A Web-Based Distributed Virtual Educational Laboratory

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***Abstract*—Evolution and cost of measurement equipment, continuous training, and distance learning make it difficult to provide a complete set of updated workbenches to every student. For a preliminary familiarization and experimentation with instrumentation and measurement procedures, the use of virtual equipment is often considered more than sufficient from the didactic point of view, while the hands-on approach with real instrumentation and measurement systems still remains necessary to complete and refine the student's practical expertise. Creation and distribution of workbenches in networked computer laboratories therefore becomes attractive and convenient. This paper describes specification and design of a geographically distributed system based on commercially standard components.**

***Index Terms*—Distributed measurement systems, educational laboratory, remote measurement, virtual systems.**

I. Introduction and Motivations

RECENT developments in virtual instrument technologies, remote measurement, distributed systems, and interactive educational environments [1], [2] greatly changed the traditional approach to teaching and practical experimentation at any educational level, from technical high schools and undergraduate academic courses through master's and Ph.D. studies to continuous education and training in the industry. Practical experimentation has a great and even increasing importance in education to understand better the use of new complex technologies through trial-and-error methods, especially when it is difficult to capture and formalize system behavior in a simple mathematical description.

The interest in virtual instruments is mainly due to the cost of experimental laboratories both at educational sites with a large number of students and in industry where instrumentation is used for development or production. Simulators are not expected to replace the real instruments but can be a powerful auxiliary didactic tool for the students in order to help them to become acquainted with the instrument and its controls and operations both in the class and remotely. This helps in reducing training costs by restricting the tutored activities only to substantial matters.

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Remote access to educational resources is attracting an increasing interest to realize distance learning. Continuous training is in fact a key factor to maintain the leading edge and improve the quality of production, products, and personnel in many small and medium-size enterprises. Distance learning allows one to limit the costs for continuous training both by providing in-house educational facilities that can be used with a flexible and adaptable schedule and by reducing the time spent in an educational laboratory outside of the company.

Real measurements of physical phenomena are relevant to more accurate training and to providing a better feeling to students about measurement procedures and measurement system design. The access to remote instrument-equipped sites connected through a computer network becomes an interesting solution to limit training costs without constraining educational opportunities. Also in this case, further direct experimentation on real systems can be considered after the preliminary remote practice, but limited to a better understanding of the course topics. This will reduce the cost and time for student mobility, while preserving most of the learning opportunities on real phenomena. The limitation consists in the possible restrictions in real-time measurement and control of complex systems due to bandwidth constraints and shared use of the measurement system.

Last, the use of local acquisition boards allows for an even more detailed experimentation without possible delays, time inconsistencies, or operation constraints due to the networked interconnections. This approach is, however, more expensive than the previous solutions since the acquisition boards must be acquired locally. However, since the virtual system is programmable, it can be used for several applications and, consequently, will be cheaper than dedicated instrumentation.

The wide spectrum of data acquisition and treatment solutions described above provides different degrees of performance and accuracy, at correspondingly increasing costs, to match better the evolving needs of students without wasting precious resources. Capitalization and sharing of authors' previous experiences led to creation of a unique educational environment for training and experimenting in electrical and electronic measurements. In particular, the authors merged the system created for Web-based interaction to create and download virtual benches [3] and the system created for remote measurement [4]–[6]. This paper presents the system features and architecture of a distributed educational environment based on Web technologies and remote measurement. Such an environment can be used to acquaint students to the measurement procedures and laboratories, as a preliminary phase that does not replace practical activities on real instrumentation and systems but reduces tutored activities and related costs. The flexibility of the environment allows for supporting different kind of didactic activities, while the teacher will be responsible of selecting the most suited approach to be used according to the specific needs of the students and the desired curricula.

II. System Specifications and Features

The goals and features of a distributed virtual laboratory for measurement technologies and applications follow.

A. Educational Goals

1) Initial Approach to Instruments, Measurement Procedures, and Applications: The system must support students in familiarizing themselves with measurement problems and technologies through the use of simulators of real instrumentation, measurement devices, and systems. Although desirable for specialists, the large majority of students do not necessarily need to learn creation of new instrumentation and measurement procedures.

