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RESEARCH ARTICLE

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Virtual laboratory for microwave measurements

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Abstract
The study introduces an approach in developing a virtual laboratory that can be used for classroom instruction as well as distance learning and is a good alternative to highly expensive microwave measurement equipment. The software package is written in C++. The testing results of applying a virtual laboratory for radiophysics measurements are considered.

KEYWORDS
computer simulation, distance learning, laboratory classes, measurement instruments, virtual laboratory

1 | INTRODUCTION

Training laboratories used for instructing highly qualified specialists should be equipped with cutting-edge measurement instruments. However, the high cost of equipment limits the number of measurement setups and the number of students who can simultaneously conduct assignments. In addition, distance learning, which is a current trend in higher education, requires lab sessions to be performed remotely [5,15]. As a result, traditional hands-on laboratory classes are not suitable. Besides, there may be some other reasons why training laboratories are unavailable for students (e.g., overloaded with other experiments, budget constraints, outdated equipment, and maintenance problems).

A good alternative is the use of virtual laboratories that can provide technical specialists with all necessary skills. Virtual laboratories can significantly change the teaching mode and, as a result, help to reduce equipment expenses, overcome time and space limitations, and the lack of experimental resources. Many authors emphasize the importance of virtual laboratories for training engineering specialists. Computer simulations have been increasingly more accessible for teaching and learning in various areas of physics and electronics [3,7,13,14,17]. Interactive virtual laboratories are globally used in a wide range of educational establishments and are often a key subject of international conferences and research projects [1,8]. Currently, virtual laboratories are being developed using various modeling software (Maple, LabView, MATLAB, Simulink) and programming languages [4,7].

Computer simulations of different processes [11,14,17] and remote access to real laboratory equipment via modern communication technologies, including cloud technologies [20] have been recently studied by many authors. A great number of studies have focused on the main problems of simulating tasks in radiophysics [2,6,11,12,16–19]. Of particular interest are those [18,19] aimed at the development of simulation software in radiophysics with the virtual model interface of measurement instruments being almost identical to those of real prototypes. The modeling of measurement equipment that does not differ from its prototypes in terms of the principles and the order of measurements is especially important [7]. However, most of the known virtual laboratory tools have a significant drawback, although they correctly describe all the necessary processes, the user interface of the computer model has only a conceptual similarity to the real prototype or no similarity at all. Such models can hardly provide practical skills required for working with real equipment since they are designed primarily for the in-depth and accurate analysis of physical phenomena rather than for studying the operation of particular devices.

Therefore, the key issue is to develop virtual laboratory software, aimed at both studying the physics of the underlying processes and the techniques of working with modern measuring equipment. Simulated devices and tools should have physical resemblance to their "real" counterparts and provide access to "real" control elements. The proposed approach to creating and applying computer models of microwave measurement devices and tools enables us to develop easily configurable and expandable virtual laboratories designed to study microwave devices and acquire skills for operating real microwave measurement equipment.

2 | PROBLEM STATEMENT

In realistic laboratory work, a set of instruments and devices is interconnected in a certain way. Each device or tool has a number of input and output signals with which they can connect to each other and transmit necessary data. Therefore, the underlying principle of the developed approach [10] is the idea of describing devices and tools using a set of input and output signals and the functions they perform. From this perspective, any measurement device can be represented as an abstract entity (class Abstract Device) with a particular set of properties (device type, input and output signals, transformations performed, etc.) and a given behavior related to other devices. To describe the interaction with them, an abstract class was created (Abstract Func), outlining the operations performed with the input signals based on their own parameters, which depend solely on the features of specific real devices.

When configuring virtual laboratory software, the next step is to interconnect the input and output signals of the measurement instruments and devices in a similar manner to configuring real laboratory equipment.

The software modules of the devices being developed are dynamically linked libraries with a single exportable interface. The last stage is to use a digital photograph of the front panel of a real instrument as an external interface of a simulated measurement instrument (interface displayed on a computer screen) [7].

To develop easily expandable and upgradable virtual laboratories, it has been proposed to connect the models of measurement devices and instruments into a single network by means of a special module (configurator) and save the result of the connection in a database. To expand the laboratory and replace some devices with other ones, a corresponding module can be launched that "scans" a catalog. In this catalog, our software is installed to find all the libraries (dll) of the instruments and devices, and thus, a dynamic list of the equipment is available to the user. This approach allows to use the same instruments in different simulations and easily replace them with one another. In addition, this methodology makes virtual laboratory easily expandable and upgradable. In the present paper, we will focus on the program implementation of virtual laboratory in more detail.

