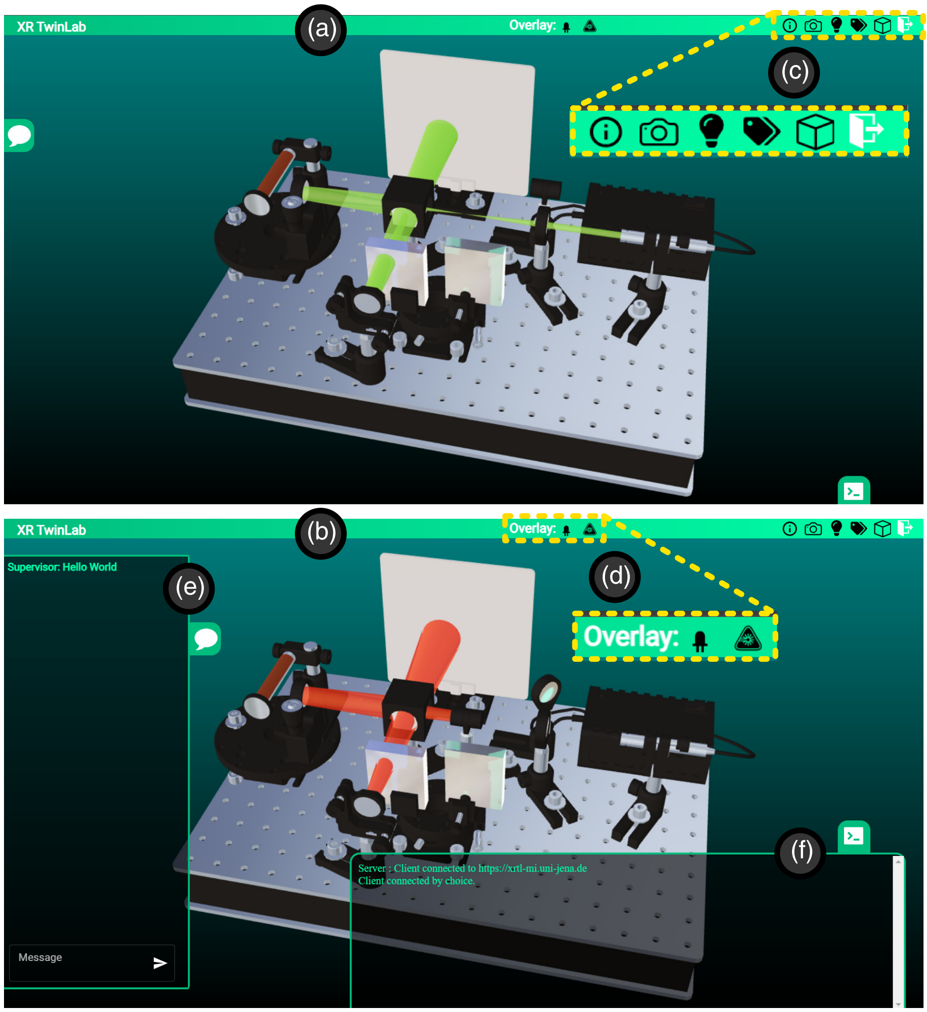

Fig. 6 (a), (b) Two screenshots of the XRTL SPA's GUI. Experiment-specific parts are the interactive 3D model and the overlay that can be configured (d) to show a stylized light path, for example, (a) the laser light or (b) the light of the red LED. Universal parts are components, such as (e) chat, (f) console, (c) navigation bar including login, display options, real top light, overview camera, and manual.

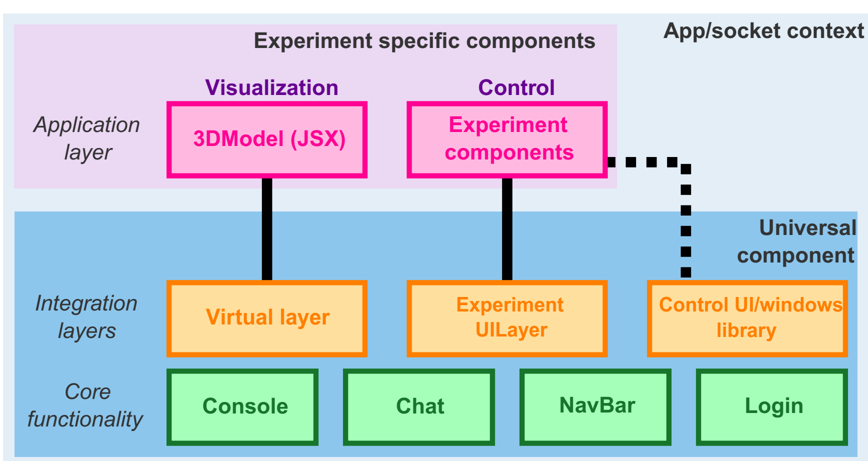

Fig. 7 Structure of the main React.js components in XRTL SPA. The classes of the program can be divided into components that are necessary for every XRTL remote experiment and are therefore universal and experiment-specific components that can be created individually. More details can be found on our GitHub software repository.[37]

