Measurement 42 (2009) 485–493

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

Hardware and software to design virtual laboratory for education in instrumentation and measurement

Domenico Grimaldi [a,*], Sergio Rapuano [b]

[a] Department of Electronics, Computer and System Science, University of Calabria, Rende-CS, Italy
[b] Engineering Faculty, University of Sannio, Piazza Roma, Benevento, Italy

ARTICLE INFO

Article history:
Received 2 January 2008
Received in revised form 23 July 2008
Accepted 7 September 2008
Available online 18 September 2008

Keywords:
Virtual laboratory
Virtual instrument
Distributed laboratory
Education

ABSTRACT

The multimedia tools play an important role in both the management of the lectures and the organization of the course programs on instrumentation and measurement. In this scenario, the virtual laboratory (VL) represents the environment in which the learning activities are performed. Starting from this observation, in the paper an overview on the VL-based education on instrumentation and measurement is given. The fundamental aspects concerning both the software and the hardware to design the VLs are examined. Emphasis is devoted to innovative criteria and interesting requirements arising from the increasing diffusion of the VLs. In order to highlight as these aspects can be powerfully addressed in practice, both the general architecture and the delivered services of innovative VL are described.

Contents

1. Introduction

What is the Virtual Laboratory (VL) and why it is used in the education on instrumentation and measurement?

In the past, the traditional Technical University teaching in the field of the instrumentation and measurement was based on (i) face-to-face lectures, (ii) laboratory experiences, and (iii) consulting with the teaching staff.

In order to understand the measurement procedures and measurement system design, it is necessary to repeat many times the same experience involving actual measurements of physical phenomena in order to make the

* Corresponding author.
E-mail addresses: grimaldi@deis.unical.it (D. Grimaldi), rapuano@unisannio.it (S. Rapuano).

0263-2241/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.measurement.2008.09.003

learners able to operate the measuring instrumentation [1–3]. Some drawbacks make it difficult to provide a complete set of updated workbenches to each learner.

Nowadays, owing to the fast development of the software and the hardware technologies, several solutions are available to overcome these drawbacks, and, consequently, several changes have characterized the teaching activities [4–19]. The multimedia tools based on the newest software and hardware technologies play an important role in the management of the lectures and in the organization of the course programs [20]. They permit to introduce new and interesting arguments otherwise difficult to teach and to learn [21].

From the teacher point of view, this approach allows to (i) speed up the teaching, (ii) analyze the problems more deeply, and (iii) made the arguments exhaustive.

As a consequence, the lecture lost the traditional organization and it is assuming new distinguishing marks. Moreover, the progress of the multimedia tools and the novelties available on the multimedia market cause the continuous upgrading of (i) the organization, (ii) the topics, (iii) the goals, (iv) the quality, and (v) the effectiveness of the lectures [22–26].

From the student point-of-view several advantages can be achieved. The student is involved into a new learning scenario different from the traditional well-defined environments, the classroom and the laboratory. The VL replaces they with a virtual environment in which all the learning activities can be performed on the basis of individual requirements. In particular, the VL can be used for providing the same goals as the traditional teaching (face-to-face lectures, laboratory experiences, and teaching staff consulting [27–30]), but with better quality [31], good outcome [32] and much more opportunity to expand [33].

The adoption of advanced technologies for the remote teaching [34] and, in particular, the exploit of Internet as a channel to reach the learners at their homes was soon recognized [35–37]. Currently a lot of teaching material can be found as (i) web-based lectures and seminars, sometimes interactive, provided by hardware or software producers, (ii) web support to university courses, including slides of lectures and exercises [38,39], (iii) simulation of actual experiments to be executed either remotely or on student's PC [40,41], and, more rarely, (iv) remotely accessible laboratories, where the learners can access real instrumentation through a web page [42–46].

Owing to the increasing importance that the VL is assuming, the paper is focused to (i) provide the state of the art on the VL development, (ii) discuss its advantages in the education activities, and (iii) define the contest of new interesting problems to be solved. In particular, the main topics concerning both the software and hardware criteria to design the VL for education in instrumentation and measurement are examined. Emphasis is devoted to the interesting aspects and requirements concerning the education activity in terms of (i) innovation, (ii) quality, and (iii) realism. Finally, both the general architecture and the delivered services of innovative VL are described in order to highlight as in practice the requirements and the design criteria can be powerfully addressed.

2. Overview on the VL for education in instrumentation and measurement

By following the innovation in the software and in the hardware market, the VL has assumed different structures and has increased its complexity and versatility in the years. Initially the VL was based on a Virtual Instrument (VI) only. The VI was able to control a single measurement instrument by means of an IEEE 488 standard interface, in most cases. A Graphical User Interface (GUI) permitted to achieve this aim in friendly way [7].

Successively, the availability of the local area networks and software innovations made possible the remote management of a set measurement instruments [47]. The wide diffusion of Internet permits (i) to implement the VL over wide area networks, and (ii) to use the web technology advantages [46–51]. Consequently, the VL architecture can be based on (i) stand-alone VIs that are individually accessible, and (ii) the VIs and the connecting network as components of a Distributed Virtual Laboratory (DVL).

2.1. The VL architecture

There are basically two ideas to be considered when the VI is taken into account to build the VL. The first is the possibility of controlling a real measurement instrument by a GUI more friendly. To achieve this aim the IEEE 488, the serial or the VXI interfaces can be used. In this way a set of different measurement instruments, co-operating among them, could be presented like a single, more sophisticated, one. In particular, (i) the Fig. 1a shows the classical and original architecture of the VI, (ii) the Fig. 1b shows the VI architecture to carry out complex measurement by using a number of instruments, and (iii) the Fig. 1c shows the VI architecture to carry out complex measurement by using a number of instruments and software procedures.

