

Towards Virtual Laboratories: a Survey of LabVIEW-based Teaching/ Learning Tools and Future Trends*

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The computer technology and the Internet have the potential to provide a highly interactive and powerful learning environment for engineering disciplines. Many academic courses that teach engineering subjects have already begun incorporating virtual instruments as teaching and measuring tools for student use. This paper reports some of the LabVIEW software applications. The paper aims to provide some background knowledge about the tools and to show alternative delivery methods, which may change the traditional practices. The main focus in the paper is given to the common problems (such as user friendliness, cost and compatibility) faced by the institutions and the educators, and it provides some guidance for the selection of the most suitable tools required. Finally, the paper contemplates the future trends and provides some discussion.

INTRODUCTION

AS EDUCATION and technology merge, the opportunities for teaching and learning expand even more. However, the very rapid rate of change in the fields of technology poses special problems for academic institutions, specifically for the engineering disciplines. There is of course a continual need to update and augment the content of lecture courses to keep pace with this change, but it is in the area of engineering education and experimental work where major concerns arise. The central problem still remains the same; providing for students meaningful and relevant practical experiences while being limited by very finite resources in the provision of laboratory hardware and infrastructure.

One solution to this problem is to use computer-based techniques to interface the students with the physical world, with suitable front end design to provide increasing sophistication and increased flexibility. Many academic courses that teach engineering subjects have already begun incorporating computer-based educational tools for student use, either in the lectures or in the laboratory practices or both [1–53]. Furthermore, information and experience sharing are becoming increasingly critical to educational institutions as well as to practicing engineers, mainly driven by the advancements in computer technology and the Internet.

Although a number of computer-based customised engineering courses and test systems [7] have been developed within the past ten years

to replace conventional engineering courses, they have a number of limitations such as inflexible and unfriendly programming structure, excessive cost, hardware limitations, short and long-term incompatibility issues. However, due to recent technological advances in computer technology and software, it is now feasible to implement more advanced, more efficient, highly interactive and very user-friendly systems without using very costly custom-written software and tools.

In the laboratory applications, from the technical point of view, all the engineering problems deal with some physical quantities such as temperature, speed, position, current, voltage, pressure, force, torque, etc. A computer equipped with the suitable interface circuits, data acquisition systems and software, can give a visual look to these quantities, and can process the acquired data. These experiences can be made available to the remote area user via Internet link or satellite link. Figure 1 illustrates the common features of a computer-assisted real-time experimental module.

Depending upon the target aim, the experimental system may contain all or some sections of the block diagram illustrated in Fig. 1. Therefore, before the implementation, the final aim of the teaching/learning technology should be identified to determine the sub-units required. Teaching/learning technology and computer experiences available currently may be classified under four groups: computer-based training, computer-assisted learning, computer-assisted instruction and computer-assisted experimenting. The access method to the above learning technologies may be on-site or may be from the remote area via the Internet or the Intranet. Furthermore, the overall cost of the laboratory development should be

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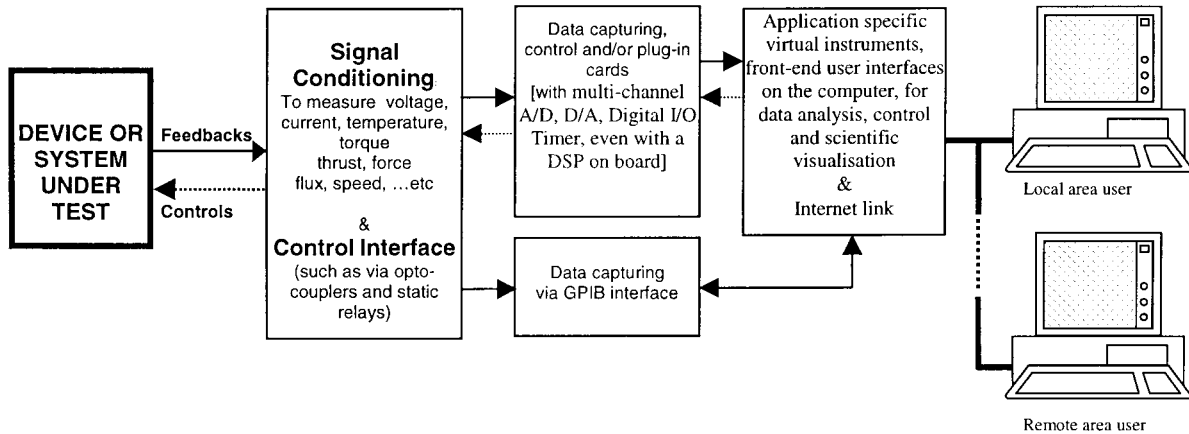


