Teaching Photonics Laboratory Using Remote-Control Web Technologies

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***Abstract*—This paper proposes a remote education system, Virtual Photonics Experiments Network (V-PEN), for teaching photonics experiments. In this approach, teaching and learning photonics become easier by the V-PEN. A design procedure for transforming real experiments to online experiments is also proposed, and a Michelson interference system as an example is employed to describe the procedures of the online experiments. This photonics experiment platform has been used for a semester. The survey of learners' feedback is also presented.**

***Index Terms*—Distance learning, online experiment, photonics education, photonics experiment, photonics laboratory, remote education, virtual laboratory.**

I. INTRODUCTION

PHOTONICS technologies have become increasingly important in recent years, and the demands on the supply of skilled graduates who are competent in the design, development, and installation of photonics systems are increasing. In view of the significance of photonics technologies, several courses or laboratories have been added into undergraduate curricula of electrical engineering to help students learn photonics as early as possible. Daneshvar [1] analyzed the similarities between optical and electrical engineering and integrated photonics topics into traditional electrical engineering curricula. Smith *et al.* [2] and Ahmed *et al.* [3] introduced photonics education in Canada and Egypt, respectively.

Well-designed laboratories and projects not only guide learners to a better understanding of abstract photonics theories, but also construct their practical skills and improve the ability to analyze and solve problems [4]. The ability to excel in laboratories or projects is also critical to enter the engineering technology profession [5]. Many instructors have adopted laboratories or projects for photonics education. Anderson *et al.* [6] designed seven carefully chosen laboratories from which students can learn many optical equipments and related skills. Lord [7] developed five inexpensive and transportable modules that provide a hands-on introduction to optoelectronics for first-year engineering students. Johnstone *et al.* [8] presented photonics laboratories with an emphasis on optical communication systems. Uherek *et al.* [9] reported a curriculum with optoelectronics education and two individual students' projects on photonics systems.

Photonics laboratories can help students learn photonics; however, some of the equipment and instruments are expensive, thus making at-home or in-class experiments unavailable or inadequate. Hassan *et al.* [4] tried to enhance the photonics teaching process by sharing photonics laboratories among many institutions with appropriate time scheduling and by using computers to perform optical design simulations. In fact, these teaching approaches can be achieved by applying Web technologies to perform simulations and experiments through the Internet. Because the Internet can be accessed at any time from any place, both learning and teaching processes will become easier.

Web technologies have been widely applied to education since the early 1990s. Their importance was revealed quite early in a special issue of IEEE TRANSACTIONS ON EDUCATION in August 1996 [10]. Many researchers [11]–[13] thereafter have made insightful contributions in education and technical perspectives of Web technologies and have found that an Internet interactive mechanism can be used to enhance learning efficiency. For example, Huang *et al.* [14] designed World Wide Web (WWW)-based, computer-aided instructions (CAI), which help students learn electronic instruments more effectively.

Nevertheless, WWW can do more than demonstrating Web pages and simulations on the Web for distance learning. Many works have been reported in literature utilizing Web-based remote-control technologies to manipulate real-time physical experiments, known as virtual laboratory or online experiments [15]–[18]. These works all demonstrated that online experiments can increase learners' motivation and enhance their learning effect. Another noteworthy aspect is that different fields of studies have different considerations in designing their online experiments. All the controllable parameters to be manipulated in the experiments should be meaningful and educational. However, no one has yet discussed the online experiment design procedure for photonics education. Some electrical engineering curricula may have theoretical courses in photonics but lack laboratories courses. One of the reasons is that the equipment needs for these experiments may be inadequate in the Electrical Engineering Department. A learning platform of well-designed online photonics experiments can be shared by many institutions and thus can reduce the cost on expensive instruments and equipment. Distance learning in photonics can also be supported. Thus, the purpose of this paper is to design and implement an online photonics experiment platform: the Virtual Photonics Experiments Network (V-PEN). This system can support online photonics experiments for learners and share the experiment resources, such as

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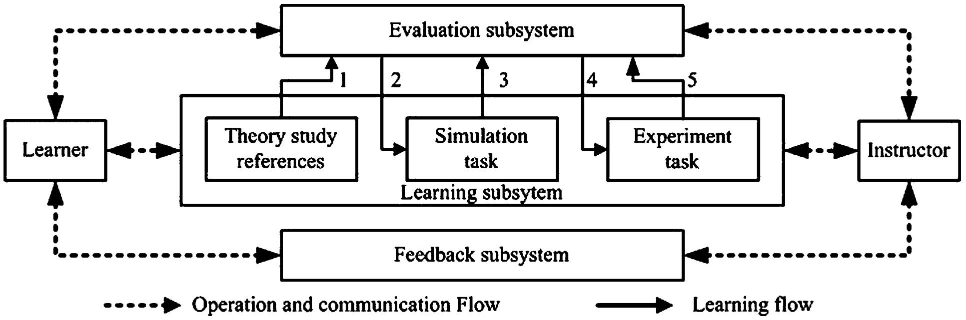


Fig. 1. Pedagogical approach of the V-PEN.

tutorials, equipment, and instruments, with the alliance of the authors' universities.

Since the components in photonics experiments are not all controlled electrically, different mechanisms may need to be determined for different remote controls. To facilitate implementation of online experiments from offline experiments, the paper presents a procedure to help design remote-control mechanisms for the offline experiments. Instructors can use this platform to strengthen their teaching effects by demonstrating real-time experiment results to learners. Other Web technologies, such as interactive discussion and streaming videos, are also employed in this learning platform to provide significant benefits to teaching and learning.