The second idea is to present a program simulating the real instrument's behaviour as a VI. Once again it is possible to use more than one algorithm to simulate complex measurements, and to present the final results as they were obtained from a single powered VI. By taking into consideration both ideas, it is possible to realize mixed systems, more sophisticated and more flexible, that provide two modules (i) one for the simulation of the experiment, and (ii) another to carry out the real measurement process. Another very interesting and important component that is widely used in measurement systems is the Digital Signal Processor (DSP). Accordance with the VI concept, it is possible to include the use of the DSP into the VI.

The general architecture of the DVL is shown in Fig. 2, where the student can access the laboratory by means of a remote client through Internet.

There are many available networks designed to meet differing requirements of the measurement applications, (i.e. Profibus, DeviceNet, Inter-bus, Ethernet). The Ethernet technology for restricted areas and Internet for geographic area are very attractive and cost-effective.

Even if the interaction between the student and the instruments takes place through the network, the main idea is still valid: the student is supplied with a graphical interface that makes the instrumentation easier and

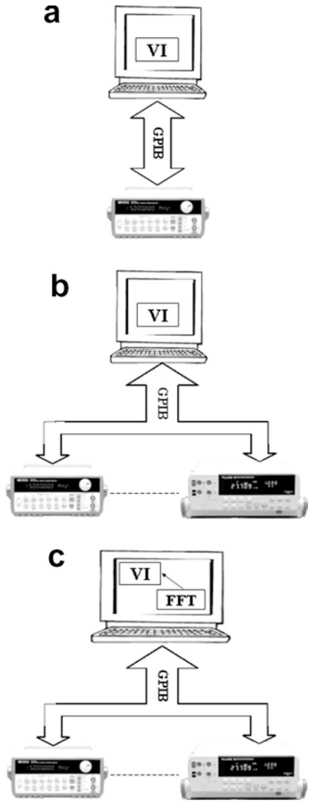

Fig. 1. Virtual instrument constituted by (a) single instrument, (b) set of instruments, and (c) set of instruments and a software procedure.

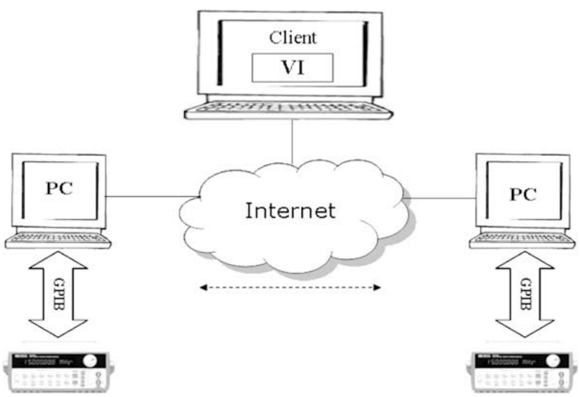

Fig. 2. Distributed virtual laboratory.

friendlier. The open questions are (i) how the real measurement procedure takes place, (ii) what kind of instruments and algorithms are used and (iii) how the communication is implemented can be made transparent to the student. Moreover, the student can know how the DVL works if it is necessary from the education point of view.

As a consequence, the general definition of the VL can be related to the presence of (i) the computer to connect the measurement instrument and to process the measurement results, (ii) the software to implement the distributed application and to display the measurement results in an easy manner, and (iii) the network connecting the VI and the users.

2.2. Innovation, quality and reality of the VL

There are several realizations of the VLs satisfying particular requirements in different fields [1–3,6–15,17,18]. Innovation and advantages that can be inferred by all these VLs are the following:

- The exercises can be customized for each student.
- The test result validation phase can be automatically performed and its quality significantly improved.
- The laboratory resources are better exploited because the students can access to the laboratory from anywhere and at any time.
- The degree of realism is clearly higher than in simulation. Even if the access to the laboratory environment is virtual, the target development system and the attached devices exist physically.
- The time consumption and the set-up efforts are optimized and the difficulties in assimilating the learning subject are minimized.
- The student safety is carried out if dangerous apparatus is used in the experiments.
- The availability of experimental benches are graded according to the student progress in the theoretical topics.

Nevertheless, any disadvantage of the VLs are:

- The high degree of realism does not solve completely the fundamental problem that the students have no direct contact with real apparatus and physical connections among parts of the analyzed measurement system. In this context, the operational skills of future engineers appears limited.
- There is no direct help and suggestions that could be given by a tutor in presence of the students. Partial solution is the online help system and tutoring.

Therefore, as suggested by the reviewer, it must be highlighted that the VL is very useful and complementary tool for teaching in the field of the instrumentation and measurement, but it cannot substitute at all traditional laboratory. In particular manual skills related to real objects of measurement must be taken into account to made complete the background of the future engineers.

Among the others there are two fundamental aspects concerning the VLs that must be taken into account (i) the quality of the education by VL, and (ii) the realism of the environment created by the VL.

The quality assessment of the VL involves several factors and it can be considered an index of its effectiveness as education tool. To this aim in the design phase it is necessary to specify a set of requirements and factors to be taken into account to achieve the desired quality level. In particular, the interest is usually devoted to (i) the graphical environment, (ii) the software supervisor that should point out operating errors, (iii) the comparison of the results with the correct ones obtained in the same operating conditions, and (iv) the accessibility to the higher skill levels on the basis of expertise acquired at the lower ones.

Also the realism of the environment is important aspect. It is possible to create the virtual environment similar to a real measurement laboratory. To this aim, the software environments must able (i) to permit to the student to develop his own VI and to easily integrate new parts (software and hardware) of the measurement station, (ii) to show the information coming from the instruments and the real experiment conditions.

