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Enabling Remote Laboratories with LabMS – Fundamental Considerations and Proof of Concept

Abstract

In recent years, new resource-sharing concepts have been developed and implemented, for example, in applications such as car sharing or office space sharing. Sharing large research infrastructures such as particle accelerators is also common. The operation of laboratories for educational purposes is an example of how we can benefit from implementing the concept of sharing knowledge, infrastructure, and facilities in the educational field. However, a corresponding networked IT infrastructure is needed to enable the sharing of laboratories between different institutions.

The joint project DigiLab4U is developing, testing, and evaluating a digitally trans-formed laboratory environment that enables cross-site networking of real and virtual laboratory facilities.

Multiple services and applications have been designed, developed, implemented, and deployed for the DigiLab4U project. One of the main components, the Laboratory Management System (LabMS) application, provides an integrated platform to manage remote experiments. Mainly, it interacts with laboratory instruments via IIoT integration protocols and provides web-based user interface for remote users. It can be run in standalone mode, or by interacting with the DigiLab4U infrastructure and services.

This paper focuses on DigiLab4U LabMS architecture, its Application Programming Interface (API) and functionalities, as well as security and safety concerns in digitalized remote laboratories.

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Keywords

Remote Laboratories, IoT, Digitalization

1 Introduction and Problem Statement

Laboratory experimentation plays an essential role in engineering and scientific education (Heradio et al., 2016). There have been several approaches to developing laboratory-network infrastructures in the past. In recent years, new and innovative types of virtual and remote laboratories, such as VR labs and serious games, have become more and more common (Adineh et al., 2022).

For remote experiments, robots can be used to automate manual operation procedures. Consider a robot arm that gets three numbers as target coordinates to move to. The goal is to develop a remote experiment that contains a user interface to get the target coordinates from the user, submit it to the robot, receive robot feedback, and return it to the user. At the same time, the user should be able to monitor what is happening inside the laboratory via a camera. Only one user at a time can perform the remote experiment and thus the user needs to book a time slot in advance. While real-time protocols are needed for time-critical operation (e.g. safety), other commands and responses may be communicated via Internet Protocol (IP). In some cases, however, there is no opportunity for the laboratory owner to provide a static IP address to the LabMS server due to university regulations. Additionally, remote experiments in universities should be able to be called from a Learning Management System (LMS) inside a specific course to simplify the learning environment. This paper contains information about our proposed Laboratory Management System (LabMS), to reduce the time and effort required to operate remote lab experiments.

Section two provides insights into the research background and prior activities. Section three explains the LabMS' architecture and its functionalities. In section four, a case study is presented to prove the usability of LabMS. In section five, outcomes and conclusions are discussed.

2 Research Background

There are already many studies and approaches about how to make laboratories available remotely, whereby the motivation differs (costs, too little equipment, practical experience, workload, ...). Their focus is on technical

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aspects and how a laboratory can be operated remotely and what technical possibilities there are in terms of implementation. For example, at the Higher Colleges of Technology in Dubai, a LabVIEW interface was designed and implemented to remotely connect to a FESTO MPS PA workstation required for process control training (Ahmad et al., 2020). At the University of Negeri Makassar, due to the insufficient laboratory equipment available, it was investigated how effectiveness and practicability could be increased through a remote laboratory (Jaya et al., 2020). The University of Parma, in cooperation with the University of Modena and Reggio Emilia (Modena) and the University of Applied Sciences Stuttgart, have designed a general multi-layer model for networked remote access laboratories based on criteria from previous work and have validated it with a mini-Delphi method (Romagnoli et al., 2020).

In general, remote IT-based operation of laboratories can be regarded as an application in the Internet of Things. Therefore, we have been looking at recent developments in IoT frameworks and protocols and we have compared existing approaches in other laboratory network developments. When the DigiLab4U (Pfeiffer & Uckelmann, 2019) project started, the main projects with somehow overlapping goals were LiLa (Richter et al., 2011), UniLabs (Saenz et al., 2015), NetLab (Siddiqui et al., 2016), and Go-Lab (Govaerts et al., 2013). However, none of them focused on utilizing recent IoT developments. Therefore, the decision was taken to develop a new architecture as well as software services to provide IoT-specific interfaces and communication protocols for the project's technical implementation. Moreover, in terms of cross-university collaboration between industry-related, physical, and digital laboratories, there is a need for a collaborating and connecting platform which is also easily adaptable to future needs.