2) Student Typologies: Different kinds of students with different needs must be supported. The system must take into account undergraduate, graduate, and doctoral students, as well as practitioners from industry. Beginners who want to use instruments and measurement methodologies need tools to understand and operate in their specific application field. More opportunities are required for students working on metrology issues. Advanced students in metrology areas will be interested in the details of procedures, devices, components, and systems: creating their own instruments and experimenting with their own measurement procedures is interesting but requires the access to suited development systems. Since these last tasks are for specialists and have high costs, we do not consider this opportunity in the present system version.

3) Adaptability to User Needs and Scalability to User Level: The system must adapt operations and support to specific users. Students with different backgrounds and needs must be allowed for defining the resource view (i.e., devices, components, instruments, generators, data acquisition systems), without being overwhelmed by too much information. The system must scale transparently features and resource view according to the level of competence, experience, and confidence of the students.

4) Tutoring Aids: The educational system must support different types of interactions between students and educators. Tutors in laboratories and computer classrooms can provide assistance to students during classes. When the student alone is using the simulation environment, educational supports will be appreciated. On-line help for using the simulation environment and the individual measurement resources can be introduced by using standard programming techniques available in the user interface. Multimedia pages are attached to each object of the workbench front panel to explain meaning, theory, features, and use of the selected component. Possible links can also be placed to more extensive descriptions on Web sites. Multimedia and hypertext technologies through web or CD-ROM distribution allow for realizing an electronic book on measurement methodologies and instruments that can be used by students during training. This book refers on-line to the distributed measurement educational environment and remote sensing resources to provide examples of theory and measurement methodologies. The student can thus experiment immediately in the virtual simulation environment.

B. User Accessibility

1) User Friendliness: User's activities must be performed in a way that is simple and easy to understand, even for people who are not experts in information technologies.

2) Simplicity of Accessing the Laboratory Resources: The system features must be accessible easily and homogeneously within the university hosting the servers, from other universities, from companies, and by students at home. Access and operation transparency guarantees effective and efficient use.

3) Different Accessing Typologies: The educational system can be accessed by using personal computers connected to the international computer network in different locations and with different kinds of connection. Instrument-equipped computers (i.e., computers with acquisition boards) may be anywhere, provided that they are connected to the educational server through Internet and to the system or the plant to be measured. They can be in the same institution hosting the educational servers, or in another institution or company, or even at a student's home. For simulated or remote measurement, client computers may be located in any computer classroom, university office, institution, or company, when suited network connections and access authorization are provided to the network of the required educational servers. For remote use, computers must be connected to the Internet via transport control protocol/Internet protocol (TCP/IP).

C. Cost Limitation and Hardware Resources Sharing

1) Limitation of Laboratory Costs: Virtual instrument technologies, possibly with a limited number of local physical resources, must be used to minimize the costs of laboratory setup and maintenance. In fact, run-time licenses of the simulation software must be purchased to run simulations and not only during development. This greatly affects system cost. Acquisition of licenses cannot be delegated to students for cost and political reasons, even if student licenses begin to appear on the market at highly reduced costs. Conversely, the cost for all students cannot be placed on the university budget due to fund limits. Few licenses must be therefore bought by the universities and provided temporarily to students as floating licenses valid during the system use only.

2) Differentiation of the Hardware Supports: Experimentation on purely virtual measurement systems is useful as first experience. A better understanding of the involved phenomena and measurement problems (e.g., delays, sampling frequency, accuracy, and calibration) may need real data. Students with knowledge and practical skills derived from the virtual environment perform this advanced training phase more quickly, thus using expensive and sophisticated physical measurement resources for a shorter time. A smaller amount of these resources are sufficient to satisfy the students' needs, leading to a reduced laboratory cost. Moreover, the limited cost and the restricted installations allow for improving resource updating, thus maintaining the leading edge of educational sites and the adequacy for industrial applications. Hands-on experimentation for simple and relatively cheap acquisition systems and application plants are obtained by using dedicated components available in specific laboratories or individual computers. Remote sensing, acquisition, and actuation on centralized sites become attractive to limit the laboratory costs for expensive components, systems, and plants.

3) High Availability and Sharing of Complex and Expensive Measurement Resources: Networking expensive resources for measurement and application allows for better exploitation of resources and for sharing costs. High-quality training environments and up-to-date technologies are achieved at a cheaper cost per student.