3 | SOFTWARE STRUCTURE

The software of virtual laboratory consists of the main unit and independent dynamically connected libraries simulating the operation of the measurement instruments and devices. The main unit is responsible for the creation and execution of laboratory work.

The main unit consists of four interconnected software modules and a database of laboratory assignments (Figure 1). In particular, the main unit consists of the configurator and visualizer modules which are independent and not related to each other. Both modules access the database which stores information on the "arranged" (created) virtual lab assignments. In addition, the main unit includes the mode selection module, initial settings, and authentication modules (Figure 1).

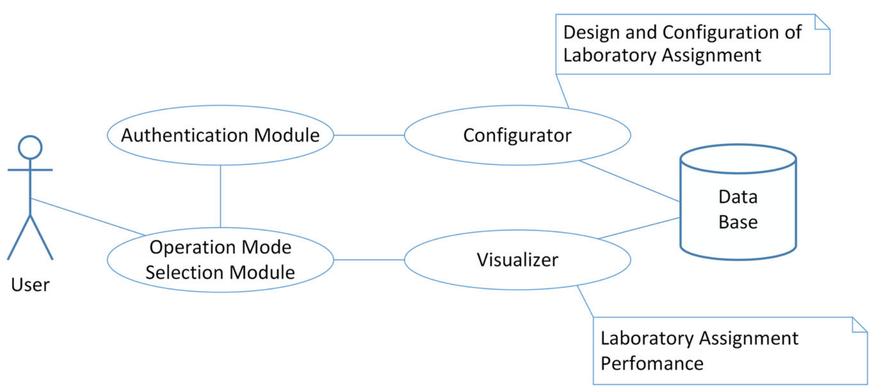

FIGURE 1 Structure of main unit

The mode selection module enables us to choose the user interface language (English/Russian), obtain information about the software product, visit the developer's website, exit the application, or launch the program in the configurator mode or virtual lab.

The authentication module provides the user with a choice between logging in by login and password as an administrator (teacher) or as a guest (student). The principal difference is the access rights to modify previously created laboratory assignments.

In the configurator module, an unauthorized user can create a new laboratory assignment or edit/delete an existing one (provided that this assignment was created by the user with the same rights). In addition, it is possible to control all laboratory assignments created by both administrators and guests. When creating a laboratory assignment, it is also possible to add any number of devices, establish interaction between the devices, specify the name of the assignment, which appears in the title of the windows and in the list of laboratory assignments, and attach a file of teaching materials which become available for the user while performing the laboratory assignment.

The visualizer module provides the following functions: Displaying a list of laboratory assignments, loading the user interface of the virtual devices of the selected laboratory assignment, setting up the display, and the location of devices on the screen and displaying information regarding the performed assignment, descriptions, and guidelines.

3.1 | Database module

The auxiliary database module performs all database operations. Therefore, when an application is started, the new database is created if the existing one is not detected. The database of the assignment includes five tables:

- devices – stores the data about virtual device used in the assignment (unique device identifier; its name);
- lab_facilities – stores the data about created laboratory assignments (the name of the laboratory assignment; its unique identifier; its developer: either an administrator or a student);
- manuals – stores data regarding the guidelines for laboratory assignment (a unique identifier for the guideline; a link to the file with the assignment description);
- order_list_dev – stores the list of virtual devices used in each laboratory assignment (identifiers of the laboratory assignment and devices; the serial number of the device used in the laboratory assignment); and
- connections – stores data regarding the way in which virtual devices are connected to other virtual devices within a particular laboratory assignment (references to other tables; emitter and receiver serial numbers; input and output connection keys).

Clearly, the database contains all the information on the "arranged" (created) laboratory assignments, guidelines, equipment applied, and, most importantly, the way they are connected to each other, that is, what input/output signals are connected and how (table of connections).

In addition, according to the requests of other application modules, the database module generates a list of laboratory assignments (based on the lab_facilities table), and when the laboratory assignment is ready to be performed, this module forms lists of the equipment used and provides the information regarding its connection.

3.2 | Configurator module

The configurator is one of the modules of the main unit responsible for developing and editing lab assignments. When this module is set up, all available device modules (dynamically linked libraries) are loaded in turn, a temporary object instance of each device is created, and the information regarding the loaded devices (device type, name, set of output signals, and list of available input signals) is obtained. This approach enables adding a new device to the laboratory by creating a computer model of the device and copying the corresponding dynamically connected library (dll file) to the working directory of the previously installed shell of virtual laboratory. After loading the libraries, a program linker sends a request to the database interaction module, and when the response is received, generates a list of the laboratory assignments created and stored in the system. This module checks out the dynamically connected modules.