Thus, within DigiLab4U we defined a modular IoT-based architecture including different services and applications. Some of them are running on central servers and shared among laboratories, e.g. Learning Management System, Billing, Booking, Research Data Management and Learning Analytics. However, the LabMS was developed to be operated within the laboratories home institutions. This on-site application should be compatible with the shared services mentioned above and the general DigiLab4U architecture. Moreover, it must be able to interact with laboratory instruments to operate them while running the users' requested remote experiment. Basically, LabMS tries to abstract the laboratory in such a way as to be available as a software service through the Internet. This complies with the concept of Laboratory as a Service (LaaS), as described in Halimi et al. (2018). Figure 1 illustrates standard layers for remote Laboratories as a Service. As

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regards DigiLab4U specifications and requirements, the LabMS architecture is generally the improved and customized version of this architecture.

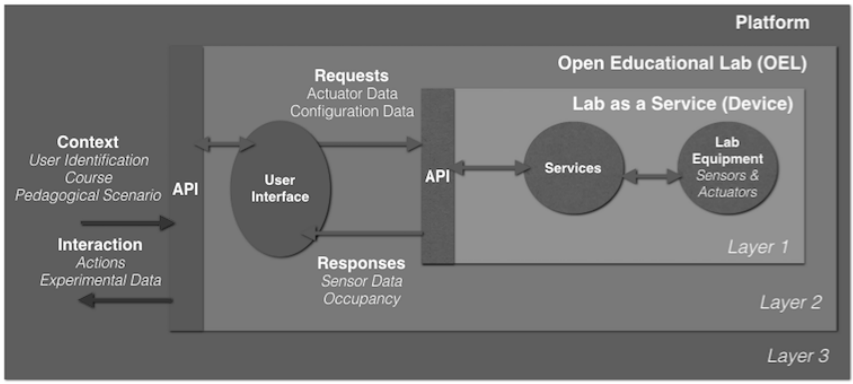

Figure 1. Standardization Layers for Remote Labs Integration (Halimi et al., 2018)

3 Laboratory Management System (LabMS)

For communication between the laboratory devices and the end users a middleware is needed to simplify remote access and enable the integration of laboratories into a shared lab environment (DigiLab4U). DigiLab4U LabMS was designed, developed, and implemented for this purpose. To achieve this goal, the following requirements were considered in LabMS:

1. Enable remote experiments
2. Interact with laboratory infrastructures in engineering disciplines
3. Provide means for lightweight access (e.g. REST)
4. Support laboratories with constrained access capabilities (e.g. if no static IP address laboratory servers can be provided; more information about this requirement can be seen at Adineh et al. (2022))
5. Interact with common Learning Management Systems (Moodle) and other DigiLab4U shared services (e.g. booking, data management)
6. Consider security and safety requirements (see (Uckelmann et al., 2021))

DigiLab4U LabMS libraries are a set of Java classes and packages which has been written by the DigiLab4U technical team based on the Spring Boot framework. In many cases, requirements mentioned in the "Introduction and Problem Statement" section could be covered automatically by imple-

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menting LabMS libraries. It makes the development process easier and more flexible.

In the case of developing remote experiments with LabMS libraries, by using the provided sample LabMS, the focus is on how to run the remote experiment from the laboratory's side. In a similar way to creating a new Maven project, relevant dependencies (e.g. LabMS and Spring boot packages) are added, a Java class that extends "LabExperimentRunner" is defined, and overriding the "startExperiment" function is implemented in line with the logic of the experiment. In the following a suitable web-based user interface (UI) for the experiment can be developed and the lab experiment can be executed.

To monitor the experiment via camera, LabMS uses the WebcamXP application. This application should be configured to capture the camera's video while its internal web server is running. LabMS is able to get captured frames and send them to the UI via REST API. To manage bandwidth consumption, these frames could only be shared with the user during the experiment's running time.

