DigiLab4U: General Architecture for a Network of Labs

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Abstract: The paper presents the architecture designed to create a network of remote and virtual laboratories, to integrate and enhance them with new technologies and methods for lab-based education, within five universities inside the Open Digital Lab For You (*DigiLab4U*) project. Many factors lead to an increase in interest in networks of labs. The main ones aim on increasing the exploitation of laboratory equipment, together with the increasing necessity of practical experience in students' careers. Lead by this necessity, the network developed an education environment with a strong focus on Industry 4.0 and Industrial Internet of Things. Moreover, its aim is the integration of new technologies and alternative teaching methods within the environment through an iterative approach. Compliant with these objectives and considering the standards available for such concepts, a new architecture of a network has been created based on the Industrial Reference Internet Architecture. With respect to these standards, the general architecture has been built as a client-server architecture composed of three elements: (i) Client, (ii) Web server, and (iii) Local server. We also took into consideration that the project aims to enlarge the network in the future, making it accessible from different institutions all over the world, to enable the learners to perform new experiments and enhance their skills. Besides, it enables the integration of technologies such as Serious Games and Learning Analytics, as they are becoming more and more widespread and necessary for teaching and assessing the students. To ease the understanding and the scalability of the network, three different points of view architecture has been proposed, by splitting and describing it into software, hardware, and logical perspectives.

Keywords: Remote Laboratory, Virtual Laboratory, Internet of Things, Industry 4.0, Lab-based Education, Reference Architecture

1. Introduction

Laboratories and experiments are gaining more meaning in Science, Technology, Engineering, and Mathematics (STEM), thanks to the possibility to apply theoretical knowledge within real physical environments, which, nonetheless, have their limits and problems. (Burghardt, 2020). An experiment is one of the main ways to comprehend the fundamentals of science. Experiment results, received by students, stimulate their thinking, lead to discussion, and help make conclusions. This optimizes the learning process. People are curious and a laboratory is a good place to satisfy curiosity (Ardistoni, 2013). Yet some demerits in lab-based education are present. For example, providing necessary equipment and materials to many students can be challenging, especially in dynamic technical environments such as IoT-labs. Moreover, it becomes increasingly difficult for universities to maintain laboratories, and the integration of new ones requires a lot of investments. A solution to these issues can be the creation of networks of laboratories, which is an environment that combines at least two physically isolated laboratories, either virtual or remote, that are distributed between two or more institution and connected online, so that users from an institution can access labs of another one, increasing the exploitation of labs' equipment. Indeed, the aim of the Open Digital Lab For You (*DigiLab4U*) platform, a cross-universities project under which the work described in this paper has been done, is to create a network of labs to fix such issues and allow for a more fruitful and innovative experience. The concept for the DigiLab4U network is (i) focused on I4.0 and Industrial Internet of Things (IIoT), which are hot topics many industries are considering in recent years, and thus generate a lot of interest for industrial engineering students. However, their teaching is usually limited to theoretical knowledge instead of the development of practical skills (Pfeiffer and Uckelmann, 2019). Moreover, the network is (ii) developed in line with the Industrial Internet Reference Architecture (IIRA), (iii) easily scalable for virtual and physical laboratories through the creation of a custom Laboratory Management System (LabMS), (iv) enhanced with alternative teaching methods and technology like Self-Regulated Learning (SRL) (Shuy, 2010), Collaborative Learning (CL) (Laal, 2012), Serious Games (SGs) (Susi *at al.*, 2007) and Learning Analytics (LA) (Elias, 2011), and (v) designed with a Deming Cycle based safety and security guidelines. These characteristics are developed with the aims to (a) make the network grow by reaching the largest number of students, (b) increase the number of I4.0 topics taught, and (c) raise the involvement of users in these topics. Since many attempts at creating networks of labs have already been made, a literature review has been performed to better understand criticalities in architecture's components. The rest of the paper is organized as follows: Section 2 sets the educational environment within the described architecture, Section 3 describes the literature review performed and the structure of IIRA reference architecture, Section 4 and 5 present a new approach created by DigiLab4U, and Section 5 deals with discussion and directions for future works.