2.3. Design criteria of DVL

The main design objectives to develop a DVL usually are:

1. *Portability:* The visualization environment has to be portable on different hardware platforms and operating systems.
2. *Usability and accessibility:* The visualization and the management of an experiment should be easy to understand and to perform, even for users that are not expert of information technologies, and the system features have to be accessed easily and homogeneously by students operating at University laboratories or at home.
3. *Maintenance:* The maintenance costs should be reduced and the procedure simplified. This can be made possible through a client-server approach that eliminates the need for installing and upgrading code application and data on client computers.
4. *Client-side common technologies:* The students have to access to the system using their desktop computers based on common hardware and software technologies, with no need of powerful processors or high memory capacity. The access to the laboratory should be granted through dialup connections with low speed modems without a significant performance decrease.
5. *Scurity with respect to the network instruction:* The remote access of the students through the Internet must preserves the integrity of recorded and transmitted data as well as the system functionality.
6. *Safety with respect to network intrusion:* The remote access must be guaranty by proper setting of the fire wall.
7. *Privacy assurance:* The students' data should be protected against unauthorized access.
8. *Scalability:* The system performance has not to degrade with the growth of the connected users.
9. *Queue management:* The system must able to select the connecting paths into the DVL characterized by lower value of the delay time of the communication.

3. Software environment for VL

Two different approaches to develop the measurement software of the VL can be taken into account: the first one refers to the use of the commercially available integrated development systems, i.e. LabVIEW [52] and related software tools like Measurement Studio. The second approach, also adopted in the literature, is based on the Object-Oriented Programming (OOP) like Java and related technologies [53]. The main aim of the VL can be achieved by using both the approaches, but both have advantages and disadvantages that should be considered before designing the architecture.

In both these approaches the communication structure is highly important. When a standard communication structure is not used, the reusability and the interoperability of a VI is greatly limited to the specific laboratory application and the expandability of the system is bound from the availability of skilled technicians able in developing new VIs to be included in the system.

In the case that the VL is part of a distance learning platform, it is necessary that the GUI is integrated into the Learning Management System (LMS). The LMS is the software platform used to manage the learners, keeping track of their progress and performance across all types of training activities. The LMS also manages and allocates learning resources such as registration, classroom and instructor availability, instructional material fulfilment, and online learning delivery [45].

3.1. The LabVIEW-based approach

LabVIEW is a powerful graphic environment for the development of virtual instruments. It allows to create the VI functionalities just connecting graphical objects that are made available from the environment. The GUI can be developed visually in a similar straightforward way. LabVIEW can generate code for each VI, but it is not platform independent as it can be executed only by the LabVIEW Execution System (ES) for the current platform. The generated code is subdivided into clumps that can be executed in a cooperative mode. When the operating system where the ES runs provides multithreading, the code execution can take full advantages of this operating system functionality [54].

There are two inconveniences to be highlighted in this approach. The first, as mentioned above, the generated code is not portable across different platforms, or better any change of platform requires regenerating the code. The second, to be able to execute the VI code the user needs the run-time environment, and therefore run-time license is required. This can be a problem when LabVIEW is used for teaching purposes in the University environment.

LabVIEW provides native network functionality that can be used for remote control of instrumentation. Technologies like DataSocket are also available to easily share measurements across a network. Although the communication over the network is based on the TCP/IP protocols, its use is completely hidden to the user. The development of intelligent remote measurement nodes and measurement publishing systems is simplified. There is one additional benefit of the DataSocket technology for publishing measurements: the remote users do not need an application development environment installed. Instead, it is possible to create a web interface to receive measurement information from the remote instrumentation, and therefore to use a standard web browser on the user side [55].

LabVIEW makes possible to increase the processing power by the distribution of the executable code to several PC nodes. Therefore, distributing measurements and executable code, it is possible to create measurement systems over large-scale networks.

When real-time constrains are required, the LabVIEW RT can be used [56]. The main idea is to execute the critical code on a dedicated processor, therefore dedicated systems can be developed (for instance a data acquisition board with an embedded processor). The LabVIEW RT provides a dedicated kernel with multithreading support and some I/O drivers. The VI that is implemented with LabVIEW RT is executed on the dedicated system, and can be visualized on a different PC node. The communication between those two parts can be achieved using the VI server technology.

Some cross-platform solutions for remotely accessing VIs written in LabVIEW are proposed in [42], [45] and [57]. Basically all of them rely on Java applets reproducing the VI front panel. The use of Java ensures a native portability of the VIs on different client operating systems. Moreover, this kind of solutions does not oblige the student to download heavy plug-ins from Internet. By following the same approach the commercial software AppletView, from Nacimiento produces Java applets that constitute a remote interface of LabVIEW VIs. In such a way it is possible to reuse the wide number of already developed VIs for integrating existing instrumentation in a remote laboratory without developing new software. An alternative approach, using the RDP (Remote Desktop Protocol) [58], proposes to grant to the student a limited access to the desktop of the PC connected to the instrumentation where a LabVIEW instance runs. In this manner, the student can even build his/her own VI, given a set of programmable instruments. The architecture of the DVL developed using that approach is reported in Fig. 3.

3.2. The Object-Oriented Programming-based approach

The OOP is widely used for measurement system development [59], [60]. The physical instruments, the drivers interfacing the instruments with the communication bus and the front panel graphical components can be represented in software as objects. Moreover it is possible to create an extensible hierarchy of instruments based on the inheritance and polymorphism as suggested in [61].