5 Integrating the Remotely Controllable Michelson Interferometer into a Running Curriculum

While Sec. 4 was devoted to the general concept of the XRTL framework and its creation, this section describes in detail the experimental operation as well as the implementation of the remote-controllable Michelson interferometer into an international Master's degree program at a German university. Performing the experiment results in 4 to 5 h of student-level activity content. Figure 8 shows an overview of the entire experiment and consists of a photo of the real

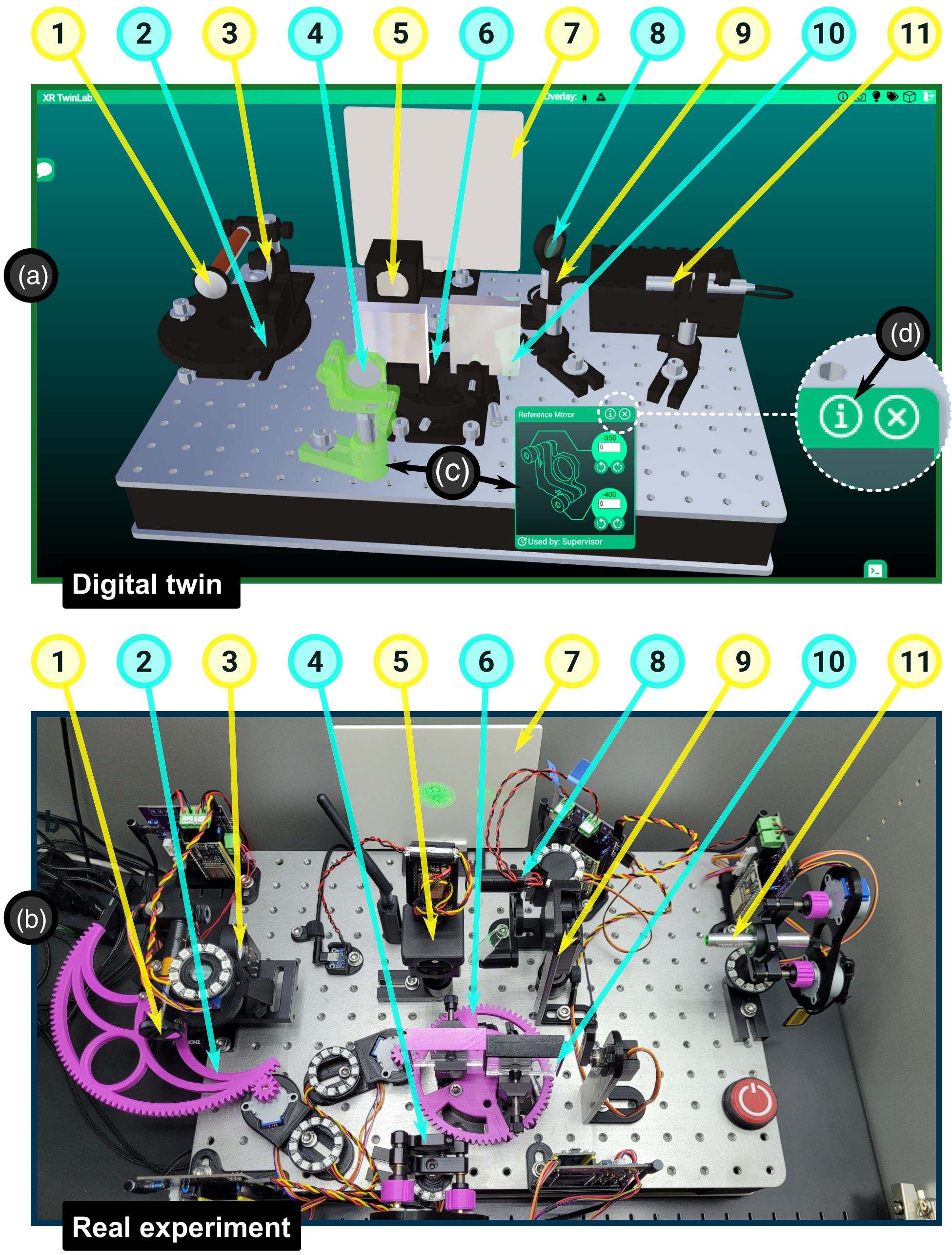

Fig. 8 Overview of the entire setup at the example Michelson interferometer XRTL experiment. It consists of a control app (a) that allows the experimenter to remotely control all necessary components of the real experiment (b). In addition to the basic interferometer, there are further components to carry out various experimental tasks. For each real component, there is a digital twin (1-11), which can be selected to open a window (c) with access to the adjustable parameters. (d) Within the window, an informative view can be accessed to get a brief description of the selected component and its functionality.

setup and a screenshot of the corresponding digital twin, which is the browser application to control it. For every component in the real experiment, there is a digital twin that can be selected to control the corresponding actuators and sensors, as marked in Fig. 8 with numbers from 1 to 11. The real setup was built and aligned such that a good result (e.g., a clear interference pattern) is achievable for all required tasks within the parameter range. Nevertheless, misalignment is still possible following the teaching concept of allowing the learners to gain experience from mistakes. The controls are intuitive by design. If a component is selected by clicking, a new window opens with all operating options associated with this component, exemplified in Fig. 8(c) for the kinematic mirror mount. There is also a quick explanation for each component that can be accessed directly [compare Fig. 8(d)] instead of having to search a conventional manual. Table 1 is intended to provide information about all components of the setup with their