This paper is organized as follows. The pedagogical approach of the V-PEN is presented in Section II. The overall architecture is described in Section III, followed by implementation of the online experiments in Section IV. Finally, the paper ends with a discussion and conclusion in Section V.

II. PEDAGOGICAL APPROACH

The pedagogical approach of the system is shown in Fig. 1. Learners and instructors interact with one another via three subsystems. These three subsystems will be discussed in this section.

A. Learning Subsystem

The main function of this V-PEN is to provide a WWW-based remote control for photonics experiments, and the learning process includes several specially designed experiment tasks. However, for safety reasons, no one would be allowed to perform experiments until he or she has shown adequate knowledge of experiments. Wrong parameter inputs, because of insufficient knowledge of experiments, may also lead to wrong operations of experiments. Therefore, a learning flow is designed for learners to gain prerequisite knowledge before doing an experiment.

As shown in Fig. 1, a reasonable learning procedure includes understanding the principle of an experiment, completing the simulation, and performing the experiment. Thus, the V-PEN can provide some materials, such as tutorial, simulation tasks, and reference links for the experiments that are listed in Table I. However, not all learning procedures are required to be online; e.g., the simulations may be using offline the software of MATLAB (by The MathWorks, Inc., Natick, MA) or ASAP (by Breault Research Organization (BRO), Tucson, AZ). After learning the principle of related theories and experiments, the learner will be tested and evaluated. After passing the tests, learners are given access to the experiment to be performed. This mechanism not only ensures the safety of each experimental operation but also helps learners gain knowledge of the experiment. After completing an online experiment, learners may take a simple questionnaire or send an experiment report through the feedback subsystem to complete the final evaluation, depending on the requirement from instructors. All learning procedures are recorded for future reference and analysis.

B. Evaluation Subsystem

To use this V-PEN to achieve the learning effect, the instructors first assess learners' prerequisite knowledge of the experiments through the evaluation subsystem and then permit the learners to access the online experiments.

Several types of evaluations are used in this system. The simplest way is to use a questionnaire that contains true/false questions, single questions, and multiple-choice questions. Instructors may also ask learners to submit simulation results or reports of the simulation tasks via e-mail and then evaluate the results manually.

Another possible way of online evaluation that is currently being considered is a peer review method. An experienced learner who has been trained can be assigned as a teaching assistant (TA) for that experiment. The TA can talk to, or correspond with, anyone who requests permission to do that experiment. Once this TA believes that the new learner has adequate knowledge of this experiment, he or she can grant access to the experiment for this learner. In this way, the instructors load can be reduced.

C. Feedback Subsystem

A feedback subsystem plays an important role in improving the performance of the learners and the use of V-PEN. Feedback to learners often includes evaluation results and suggestions on learning, while feedback to instructors and supervisors often includes problems reports on the V-PEN and questions during the learning process. Peer or learner–instructor interactions are both significant in this feedback subsystem.

In the V-PEN, the authors have developed several feedback mechanisms. Feedback to learners may be provided instantly from predefined functions or from an instructor or administrator with a certain time delay. e-mail is one of the easiest ways for learners to communicate with instructors. Discussion forums or online chat rooms also provide different environments for

TABLE I
CLASSIFICATION OF ONLINE PHOTONICS EXPERIMENTS

Classes	Topics/Experiments	Learning Goals
I. Optical Signal Processing	1. Basic Fourier optics experiment (optical image processing and spatial spectrum analysis) 2. Holography 3. Diffractive optical element (DOE) design, etc.	Let users be familiar with the basics of Fourier optics and its applications.
II. Photonics Instrumentation	1. Interferometers (Michelson, Mach-Zehnder, Fabry-Perot, etc.) 2. Visible/Near IR spectrometer 3. Ellipsometer/Reflectometer 4. MTF (modulation transfer function) measurement system 5. Optical power measurement system	Let users understand that photonics instrumentation has played an important role in precision measurement technology through the online manipulations on these individual measurement platforms.
III. Optical Fiber Sensing and Communication	1. Fiber Bragg grating sensing experiment 2. Basic fiber communication experiment	Learn the basic principles and practices of fiber sensing and communication techniques
IV. Crystal Optics	1. EO (electro-optical) modulator 2. PEM (photo-elastic modulator) 3. SLM (spatial light modulator), etc.	Let users be familiar with the interaction of light with matters and the modulation of light
V. Optomechatronics	1. Laser scanning system 2. DVD player simulation system	Learn how to integrate optics, mechanics, and electronics components into some useful systems