In order to carry out the measurement, some specific steps should be completed. The logic of the measurement procedure can be delegated to a Supervisor object. The implementation of the system is almost straightforward by using any OOP language like C++, Java or C#.

Although the proposed model is adequate for local measurements, it is easy expandable for the remote control of instrumentation. Indeed, using the client–server model and the features of the Java programming language, it is possible to provide the remote control mechanism. The pattern proposed in [62] provides a server for the measurement procedures and a web server exporting over Internet these procedures. On the client side it is possible to download the control panel of the VI implemented through C++, Java or C#, relying on a standard browser. The communication between the client and the server can be implemented using Java RMI (Remote Method Invocation) or CORBA (Common Object Request Broker Architecture) standard [63] or Web Services relying on XML (eXtensible Markup Language) and the SOAP (Simple Object Access Protocol) [64], [46].

The same model can be further extended to develop a DVL. The local measurement system can request/supply services from/to another remote system. The cooperation between subsystems should follow opportune protocols to achieve the common goal. The network communication can be again based on CORBA, RMI or Web Services. It is worth noting that the CORBA standard allows the

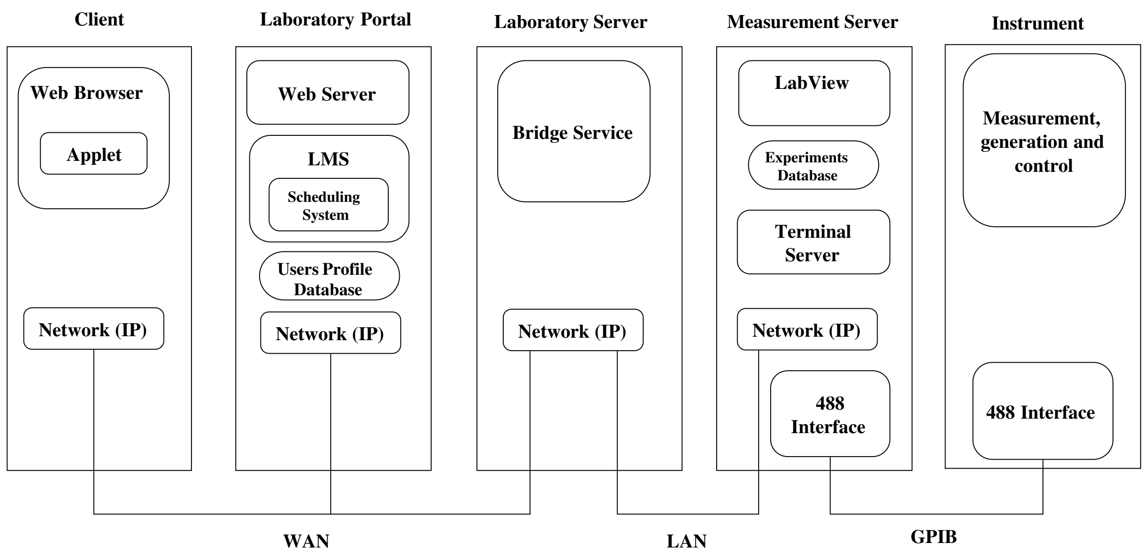

Fig. 3. Architecture of the VL accessing the instrumentation by means of RDP [55].

cooperation between pieces of code written in different programming languages while RMI is limited to Java based environment.

An interesting evolution of this approach was proposed in [65] where the system is implemented using a mobile agent technology. In such a distributed measurement system, the different tasks are carried out in different measurement stations, and the cooperation between them is delegated to the mobile agents. Each mobile agent is characterized by a path to follow and a set of subtasks to perform on each node of the path in order to fulfil the distributed execution of the overall measurement task.

A slightly different distributed architecture was proposed in [66]. The idea is to create a Virtual Instrument Bus (VIB) witch makes a large number of physical buses on a computer network look like a single bus. The VIB software makes all instruments to appear to be connected to the same bus, and provides easy code reusing for program development. The VIB is developed by using the remote procedure call approach.

The solution based on Web Services over XML and SOAP, instead, allows the creation of dynamic web pages publishing the instrument front panels whichever is the programming language used for developing them. The main drawback of this solution is the information overhead needed for abstracting the data source, that slows down the communication. In Fig. 4, an example of VL using Web Services for network communication is shown.

The DVL based on the previous considerations have satisfactory performance when no real-time constraint exists for the network communication. Indeed, the communication over the network is based on the non-deterministic TCP/IP protocols. When real–time constrains have to be faced new real-time protocols like ReSerVation Protocol (RSVP) or Real Time Protocol/Real Time Control Protocol (RTP/RTCP) [67] could be implemented in order to guarantee deterministic data delivering and timing.

4. Example of architecture and delivered services of innovative VL

An architecture of DVL that meets in practice the requirements, the innovations and the design criteria [68] is described in [69–71].

In order to allow the student to access the remote and geographically distributed didactic laboratory, the web-based multi-tier distributed architecture is implemented centered on the Learning Management System (LMS) that can be considered as the core component of the overall system[70,71]. The primary objective of the LMS is to manage learners, keeping track of their progress and performance across all types of training activities. The LMS manages and allocates learning resources such as registration, classroom and instructor availability, instructional material fulfilment, and online learning delivery. In particular, concerning the students, the LMS permits to design their own learning process, by carrying out both the collaborative and the project-based learning. Concerning the teachers, the LMS makes possible (i) to track the activity of the students and (ii) to carry out the interactive experiment in the virtual classroom.

The realized multi-tier architecture is composed of three tiers:

Tier 1. The presentation-tier: it manages the experiment visualization on the client side. It is based on standard web browsers with no need of specific software components.

Tier 2. The middle-tier: it manages the system logic on the server side.