Fig. 1. The general block diagram of a computer-based laboratory system.

analysed. An advanced teaching/learning laboratory can be developed by purchasing completely new equipment. However, this approach is the most expensive solution for academic institutions. An alternate cost-effective solution is to take the old laboratory, proven systems, and retrofit them with the computer data acquisition systems and develop custom-written software to suit the existing experimental modules.

In the next section of the paper, the selection criteria of the software for a technology-intensive laboratory development are given. In the following sections, the paper classifies and reports some of the major applications in the area of computer-based engineering practice, and aims to provide some insights for the future developments.

CHOICE OF THE SOFTWARE

The current perception among the engineering disciplines is that multimedia tools are appropriate only for the courses which offer very little individualised help for students, and therefore, they are not suitable for the engineering subjects which require technology-intensive hands-on experience. However, recent developments and applications, specifically the LabVIEW-based applications, have shown that many pure lecture-based engineering courses and conventional experiments (which are heavily dependant upon specialised instruments) can be updated and integrated with custom-written virtual instrumentation (VI), and can be delivered by computers. In addition to this, the courses and experiments can be delivered remotely without having multiple copies of the experimental setups. Additional scientific visualisations and advanced analysis can also be added in the form of virtual instruments with minimal cost, which is limited or not possible in the conventional laboratory practice. Moreover, the virtual instrumentation approach is open to further improvements and developments, which may increase the student participation and enthusiasm while providing an ideal delivery environment.

However, due to the diverse nature of the lectures and the laboratory courses in every institution, custom-built software and hardware development is required most of the time. In addition, due to the fast developments in technology, the choice of the software and hardware should be considered carefully along with the cost.

A number of interactive computer-delivered simulation, control, and scientific visualisation software solutions are available in the market, and many application-specific tools have already been reported in the literature [7], which use diverse software, such as Hypertext, Authorware, Director, Labtech, Visual C++, Visual Basic, Matlab/Simulink, and LabVIEW. It is found that the following criteria may be contemplated [8] for selecting application software to build virtual instrumentation used in engineering education:

- *Modularity*, allows to test individual modules easily and to develop applications quickly.
- *Multi-platform portability*, enables designers to work on separate parts and compile them on one platform.
- *Compatibility with existing code*, allows incorporating with previous applications, and also with the previous versions of the software.
- *Compatibility with hardware*, to be able to gather data from different interface hardware.
- *Extendable libraries*, to let the designer build libraries of low-level routines to link them in higher level systems.
- *Advanced debugging features*, to optimise product design and to determine a defect in the code.
- *Executables*, to avoid alteration, to hide the code or to create standalone applications.
- *Add-on packages*, which indicate the market acceptance of the product and speed the development.
- *Performance*, to ensure that the end product meets the required performance.
- *Intuitive Graphical User Interface (GUI)*, enables a user to look at it and see what needs to be done

- *Multimedia capabilities*, for future developments.

The ideal software tool should have all the features listed above. However, the commercial packages available in the market for the engineering courses are either very complex to use or do not provide all the necessary functions to achieve the certain tasks, or are too expensive.

Because of its overall versatility as an engineering tool, the software package LabVIEW™ is chosen in most of the engineering problems. It is a graphical programming language that allows engineers and scientists to develop their own virtual instrument, which is flexible, modular and

economical. Furthermore, the software meets most of the software selection criteria, and it not only does the data manipulation, analysis, and control, but also has some multimedia authoring capabilities with the help of the add-on tools.