2. Educational environment

Considering the aims described, the network provides innovative and stimulating ways to approach the subjects above mentioned, centralizing different scenarios for each laboratory. The users have a central shop where they can select the desired learning resources. Each scenario corresponds to an experiment and can be characterized by (i) suggested key users, (ii) reference topic, and (iii) learning objectives. The main key users are university students. Still non-university students (i.e. high school), industrial operators, or researchers; can benefit from the learning resources. RFID, Supply Chain Management, Logistics represent some of the reference topics that compose the educational environment around I4.0 for the DigiLab4U. Learning objectives will drive the key users' choice. Indeed, they describe the skills that learners will acquire once they have completed the scenario successfully. The scenarios developed go through a continuous improvement process, for the adoption of new technologies and alternative teaching methods, such as Virtual reality-driven digital twins of existing physical laboratories, and Serious Games. This effort is made to be able to engage key users in various ways and to widen the possible ways to experience lab-related education. For further information on these topics, the interested reader can refer to (Kammerlohr, Pfeiffer and Uckelmann, 2020). To deliver these objectives, innovative ad-hoc architecture is required. Indeed, as later detailed, most architectures implement key components such as Learning Management Systems (LMS) but miss some additional units as Learning Analytics (LA), which can have an impact for educational effectiveness and thus should be considered in the architecture design phase. Indeed, a Client-Server architecture is developed with a shared LMS as the main platform capable of managing laboratories and providing learning materials. The network is developed with a Learning Analytics service as an integral component to track students' progress and enhance lab-based education. A custom-developed laboratory management system is responsible for the management of local physical laboratory appliances. A REST-API framework is designed to collect data from and to physical labs, serious games, and virtual reality digital-twins scenarios. Finally, the architecture's units are separated into hardware, software, and logic layers, for an easier implementable structure in which the connection and interaction of the elements is clearly defined and the inner logics are thoroughly explained.

3. Literature review

The number of offerings of virtual and remote laboratories is actively developing, over the past ten years, it has grown more than six times. The implementation of these laboratories is described in numerous works. According to the bibliometric analysis of (Heradio *et al.*, 2016), simulations of experiments, especially in engineering, are becoming popular in most of the networks of labs. Among them, new powerful cross-platform serious game engines are used to allow to reproduce experiments as accurately as possible. Moreover, usage of additional equipment (as helmets of virtual reality and contactless manipulation devices), to obtain a more complete immersion effect is becoming more common. Research has been done on literature from 2000 to 2020 with a focus on virtual and remote laboratories, networks of laboratories, and the educational aspects linked to them. Still, more than forty papers on as many laboratories have been analysed with a focus on the architecture implemented. We focused on those that are still ongoing and that shared most of our objectives LiLa (Richter, Tetour and Boehringer, 2011), UniLabs (Sáenz *et al.*, 2015), NetLab (Husain Siddiqui, Purohit and Mane, 2016), and Go-Lab (Govaerts *et al.*, 2013). The architecture of *LiLa*, a European funded project, consists of four components: (i) Web server; (ii) database for storing experiments data; (iii) database for managing booking system; and (iv) LMS, the main entry point for learners. However, it must be stressed that their implementation provides only a SCORM package (by now a technology replaced by REST-API interface) without a proper integration within their network. *NetLab* focuses on microcontroller-based laboratory experiments, with the following architecture: (i) internet connectivity; (ii) local lab network; (iii) a webcam for video streaming; (iv) no LMS is included, a Web server provides tutorials, procedures, user information, and handles booking. The *Go-Lab* architecture consists of (i) a lab repository and (ii) Inquiry Learning Space, which contains course templates and learning materials, (iii) a user management component for authentication, (iv) a LA tools for monitoring students' progress. (v) a *smart device paradigm* to abstract details of each lab by providing a set of web services. *Unilabs* is a network of 15 remote and virtual laboratories from different Spanish Universities. Its core consists of an LMS, which stores all the applications and dashboards for remote experiments, resources and materials, and learning activities. Communication, data acquisition and control, and logging are performed by the hardware control. The Remote Hardware Interoperability (RHI) Protocol aims to provide an interface for the experiments' management and user requests. For example, Herrera et al. (2019) describes enhancements of the architecture proposed in earlier work (Borrero et al (2013)): mainly, the solution proposed is renewed with the integration of cloud services, to improve the management and configuration of labs. Notable the use of Websockets in the work by Sáenz et al. (2019) to exchange data in JSON format between clients and servers. Morales-Menendez et al. (2019) propose a cost-effective solution for teaching industrial automation courses via virtual and remote labs. Finally, Cornetta et al. (2020) propose their solution to enhance existing FabLabs, making them remotely accessible: this further stresses the appeal showed for networks of remote labs.