Tier 3. The storage-tier: it performs the data management, related for example to the management of the user profiles and the distributed management of the data of the available experiments at the different measurement laboratories. It is based on a

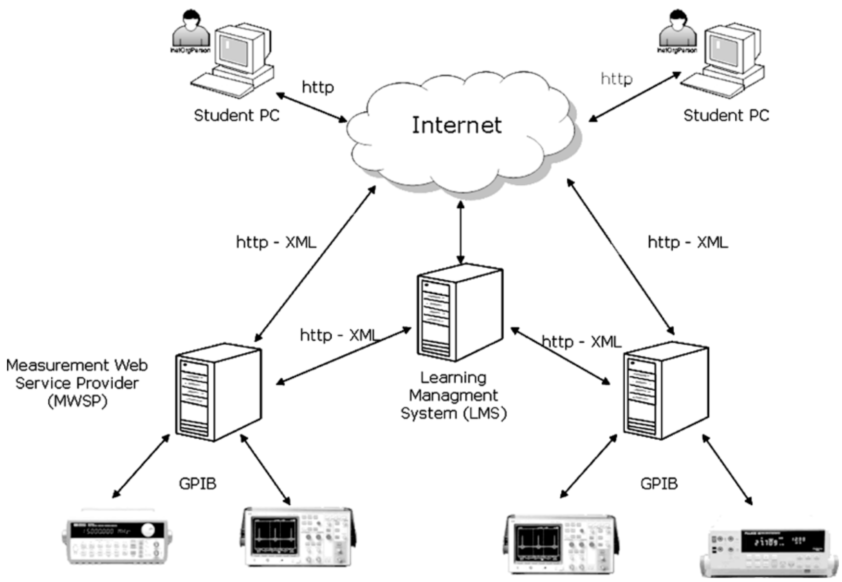

Fig. 4. Architecture of the VL based on Web Services.

series of geographically distributed databases, managed using the Relational Data Base Management System.

4.1. Architecture of the innovative DVL

The LMS is executed on a central server of the distributed laboratory, called Laboratory Portal. The LMS interfaces to the users through a Web Server that is hosted on the same machine. The Laboratory Server (LS) is used to interface a real measurement laboratory with the rest of the distributed architecture. There is a LS for each measurement laboratory involved in the project. It delivers the access and the control to the laboratory measurement equipment through a service, called Bridge Service. Moreover, the LS is the only machine in a measurement laboratory directly accessible through the Internet, while the other server machines are not accessible and typically constitute a private local network. For this reason the LS can also be used for security purposes in order to monitor the accesses to the measurement laboratory and to protect it against malicious accesses. The Measurement Server (MS) is a server located in a measurement laboratory that enables the interaction with one or more instruments. A MS is physically connected to a set of different electronic measurement instruments through an interface card. The GPIB interface has been used to connect the MS to the instruments. The used VIs are stored in a database of the MS, where the LabVIEW environment is installed. No adjustment is necessary to include the VI in the virtual learning environment. Therefore, the wide number of existing VIs can be reused without requiring additive work. In order to overcome the well-known security weakness of Microsoft based networks, each LS is protected by a Linux-based gateway machine. One of the most relevant problems designing the laboratory subsystem is the remote visualization and control of the experiments.

4.2. Delivered services

The main services delivered to the student are the following:

Level 0. Experiment Demonstration: this service allows the students to observe, online, how the teacher controls the instrumentation. The student observes on his computer the server desktop used by the teacher to control the measurement instruments involved in the experiment.

Level 1. Experiment Visualization: this service allows the student to observe the laboratory activity of the teacher. The student receives on his computer the server desktop used by the teacher to control the measurement instruments of the experiment at "*level 0*". The experiment is carried out by the student operating on the front panel of the LabVIEW VI controlling the involved instrumentation.

Level 2. Experiment Control: this service allows the student to perform an experiment by controlling remotely one or more actual measurement instruments. The student can choose a specific experiment in a set of predefined ones and can run it if the required measurement instruments are currently available.

Level 3. Experiment Creation: this service allows the student to remotely create an experiment interacting directly with specialized software executed on the servers used to control the measurement instruments. This feature enables the adoption of PBL as didactic model. Under the supervision of the teacher, the students can develop a specific project by producing a VI to control a set of real instruments.

At the end of the theoretical lessons and the experiments the self evaluation tests are given.

The services delivered to the teacher are related to the remote handling of the available experiments (remote creation, modification and removal of experiments, etc.). Finally, the administrator is responsible of the correct working of the overall distributed system and of handling of user profiles.

5. Conclusions

The paper have given an overview on both the software and hardware realization of Virtual Laboratories (VLs) showing the innovative topics introduced from such systems in the education of instrumentation and measurement. Nevertheless, it has been highlighted that new and interesting aspects must be examined, too, in the design of VL. Emphasis is devoted to innovative criteria and interesting requirements arising from the increasing diffusion of the VLs. These can be clustered around the following basic aspects: (i) the quality of the VL for education purposes, and (ii) the realism of the virtual environment in comparison with the real laboratory.

In this contest has been noted that in spite of the effort, the fundamental problem that the students have no direct contact with real apparatus and physical connections among parts of the analyzed measurement system is not solved completely.

In order to highlight as these aspects, together that arising from the design and management of the VL, can be power-fully addressed in practice, both the general architecture and the delivered services of innovative VL are described.