The LabVIEW software allows for the creating of application-specific templates (sub-virtual instruments) to reduce the production time for the identical subjects. Many useful functions can be incorporated with the LabVIEW programs to perform very useful tasks in a laboratory virtual instrumentation system design. Some of these useful functions [9] are listed below:

- adding warning/message sounds or voices;

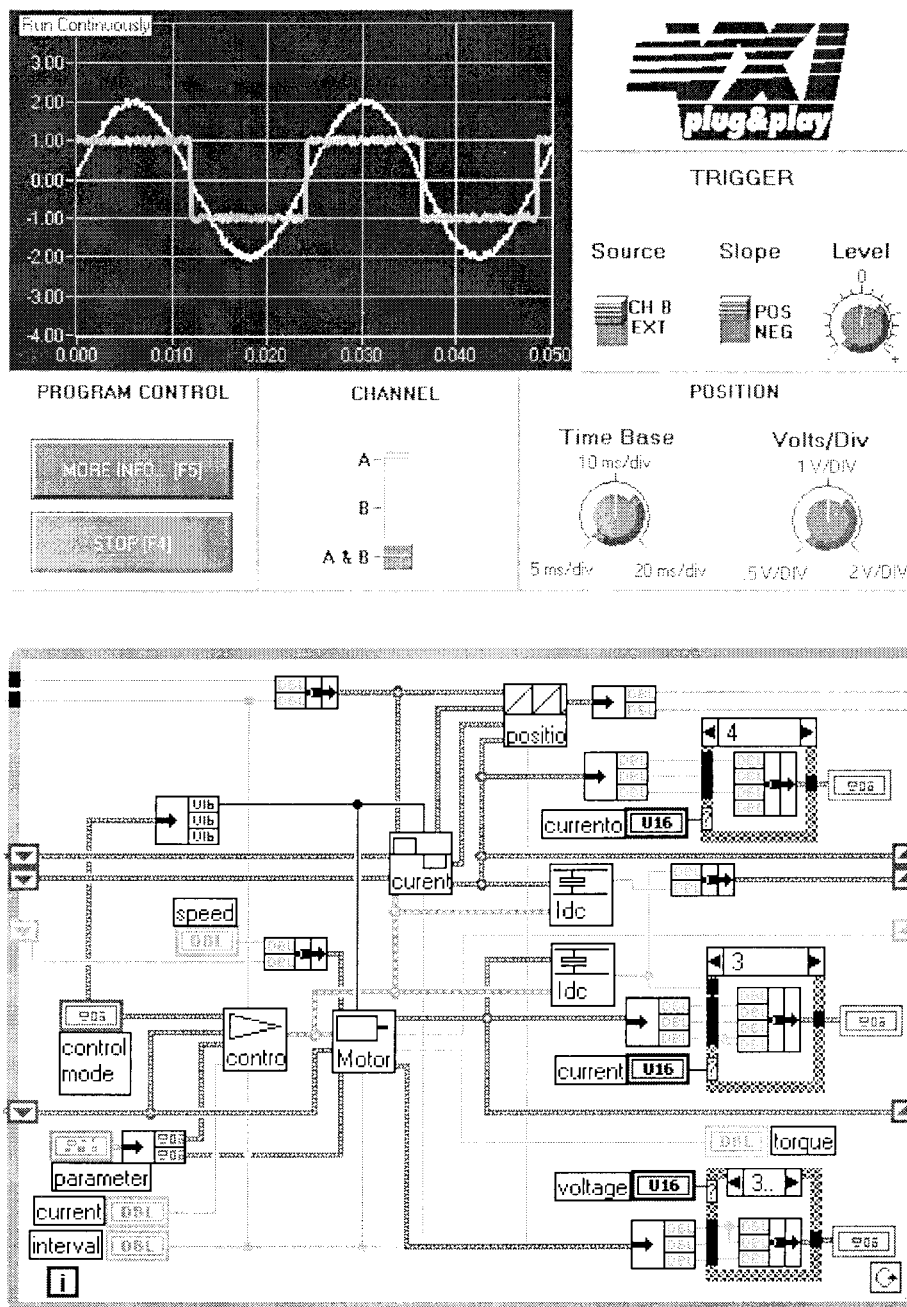


Fig. 2. A sample front panel, GUI, (a) and a sample diagram (b) in LabVIEW.

- providing instructions, pre-practical tutorials and/or interactive short-tests [11];
- generating a test report or a data file in a common text format;
- printing a specific chart or a part of the user front panel;
- linking to other currently available systems and software;
- inclusion of passwords to limit the access;
- animating the system or subsystem operation for easy understanding;
- providing GUI that mimics the real instruments;
- playing a video.