IIRA

Two main reference architecture frameworks were considered: Industrial Reference Internet Architecture structure (IIRA) and Reference Architecture Model Industrie 4.0 (RAMI 4.0) (Weyrich and Ebert, 2016). Indeed, both architectures are relevant: RAMI4.0 drives all the major German industrial companies and foundations, and IIRA is the reference architecture delivered by some of the major global companies through the Industrial Internet Consortium. IIRA structure was chosen, mainly because it offers an overall industry focus, moreover, it provides broader guidelines on how safe, secure, and resilient systems can help realize the vision behind the industrial internet. It addresses a few specific system concerns, like integrability, interoperability and composability, connectivity, analytics and data management, and automatic integration (Ishiguro *et al.*, 2009). Thus, from a learning perspective, its broader scope allows us to address different implementation approaches for the IoT. Students need to understand that there is not a *single* IoT-standard instead, *multiple* approaches are competing. Due to the different lectures for the specific IoT-implementations in different vertical industries that DigiLab4U will provide, the utilization of the IIRA structure for the new architecture is the straight-forward approach to adopt fundamental techniques combining them with already existing solutions. The core of IIRA is composed of 4 viewpoints: (Ishiguro *et al.*, 2009) (i) *business* – concentrates on the attention of stakeholders and their business vision; (ii) *usage* – pitches into expected system management; (iii) *functional* – focuses on functional components in an IoT system (i.e. physical systems, sense and actuation, information, control, etc.); (iv) *implementation* – deals with the technologies needed to implement functional components, their communications schemes, and the interfaces protocols. Each viewpoint of the system is composed of five functional domains, which represent the building blocks of an industrial system and illustrate data and control exchange among these domains. The need to design a new general architecture from hardware, software, and logic point of view, led to focus on the functional and implementational point of view, leaving viewpoint like business and usage more specialized on organizational solutions. Our approach is based on functional viewpoints' five domains: application, information, operation, control, and business. Figure 1 demonstrates how the domains relate to each other concerning data exchange (green arrows) and control flows (red arrows) and the physical system of the alleged lab.

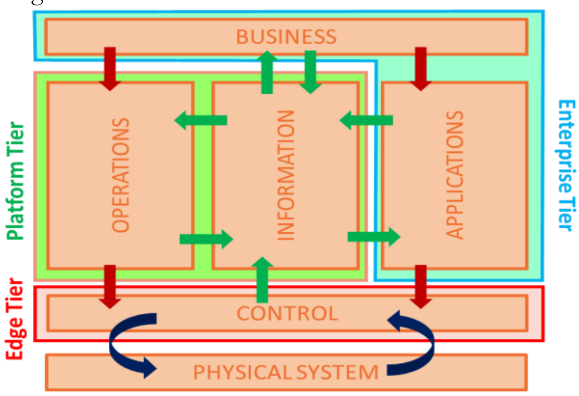

Figure 1: IIRA Functional and Implementation Viewpoint

1) The <u>business domain</u> functions enable end-to-end operations by integrating them with traditional or new types of industrial internet systems specific business functions including those supporting business processes and procedural activities.

2) The <u>operations domain</u> represents the collection of functions responsible for the provisioning, management, monitoring, and optimization of the systems in the control domain. Existing industrial control systems mostly focus on optimizing the assets in a single physical plant. In our scenario, the instrument controller acts as a physical system.