When developing a new laboratory assignment, the configurator requests the user to enter the name of the assignment, specify the path to the guideline file and choose the devices required for this kind of laboratory assignment (Figure 2). Notably, the list of available devices is formed when the configurator is launched, and this list is completely displayed on the screen (Figure 2 bubble 1). The user can select any device and use its instance when creating the lab assignment. After selecting the devices the user will be able to connect the devices to each other (Figure 2 bubble 2). At the same time, it is necessary to choose a device, its type, and specify the receiver and the transmitter. For example, while connecting the filer to the measurement instrument the user connects the input of the filter to port 1 of the network analyzer by the virtual cable (Connection type – Regular) as shown in Figure 2: "Source Agilent E8363: Output P1 -> Receiver LCfilter:

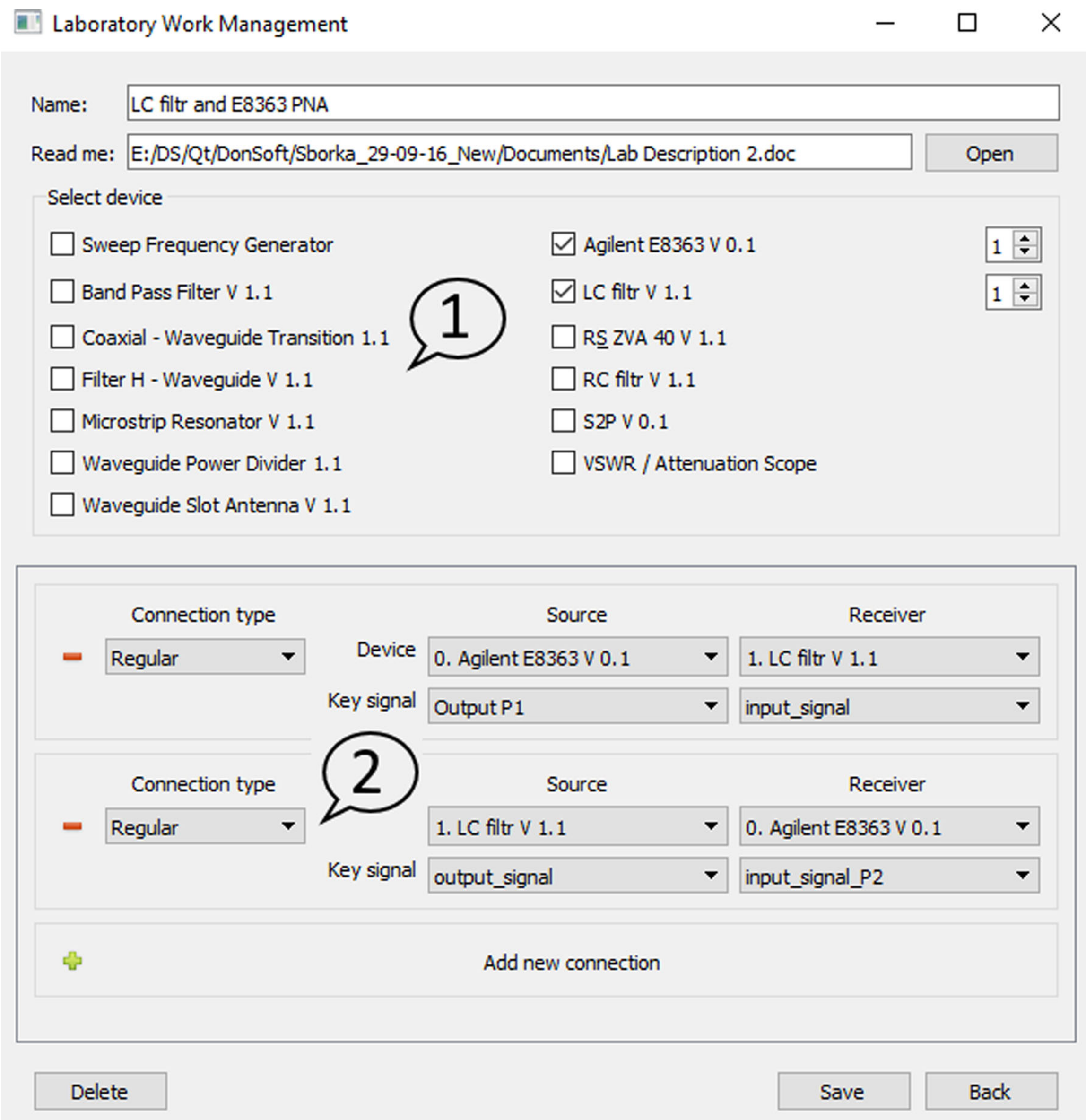

FIGURE 2 User interface of virtual laboratory configuration

input_signal)" and connects the output of the filter ("Source LCfilter: output_signal") to port 2 of the network analyzer ("Receiver Agilent E8363: input_signal P2") by the second virtual cable.