Figure 2 illustrates a sample front panel of LabVIEW virtual instrument that mimics a two-channel oscilloscope, and a sample block diagram that shows the simulation of a motor control drive in LabVIEW. As can be seen in Fig. 2b, the modularity of LabVIEW programming allows the designer to simplify the programming structure by using sub-virtual instruments (sub-VIs), which may require thousands of lines of codes in other programming software tools.

The full-development LabVIEW software comes with a number of additional tools that provide some exceptional features. For example, the GMath Toolkit delivers numerical recipes in G source code, which can help the user to solve advanced math problems. The Internet Developers Toolkit is a collection of libraries for converting virtual instruments into Internet-enabled applications, and offers unique and innovative distance learning solutions. The Fuzzy Control Design software can help to create fuzzy control systems with LabVIEW. The Picture Control Toolkit allows the user to customise their GUIs. The standalone applications can provide an integral key to information access. The projects created by LabVIEW can be converted into standalone applications by using the Application Builder Toolkit, which does

not require a copy of LabVIEW to run. In addition, in a time-critical real-time application LabVIEW RT or LabWindows/CVI software may be used.

One of the features of the LabVIEW programming is the hierarchical nature of VIs. Once a VI is created, it can be used as a sub-VI (analogous to a subroutine in C) in the block diagram of a higher level VI. Figure 3 illustrates a hierarchy of an application, which displays a graphical representation of the calling hierarchy for all VIs used in the application.

SOME OF THE APPLICATIONS OF LABVIEW

Although a main focus of this special issue is about engineering education with LabVIEW, the major developments in LabVIEW programming cover a wide range of engineering solutions varying from space technology to the nuclear power area. Furthermore, due to the modular structure of the software, any of these engineering applications may be integrated to the engineering courses.

The market and the user responses indicate that LabVIEW is one of the primary choices in designing control and analysis solutions in the area of engineering technology and education. Some of the exceptional LabVIEW user solutions listed below are reported, as 'user solutions' by the National Instruments Corp. [9], which all are multidisciplinary engineering solutions:

- maintaining emission standards in automotive industry;
- remotely operating motion control applications and teaching automatic control techniques;
- making waves in laboratory and process control;
- radio linked environmental monitoring and display system;
- engaging in pre-flight satellite manoeuvres;

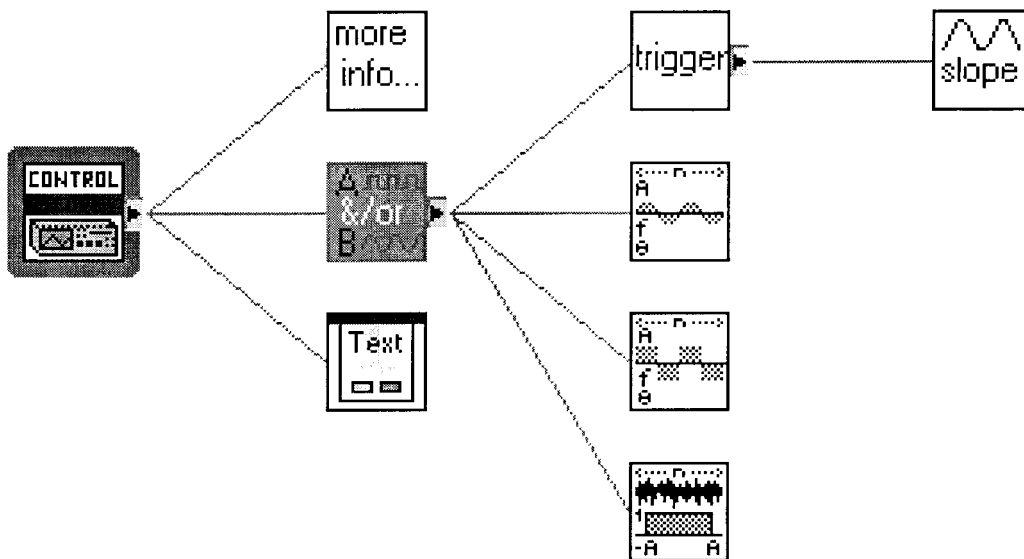


Fig. 3. A sample hierarchy window, two-channel oscilloscope (Fig. 2a).