4) Shared-Resource Networking: Resources must be easily and directly accessible by students, even remotely through the computer network as they were local in the laboratory or even in the computers on which students are working. Transparency of resource networking is relevant to guarantee easy usage independently from the location.

D. Software Cost and Sharing

1) Limitation of Efforts and Time to Build Simulators: The software developing tools based on graphic, object-oriented programming methods make this job easier and feasible to a wider population, even with limited experience in computer programming. Development and maintenance costs are reduced.

2) Standard Components and Technologies for Simulators: Standard virtual environments for simulation and simulator development make creating and testing new environments simpler and cheaper. This approach should be preferred instead of building the whole instrumentation with programming languages and graphic tools since it reduces realization time and cost, increasing quality, correctness, portability, adaptability, and extendibility.

3) Engineering the Simulator Components: High quality, accuracy, and correctness of simulation environments can be achieved by using software engineering.

4) Reuse of Simulator's Components: Availability of a component library and use of standard design techniques allow for reusing and enhancing development and costs.

E. Real-Time Operation

1) Real-Time Operation and Constraints: If the system to be measured or controlled is connected to the student's computer directly through suited acquisition boards, real-time operation of the virtual measurement system is possible. When signal generators are simulated, the real-time behavior is related only to the characteristics of the simulation environment.

Some researchers and companies claim that real-time operation in virtual instruments and environments with remote sensing is always feasible and correct under any operating and environmental condition, including geographical computer networks. This is exactly correct only under some restrictive conditions. Sampling of all quantities used by the measurement workbench is not guaranteed to be obtained exactly at the same time when acquired by different systems that cannot share the same sampling clock.

Data analysis for monitoring and control must therefore consider explicitly the time at which samples were taken. Traditional control algorithms need a consistent picture of the inputs, sampled contemporaneously. Practically, analysis and control are still correct even if sampling is not performed contemporaneously on all input signals, but in a time period short enough to allow for considering the input values invariant within this period. This occurs when system dynamics are slow enough with respect to the period. Conversely, when input signals varies at very high frequencies, the above approximation is not correct and remote sensing should not be used for monitoring or control. In control, improper use of remote sensing may lead to system instability and safety problems.

An alternative approach could be envisioned by running the whole monitoring and control algorithm on the remote site. In this case, the interaction with the remote server should be limited to setting up and starting the experiment and, then, to retrieve the results. However, this requires transfer of the control algorithm from the client to the server. This is usually not acceptable for safety reasons of the plant connected to the remote server.

F. Distributed System Engineering

1) Modularity: It is relevant for the simulation system and the component library. Modularity allows for combining individual components easily to create the workbench or new components, without any need of software development or adaptation.

2) Expandability: The component library must be easily expandable. New components should be directly added and made usable to students without any need for library rebuilding or restructuring. Local integration of components allows for distributed libraries with possible specific adaptation to local needs.

3) System Portability: The simulation environment and the component libraries should be portable on different hardware platforms and operating systems. When the system is built by using programming languages, portability is achieved with an absolutely portable language (e.g., nowadays, Java). We can accept a reduction of portability in exchange of a higher simplicity in creating components and measurement systems. In most educational and industrial laboratories, sufficient portability is provided by commercially standard virtual environments for measurements and by limiting the use of object-oriented programming (C++ used in a standard and portable way).

4) Interoperability: Hardware and operating-system independence of the simulation environment also provides interoperability, i.e., the ability of running some activities on different computers, connecting to different servers for remote measurement services, using different measurement servers written on different machines with different languages, and downloading components from different servers. All these features are provided transparently and homogeneously to the users.

G. Cooperative Development, Management, and Maintenance

1) Sharing Resources and Experiences Among Universities, Institutions, and Companies: The global communication network and high-level languages allow for allocating simulation and remote acquisition programs on different servers. Universities, measurement institutions, and companies may join the resource developing teams so that the burden of simulator development and maintenance can be distributed on all participating bodies with mutual benefit. The adoption of de facto standards and widely used development and simulation environments for virtual instrumentation (e.g., LabView by National Instruments) maximizes the opportunities for mutual exchanges of components and experiences.