3.1 LMS integration

DigiLab4U uses Moodle as its central LMS. All user credentials as well as courses are defined within this Moodle. LabMS, as an external service of the Moodle, needs to receive the credentials of the user who is running the remote experiment. To provide this single sign-on feature, LabMS benefits from IMS LTI to enhance secure interactions with Moodle. The Learning Tool Interoperability (LTI) from Instructional Management Systems (IMS) is a specification which describes easy and secure communication between LMS and other learning applications (Gavin Henrick, 2012). In our scenario, by clicking on the remote experiment link inside a Moodle course, the user's ID as well as roles will be shared securely with LabMS through the LTI protocol.

3.2 Connecting to Laboratories without Static-IP

Every LabMS server must provide a static IP address to be able to be called up from the Moodle server as well as by remote users. Some laboratories are not able to provide such a capability. This problem is discussed in detail in the paper "Challenges and solutions to integrate remote laboratories in a cross-university network" (Adineh et al., 2022). It showed that combining AMQP (Advanced Message Queuing Protocol) and RPC (Remote Procedure

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Call) protocols makes local laboratories (without a static IP on the laboratory's side) addresses available to remote users (Figure 2).

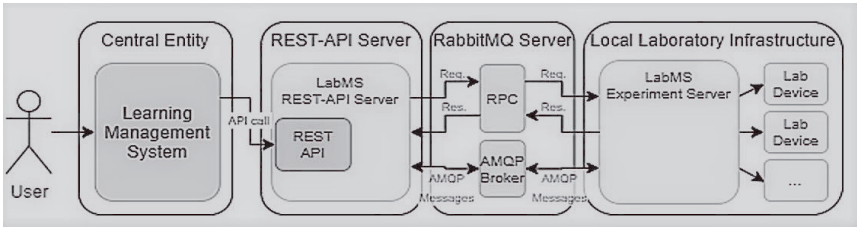

Figure 2. Combining AMQP and RPC protocols can enable communication for remote users with local laboratories without IP addresses (Adineh et al., 2022)

We continue this section with the help of an example. Consider that you have developed a remote laboratory application based on LabMS libraries. This application could be installed and run in your laboratory server and serve the web-based experiment requests as well. The server has access to the Internet, but the remote users do not have access to it. Hopefully, you can have access to a Virtual Private Server (VPS), maybe outside your laboratory. This VPS could be accessed from all over the world via its IP address or domain name. Now you just need to install and run an exact copy of your remote laboratory application. LabMS libraries, from version 0.9 could internally manage this situation.

LabMS is able to automatically adapt itself to its desired role by reading the value of "SERVICE_TYPE" parameter from its configuration file. This parameter could be set up by one of the following values:

- "LabMS": This value means that the application is running on a laboratory server which has a static IP address. So, it could server requests in a standalone mode.
- "ExperimentService": LabMS applications with this service type, run in a laboratory which does not have a static IP address and could not be seen directly by remote users. Thus, it should communicate with its partner LabMS via the VPS mentioned.
- "RestService": This value reveals that running a LabMS application is the partner of the ExperimentService mentioned. Then, it is responsible for receiving requests from remote users, sending them to the ExperimentService, receiving the results from it, and submitting them to the users.

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As mentioned earlier, all those situations are handled dynamically by the LabMS and would not require extra development efforts from the developer. The communication between the RestService and ExperimentService is coordinated through an AMQP broker named RabbitMQ. The laboratory credentials of a RabbitMQ broker should be added to the relevant parameters in the LabMS configuration file.

4 Case Study: Remote RFID Lab at HFT

Radio Frequency Identification Transponders (RFID) are used in logistics to track the flows of goods or production processes, both within and across companies. In order to meet the requirements of the various use cases, there are many different RFID transponders on the market.

The RFID laboratory at the Stuttgart University of Applied Sciences (HFT Stuttgart) has been used as the first laboratory test-case to be implemented via LabMS. Interacting with industrial robots, operating the RFID measurement chamber, identifying security and safety challenges, as well as providing a media didactically designed user-friendly web-based user interface (as described in Pfeiffer et al. (2022)) were the main requirements for the technical concept.