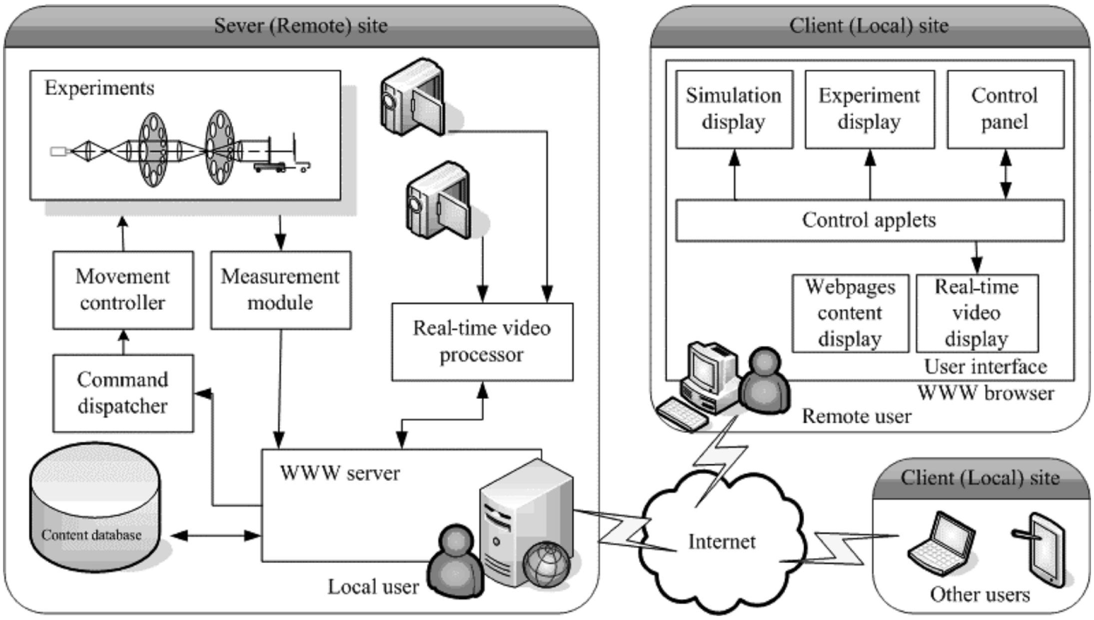


Fig. 2. Architecture of the V-PEN.

learners to discuss a specific issue, whether with peers or with instructors. Instant messages may also be a good way to obtain instant feedback from online users, but this procedure must be pursued in the future.

III. THE V-PEN SYSTEM DESCRIPTION

The V-PEN is based on a client–server architecture, as shown in Fig. 2 [15], [18]. This system is currently maintained by the

Opto-Electronics Systems Laboratory (OESL) of the Department of Mechatronic Technology, National Taiwan Normal University, Taiwan, R.O.C. First, the implementation will be presented, followed by the administration of this system.

A. V-PEN Architecture and Implementation

1) Experimental Setup: Experiments are set up at the server site. Equipment used in these experiments varies depending on what kind of photonics experiments are being planned. For example, a simple Michelson interference experiment contains He–Ne lasers (wavelength 632.8 nm), pin hole (10 μm), beam splitter (T: 50% and R: 50%), and mirrors, as shown in Fig. 5. More complicated optical systems may include some other components, such as gratings, optical fibers, linear polarizers, and diffraction optical elements. Each component has its own specification and should be listed in an equipment list of each experiment.

Besides components required in these experiments, additional equipment is needed for the purpose of remote control. For example, a motorized rotary stage (e.g., SGSP-60YAW by Sigma-Koki Company, Tokyo, Japan) is used for circular movements, and two- or three-dimensional motorized linear stages (e.g., SGS14-10(Z) by the same company) are used for linear movements. Some components that can be controlled by electronics signals can also be used for remote control. For example, spatial light modulators (SLMs) and photoelastic modulators (PEMs) can be controlled by a personal computer (PC) because of the electrooptical effect. Online photonics experiments can be obtained by integrating these PC-controlled components at suitable places into the offline photonics experiments according to a design procedure shown in Fig. 4. To find what parameters can be controlled through the Internet is important for experiment designs, and the authors will explain the design procedure clearly in Section IV of this paper.

To measure the results of different experiments, various measurement modules are used to obtain the experiment results. Unlike offline experiments where learners can see the results of the experiments by placing screens at desirable positions to see the results by the naked eye, remote users can only see the image of experiment results by the assistance of charge-coupled device (CCD) cameras. In this Michelson interference experiment, a one-third-inch high-resolution digital black-and-white CCD camera is adopted. Other kinds of PC-based instruments that are used in the offline experiments can also be used for remote measuring purposes. For instance, PC-based spectrometers can be applied in fiber-optic experiments.

2) Server Site Setup: PCs installed with a Microsoft Windows 2000 Server are used as servers. Internet Information Services (IIS) within the operating system can provide a WWW server for displaying course materials, simulations, and applets. Web programming languages are used to accomplish interaction parts of this V-PEN. Microsoft SQL Server 2000 is currently used as the content database.

PC-controlled parts and video cameras are connected to servers either by RS-232 or USB connections. The video cameras are linked to this server to capture real-time images of experiments. Control programs are developed by Microsoft Visual Basic 6.0 and then converted to ActiveX components for remote control. ActiveX applets can get instant control signals from remote users through the Internet and then dispatch these signals to control the experiments directly. Real-time video images are captured directly by ActiveX applets and sent to remote users; this activity may require considerable transferring bandwidth. Compressing these video data or using Microsoft NetMeeting [19] may improve the efficiency of real-time images, but this must be left for future study.

3) Client Site Requirements: Standard Web browsers that support Microsoft ActiveX technology are used to access the system from remote sites. Applets that use ActiveX technologies will be used to operate the remote control of the online experiments and show the experiment results. Other available learning resources, such as related tutorials and simulations, are presented in their own format so that the users can view or execute them by simple clicks on the hyperlinks. For speeding up the transferring rates, high-speed connection, such as T1 Internet connection, is recommended but not required in doing these online experiments.

B. System Administration

1) Experiment Administration: Every experiment in V-PEN has its own server because of limited control ports available in a PC and for easy maintenance. Remote users first log in to the main server and then will be directed to the specific server when doing experiments. Before an experiment is available online, it should first be tested to verify the correctness of experiment results and the stability of the experiment setup. The power of the experiment is available 24 hours a day. Supervisors routinely check the status of each experiment to make sure that each of them is functionally correct and available for use.