2) Specialization and Quality: Partitioning of design, implementation, and maintenance of the measurement components and plants among several partners allows for assigning tasks to the most suited experts. Specialization leads to a higher quality of the individual components, measurement resources, and services.

3) Centralization for Standardization: Centralizing design, implementation, and maintenance of resources and servers allows for better control and coordination of the whole system. Centralization must not necessarily be complete: Some excellence centers can be selected to manage specific tasks as well as realize and maintain specific resources and components, in a coordinate way. Centralization favors educational tool standardization and adherence to commercial and formal standards.

4) Multiserver System: For system decentralization as well as for centralization and cooperation in creating and maintaining the measurement resources and components, the system must be realized on a multihost platform. Each host computer runs part of the system features and resources, in cooperation and coordination with the other servers. To enhance the system performance and fault tolerance, mirrored sites are adopted to replicate services and resources in different locations. Users access the nearest server available on the network at that time. Suited policies and strategies must be envisioned for automatic alignment and system consistency. Other considerations on multiserver systems are found in [4] and [5].

H. Security

1) Preservation of Intellectual Rights: The use of simulation environment licenses must be guaranteed and protected from unauthorized accesses. Similarly, protection must be assured also to the distribution of the virtual instrumentation developed for training purposes.

2) Security: The access through the Internet must preserve the integrity of data and systems.

3) Safety and Security of Measurement and Application Resources: Access and use of remote physical resources as well as instrument-equipped systems and plants must be allowed only to authorized users, according to the agreements for training programs and cost sharing and by taking into account suited security and safety operating conditions for the instrument-equipped system or plant.

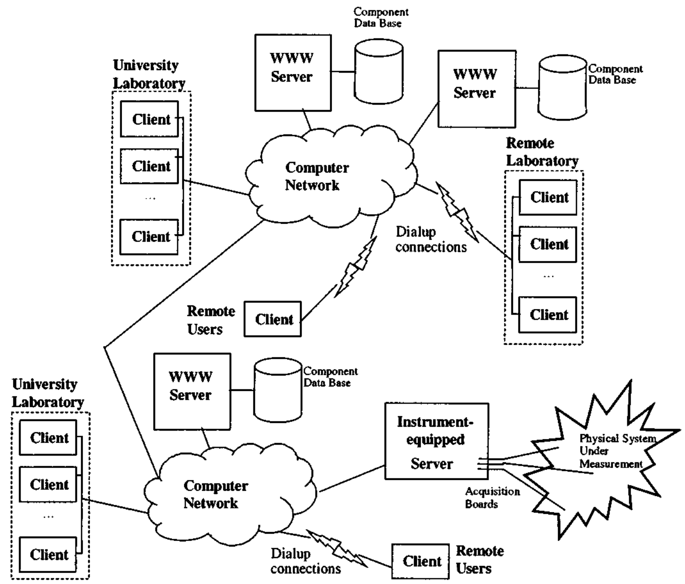

Fig. 1. Distributed system architecture.

III. System Architecture

The system design and experimentation took into account all characteristics and features discussed in Section II. A homogeneous distributed framework was created for workbench construction, storing, and distributing as well as for remote sensing to support different educational activities.

The client–server distributed environment composed by a multiserver architecture is shown in Fig. 1. The *distribution servers* store the basic components of the virtual instruments and generators that can be used by the students to build their own workbench. The *instrument-equipped* servers are directly connected to instruments in order to measure physical quantities in the field for remote sensing applications. Servers can be located everywhere on the network, but physical connections and access authorizations are given to every user.

Clients allow students to connect to servers for creating the virtual workbenches, which encompass stand-alone generators, virtual instruments fed by virtual generators, virtual instruments connected to real acquisition boards installed in the client, virtual instruments fed by remote sensors through the network, and virtual generators providing control signals to either local or remote actuators. Clients can be connected to servers on the same local-area network (LAN) of the laboratory or the campus as well as remotely in other LAN's or even through ISDN or dialup connections through the Internet.

For all connections, international commercial standard protocols are adopted for the widest access, namely, TCP/IP, file transfer protocol, hypertext transfer protocol, and secure hypertext transfer protocol (SHTTP) [3], [4]. This allows any user of the simulation environment for virtual laboratories to simply plug his client computer to the international network and obtain the simulation environment and the instrumentation components directly from the server without any preliminary acquisition of specific software, except the suited access authorization.