Table 1 Overview of all components of the XRTL experiment. The components are listed order as numbered in Fig. 8. Some of these cannot be adjusted intentionally. Still, we provide an information window in the app. The last three components (I, II, III) were not previously listed as they are not visible in the overview and are mentioned here for completeness.

Nr.	Name in the App	Hardware	Adjustable parameters
			Measurable parameters
1	Heatable mirror stage	Foil heater	Heating power of tape
	Mirror mounted on an aluminum rod	Temp. sensor	Temperature of rod
2	Mirror changing stage	Stepper motor	Rotation of stage
	PR01/M rotation stage		
3	Linear movable mirror	Stepper motor	Linear movement of mirror
	SM1ZP/M translation mount		
4	Reference mirror	Stepper motor	Tilting of mirror
	KM100 double rotary control	Stepper motor	Rotation of mirror
5	Beam splitter cube		
	50:50 non-polarizing beamsplitter		
6	Plate rotation stage	Stepper motor	Rotation of stage
	PR01/M rotation stage		
7	Screen	Camera	View of pattern
	Screen with interference pattern		
8	Multi-component selection	Servo motor	Swapping components
	Custom revolving mount	Red LED	On/off red LED
		White LED	On/off white LED
9	Lens	Servo motor	Insert/extract pinhole
	Bi-convex 50 mm focal length		
10	Differently sized acrylic glass plates		
	Objects for measurement		
11	Laser alignment	Stepper motor	Tilting of laser
	KM100 double rotary control	Stepper motor	Rotation of laser
I	Power supply	Relay	On/off laser
	5V laser power supply		
II	Light source	Relay	On/off top light
III	Overview cam	Camera	View the whole setup

remote-controllable adjustment options followed by a description of the individual tasks of the students in the lab course. All components in the table are listed as numbered in Fig. 8.