2) Server Site Administration: Since the ActiveX program can get direct access to system resources, the systems needs some protection to avoid hackers or virus attack. A good firewall can provide protection. The remote experiments offered on the Web can also be done locally, i.e., using the control programs on the server without connecting to the Internet. However, the authors do not suggest direct control of the experiments at the server site since this may lead to system conflicts between the offline and online modes.

3) Client Site Administration: Because of Internet security regulations, remote users need to install control applets before doing experiments. The user interface is set to be as user friendly as possible, and the user operations of the system are performed, basically, by clicking a mouse and typing on a keyboard.

Several clients can connect to the V-PEN simultaneously. However, Internet bandwidth becomes extremely narrow when too many remote users request use of this system. Less than three concurrent remote users are suitable in Internet connection for each experiment. However, each experiment in V-PEN can be operated by only a single remote user at a time. The system thus considers each experiment as a "resource," and remote users who wish to operate a specific experiment should first get permission to operate the experiment. Once the resource is in use, other remote users cannot access the resource because it is "locked." All the remote users without the access permission can see only the online real-time video of that experiment.

This mechanism can be used to avoid the conflicts of multiple operations on each experiment.

IV. IMPLEMENTATION OF ONLINE PHOTONICS EXPERIMENTS

Recently, much work has been done in implementing virtual laboratories or online experiments in several fields of studies [15]–[19]. There is plenty of room to promote the development of online learning systems for photonics experiments [6]–[9]. However, some offline experiments cannot easily be extended to corresponding online ones because of their inherent physical constraints and related engineering difficulties. In other words, how to design online photonics experiments is a critical issue and needs to be discussed in detail.

In this section, the implementation of online photonics experiments on the basis of the original offline ones is presented. First, the photonics experiments are classified, and their configurations are identified from photonics texts. Then, a general design procedure is presented to bridge the gap between the offline and corresponding online experiments. Based on the identification of the experiment configurations, the design procedure mainly involves the two steps of finding the controllable parameters and constructing a remote-control mechanism. A typical Michelson interference experiment is adopted as an example to express the ideas behind the design procedure. A sample graphical user interface (GUI) of this experiment is also used to describe the interaction of users with the learning system.

A. Classification of Photonics Experiments and Identification of Their Configurations

In this paper, the authors categorize photonics experiments into five classes, as listed in Table I. They are optical signal processing, photonics instrumentation, optical fiber sensing and communications, crystal optics, and optomechatronics, respectively. In addition, some topics or experiments with the similar attributes are grouped into the same class. For example, in the class of photonics instrumentation, there are interferometers, visible/near-infrared (VIS/NIR) spectrometers, ellipsometers/reflectometers, and modulation transfer function (MTF) measurement systems. Two or more individual topics may be correlated with each other. For instance, a spectrometer incorporated with a specific light source can be used as a basis to perform thickness measurement in a reflectometry configuration. In addition, a spectrometer-based platform may be extended to build up a spectroscopic ellipsometer. Thus, this paper merely gives a simple classification for the photonics experiments.

As described later, identifying the class of an experiment or its configuration will be crucial to implement the online learning in the V-PEN. Regarding the configurations of the experiments, interferometers may serve as an example. Fig. 3 illustrates the interference configurations, i.e., Michelson, Mach–Zehnder, and Fabry–Pérot interference systems. From many texts, one can see that the first two configurations belong to a kind of amplitude-division interference, and the last is a kind of multibeam interference. Thus, one can readily identify the configurations of interference systems.