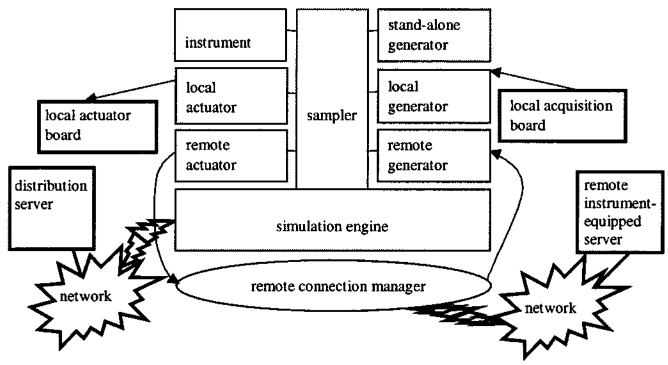

Fig. 2. Client software architecture.

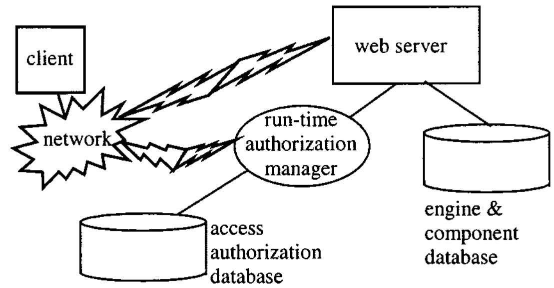

Fig. 3. Software architecture of the distribution server.

To protect the server, an approach based on access restriction through user validation was adopted [3], [4]. User operations are controlled through verification of password and IP address of either the client or the gateway through which the client connects to the server.

In the experimental setup, the authors installed a distribution server in the Como Campus of Politecnico di Milano (Hewlett-Packard 9000 715/50, HP-UX 9.0, Hughes Technologies' mSQL, NCSA's HTTPD WWW server) and an instrument-equipped server at the Universita' di Padova (Hewlett-Packard Kayak XU, Windows/NT 4.0, connected to HP 33120A arbitrary waveform generator, HP 34401A digital multimeter, HP 54615B digital storage oscilloscope, HP 35660A digital signal analyzer, and HP 8591EM EMC analyzer).

Students use IBM-compatible personal computers, with MS-DOS and MS-Windows 3.11, MS-Windows95, or MS-Windows/NT, Netscape Navigator 3.0 or MS-Explorer 3.0, or subsequent versions. They can access both servers from the Instrumentation and Measurement Laboratories of these two universities located in Milano and in Padova, as well as from a classroom in the Como Campus. Students with ISDN or dialup connections access from their home either through Internet service providers or two sets of modems of Politecnico di Milano.

A workbench is composed by the simulation engine and by instrument and generator components (see Fig. 2). For interaction with remote boards, a system process (the *remote connection manager*) is introduced to manage all interactions with the remote instrument-equipped server.

Different types of virtual components are available to support different approaches to measurement experiments:

- instruments;
- stand-alone generators, which can be used to simulate the external environment by computing the desired signal function;
- generators connected to real acquisition boards installed in the client;
- generators fed by remote sensors through the network;
- actuators, which can provide control signals to local boards;
- actuators, which can generate controls for remote boards;
- samplers and timers, which are used to provide, when necessary, the suited timing and synchronization among all input channels for realistic observation in the virtual instrument.

Different generator, instrument, and actuator variants with the same appearance can be created, according to the source (i.e., simulated, acquired from a local board, or remote) of the signal to be delivered to the other components in the workbench.

Simulation engine, sampler, and virtual components are created in LabView, a widely used virtual environment for measurement areas produced by National Instruments. The versions supported are 4.x and 5.01.

The engine is an executable program that contains the run-time support of LabView and interprets the selected components' definition to realize the virtual workbench [3], possibly with connections to the local acquisition boards or the remote instrumentation. It contains also some checkpoints to verify continuously the user floating license by interacting with the distribution server. Operation of the simulation engine is described in detail in [3]. The simulation engine and remote connection manager are downloaded only once when the client is configured and installed with a self-decompressing and self-installing procedure. The Web browser configuration is automatically updated for direct recognition, management, and execution of workbenches and virtual components.