Two different types of motors are used in the individual tasks: while the stepper motors (Table 1 items 2 to 4, 6, 11) can be adjusted almost continuously (4096 steps per full turn for the type of motor used in our setup), servo motors are capable of reproducing positions on a value range (Table 1 items 8 and 9). Stepper motors are therefore used, for example, to adjust the beam path very precisely via mirrors. The servo motors, on the other hand, move components with a predefined orientation, such as an additional beam splitter plate, a red or white LED, or a pinhole. The "Multi Component Selection" (Table 1 item 8) can swap various components (LEDs, beam splitter plate) in and out of the optical beam path similarly to a filter wheel. The additional beam splitter facilitates observation of the interference pattern at the interferometer's second output in comparison to the first. Instead of the laser, a red or white LED can be used as an alternative light source to, for example, assess their respective properties regarding spatial coherence. The most important components for the immersivity of the online experiment are the two cameras (Table 1 items 7 and III). While the overview camera (Table 1 item III) offers the experimenter a very similar view compared to Fig. 8(b), ensuring they are well informed about the ongoing activities, the screen camera displays the interference pattern on the screen. Since the aspects to be observed on the screen are to be assessed by the experimenter, the screen camera offers the possibility to adjust the exposure time and contrast settings. The Michelson interferometer as a learning experiment has the inherent advantage that all measurements are performed by observing and interpreting the interference pattern and its changes, which is made possible solely by the screen camera. At this stage, the setup, complete with all actuators and sensors, provides students with 4 to 5 h of hands-on experimentation alongside documentation including tasks that guide them through the process. They then analyze and interpret their data and record it in a report to be submitted as in an on-site lab course. To provide insight into the learning scenario experienced by the students, we would like to describe one task as an example of the XRTL experiment and explain what the students can do, observe, and learn. The selected task is: "adjust the acrylic glass plate such that it stands perpendicular to the beam path." This is a mundane adjustment task that reflects the hands-on experience that the students receive. The results of the adjustment are then used further. Figure 9 summarizes the perspective of an experimenter completing the task. At this point of the experiment [Fig. 9(a)], we assume that the laser is switched on, the setup has been adjusted such that an interference pattern can be clearly seen [Fig. 9(b)], and one of the two available acrylic glass plates has already been placed close to perpendicular in the beam path [Fig. 9(c) dashed line]. With the help of the plate rotation stage (Table 1 item 6), the two acrylic glass plates to be examined later in the experiment can be positioned alternately in the beam path. Via the control window [Fig. 9(d)], the rotation of the stage in steps of the stepper motor and their direction can be selected. A full turn of the stage requires 26,450 $\pm$ 25 steps, resulting in an adequately high angular resolution. This value should be determined by the students themselves at the end of this task and used for their further analysis. As the plane-parallel acrylic glass plate approaches the desired perpendicular position, the optical path for the passing laser beam becomes steadily shorter. The rings of the interference pattern continue to grow during this approach [Fig. 9(e)], which is even more evident in the live view than in the still images shown in Fig. 9(e). A movement range in the order of 10 steps per move should be chosen through experimentation. One step would be far too small to see a change and be completed in a finite amount of time. On the other hand, 100 steps would be too rough to fully utilize the accuracy of the setup. The changes in the interference pattern with constant movement intervals become smaller as the correct position is approached [Fig. 9(f)]. At the point where the perpendicular position has been exceeded, the rings begin to shrink again as the stage continues to rotate [Fig. 9(g)]. The reversal point of the change in the pattern defines exactly the desired position [Fig. 9(h)]. In the search for this point, the students are challenged with the inadequacies of the analog experiment as if they were in the lab, since the rotation in one direction works very precisely. But when the direction of rotation is reversed, a hysteresis of $\sim$30 steps occurs. After determining the reversal point, the students should carry out a full turn of the stage [Fig. 9(i)], find the exact perpendicular position again, and then determine the ratio of angles per step. The learning content conveyed in this task includes the application of the concept of optical path length and the interpretation of interference patterns. When processing the self-determined values and assessing their