In the current version of the software the visualization of the connection of the devices to the measuring instruments is not available and will be available in future releases. When a new or modified laboratory assignment is saved, all the necessary data are recorded in the database and can be used by the configurator or the visualizer module in the next setup.

When performing an existing laboratory assignment, the user can learn about its composition, the connection of devices, and, if necessary, make changes. The interface of the editing window is similar to Figure 2.

3.3 | Visualizer module

Let us consider a visualizer module in which users can perform laboratory assignments created in the configurator. When this module is put into operation, a request is sent to the database interaction module and, upon receiving a response, an interface that provides the selection of the available created laboratory assignment is displayed (Figure 3).

After the user selects a particular laboratory assignment, the interaction between the module and the database is triggered, providing all the information regarding the list of necessary devices and all connections between them. Next, the required modules are loaded, and the necessary number of devices is created followed by their connection using the

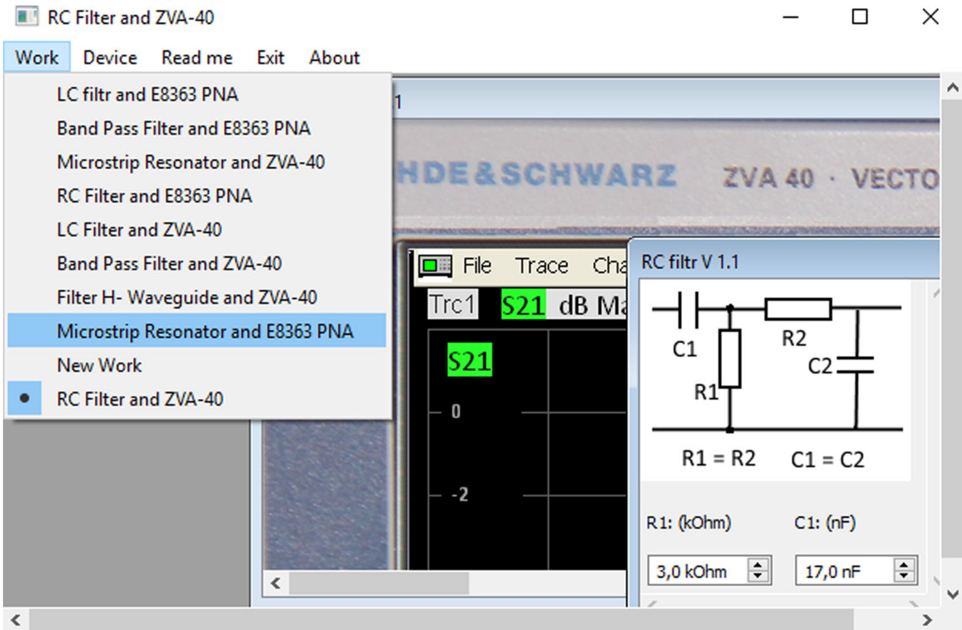

FIGURE 3 List of available laboratory assignments

indicated mode. Afterwards, the user interface of virtual laboratory is displayed, and the control of the software modules of these devices (for example, Figure 4) is executed. The user can arrange the windows with the displayed interfaces of the devices in the most convenient way or select one of the provided modes from the menu (Cascade, Tile, Laying). Thus, the overall functionality of the package is easily expandable and depends solely on a set of device modules that can be easily added to the system with dynamically linked libraries. To do this, it is necessary to just copy the newly created device module (dll file) into the working directory of virtual laboratory on a personal computer (PC).