The sampler is a standard connection component provided with the simulation engine for input/output signal synchronized sampling on the channels when synchronization is relevant for proper system operation.

Definitions of components are created off-line by experts in instrumentation and measurement procedures by using the visual editor of LabView. These definitions (which are not yet executable) are stored in files in the component data base of the distribution server. They are in a format that can be read and interpreted by the LabView run-time support. Interpretation and use of Web technologies allow for portability and interoperability.

The components and the engine as well as the run-time authorization checking are stored, held, and managed in the distribution server. The software structure of this server is shown in Fig. 3. To distribute the engine and the components as well as to create the workbench while protecting the intellectual property, a Web-based interface was adopted [3]. This provides a very user-friendly interface, with high portability and independence from the client computer. To create a workbench, the student must connect to the distribution server by using the suited authorization code. Then, he can select from among the predefined components representing instruments or generators, contained in the component database. To simplify dynamic linking of the

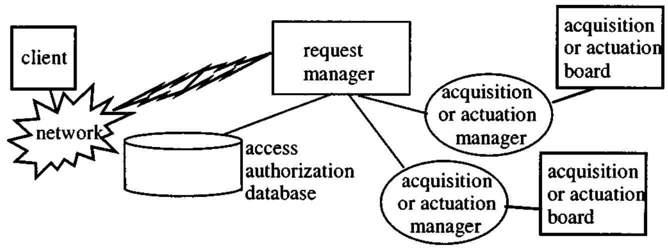

Fig. 4. Software architecture of the instrument-equipped server.

selected components, a standard bench framework is provided with space for a predefined maximum number of instruments and generators. The configured workbench is downloaded and run on the client automatically. Since components are not able to run without the simulation engine and cannot be stored on the client separately, run-time verification of the user authorization performed by the authorization manager allows for saving their intellectual property.

The remote connection manager in the client is an executable program running in parallel to the simulation engine [4], [6]. It maintains and manages the operations with the instrument-equipped server over Internet. When a client needs a set of samples, a request message with the suited parameters is sent by the virtual component representing the generator to the connection manager.

The software structure of the instrument-equipped server is shown in Fig. 4. The request manager in the instrument-equipped server verifies the client's authorization, acquires the desired samples through the acquisition manager of the desired board, and sends them back to the remote connection manager on the client. In turn, this manager in the client delivers the remote sampled data to the virtual generator so that it can provide them to the other components as they were obtained either from a local board or simulation. Actuators operate similarly.

Detailed help pages can be added to relevant graphic Labview elements of each component (e.g., indicators, buttons, counters, and graphs) to support self-training. Explanatory Web pages can provide enhanced on-line tutoring to students, to answer indirectly most of their questions on the real instruments and on the simulation environment arising during the use of the simulator and the virtual systems. For components created with Labview 5.0, these pages are linked as properties of the related elements and can be activated simply by clicking with the right button of the mouse on the corresponding element. For Labview 4.0 components, a similar feature is obtained by defining a sensible area enclosing each relevant element and by associating the Web page to such an area.

Hypertext and multimedia technologies allow also for creating navigation paths through the material available on the Web site. A hypertext book can be created to guide and support the students with advanced self-training approaches, a complementary tool for traditional teaching. Experiments can be set up to test immediately the acquired knowledge and verify the comprehension degree on the field. The multimedia technologies are in this case instrumental to enhance the readability and understandability of the book by reconstructing as much as possible the real working environment through images, graphics, short movies, sounds, and so on.

IV. Experimental Use and Conclusions

The distributed multiserver system was realized in a distributed environment encompassing the University of Padova, Politecnico di Torino, and Politecnico di Milano. The system specifications, which have been described in the previous sections, have been fully implemented to test the different modes of use. The participating universities contributed to create the initial database of virtual instruments and generators as well as to set up some experimental remote measurement sites.