- monitoring isolated well-drilling pumps across the Internet and over satellite up-links;
- identifying manufacturing defects, nabbing defects in robotic welding;
- image recognition;
- monitoring power plants over the Internet;
- calculating gas containment;
- testing and producing performance characteristics of motors;
- tracking weapon explosions;
- real-time dynamometer control;
- control system for experimental supercritical water;
- thermal mapping of integrated circuits;
- automating seedling analysis;
- nuclear power plant monitoring [4].

In the paragraphs below, a survey result of LabVIEW-based virtual instrumentation applications that are implemented in engineering education are given. However, due to the large number of applications, the classification is done based upon the engineering disciplines identified. It should be noted that many of the applications reported here, are predominantly interdisciplinary applications.

References [1] and [4] contain two major collections of LabVIEW software applications in general engineering, and due to the large number of papers reported in these references, the papers in the proceedings are not summarised separately below. The reference [1] contains 33 papers and covers: mechanical engineering, electrical and nuclear engineering, physics, biomedical engineering, chemistry and chemical engineering, and data acquisition and instrument control over the Internet. The second reference [4] also covers similar topics and includes 30 technical papers.

Electrical and electronics engineering

- The great variety of LabVIEW Boolean and numeric controls/indicators utilised in [12], provides an excellent tool to visualise and demonstrate many fundamental concepts of digital electronics.
- The work reported in [13], Microsoft Visual C++ and LabVIEW together are utilised to teach a comprehensive digital signal processing course. This is a good example of software integration to meet the complex course structure while providing students an intuitive understanding of DSP concepts.
- A basic power electronics simulator and its application to the power systems is reported in reference [14]. The complex simulator at ABB Transmission Technology Institute is a physical representation of one portion of a very large power transmission system, for example a high voltage DC transmission system or a system using other power electronics devices. The simulator uses a sophisticated DAQ system, scales high voltage and currents to appropriate levels and configures the simulator with electrical models of circuit components. Other applications of power electronics are reported in [15, 50]. A number of VIs are designed for data acquisition, data preparation, analysis and data visualisations in these applications.
- The applications of electrical circuits, electrical machines and electromechanical energy conversion devices in engineering education are reported in references [2, 11, 16–18], which describe four typical test systems varying from the pure-simulation to the real-measurement in the electromechanical systems. The VIs described in these references include Linear Actuator Controller, Determination of Induction Motor Characteristics, Evaluation of Dynamic Hysteresis Loops, Investigation of Magnetic Properties of Magnetic Circuits and Induction Machine Drive Simulator. References [19–21] report three instrumentation and one simulation projects all in the area of electrical machines. References [11, 18] summarise two complete virtual instrumentation solutions in the area of electrical circuits and machines. The works reported in reference [18] provide real-time laboratory modules as well as a self-studying courseware for electrical engineering students.
- A creative idea for an interdisciplinary electrical and electronic engineering elective course, electric vehicles, is reported in [22]. The course developed in this reference integrates different technologies by the help of LabVIEW software, which range from power electronics, computer simulation, data acquisition, DSP and microprocessor control, neural networks, fuzzy logic, and electromagnetics.
- The paper given in [23] describes some new laboratory experiments conducted in an analog electronics course by using a microcomputer-based workstation. The workstation consists of programmable electronic instruments interfaced with LabVIEW through the IEEE-488.2 interface.
- The implementation details of four new experiments in the area of optics and photonics are given in [24]. The LabVIEW graphical programming environment is utilised to implement computer control of the experiments via a GPIB interface since the dynamic measurement is entailed in the experiments.
- A new introductory circuits laboratory is described in [25]. The laboratory is structured around a basic wireless control system, which includes the basics of signal conditioning, automatic instrumentation using LabVIEW, and the elements of wireless communication and control.
- A course development is reported in [52]. The course teaches modern measurement and simulation techniques in electronics. The emphasis is on learning by doing, and the purpose is to get the students simulating, building, measuring and testing electronics circuits as rapidly as possible.

The measurement and test section of the course involve ready-to-run virtual instruments, using VirtualBench™ of National Instruments.