3) The <u>information domain</u> represents the collection of functions for gathering data from other domains, and transforming, persisting, and modelling or analysing those data.

4) The <u>application domain</u> represents the collection of functions implementing application logic and applies rules and models that realize specific business functionalities. Requests to the control domain from the application domain are advisory so as not to violate safety, security, or other operational constraints.

5) The <u>control domain</u> represents the collection of functions that are performed by control systems, i.e. reading data from sensors, applying rules and logic, and exercising control over the physical system through actuators. The control domain also contains a set of common functions, for example, actuation, sensing, communication, etc.

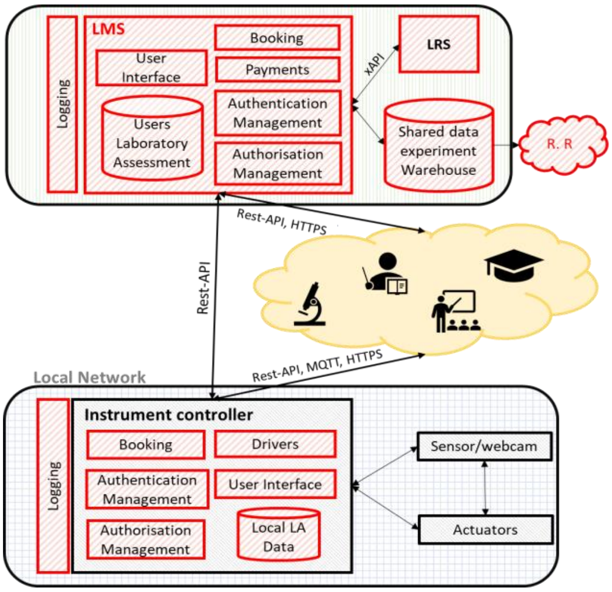

Figure 2: Software, Hardware, Communication Interfaces

4. Structure definition

Considering the DigiLab4U goals, the literature analysed and the IIRA framework, the general architecture is designed. The structure is composed of Clients connected to a Shared Network and a Local Network (Fig. 2). Here is possible to find some function/software duplicated in Shared and Local Networks, like 'Booking', and 'Authorization and Authentication management', due to users' need to access directly in both Networks. On the other hand, functions like 'Payments', are centralized in the LMS to avoid information overlapping. The Shared Network is composed of three servers distributed within the consortium and comprises three main components that are:

- Learning Record Store (LRS): which objective is to gather LA and supply personalized data and statistics for the users (anonymously).
- Shared Data Experiment Warehouse: collects from the experiments. Learners and professors can access to this data to elaborate them; it is also suitable for research purposes.
- LMS: it represents the focal node of DigiLab4U architecture. It is the main entry point for most users (i.e. learners, professors). Indeed, the LMS manages the booking and payment function, comprehends authentication, and authorization management. It also provides a User Interface for account management, data interaction, and connection to laboratories and experiments; finally, a User Laboratory Assessment component holds the (anonymous) records of users' activity in the laboratories.

The Local Network represents each laboratory of the network. Thus, each instance will be different, to accommodate each lab's needs. The Instrument Controller's main role is to establish a communication between the Shared Network and the hardware facilities of the experiment (i.e. sensors, actuators), indeed its scope is to manage the experiment execution and so the hardware components. Moreover, it contains the counterpart of shared components like Booking, Authentication, and Authorization Management. Also, it exposes its User Interface, and it contains a local repository for the temporary storage of the LA data collected. Given the central importance within the architecture of the Instrument Controller, one of the main future works is the creation of a framework software package (LabMS) which would encapsulate all the software and logic components needed and is already designed to communicate through REST-API to the central LMS. Such a software package can be provided to future new labs that want to join the network, easing the work needed for their integration. The Local Network also represents Serious Games or AR/VR infrastructures, which will be most directly accessed by users, but that still needs to communicate with the central LMS, to exchange LA data and to provide to learners a coherent and centralized management system of the different learning resources. It will create the User Interface for the experiment in the LMS. In both Local and Shared Network is possible to also find the Logging. It aims to record the system activities and communications for debugging and troubleshooting purposes. These elements can be easily mapped within the IIRA structure. Indeed, focusing on the Functional Viewpoint previously described, it is possible to see the Shared Network enclosing the BUSINESS section with the LMS, the User Laboratory Assessment, Authentication and Authorization Management, Booking & Payments and Logic & Rules for Users and Labs, the INFORMATION part including the Shared data experiment warehouse and the Learning Record Store. Within the Local Network it is possible to find:

- the APPLICATIONS where is possible to find the Local LA data, which will be exchanged and stored according to the Experience API (xAPI) specification, the User Interface and Logic & Rules for an experiment, a sub-function of the Instrument Controller,
- OPERATION sector will have the function of device management
- CONTROL encloses the other function performed by the Instrument Controller like Executor, Modelling, Assets Management, and Entity Abstraction.

5. Hardware, Software, Logic and Communication Interfaces

After the definition of the general architecture, and its parallelism with IIRA, a viewpoint focused on the implementation part was needed. To do so, the components have been distributed in three different layers, Software (Fig. 2 – red), Hardware (Fig2. – black), and Logic (Appendix A), according to their nature. The goal is to set a starting point to decide which software has to be implemented according to the functions needed, the hardware to be set or acquired, and which logic work behind the architecture and the process is needed within the DigiLab4U.

Software

Here it is possible to find all those components that are either software or data storage. Indeed, in software layer there is data storage like (i) Users Laboratory Assessment, (ii) Shared data experiment warehouse, (iii) Local LA Data, where the rough data coming from LA are locally stored and (iv) Research Repository (R.R.) that contains the data that can be shared with partners outside the project (i.e. external research institution, companies). As software is

Domain	Hardware	Software	Logic
BUSINESS	LMS Server, LRS Server	LMS, LRS, Users Lab Assessment, Authorization & Authentication, Logging, Booking & Payments	Logic & Rules for Users and Labs
APPLICATION	Local LA Server	Local LA Data, GUI	Logic & Rules for Experiment
OPERATIONS	Instrument Controller	Device Management	
INFORMATION	Shared data Server	Shared data experiment warehouse	
CONTROL	Sensor/Webcam, Actuation	GUI, Authorization & Authentication M, Logging, Booking & Payments	Executor, Modelling, Assets Management, Entity Abstraction

Table 1: Parallelism between DigiLab4U Architecture and IIRA

possible to find (v) Booking & Payments, that are directly linked with (vi) Authentication and Authorization Management, the (vii) Graphical User Interface, and (viii) Logging. All these items can be considered as plugs-in or expansion of the main software that is the (ix) LMS.

Hardware

Excluding the three servers already introduced, the hardware components can be found in Local Network and are (i) Instrument Controller that consists in a local server which contains the logic and software used to connect the Shared Network to the instruments and sensors, (ii) hardware part of the experiment composed by the items necessary to actuate, run the experiment and elaborate the data, and (iii) sensor/webcam used to collect raw data and keep track, via video, of the experiment.