4 | SOFTWARE IMPLEMENTATION

Let us briefly consider the software implementation in C++ MSVS 2015 using Qt for application development. The

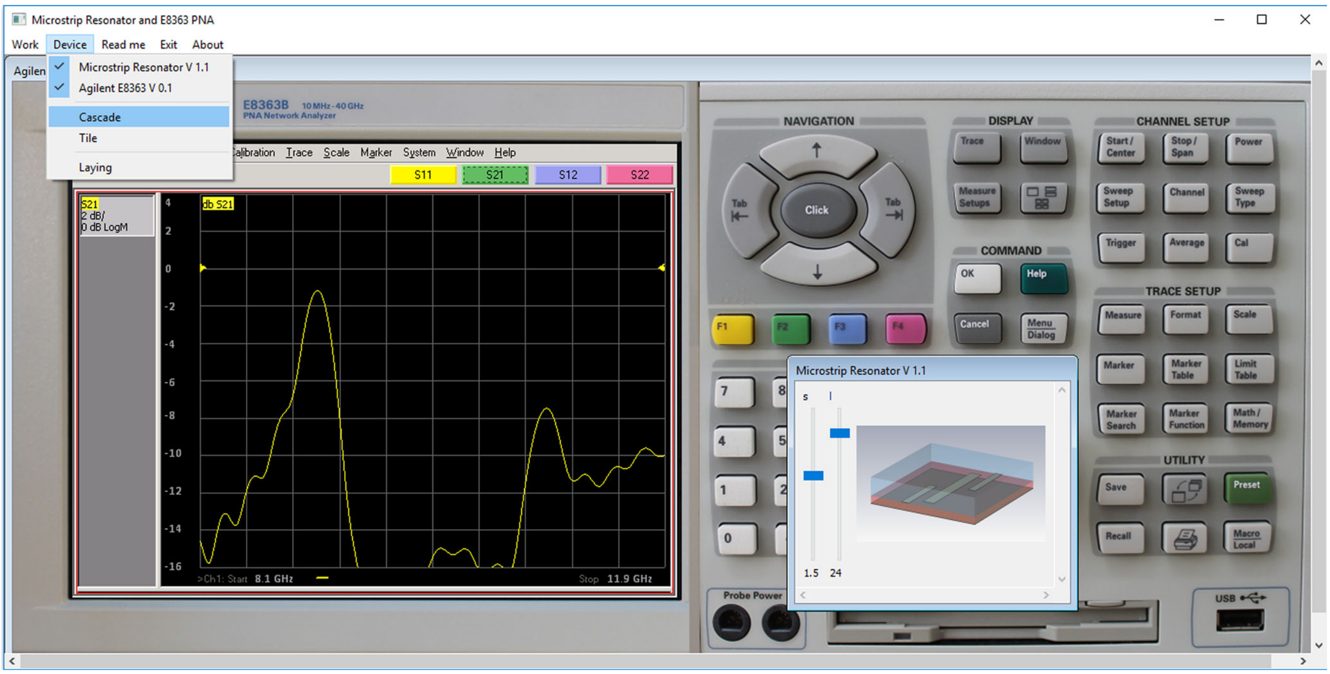

FIGURE 4 User Interface of virtual laboratory

main software unit (Figure 1) implements the functionality of the main window of the application with the choice of operating mode, installation of various settings, interaction with the database, and transition to one of the main modes: “Configurator” (for developing and editing lab assignments) and “Visualizer” (for performing previously created laboratory assignments). The structural diagram of the main unit is shown in Figure 5. Therefore, this module includes classes that implement the operation of the “Configurator” and “Visualizer” modules, provides access to the database and describe the generic external interface to connect the modules of different devices and instruments. Figure 5 shows that the implementation of device models is based on a common basic set of functions which must be specified while implementing real measurement devices. In virtual laboratory assignment, the use of more than one device of the same type (e.g., two generators of the same type) is allowed. This is provided by appropriate organization of the program interface of the main module, using which it is possible to create an unlimited number of identical devices.

Implementing a computer model of a specific device includes several steps. Thus, almost all functionality of the final device must be based on a common basic set of functions that identify and return information about the device (its type, name, unique device identifier, and some additional information). Qt for Application Development and the functionality of Qt library and its extensions are available to design the visual part of the module which allows using its digital photo as the user interface of the measurement device and thereby implementing a fully realistic computer model interface (analog of the real device, Figure 4). To control the model of the device the user can operate a computer mouse to “push” the buttons on the instrument panel, as if it was real [7]. In addition, the use of Qt libraries allows for the exchange of information between the models of devices that are part of the laboratory study with the help of a signal/slot system.

General functions of data exchange and interaction between devices whose connection is defined in the configurator and described by connecting the input and output signals (Source/Receiver, Figure 2) are also implemented in the basic set of functions and specified in the final models of devices. With this approach an arbitrary parameter definition gives a greater degree of freedom, which allows you to make different implementations depending on the device interconnection in the configurator. For instance, when connecting a filter to a vector network analyzer using various parameters passed to the function for exchanging data between devices [9], we can request the operating frequency range, the availability of certain data, as well as the data necessary for their visualization on the screen of the measuring device. When being called, this function should return the necessary data to the calling device on the basis of the analysis of the parameters passed.