The system has been tested by individual students for classes in electrical measurements in different connection and operating conditions. Students were allowed to use the components, but only tutors, Ph.D. students, and some selected students in advanced measurement courses were allowed to contribute in the creation of the components. The whole Labview development environment is in fact required to develop new components as well as to modify the existing ones. Since the cost of this environment does not allow for buying and installing as many copies as the computer in the laboratories and classrooms, only a limited number of advanced students can benefit from virtual instrument creation.

On the other side, creating virtual environments in a suited visual programming language, even if feasible, means building the whole system. This is often too complex and time-consuming when the goal of the experimental classes is focused on the use of instruments rather than on building the instruments and the measurement procedures themselves. The first case occurs for a large number of students, especially when they must only learn how to use instruments and measurement procedures. The second case is usually of interest to a restricted number of specialized students, and, as a consequence, different policies may be adopted (e.g., acquisition of development licenses).

During classes, students were required to create some simple workbenches (e.g., some waveform generators with an oscilloscope, a monitoring system for observing electrical quantities measured remotely, a simple control system to stabilize the room temperature) by using the components available in the system library. Simulated, local, and remote measurements have been performed to observe the differences between the theoretical model of the simulated generator and the real cases. Real-time operation has been analyzed by observing the differences among the acquired waveforms in the case of remote and local acquisition configuration. Students were asked to perform other experiments by using different generators and remotely monitored quantities as homework after regular classes at their convenience: they were required to report results after ten days. Students performing these experiments during classes were located in laboratories at Politecnico di Torino, at the Universita' di Padova, and at both the Milano and the Como Campuses of Politecnico di Milano. They connected to the servers also from homes located in different towns and villages in Lombardy, Piemonte, and Veneto. Last, some practitioners from industry in Milano and Torino experimented with the remote connection from their company offices.

Experiments have shown that the proposed environment is effective for the two main goals: cost reduction and students' satisfaction. As tutoring costs are concerned, we were able to reduce the number of hours of tutored activities—and the related tutors' cost—in the real laboratory to about 40%. On the other hand, students have shown their appreciation for the virtual environment since they were allowed to perform experiments more freely, even by exploiting additional hours when it was more convenient for them. This allowed them to organize and personalize their schedule to better match their educational needs and extracurricular activities. They did not suffer from the lack of tutor support in laboratory classes. After a brief introduction to the distributed environment and the preliminary individual practice with the virtual environment, tutors refined the practical expertise acquired by students both with additional classes on the theoretical aspects and with guided practice on real instruments and systems.

The multiserver system therefore has been proved a viable, effective, and cost-effective aid to the educational activities both for classes and for continuous education.

Further experimentation will involve the use of the whole distributed multiserver system during classes. Further development will afford the realization of a wide library of components as well as the creation of a more extensive Web-based tutoring environment directed to electrical instrumentation and measurement courses.

REFERENCES

[1] L. Cristaldi, A. Ferrero, and V. Piuri, "Programmable instruments, virtual instruments, and distributed measurement systems: What is really useful, innovative, and technically sound," *IEEE Instrum. Meas. Mag.*, vol. 2, pp. 20–27, Sept. 1999.

[2] H. J. W. Spoedler, "Virtual instruments and virtual environments," *IEEE Instrum. Meas. Mag.*, vol. 2, pp. 14–19, Sept. 1999.

[3] A. Ferrero and V. Piuri, "A simulation tool for virtual laboratory experiments in a WWW environment," in *Proc. IMTC98*, St. Paul, MN, May 1998, pp. 102–107.

[4] M. Bertocco, F. Ferraris, C. Offelli, and M. Parvis, "A client-server architecture for distributed measurement systems," in *Proc. IMTC 98*, St. Paul, MN, May 1998, pp. 67–72.

[5] M. Bertocco and M. Parvis, "An auto-routing multiserver architecture for high-education training on instrumentation and measurement," in *Proc. IMTC 99*, Venice, Italy, May 1999, pp. 1857–1862.

[6] M. Bertocco, F. Ferraris, and M. Parvis, "A remote and distributed student laboratory," in *Proc. XV Imeko Int. Conf.*, vol. II, Osaka, Japan, June 13–18, 1999, pp. 61–67.

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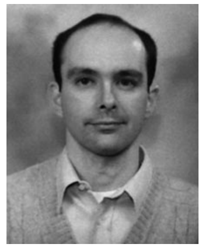

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