Logic

The logic point of view represents these components that enclose the rules for the functioning of the network. Here it is possible to see (i) Logic and Rules for Users and Labs, which contains the rules to manage the access of the users in the LMS, and in the labs, (ii) Logic and Rules for Experiment manage the logic behind each experiment controlling if the parameters set are correct or can cause errors or malfunctioning, (iii) Executor applies the parameters of the experiment, establish and schedule the action to run the experiment, after that the condition of the physical system is checked by the (iv) Asset Management, also it tests the system at each interaction during the run of the experiment, the (v) Actuator runs the action scheduled by the Executor and stops the experiment when the actions are finished, in the end, the data are elaborated by the (vi) Modelling and are sent to the LMS. In the logic point of view is also possible to find the (vii) Entity Abstraction, it defines the entity that is used across the different logic components like Executor, Asset Management, Actuator, Modelling, and in the Sensors. The logic point of view outlines the rules and logic that are behind architecture operations. Starting from the moment where a user wants to enter the network the logic components work in the background. A practical situation where logic elements are involved could be described as follow (see Appendix A): (i) user wants to log-in into LMS and then enter in a lab to execute an experiment, Logic & Rules for Users and Labs manage the logic behind the permission to enter in the LMS and to access to the lab; (ii) once the user has submitted the parameters, the Logic & Rules for Experiments validates parameters; (iii) after that the Executor receives the parameters and check, through the Assets Management, if the system is available and ready; (iv) having a positive reply from the Assets Management, the Executor establish and schedule the actions; (v) the experiment starts and involves three components: Actuator, Assets Management, and Sensor. The actuator will run the actions; (vi) at each interaction the Assets Management check if the equipment is working correctly, if not, the actuator stops the experiment, if everything is working the Sensors collects data; (vii) the Actuator checks if there are actions left, if there are then, the next action is done, and the process restarts from passage 5. Otherwise, the experiment stops; (viii) the rough data are sent to the Modelling and are elaborated. In the end, the final data are sent to the LMS.

Communication Interfaces

To have a highly scalable network, the main problem was the communication protocol to be applied. To ease the integration has been decided to apply a widely accepted communication interface like REST-API (Fielding and Taylor, 2000). These are characterized by the utilization of web assets that are identified uniquely by Uniform Resource Identifiers (URIs) (Luo *et al.*, 2016). It is possible to distinguish two different types of URIs, collection URI, and item URI. URI collection is like a homogeneous container of URI item that represents a particular resource, both can run using HTTP(S) methods. This interface will be applied in the communication between the Shared Network and Local Network. For all the communication established with the LRS the experience API (xAPI) is used. Using this tool is possible to have statements that stored in an LRS, describe a set of experience. These statements are composed of a triplet that are Noun, Verb, Object, each one of these three elements can be completed with a word coming from a common vocabulary. In that way, the sentence will be more flexible and interoperable. Indeed, any type of device can elaborate and send xAPI statements and without the necessity of a stable internet connection.

6. Discussions: Pros & Cons

Being the DigiLab4U educational environment focused on IIoT and I4.0, a consequent architecture was needed to be implemented. Also, the scenarios already created, their upgrade, and future scenarios, require new technology and alternative methods that need to be considered during the architecture conception. Furthermore, in pursuance of an easier and cheaper integration of new laboratories in the network, the structure must be developed with a focus on scalability and sustainability, and be secure to grant the availability for students/teachers and compliant with GDPR for data protection. The literature study existing lab networks and their architectures, merged with the objectives set by the DigiLab4U consortium and the IIRA approach, lead to the creation of a new architecture compliant with I4.0 and IIoT principles. The proposed architecture attempts to collect the most important requirements from other projects to get a generic architecture that allows the following aims: implementation, security, scalability, and sustainability in a remote learning environment. The solution enables the possibility to integrate a wide number of different types of experiments: hands-on, virtual, mixed reality; as well as different learning methods like SRL, CL and SG, and new technologies like LA. The centralization of the virtual laboratories permits access even if the local server is offline. Likewise, the centralization of certain functions permits optimal management of an operational logic of laboratories (i.e. booking & payments, authorization management). With a centralized data repository and LRS, learners and professors can consult data and statistics also if the local server is offline. Still being compliant with data protection, security, and privacy regulations. Likewise, the LMS is planned to be moved to a cloud service. Regardless, the use of largely employed communication framework REST-API for connecting labs with shared network helps to include new laboratories. The difficulties that can occur in that case are the translation of the input data from REST-API to experiment language and the reverse, as well as the creation of a user interface on the LMS for input data for the experiment. Future improvements will include creation of (i) REST-API documentation, (ii) a framework of a semi-automated software package that will ease the integration of new labs in the network (LabMS), and (iii) the detailed definitions of functions and plug-ins that will be implemented both: in LMS and LRS. The architecture presented in the paper is currently under implementation from a technical and organizational point of view. Issues and outcome deriving from its implementation will be presented in the future, as well as an evaluation of the objectives achieved, and lessons learned.

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Appendix A. Logic Point of View