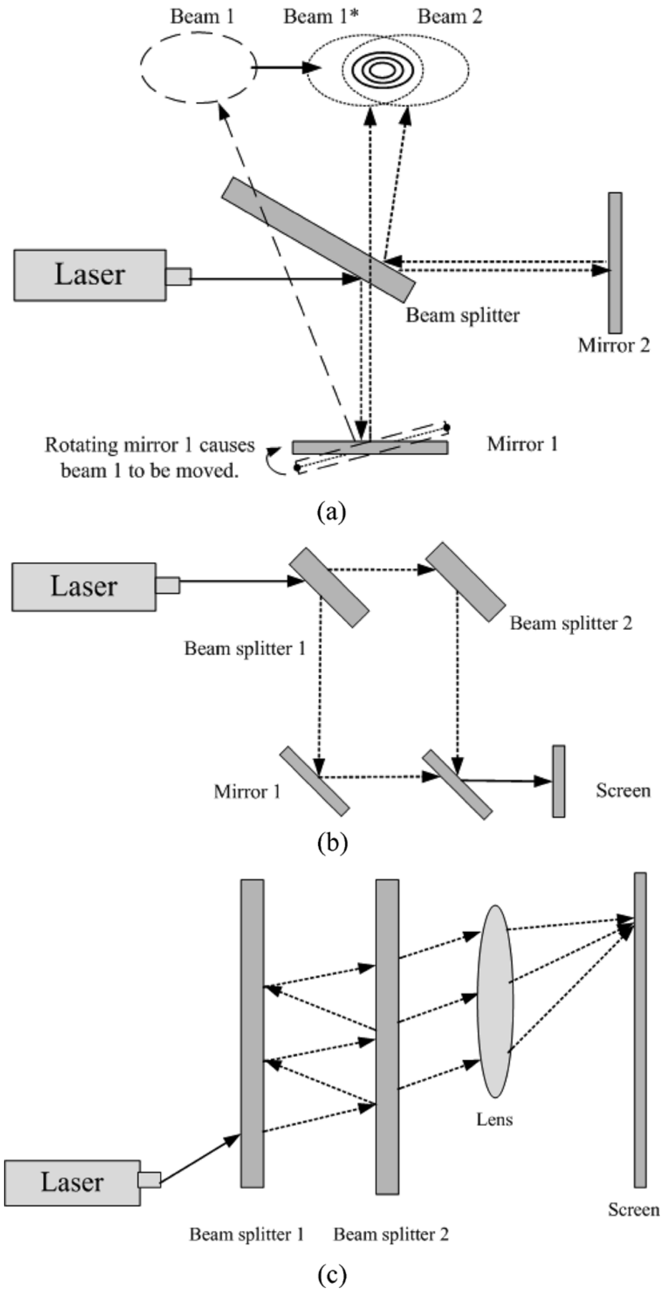


Fig. 3. Interference configurations of the (a) Michelson interference experiment, (b) Mach–Zehnder interference experiment, and (c) multiple-beam interference.

B. From Offline Photonics Experiments to Online Ones: A Design Procedure

To implement the online experiments from the original offline ones, a proposed design procedure and its flow diagram is shown in Fig. 4. In this procedure, controllable parameters must be found after the identification of the experiment configurations, since controlling them should be instructive and beneficial for learners to understand more about the experiments. Then, the remote-control mechanisms with the parameters can be constructed. As a result, a corresponding online experiment is implemented on the basis of the offline one. Moreover, the online experiment may be extended to other applications by finding additional mechanisms. Therefore, the extended online experiment can provide technical diversity in learning photonics.

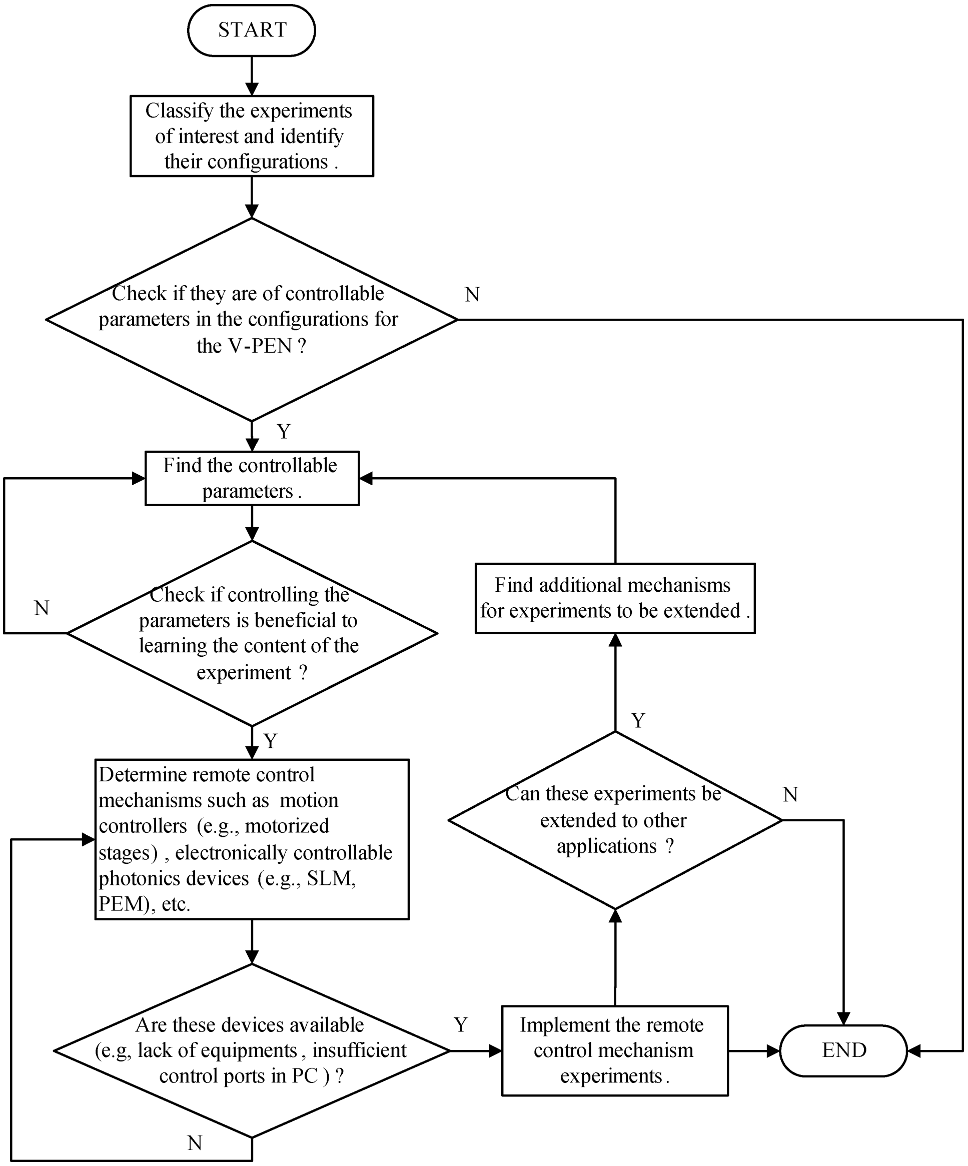


Fig. 4. Flow diagram of the design procedure for implementing online photonics experiments.