Mechanical engineering

- Reference [26] reports a successful conversion of a conventional thermal science laboratory to a laboratory with electronic instrumentation and integrated data acquisition throughout. In this work, no new laboratory equipment was purchased as manual systems were retrofitted with new instrumentation and data acquisition using LabVIEW. Integration of MathCAD-based equation solving software was achieved with LabVIEW-based data acquisition equipment for the Experimental Methods in Fluid and Thermal Sciences course described in [27].
- The work presented in [28] can be incorporated in mechanical engineering teaching as a laboratory experience or classroom demonstration to be used in conjunction with thermodynamics, fluid mechanics, or gas dynamics lecture courses or a thermal science laboratory course. Two experiments described in this work utilise the virtual instruments.
- A well rounded education in data acquisition systems is essential for today's graduates. Although the students in mechanical engineering have traditionally avoided electronics and computers, it is shown in [29] that LabVIEW-based data acquisition systems are received enthusiastically by the students.
- An innovative method is developed in [30] to measure the thermal conductivity of a non-Newtonian fluid. The measurement and control in this study was accomplished and integrated by using a comprehensive virtual instrument developed using the LabVIEW software.
- Combining LEGO™ building blocks with LabVIEW software produced a highly successful, low cost alternative method of teaching in mechanical engineering [31]. The experimentation class is composed of three distinct sections: data acquisition techniques with LabVIEW, signal processing and report writing and the final project that allows the students to discover many engineering concepts in the laboratory environment.

Biomedical engineering

- A sequence of two biomedical instrumentation courses is described in [32]. The experiments designed in these courses aimed to provide motivation and hands-on experience in the use of laboratory instruments, such as oscilloscope, power supply, function generator and data acquisition via LabVIEW.

Control, instrumentation and computer-assisted general purpose laboratories

- An instrumentation and controls laboratory is described in [33]. The paper presents some of the experiences gained and also provides very useful guidance for future developers. It is

indicated that virtual instruments and other basic programs can easily be integrated, which may reduce the cost while providing an advanced laboratory environment for engineering technology students.

- An intuitive introduction to automatic control concepts is given in [34]. This work integrates several complementary instruction components, such as an inverted pendulum process and computer-aided instruction tool. The paper also discusses the educational benefits of the implemented method.
- The paper in [35] reports the experience gained in designing a computer-assisted scientific visualisation laboratory. The paper answers many questions that may be raised during a planning stage of an engineering laboratory.
- The Control Systems Laboratory at the University of Tennessee at Chattanooga provides full control and monitoring facilities to the students, which are accessible remotely via the Internet [43]. The hardware and the physical systems are controlled and monitored using National Instruments data acquisition cards and custom-written virtual instruments in the client computer. The communication is obtained by using the low level analog and digital signals.
- The Integrated Teaching and Learning Laboratory (ITLL) at the University of Colorado at Boulder is one of the remarkable university-wide initiatives targeting the enhancement of undergraduate engineering education [51]. The laboratory accommodates many computer-controlled experimental setups, which are supported by the virtual instruments.
- A LabVIEW-based harsh environment test bed is implemented by Oak Ridge National Laboratory [36], which opens the possibility to access the dangerous labs. The lab consists of a vapour generator, in which the gas flow has remote on/off control and is metered through individual mass flow meters. Three video cameras are located at the laboratory for video conferencing and for viewing inside the test bed.

Chemical engineering

- The mobile fluid-flow apparatus finds a wide range of applications in chemical engineering. Such apparatus is developed and duplicated for the Integrated Teaching and Learning Laboratory at the University of Colorado, which is controlled by LabVIEW software running on a notebook PC [37].
- The transfers of LabVIEW into laboratories in chemistry and physics have been reported in [38]. The paper also reports some management aspects of introducing LabVIEW-based laboratory systems. To take advantage of the improved data collection, three experiments were developed in this work: photo gate experiment, sonic range experiment and force sensor experiment, which can easily be utilised in other engineering disciplines.

Environmental engineering

- A new undergraduate laboratory course in Environmental Engineering was designed at Cornell University [39]. The principal goal of the course implementation was to integrate computer-control and data acquisition without making the computers and software the course focus. In addition, it was expected that a minimal time should be spent learning how to use the new software that is based on LabVIEW. It is reported that the consistent interface design helped to the students quickly learn how to use new instruments.