4.1 Automation and Safety

Normally, a person should be present in the laboratory to move the RFID tags between the Tag-bank and RFID Measuring Chamber. The remote experiment does not depend on human operation in the lab. This means, at least, that manipulating RFID tags should be done automatically.

Implementing a Mitsubishi RV-2SDB MELFA robot arm enabled this process to be automated. Using MELFA language, this robot was programmed to operate as a server, get commands from the LabMS via TCP sockets, perform relevant movements and finally send an acknowledgement back to the LabMS.

Operating an industrial robot arm at a laboratory site raises safety concerns. On-site operation, maintenance and configuration, remote experimentation, and users with different skill levels need to be considered. In order to be able to guarantee on-site security at all times, different components and technologies are used. These are connected with one another by means of the LabMS in order to be able to ensure a secure process during a remote exercise, both online and on-site.

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The RFID measurement cabinet was first used in an open-shared lab space. Multiple user-groups have access to this area. While safety was provided through a laser-based surveillance-system, every safety incident caused an emergency stop. The restart had to be done locally—which conflicted with the requirement of fully remote operation. Additionally, the old Mitsubishi robot caused other problems due to lacking interfaces and documentation, defective and rare batteries, and limited reach. Thus, it was replaced by a new collaborative robot. However, generally the process and interaction with the LabMS is the same. For additional resilience and safety, we added a machine protection fence including a door sensor, which in turn is connected to the robot via an I/O interface. These systems are described below in more detail.

4.1.1 Cobot

An Aubo i10 robot is used to load RFID probe-tags to the RFID measuring chamber. This robot is a cobot (collaborative robot). This type of robot is designed to be able to act in direct contact with humans without seriously injuring them. To ensure this, the Aubo i10 is equipped with sensors that can detect blockages in its movements. The sensitivity can be set to ten different levels (collision class 1 to 10). The higher the level, the less force is required to stop the robot after collision detection. According to the User Manual, the robot is configured before shipping so that it can be operated without additional safety devices. However, for a concrete risk assessment by the robot manufacturer, the intended operational workplace must also be taken into consideration.

4.1.2 Laser-based Safety System

The system from Pilz, a German manufacturer of safety systems, consists, in our case, of a laser scanner and a non-contact safety switch. The laser scanner divides the known area of the robot's environment into three different zones and can thus recognize and distinguish whether a person is inside or outside a safety-relevant area. In the first area, the person is outside the safety zone or no person is present and the robot operates normally. If a person is in the second area, the robot moves at reduced speed. If a person enters the third safety zone while the robot is moving, it immediately stops all movement.

The non-contact safety switch is used to detect the status of the door of the measurement cabinet. If the door is or is about to be opened during a measuring process, the robot will immediately stop any movement.

Due to benefiting from real-time reactions, this safety system is directly connected into the robot instead of the LabMS.

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4.1.3 Safety Fence

After the measurement cabinet and the robot have been moved to a more secure room with limited access, a machine protecting fence is installed to separate the robot and the measuring chamber into a safe area (Figure 3). This machine guard complies with European and international standards: EN ISO 14120, EN ISO 13857, EN ISO 14119, EN ISO 10218-2.