References

[1] K. Mallalieu, R. Arieatas, D.S. O'Brien, An inexpensive PC-based laboratory configuration for teaching electronic instrumentation, IEEE Trans. Educ. 37 (1) (1994) 91–96.
[2] L. Finkelstein, Measurement and instrumentation science – an analytical review, Measurement 14 (1) (1994) 3–14.
[3] S.S. Awad, M.W. Corless, An undergraduate digital signal processing lab as an example of integrated teaching, in: Proc. of IE EE IMTC-97, Ottawa, Canada, 1997, pp. 1314–1319.
[4] G.G. Karady, M. Reta-Hernandez, A. Bose, Role of laboratory education in power engineering: is the virtual laboratory feasible? II, in: Proc. of IEEE Power Eng. Soc. Sum. Meet., Seattle, WA, USA, vol. 3, 2000, pp. 1478–1483.
[5] G.G. Karady, G.T. Heydt, K.J. Olejniczak, H.A. Mantooth, S. Iwamoto, M.L. Crow, Role of laboratory education in power engineering: is the

virtual laboratory feasible? I, in: Proc. of IEEE Pow. Eng. Soc. Sum. Meet., Seattle, WA, USA, vol. 3, 2000, pp. 1471–1477.
[6] V.L. Stonick, Teaching signals and systems using the virtual laboratory environment in ECE at CMU, in: Proc. of IEEE Int. Conf. on Acoust. Speech, and Signal Processing, ICASSP-93, Hong Kong, vol. 1, 1993, pp. 36–39.
[7] P. Daponte, L. Nigro, F. Tisato, Virtual laboratory: an object-oriented framework, in: Proc. of IEEE IMTC-94, 1994, pp. 11–16.
[8] T. Laopoulos, Teaching instrumentation and measurement in the complex systems era, IEEE Instrum. Measur. Mag. 2 (1) (1999).
[9] Stonick V.L., Teaching signals and systems using the virtual laboratory environment in ECE at CMU, in: Proc. of IEEE Int. Conf. on Acous., Speech, and Signal Proc., ICASSP-93, Hong Kong, vol. 1, 1993, pp. 36–39.
[10] Barker P, Use of a virtual laboratory for teaching instrument design, in: Proc. of IEE Coll. on Comp.-Bas. Learn. in Eng., London, UK, 1994, pp. 5/1–5/5.
[11] A.P. Sakis Meliopoulos, G.J. Cokkinides, Role of laboratory education in power engineering: is the virtual laboratory feasible? III, in: Virtual power system laboratories: is the technology ready, in: Proc. of IEEE Pow. Eng. Soc. Sum. Meet., Seattle, WA, USA, vol. 3, 2000, pp. 1484–1489.
[12] Z. Illyefalvi-Vitez, P. Nemeth, J. Pinkola, G. Ripka, M. Ruszinko, Virtual laboratory support for microelectronics packaging education, in: Proc. of 49th Electr. Comp. and Tech. Conf., San Diego, CA, USA, 1999, pp. 1068–1073.
[13] T. Huan-Wen, T. Chin-Ming, Design of a virtual laboratory for teaching electric machinery, in: Proc. of IEEE Int. Conf. on Systems, Man, and Cyb., vol. 2, Nashville, TN, USA, 2000, pp. 971–976.
[14] Moros R, Luft F, Papp H. Virtual laboratory course in chemical engineering and unit operations (VIPRATECH)-tutorials, simulations and remote process control, in: Proc. of Inter. Conf. on Comp. in Educ., Auckland, New Zealand, 2002, pp. 1447–1448.
[15] J.M.G. Palop, J.M.A. Teruel, Virtual work bench for electronic instrumentation teaching, IEEE Trans. Educ. 43 (1) (2000) 15–18.
[16] C.C. Ko, B.M. Chen, S.H. Chen, V. Ramakrishnan, R. Chen, S.Y. Hu, Y. Zhuang, A large-scale Web-based virtual oscilloscope laboratory experiment, Eng. Sci. Educ. J. 9 (2) (2000) 69–76.
[17] U. Pisani, F. Cambiotti, F. Corinto, G. Romano, A fully simulated laboratory for instrumentation and electronic measurements, in: Proc. of the IEEE IMTC-04, Como, Italy, vol. 2, May 2004, pp. 1277–1281.
[18] P. Tyml, D. Slepika, J. Roztocil, Virtual measurement system for distance education and training, in: Proc. of the IEEE IMTC-04, Como, Italy, vol. 2, 2004, pp. 1269–1271.
[19] V.A. Spasic, Intelligent virtual systems in learning [and biomedical application, in: Proc. of the 22nd Ann. Int. Conf. of the IEEE Eng. in Med. and Biol. Soc., Chicago, IL, USA, vol. 2, 2000, pp. 1016–1018.
[20] G. Muzak, I. Cavrak, M. Zagar, The Virtual Laboratory project, in: Proc. of the 22nd Int. Conf. on Information Technology Interfaces, Pula, Croatia, 2000, pp. 241–46.
[21] M.E. Macias, V.M. Cazares, E.E. Ramos, A virtual laboratory for introductory electrical engineering courses to increase the student performance, in: Proc. of 31st Annual Conf. on Frontiers in Educ., Reno, NV, USA, vol. 3, 2001, pp. S2C–S13.
[22] C. Levert, S. Pierre, Security, interoperability, and quality of service aspects in designing a telecommunications platform for virtual laboratories, in: Proc. of IEEE Canadian Conf. on Elect. and Comp. Eng., Halifax, Canada, vol. 2, 2000, pp. 811–815.
[23] A. Bagnasco, M. Chirico, A.M. Scapolla, XML technologies to design didactical distributed measurement laboratories, in: Proc. of the IEEE IMTC-02, Anchorage, AK, USA, 2002, pp. 51–655.
[24] M.G. Russell, The "virtual laboratory": alliances for technology transfer, in: Proc. of the 27th Hawaii Int. Conf. on Syst. Sci., USA, vol. 4, 1994, pp. 478–482.
[25] W. YuLung, C. TeYi, J. BinShyan, L. TsongWuu, L. YaoHui, A Web-based dual mode virtual laboratory supporting cooperative learning, in: Proc. of 18th Int. Conf. on Adv. Inf. Netw. and Appl, vol. 1, 2004, pp. 642–647.
[26] S. Zagoranski, S. Divjak, Use of augmented reality in education, in: Proc. of the IEEE Region 8 EUROCON 2003, Comp. as a Tool, vol. 2, 2003, pp. 339–342.