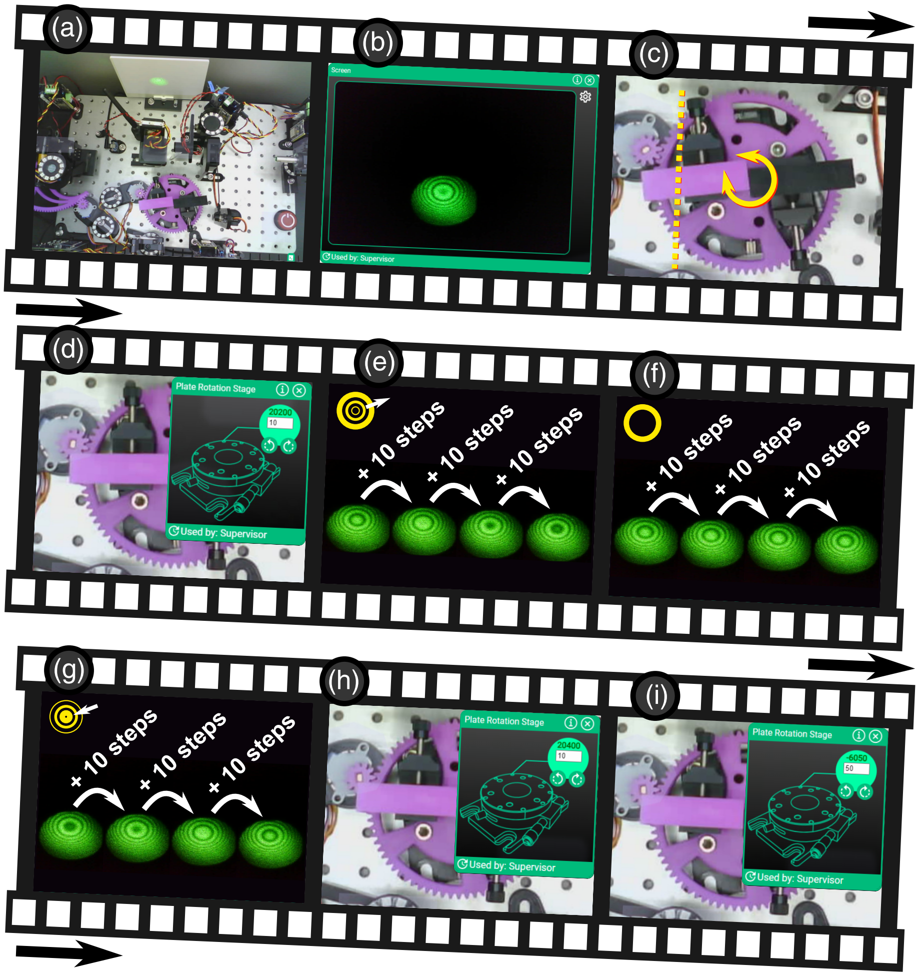

Fig. 9 Sequential illustration of the workflow of the experimental task "adjust the acrylic glass plate such that it stands perpendicular to the beam path" carried out by a student. (a) View given by the overview cam (Table 1 item III), (b) view given by the screen (Table 1 item 7), (c) detail of the overview with beam path indicated as a dashed line, (d), (h), (i) detail of the overview with component control window, (e)–(g) consecutive views shown from the screen. A description of the sequences is given in the text.

trustworthiness, the students internalize considerations of inaccuracy and the propagation of errors. The comprehension of the optical beam propagation, the alignment procedure as well as the inadequacies of the real setup are important aspects of the delivered learning content.

6 Summary

Remote-controllable setups for education are important as they offer a new, innovative, low-hurdle instrument to transfer expert knowledge and practical training to students regardless of their physical location. Giving wide access to such technologies to teachers, lecturers, trainers, and students at an academic level can boost the fascination for modern optical technologies and reach out to a much larger pool of young talent and future optical scientists. In this paper, we introduced the XRTL as a toolset to enable all key players in academia to realize remote-controllable experiments for the broad target group of students in the natural and engineering sciences in an academic and state-of-the-art research environment. One key aspect of the approach is the real-time coupling of an analog with a virtual experiment to allow for a maximized learning experience in comparison to classical hands-on experimentation. This approach also accounts for learners with external and/or individual barriers to accessing educational resources and hence increases educational equity. To exemplify our concept in a standard optical experiment, a commercially available Michelson interferometer education kit was equipped with

3D-printed attachments for all adjustable components. Actuators are used to manipulate the movable parts of the optical components while cameras and sensors allow observation of the experiment from a distance. The basic principle of XRTL is the connection of experiment components with each other and (multiple) user endpoints. To reach the goal of an easy implementation, adaption, and reintegration of experiments or their individual components, we applied the widely used JavaScript programming language for an IoT network. We have provided the complete source code at an open-source GitHub repository for the general public.[37] It is emphasized that this workflow is applicable to a practically unlimited pool of education toolkits not only in optics and photonics but also in adjacent disciplines, which makes our approach highly versatile and transferable. We have shown that the transmitted learning content covers both fundamental learning objectives of a lab course (basic physical concepts and dependencies of certain effects on respective variables) as well as secondary learning objectives, at least to a large extent (data acquisition, error handling skills, and awareness of safety issues). Moreover, operating remote-controllable experiments also translates into a new set of skills in itself as they become increasingly important in the modernization and digitalization of research laboratories and business-related R&D environments.

Disclosures

The authors have no relevant financial interests in the paper and no other potential conflicts of interest to disclose.

Code and Data Availability

The entire source code for the frontend software, backend software, and the microcontrollers, as well as the designs for attachments and PCB can be found and viewed via our XRTL GitHub repositories (https://github.com/Lichtwerkstatt/XRTL_SPA and https://github.com/Lichtwerkstatt/XRTL_Hardware).

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