Remote area experimenting/instrument control over the internet

- Open-learning, open access flexible learning, distance learning, and interactive multimedia represent some of the methods used in modern education [6]. The major driving force for these methods, the Internet, is truly becoming commonplace in engineering education. In remote area engineering experiments, it is expected that any new initiative will encourage many people to explore diverse topics to integrate with the existing practices, which may provide a better information delivery and training platform.
- One of the emerging uses of the Internet in engineering is to make the laboratory facilities available to the wider community. Reference [40] explores the virtual instrumentation and the Internet technologies in the light of remote access. Some of the on-line laboratories that use Internet Developers Toolkit of LabVIEW are summarised below. The common feature of these laboratories is to increase the utilisation of unique resources by enhancing access via shrinking geographical distances.
- Ideally, the plants used in 'remote experimentation' should have 'full local control' by computer. The techniques used in such systems may

vary considerably simply to improve the performance and the capabilities of the experiment. Reference [46] reports an innovative solution that uses a virtual representation of the moving part instead of the real image. The block diagram given in Fig. 4 shows the basic components of the remote experiment system in the LabVIEW implementation.

- A suite of chemical engineering laboratories have been made available for students to use via the Internet [41–44]. This innovative application is one of the most successful remote access laboratory projects. Fourteen chemical engineering experiments are implemented in this work, which are accessible from remote sites. The papers referenced here provide the implementation details of the software and hardware of the system.
- Remote manipulations of a servo drive and a DC motor are reported in the references [45–47, 50]. An alternative remote laboratory experimentation is described in [48]. In this application, the oscilloscope experiment is conducted via the Internet. Reference [49] highlights another remote Internet-based laboratory. Three remote experiments are implemented in this work: model heating, operational amplifier circuits and electrocardiograms.

FUTURE TRENDS IN ENGINEERING EDUCATION

Print materials are increasingly being distributed in electronic format (either online or CD-ROM). It is expected that this will greatly change the nature of the information or how it is used. Therefore, a major emphasis in the future will be to access instructional and laboratory components via the Internet. The Intranet link at the university campus may also be used to bring the real-time

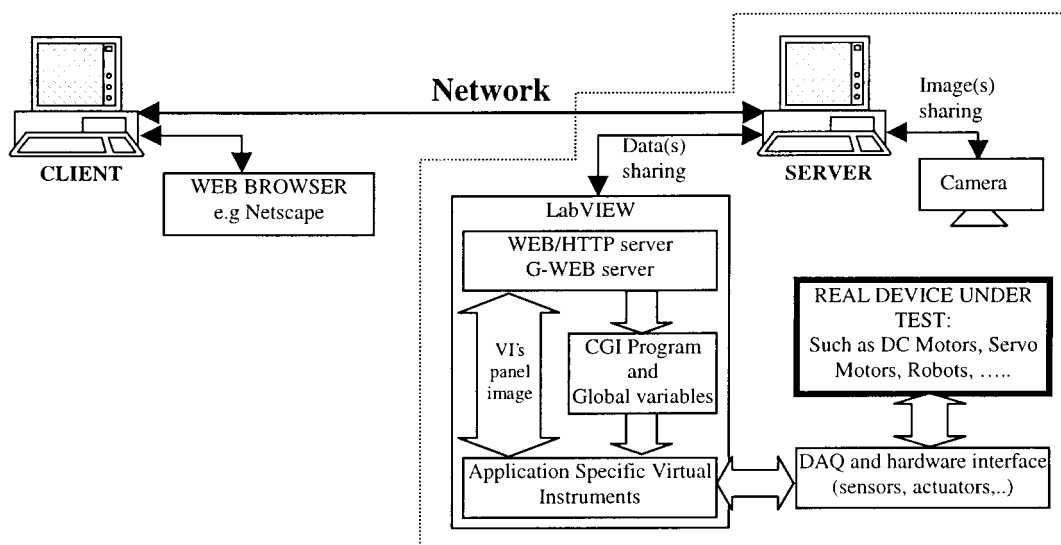


Fig. 4. A sample block diagram for instrument control over the Internet.

laboratory data into the classroom teaching to support the theory.