[27] T. Lohl, S. Pegel, K.-U. Klatt, S. Engell, C. Schmid, A. Ali, DYNAMIT – internet based education using CACSD, in: Proc. of the 1999 IEEE Intern. Symp. on Comp. Aided Control Syst. Des., 1999, pp. 273–278.
[28] L. Balmelli, S. Ayer, Y. Cheneval, M.A. Vetterli, A framework for interactive courses and virtual laboratories, in: IEEE Second Works. on Mult. Sig. Proc., 1998, pp. 501–506.
[29] S.R. Thampuran, W. Burleson, K. Watts, Multimedia distance learning without the wait, in: Proc. of 31st Annual Conference on Frontiers in Education, Reno, NV, USA, vol. 1, 2001, pp. T2F-21.
[30] Z. Nedic, J. Machotka, A. Nafalski, Remote laboratories versus virtual and real laboratories, in: Proc. of 33rd Annual Conference on Frontiers in Education, Westmiinster, CO, USA, vol. 1, 2003, pp. T3E-1–T3E-6.
[31] P. Daponte, S. Rapuano, M. Riccio, F. Zoino, Remote didactic laboratory in electronic measurements: quality of system testing, in: Proc. of Instrumentation and Measurement Technology Conference, IMTC 2007, Warsaw, Poland, 1–3 May, 2007, pp. 1–6.
[32] P. Daponte, D. Grimaldi, S. Rapuano, Recent progresses of the remote didactic laboratory LA.DI.RE "G. Savastano" Project, in: Proc. of Instrumenting the Grid, INGRID 2008, Lacco Ameno, Island of Ischia, Italy, April 9–11, 2008.
[33] P. Daponte, D. Grimaldi, S. Rapuano, A software architecture for the m-Learning in instrumentation and measurement, in: Proc. of Instrumenting the Grid, INGRID 2008, Lacco Ameno, Island of Ischia, Italy, April 9–11, 2008.
[34] M. Cobby, D. Nicol, T.S. Durrani, W.A. Sandham, Teaching electronic engineering via the World Wide Web, in IEEE Colloquium on Computer Based Learning in Electronic Education, London, UK, 1995, pp. 7/1–7/11.
[35] G.C. Orsak, D.M. Etter, Connecting the engineer to the 21st century through virtual teaching, IEEE Trans. Educ. 39 (2) (1996) 165–172.
[36] M.A. Pine, L.A. Ostendorf, Influencing earth system science education: NASA's approach, in: Proc. of Int. Geoscience and Remote Sensing, Symposium, IGARSS-95, Florence, Italy, vol. I, 1995, pp. 567–569.
[37] S.M. Blanchard, S.A. Haie, Using the World Wide Web to teach biological engineering, in: Proc. of 25th Annual Conference on Frontiers in Education, Eng. Educ. for the 2lst Cent., Atlanta, GA, USA, vol. 2, 1995, pp. 9–14.
[38] NETwork per l'UNiversità Ovunque. Available at: <http://www.uninettuno.it>.
[39] Laboratory of Signal Processing and Measurement Information, Engineering Faculty of University of Sannio. Available at: <http://lesim1.ing.unisannio.it>.
[40] Availalbe at: <http://www.educatorscorner.com/experiments/index.shtml>.
[41] V.M.R. Penarrocha, M.F. Bataller, Virtual instrumentation: first step towards a virtual laboratory, in: IEEE Int. Work. on Virt. and Intel. Measure. Syst., Annapolis, MD, USA, 2000, pp. 52–56.
[42] A. Bagnasco, A. Scapolla, A grid of remote laboratory for teaching electronics, in: Proc. of Second Int. Workshop on e-Learning and Grid Technologies: A Fundamental Challenge for Europe, Paris, France, 2003. Available at: <http://ewic.bcs.org/conferences/2003/2ndlege/index.htm>.
[43] L. Benetazzo, M. Bertocco, A distributed training laboratory, in: Proc. of Eden Ann. Conf. on Open and Distance Learning in Europe and Beyond, Granada, Spain, 2002, pp. 409–414.
[44] L. Benetazzo, M. Bertocco, F. Ferraris, A. Ferrero, C. Offelli, M. Parvis, V. Piuri, A Web based, distributed virtual educational laboratory, IEEE Trans. Instrum. Meas. 49 (2) (2000) 349–356.
[45] G. Canfora, P. Daponte, S. Rapuano, Remotely accessible laboratory for electronic measurement teaching, Comput. Stand. Interf. 26 (6) (2004) 489–499.
[46] P. Daponte, C. De Capua, A. Liccardo, A technique for remote management of instrumentation based on web services, in: Proc. of IMEKO-TC4 13th Int. Symp. on Meas. for Res. and Ind. Appl., Athens, Greece, 2004, pp. 687–692.
[47] P. Daponte, D. Grimaldi, L. Nigro, F. Pupo, Distributed measurement systems: an object-oriented architecture and a case study, Comput. Stand. Interf. 18 (5) (1997) 383–395.
[48] P. Arpaia, A. Baccigalupi, F. Cennamo, P. Daponte, A remote measurement laboratory for educational experiments, Measurement 21 (4) (1997) 157–169.
[49] F.J. Gomez, M. Cervera, J. Martinez, A World Wide Web based architecture for the implementation of a virtual laboratory, in: Proc. of the 26th Eur Conf., vol. 2, 2000, pp. 56–61.
[50] T. Huan-Wen, The design of pedagogical agent for distance virtual experiment, in: Proc. of 31st Annual Conference on Frontiers in Education, Reno, NV, USA, vol. 2, 2001, pp. F1F-18–F1F-23.
[51] J. Sanchez, F. Morilla, S. Dormido, J. Aranda, P. Ruiperez, Virtual and remote control labs using Java: a qualitative approach, IEEE Control Syst. Mag. 22 (2) (2002) 8–20.
[52] Available at: <www.ni.com>.
[53] D. Grimaldi, L. Nigro, F. Pupo, Java based distributed measurement systems, IEEE Trans. Instrum. Meas. 47 (1) (1998) 100–103.
[54] National Instruments, LabVIEW documentation. Available at: <http://www.ni.com/labview>.