To express the ideas behind the procedure, a typical Michelson interference experiment is used as an example. As shown in Fig. 3(a), it utilizes the arrangement of two mirrors and one beam splitter to produce two separated beams of light, e.g., beams 1 and 2. In this figure, as mirror 1 is rotated, beam 1 is moved to a new location, where it is marked with an asterisk so that beam 1* is nearly parallel to beam 2. As a result, the two beams interfere with each other, and their interference fringes become visible. Obviously, the rotation angle of mirror 1 is an important controllable parameter; therefore, a remote-control mechanism that includes a motorized rotary stage is needed. The setup for this experiment is shown in Fig. 5(a). Furthermore, Fig. 6 is a GUI that shows an online animation of the experiment, a real-time image of the actual installation, a dynamic fringe pattern acquired from a CCD camera, and the power spectrum. Remote users can move the specified line up and down to see the changes of the power spectrum.

On the basis of the interference experiment, additional mechanisms may be extended to different applications, as illustrated in Fig. 5(b)–(d). For the application of refractive-index measurement, a transmittable sample that is mounted on a motorized linear stage is placed in front of mirror 2, as shown in Fig. 5(b). The variations of the interference fringe patterns can be observed by moving the sample in and out of the path between the beam splitter and mirror 2. Through these observations, the refractive index of the sample can be computed. An additional controllable parameter, i.e., a linear movement of the sample, appeared to be essential and meaningful. Consequently, an additional remote-control mechanism including a motorized linear stage is needed.

Fig. 5(c) shows that the interference experiment can also be extended to the application of microstructure profile measurement. The extended system is regarded as a kind of laser phase-shifting interferometer. In addition, a white-light interference experiment can be performed by replacing the He–Ne laser with an Hg lamp, as depicted in Fig. 5(d). This experiment is beneficial to learning the basic principle of white-light interferometry in nano- or submicrostructure profile measurement.

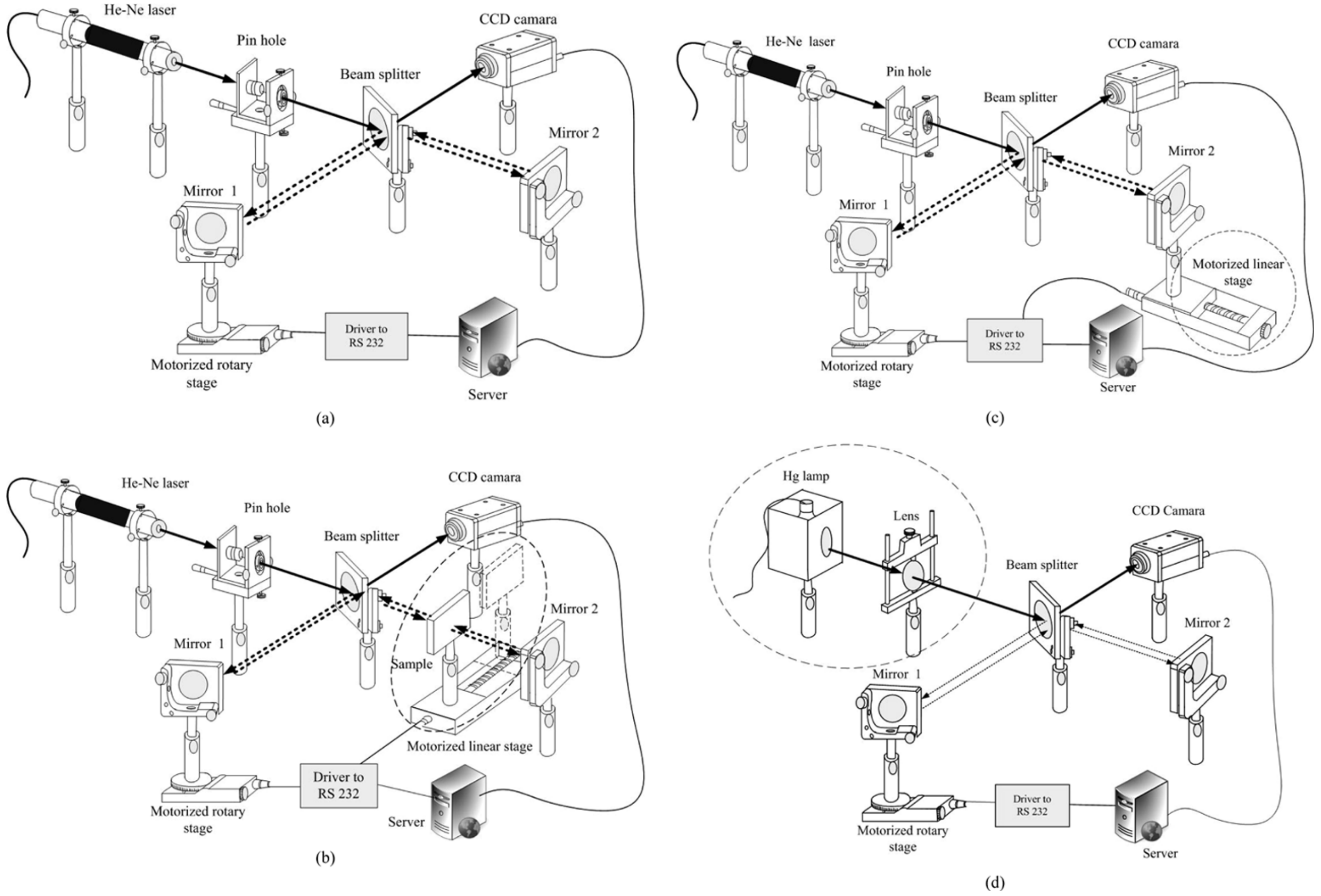
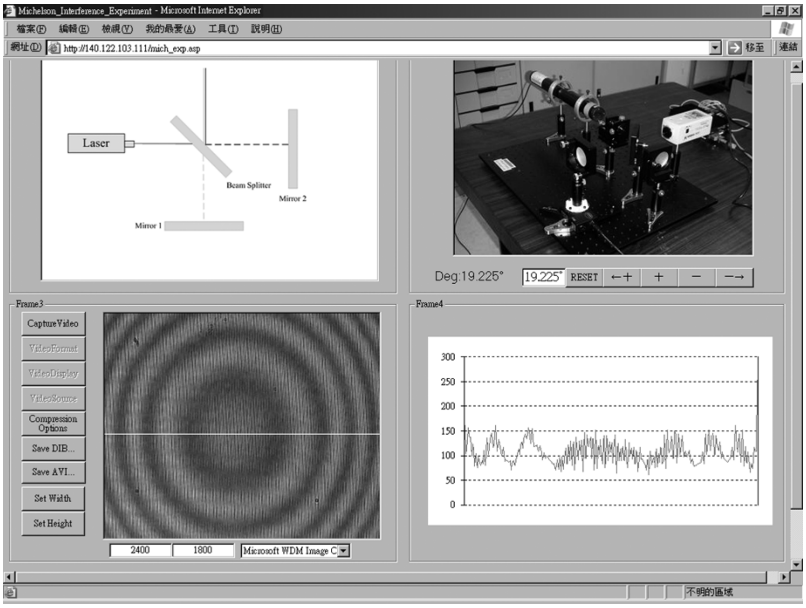