Using the example of the laboratory assignment on the microwave filter, let us consider the interaction of the modules of the created software consisting of the main module and at least two dynamically connected libraries: A vector network analyzer model and bandpass filter (Figure 6). The studied filter should be connected to the model of the network analyzer in the configurator (Section 3.2), and it should be able to display its amplitude-frequency characteristic (AFC) on the screen of its display. Its interface is shown in Figure 4. The filter model was calculated using rigorous electrodynamic methods [8]. It should transfer all necessary data for building the AFC to the vector network analyzer upon its request.

From Figure 6, it is clear that after the run of the “Visualizer,” the user receives a list of laboratory assignments available in the database and runs any of them. After that, the database is accessed, and all the necessary device models (dynamically connected libraries) are loaded, the necessary connections for data exchange between them are established and control is transferred to one of the devices (e.g., the vector network analyzer). Figure 6 shows their interaction and the

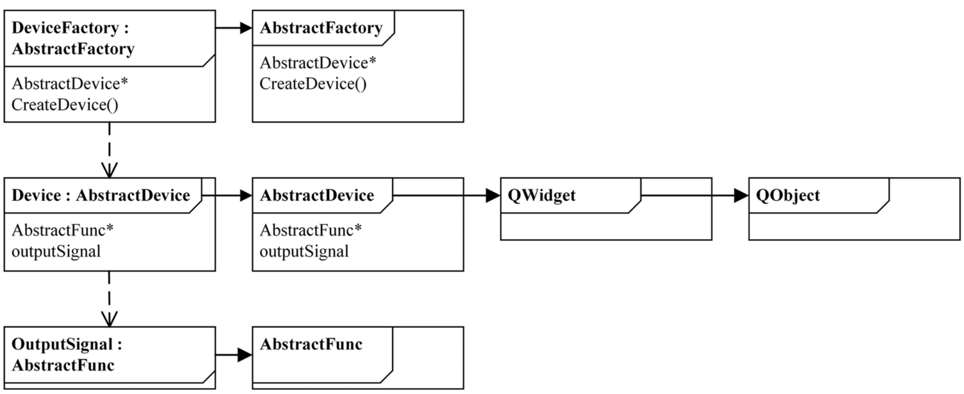

FIGURE 5 Software implementation of main unit

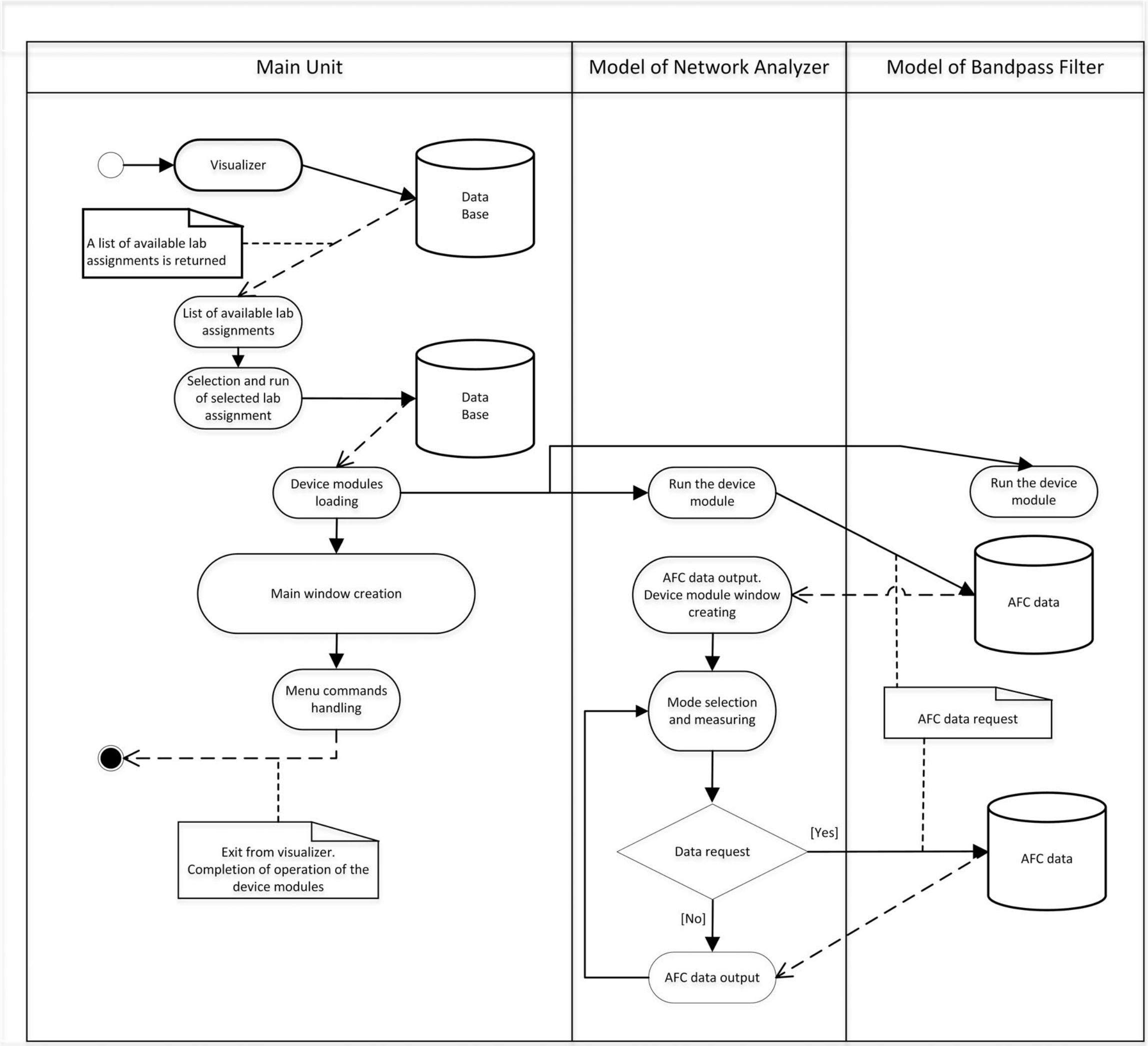

FIGURE 6 Example of interaction between modules of virtual laboratory

transfer of all data between device models. Upon completion of the AFC filter research process, the user can use the menu to choose another lab work (Figure 3) or exit "Visualizer," returning to the main window.

The developed software is compiled as an executable file and installed on the user's computer. The implemented models of measurement devices and instruments must be compiled into a dynamic library that is to be located in the working directory of virtual laboratory. This catalog is automatically "viewed" when the application is run so that all device modules will be automatically added to the laboratory and can be used to create new laboratory work.

5 | IMPLEMENTATION AND USE OF VIRTUAL LABORATORY

The developed approach allows to create virtual laboratory to study microwave devices and tools, the component diagram of which is shown in Figure 7. It can be seen that all components are divided into two groups: The main unit and the models of devices and tools which constitute the laboratory assignments themselves by connecting them together. According to the developed concept, the main unit provides an interface for connecting dynamic libraries. These libraries are the models of microwave devices and tools. The corresponding dll files of these libraries must be located in the same directory with the main module. Our example of virtual laboratory includes two vector network analyzers (R&S ZVA-40 and Agilent Technologies E8363BPNA) and three microwave devices to study. Next, the user arranges the laboratory assignment in the configuration module. She/he chooses the necessary instruments and tools, connects them to each other, and saves all necessary data in the database. After that, all the arranged laboratory assignments are available for performing (Section 3.3). Besides, descriptions and user manuals can be connected to the models