[55] National Instruments, Integrating the Internet into Your Measurement System, DataSocket Technical Overview. Available at: <http://www.ni.com/labview>.
[56] National Instruments, LabVIEW RT documentation. Available at: <http://www.ni.com/labviewrt>.
[57] W. Winiecki, M. Karkowski, A new Java-based software environment for distributed measuring systems design, IEEE Trans. Instrum. Meas. 51 (6) (2002) 1340–1346.
[58] S. Rapuano, F. Zoino, A learning management system including laboratory experiments on measurement instrumentation, in: Proc. of IEEE IMTC-05, Ottawa, Canada, 2005.
[59] P. Daponte, L. Nigro, F. Tisato, Object-oriented design of measurement systems, IEEE Trans. Instrum. Meas. 41 (6) (1992) 874–880.
[60] M. Bertocco, Architectures for remote measurement, in: F. Davoli, S. Palazzo, S. Zappatore (Eds.), Distributed Cooperative Laboratories: Networking, instrumentation and measurements, Springer, Berlin, 2006, pp. 349–362.
[61] P. Arpaia, F. Cennamo, P. Daponte, M. Savastano, A distributed laboratory based on object-oriented measurement systems, Measurement 19 (3–4) (1996) 207–215.
[62] G. Fortino, D. Grimaldi, L. Nigro, Distributed measurement patterns using Java and Web tools, in: Proc. of IEEE Autotestcon'97, Anaheim, CA, USA, 1997, pp. 624–628.
[63] P. Arpaia, P. Daponte, M. Marinov, Measurement systems distributed on geographical networks for educational purposes, in: Proc. of IEEE International Workshop on Virt. and Intel. Measure. Syst., Annapolis, MD, USA, 2000, pp. 62–68.
[64] A. Bagnasco, M. Chirico, A.M. Scapolla, XML technologies to design didactical distributed measurement laboratories, in: Proc. of IEEE IMTC-02, Anchorage, AK, USA, vol.1, 2002, pp. 651–655.
[65] G. Fortino, D. Grimaldi, L. Nigro, An agent based measurement laboratory over Internet, in: Proc. of IEEE Autotestcon'99, San Antonio, TX, USA, 1999, pp. 61–66.
[66] D.J. Rawnsley, D.M. Hummels, B.E. Segee, A virtual instrument bus using network programming, in: Proc. of IEEE IMTC-97, Ottawa, Canada, pp. 694–697.
[67] Liu C., Multimedia over IP: RSVP, RTP, RTCP, RTSP. Available at: <http://www.cis.ohio-state.edu/jain/cis788-97/ip_multimedia/index.htm>.
[68] D. Grimaldi, S. Rapuano, T. Laopoulos, Aspects of traditional versus Virtual Laboratory for education in instrumentation and measurement, in: Proc. of IEEE IMTC 2005, Instrumentation and Measurement Technology Conference, Ottawa, Canada, 17–19 May, 2005.
[69] D. Grimaldi, S. Rapuano, T. Laopoulos, Exploring the capability of web-based measurement systems for distance learning, in: F. Davoli, S. Palazzo, S. Zappatore (Eds.), Distributed Cooperative Laboratories: Networking, Instrumentation and Measurements, Springer, Berlin, 2006, pp. 373–393.
[70] G. Andria, A. Baccigalupi, M. Borsic, P. Carbone, P. Daponte, C. De Capua, A. Ferrero, D. Grimaldi, A. Liccardo, N. Locci, A.M.L. Lanzolla, D. Macii, C. Muscas, L. Peretto, D. Petri, S. Rapuano, M. Riccio, S. Salicone, F. Stefani, Remote Didactic Laboratory "G.Savastano": the Italian experience for the e-learning at the Technical Universities in the Field of the Electrical and Electronic Measurements: architecture and optimization of the communication performance based on the thin client technology, IEEE Trans. Instrum. Meas. 56 (4) (2007) 1124–1134.
[71] G. Andria, A. Baccigalupi, M. Borsic, P. Carbone, P. Daponte, C. De Capua, A. Ferrero, D. Grimaldi, A. Liccardo, N. Locci, A.M.L. Lanzolla, D. Macii, C. Muscas, L. Peretto, D. Petri, S. Rapuano, M. Riccio, S. Salicone, F. Stefani, Remote Didactic Laboratory G. Savastano: the Italian experience for the e-learning at the Technical Universities in the field of the electrical and electronic measurements: overview on didactic experiments, IEEE Trans. Instrum. Meas. 56 (4) (2007) 1135–1147.