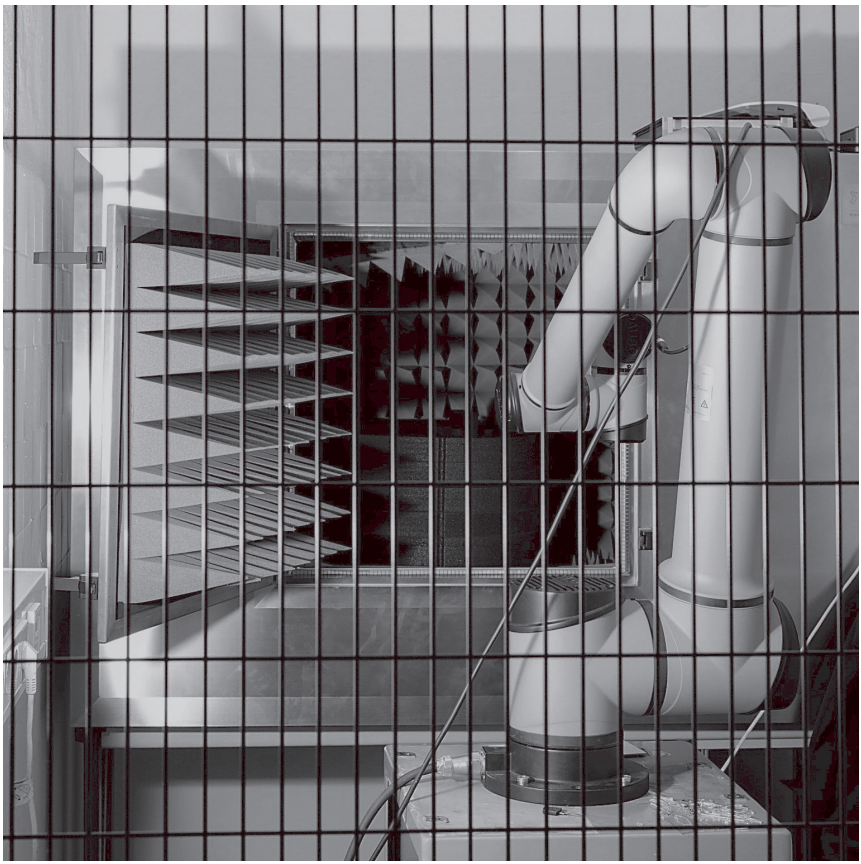

Figure 3. The Cobot and RFID Measuring chamber are behind safety fences

For additional safety, a safety lock is installed on the door of the fence, which can be locked from the outside but can still be opened from the insi-

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de at any time. So, if a person is in the safety area, they can leave anytime. The fence helps to avoid unintended safety stops caused by passing people. This fence is not connected into the LabMS. Mainly it is used to prevent unauthorized persons from accessing the robot working area at laboratory.

4.1.4 Surveillance Camera

In order to be able to monitor the course of the experiment even while the laboratory is being operated remotely, a surveillance camera is installed in the laboratory in such a way that the room inside the protective fence, in which no people may be present during the measurement, is imaged. IP-Cameras, mainly providing an URL, can be used to get the current snapshot of the environment. By inserting this URL as the "IPCAM_IMG_URL" parameter into the LabMS configuration file, you will be able to retrieve the current laboratory image from your developed remote experiment user interface. The LabMS will provide it for you if the endpoint "/getVideoCamImage" of your API is called up. By calling up this API periodically, the remote user can see what is happening during the experiment. As far as security, privacy, and bandwidth management are concerned, the live view feature of the LabMS is only available during the measurement.

4.2 Integrating with Moodle and Booking

The open-source Moodle plug-in, named Scheduler, is used to organize the appointments offered to students and researchers. With this plug-in, teachers can open time slots for students, which can then be booked by them. It is possible to determine whether an appointment can only be booked by one student or by several ones. It is also possible to allocate the appointments. Since the plug-in can be installed very easily in every Moodle course, it is convenient for both teachers and students to use.

5 Conclusion and Future Works

Designing and developing a Laboratory Management System is a complex task. Different infrastructures, university guidelines, safety and security issues, as well as recent developments and synergies concerning the Industrial Internet of Things (IIoT) need to be considered. However, the LabMS developed has shown that it is flexible enough to be adjusted to current and future needs. Now, educational laboratories can implement a LabMS with reasonable effort. Implementing a LabMS improves the development of

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remote experiments and simplifies the integration of laboratories into the DigiLab4U platform.

We have also discussed digitalizing the RFID laboratory with a LabMS while considering safety issues. The effort to automate experiments with robots should not be underestimated.

A LabMS, as it is, can manage remote laboratories and remote experiments. As part of its next steps, it could be improved to coordinate multiple laboratories as a central cloud-based service. In this case, a central LabMS will be developed and run in DigiLab4U servers to serve and manage interactions between DigiLab4U-shared services and remote laboratories.

Moreover, through improvement of its user interfaces, manipulating experiments (adding, removing, and editing them) could be done in a simple, user-friendly manner.

Providing mechanisms for a LabMS to enable it to interact with other digital laboratory platforms can be mentioned as another future plan.

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