Fig. 5. (a) Typical setup for Michelson interference experiment and its application in (b) measuring the refractive index of a sample and (c) laser phase-shifting interferometer to measure microstructure profile, and (d) using Hg lamp to test the feasibility of white-light interferometers.



Michelson_Interference_Experiment - Microsoft Internet Explorer

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Fig. 6. User interface of the Michelson interference experiment in the V-PEN.

To demonstrate further the effectiveness of the design procedure, the implementation of the online experiment for basic Fourier optics (FO) (Table I) is briefly introduced by illustrations from Figs. 7 and 8. The goal of this experiment is to let users be familiar with the techniques of optical image processing and spatial spectrum analysis. As illustrated in Fig. 7,

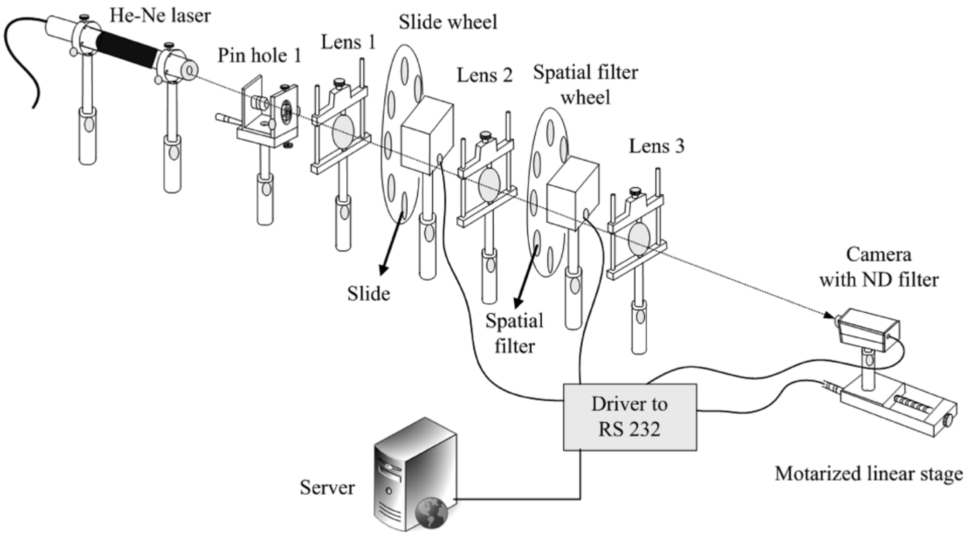
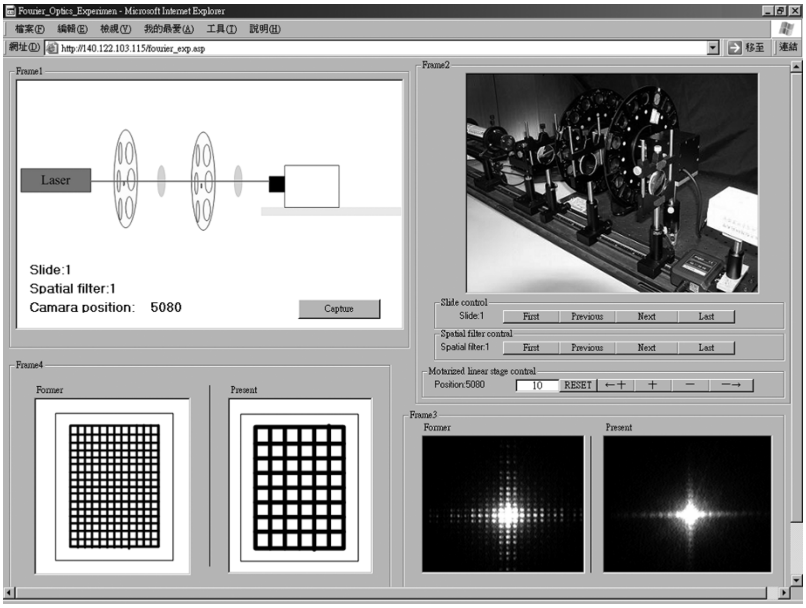


Fig. 7. Fourier optics experiment.