Furthermore, when technology-intensive teaching tools become widely available, the traditional roles of the university lecturers will change from pure classroom-based teaching to one of consultation, advice and direction giving. However, it is believed that the technology-based course will not eliminate the educators; instead it will change the type of activities the educators carry out. In the technology-based teaching/learning practice, the major activities of the lecturers may include preparation of the software packages, adopting new concepts and new teaching practices, modifying existing materials to suit the changes introduced in the latest version of the multimedia tools, and above all these they can spend time to continuously evaluating the teaching/learning outcomes.

As is reported in the literature, including the Internet resources, remote experimentation is not limited to education. In research and industry, remote access also represents an opportunity for the scientists and engineers who wish to share unique and expensive equipment. Therefore, it is expected that the collaborations between the higher education institutions and industrial organisations will increase and hence will provide opportunities to share the expensive and the complex experimental setups, training and teaching materials across the organisations. The robotics laboratory reported in [53] is a very good example of 'sharing laboratory facilities' for teaching purpose, which reduced the cost while increasing the knowledge distribution. It is also expected that 'remote experimentation' will reduce the number of identical experimental setups used in the conventional laboratory practice.

The distinction between the traditional laboratory class and the remote area experimenting via Internet may become absolute in many engineering disciplines. Therefore, the Internet and/or Intranet links may bring the hazardous and dangerous laboratory [36] into the classroom or learning environment. In the case of harsh and dangerous environment laboratories the users can access the complex, large or expensive plants remotely, and experience first hand system behaviour via the Internet that is not possible or practical in the traditional laboratory practices. However, some legal issues must be solved before sharing sensitive information between the institutions, which can easily be solved by granting a limited access to the external users.

The technology may also be used to provide hands-on industrial training facilities remotely for the engineering students. The potential employers of engineering graduates may provide a real training environment to prospective employees (UG or PG students) at the university level.

Finally, as in the 'Open University' practice, the on-line learning is more convenient and immediate for many people. Although this practice is not

widely accepted in experimental work in engineering, the computer technology may be utilised to store the real-time test results and the real experiment can be imitated later for other users.

CONCLUSIONS

The roles of teachers and students are changing, and there are undoubtedly ways of learning not yet discovered. However, the computer and software technology may provide a significant role to identify the problems, to present solutions and life-long learning. It is clear that the computer-based educational technology has reached the point where many major improvements can be made, and significant cost reductions can be achieved, specifically in the area of engineering education. In engineering, the full-course (lecture + laboratory component) may replace the existing lecture-based courses, and the virtual instruments may provide a highly interactive user interface and advanced analysis facilities that were not deliverable in the conventional methods.

From the educational point of view, it is expected that the new teaching/learning technology tools available in the market may provide common experiences to cater for students who are coming from increasingly diverse backgrounds, and whose learning is best achieved in a contextual setting. However, more designing, teaching and organisational skills are now required to establish a good course material utilising computer interaction and multimedia capabilities in engineering disciplines. Therefore, the selection criteria of a suitable software is the major issue, which should have a long life-cycle, easy interface with the hardware products, and be compatible with the existing development tools. However, it should be emphasised here that having proper equipment and technique will not ensure a problem-free system. The proper use of techniques, and methodologies are also critical in any technology-intensive teaching/learning development system.

In addition, it should be ensured that the designed work keeps up with the curriculum review and update, and the laboratory work should be relevant to the material taught in lectures. These may require continuous update of the material, which may change the role of the educator.

Furthermore, the Internet has the potential to provide a highly supporting learning environment. It can enable students to access without any time and distance limitations, and can allow them to use expensive laboratory experiments to which they usually have no access. However, it is not sufficient to expect that existing tools and techniques will translate simply and quickly. They have to be transformed in ways that learners and educators perceive to be useful and effective. The user-friendly GUI may provide a better scientific picture of the system under test. Moreover, using distance learning may attract new students and

add value to education. Equipping the laboratories with effective education tools can empower both the disciplines and the students. Hence, the effectiveness of the laboratory course in imparting knowledge increases and it enables the students to absorb the role of individual engineering disciplines and addresses the real problems.

It is clear that change is necessary because many of the things that we are doing can be done better with the help of technology. Although the initial

cost may be high, if the right technology is selected continuous improvement can be achieved with minimal cost. The cost of the development may be reduced further if the portion of the existing hardware is utilised and integrated with the existing system. If the size and the complexity of the system increase, organisations and universities may undertake laboratory developments in partnership with other universities and/or commercial partners.

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