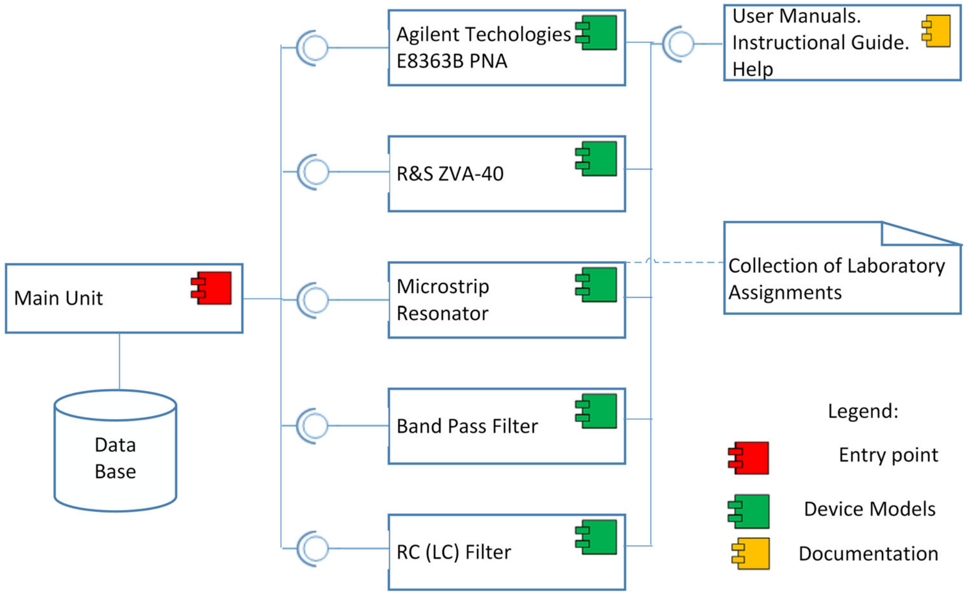

FIGURE 7 Virtual laboratory component diagram

of devices and instruments, which can be viewed when performing the laboratory assignment.

To test the performance of computer models, a real bandpass filter based on the rectangular waveguide was investigated using real measuring instruments. After that, rigorous electrodynamic calculations were applied to create a model of the same filter which was studied using created computer models of measurement instruments (vector network analyzers). The results obtained by simulation in virtual laboratory coincided with the results obtained by experiment with high accuracy. This study confirms the possibility of using the created virtual laboratory in the educational process.

This virtual laboratory was implemented and tested at the Physics Faculty of Southern Federal University. Virtual laboratory assignments have been integrated into the educational process for undergraduate students in their third and fourth year since 2018. The curriculum includes laboratory assignment in "microwave measurement devices and "microwave measurements" workshops. These workshops consist of both traditional hands-on laboratory assignment and virtual laboratory assignment. Virtual lab assignment takes 20–25% of the total amount of time. At the same time, classes are first held in terms of virtual lab assignment and then with real equipment.

Virtual laboratory provides realistic and clearly visible simulation of experiments similar to hands-on laboratory assignment and makes it possible to perform more assignments and take more measurements at the same time since there is no need to perform mechanical actions of connecting and reconnecting the devices. On the other hand, virtual lab can be applied in parallel with real laboratory equipment to make the learning process less monotonous and more diverse and exciting for students. Another argument contributing to the introduction of virtual laboratory in the educational process is that it enables students to gain skills and work experience without using expensive measurement equipment. There is no need to worry that the equipment might be damaged due to misuse errors.

Virtual labs assignments have been tested for 2 years, and more than 70 people participated in this project. Thirty-two students were trained in the autumn semester of 2019 and became a focus group to conduct a survey and obtain feedback to analyze the effectiveness of virtual labs. Most of the students noted that the text descriptions and guidelines provided by the software were user-friendly, and the representation of this material in the interface of virtual lab unit was clearly understandable. The students also noted that physical processes and operating principle of studied microwave devices were clearly represented. The participants considered that virtual and real measurement instruments are almost completely similar both in terms of the user interface and function. Most students found that operating the virtual devices was easy to understand. These students believe that virtual lab work allowed them to understand the principle of making measurements using a variety of microwave measurement devices. In general, the participants were satisfied with their studies in virtual laboratory.

Among the key aspects of implementing virtual lab classes which helped to train students in measurement techniques and the functioning of microwave devices, most of the students indicated that:

1) The process of configuring virtual laboratory assignment is easy and clearly understandable.

2) Laboratory assignment can be easily visualized.
3) Virtual experimental studies can be easily conducted.
4) Realistic simulation of the studied device or circuit with the possibility of changing its parameters or settings "on the fly" can be easily performed.
5) The ability to correct the mistakes concerning the connection or configuration of virtual instrument or device is easy.

According to the focus group reviews, more than 60% of students agree that doing virtual assignment is an interesting and effective way of learning.

In addition, according to statistics regarding the introduction of virtual lab assignments to the educational process, the rate of working with virtual devices is increased by 20% on average as compared with real equipment, which makes it possible to increase the amount of learning material. Students can first try conducting experiments in a virtual lab and therefore feel much more comfortable with taking measurements using real expensive equipment. The students also mentioned that the opportunity to perform various tasks in virtual laboratory in advance allows them to quickly master the operating principles of real devices and instruments. Consequently, the developed virtual laboratory is a useful and important tool for learning practical measurement skills and can completely replace hands-on labs in the educational process.

6 | CONCLUSION

In summary, computer models of measurement equipment with realistic interface were created. A software package of virtual laboratory imitating the work of real measurement devices was implemented. Autonomous software package of virtual laboratory is easy to upgrade and expand. This virtual laboratory can be used in the educational process as well as in distance learning and is intended to replace real expensive measurement equipment. This approach also allows users to gain measurement skills using sophisticated high-tech equipment without worrying about misuse errors.

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