Fourier_Optics_Experimen - Microsoft Internet Explorer

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Slide:1
Spatial filter:1
Camara position: 5080

Slide control: Slide:1

Spatial filter contral: Spatial filter:1

Motarized linear stage contral: Position:5080 10

Fig. 8. User interface of the Fourier optics experiment in the V-PEN.

the slides mounted on a slide wheel can be changed to produce a set of different object lights by remotely controlling the rotation of the wheel. Consequently, different spatial spectrums are acquired by a CCD camera with a neutral density (ND) filter. In addition, a set of spatial filters (SFs) that are mounted on an SF wheel can be employed to remove noise that corresponds to the collection of the object light in the images. As the camera is moved to a proper location, the noise-free image (i.e., the processed image) can be acquired. Fig. 8 indicates a GUI that shows an online animation of the FO experiment, a real-time image of the actual installation, the former pattern of object light and the present one, and the spatial spectrum distributions corresponding to the two patterns.

There are still more applications that can be developed. The applications mentioned previously demonstrate the effectiveness of the implementation of the online photonics experiments using the design procedure.

V. DISCUSSION AND CONCLUSION

The V-PEN creates a 24-hour-a-day online photonics experiment environment so that it is ideal for learning from any place at any time. Through this system, expensive photonics equipment can be shared by many institutions, and learners can perform experiments at home without driving a long distance to school. In addition, instructors from other institutions can also contribute their course materials to the V-PEN.

The V-PEN has been used to support the instructions for a semester. The result of an evaluation questionnaire to this system is shown in Table II. The 42 learners were the junior students of the department who took the course, Applied Electronics, including the photonics laboratories. The electrical engineering curriculum has introductory courses in the principles of photonics but temporally lacks supportive laboratory courses. To make a comparison between the learning results, all of the

TABLE II
EVALUATION OF THE FIRST 42 LEARNERS WHO USED V-PEN

Questions posed	Average*
Do you understand more in related theories after using the V-PEN?	7.8
Do you think that V-PEN is better than purely online simulation?	8.5
Do you think that V-PEN is better than operating a real experiment?	2.1
Do you think that the parameter set in the V-PEN is meaningful for you to understand theories better?	8.2
Do you think that online tutorial and illustrations are abundant for your self-study?	7.3
Do you think that using V-PEN is interesting?	8.2
Overall, how would you rate current V-PEN?	8.1

* Learners evaluate this system in 0-10 scores where 10 is the highest score

students are requested to operate the V-PEN and the real photonics experiments. Consequently, most of them are highly interested in doing real experiments. Only a few students think that the V-PEN is better (more interesting) than operating a real experiment. For the students with engineering background, the V-PEN system may not be a good substitute for the real experiments, which they can perform easily. This conclusion is the reason the score given to the third question is much lower than the others in Table II. This table also indicates that except for the third question, most learners give positive evaluations to the system.

The V-PEN has many advantages over the real (or on-site) experiments. Those have been revealed in supporting the teaching and learning processes. The V-PEN can expedite the students' learning processes in operating the on-site experiments since the controllable or adjustable mechanisms are all set in this system. In the teaching process, instructors can perform the real-time experiment demonstrations by remote control to enhance the teaching effects of the related theories. Moreover, the instructors can keep track of learners' performances easily through the evaluation subsystem, as described in Section II. Finally, some equipment damage, such as mirrors, can be minimized since hands-on practices are reduced. The management of the photonics laboratories becomes easy, and the utilization of expensive photonics equipments can also be increased.

In the learning process, this system plays an important role in distance learning. Compared with some online learning environments that only offer course handouts, simulation, and images, this learning platform exposes learners to real-world experiments. Furthermore, prerequisite materials and extended studies are provided so that the learning pace of each learner is self-controllable. Finally, online interactive discussion forums and chat rooms are provided to inspire knowledge sharing and brainstorming between learners.

The computer simulations for photonics experiments are performed by the use of ASAP software. Similar to those from most simulation programs, the mathematical computations of the simulations result from the theoretical basis of the photonics experiments. Evidently, the difference between the theoretical results (i.e., those obtained from the computer simulations) and the real ones (acquired from the V-PEN) depends on the completeness of the theoretical model to represent the real experiment. In Table II, most of the learners think the system is better than the simulation. If the real experiments can be remotely controlled by the V-PEN, the results from the system and the experiments are the same. Hence, the V-PEN is valuable and useful in the teaching and learning processes.

Because not all photonics experiments can be performed online, the proposed design procedure is beneficial in checking the feasibility of implementing online photonics experiments. The configurations of photonics experiments are beneficial to constructing the remote-control mechanism in the V-PEN. In this approach, instructors can design online photonics experiments more systematically, and learners can grasp the main idea of the experiments more conveniently.

Future works include adding more experiments to the V-PEN and designing more Web-based activities to enhance teaching and learning photonics experiments. Instructors are welcome to contact the authors for more information about this system.

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