A Progressive Design Approach to Enhance Project-Based Learning in Applied Electronics Through an Optoelectronic Sensing Project

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***Abstract*—In this paper, a progressive design learning approach is proposed in the course of "applied electronics" to help students to develop system design skills through an optoelectronic sensing project. This project offers a progressive guideline to lead student teams to design, build, and troubleshoot their optoelectronic systems. Such a system contains a light-source current stabilizer, a photodiode amplifier, a microcontroller system (including input and output), and optomechanical devices. In this approach, students are motivated to learn the required knowledge and skills in a future professional capacity. Those skills include designing specification, realizing teamwork and communication, and developing a variety of optoelectronic sensing techniques. Through this project, an optoelectronic sensing system is established called a spatial radiance distribution measurement system for various light sources. In particular, this kind of system is useful and important for LED industries. The course evaluations have been obtained from classmates and instructors and these results indicate that the objectives of this course are achieved.**

***Index Terms*—Microelectronics education, optoelectronic sensing technique, optoelectronics education, project-based learning.**

I. Introduction

With the rapid advance of optoelectronic system technologies, their significance has been broadly recognized in a variety of applications to industries, such as flat panel displays, fiber-optics communication, automatic manufacturing, instrumentation, consumer electronics, etc. [1], [2]. This progress has also urged the necessity for electrical engineering students to have substantial exposure to optoelectronics or photonics-related topics. Therefore, to meet the increasing requirements for the engineers, the provision of the link between universities and industries has been regarded as an important issue.

Numerous attempts have been made by scholars to introduce optoelectronic laboratories to undergraduate engineering students [3]–[7]. In addition, efforts have been made to integrate optical engineering with microelectronics engineering. Daneshvar [8] analyzed the similarities between optics and electrical engineering, and integrated optoelectronic topics into traditional electrical engineering curricula. Furthermore, Uherek *et al.* [9] reported a curriculum with optoelectronics education and two individual students' projects on optoelectronic systems. These examples demonstrate that optoelectronic technologies have gained increasing importance in microelectronics engineering education.

The Accreditation Board of Engineering and Technology (ABET) Evaluation Criteria 2000 emphasizes the system design and evaluation through projects in the curriculum of Computer and Electrical Engineering [10]. Obviously, students are required to learn to face practical, real-world problems to enhance their learning experience. To achieve this goal, project-based learning (PBL) has been regarded as an important approach [11]. However, several difficulties are described in PBL [12], [13]. For example, students tend to have problems, such as being inefficient when working with technology, troubleshooting their work, and having difficulty with time management.

In this paper, to overcome these difficulties, a progressive design approach to enhancing PBL is proposed through an optoelectronic sensing project. In this approach, beginning with simple-as-possible examples (or templates), the tasks of the project are designed, built, and troubleshooted in a progressive way, respectively. The design process is incrementally progressive in that each required task is put into the overall design without disturbing the previously completed tasks' functionality. More importantly, such a progressive design experience can enable students to enhance their creative and critical thinking [11], [14].

Photoelectric sensors, e.g., photodiodes (PDs), have been widely used in many optoelectronic systems [15]–[18]. Through the proposed project, students have the opportunities to gain deeper knowledge and skills to solve the realistic, complicated problems in the optoelectronic system technologies. For example, the design considerations in optoelectronic sensing systems are highly related to a variety of the properties of PDs. Usually, the output current of a PD is only around 10^{-11} to 10^{-9} ampere per lux, and a transimpedance amplifier (TIA) is

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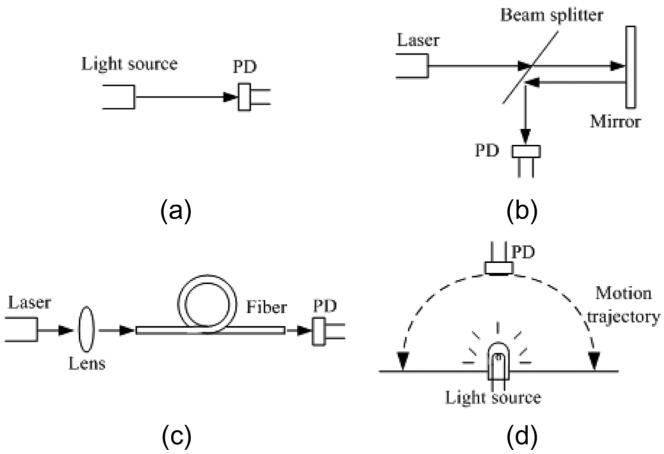

Fig. 1. Illustrations for applications of the optoelectronic sensing techniques. (a) Direct coupling for optical power measurement. (b) T-type configuration for CD/DVD players. (c) Optical coupling using fibers. (d) Spatial radiance distribution measurement for light sources.

thus required to convert the tiny photocurrent to a measurable voltage (0–5 V) [19]. Therefore, to solve such a problem, the progressive design approach is provided to guide students on the basis of PBL.

Furthermore, this approach can enable students to extend the knowledge and skills from microelectronics engineering to various optoelectronic sensing techniques. For instance, the properties of PDs can be easily extended from those of diodes. Diodes are generally discussed in a microelectronics course and the extended idea is not too difficult for students to grasp. Moreover, one may apply the same idea to semiconductor light sources, e.g., light-emitting diodes (LEDs). Spatial radiance distribution measurement, a kind of optoelectronic sensing technique, conveys important information to improve the utilization efficiency (or the characteristic of directionality) of the light sources. Thus, this technique gives rise to much attention in industries [2]. In this paper, the measurement system for the project [Fig. 1(d)] is proposed as a key basis to motivate students learning a variety of optoelectronic sensing techniques. For example, in Fig. 1(a)–(c), this technique can be applied in optical power measurement, source–receiver configuration for CD/DVD players, and optical coupling using fibers, respectively.

The objectives of this course (or educational objectives) are given as follows.

1) In the proposed learning activity, the optoelectronic sensing project is to lead students progressively to work with the case studies from basic to advanced ones and further to achieve industrial application goals.
2) Through this project, student teams are to be guided to identify, formulate, and solve the optoelectronic sensing problems.
3) This project is to enhance the knowledge and skills of electronic systems and instrumentation with an optoelectronic sensing approach.
4) To meet the requirements of industries, students are to practice their communication skills, to cooperate in groups, and to do some project management.

In this paper, the educational objectives can be specified with describing the project goal and task aims, as stated in Section II. This section also presents the educational design. Then, the project tasks are described in Section III. Section IV gives evaluation and discussion. Finally, Section V concludes this paper.

II. Educational Design

Applied electronics is treated as a part of the core body of the curricula at the department of mechatronic technology in the authors' university. This course is used for junior or senior students and offers three credits for a semester. Students are required to have taken prerequisite courses, such as microelectronics, electric circuits, microprocessors, and programming language in the first and second year undergraduate curriculum in the authors' department. In this course, the 18-week sequence of the topics consisted of a series of lectures and laboratory. In the first four weeks, a subset of the topics shown in Fig. 2 were chosen and taught by the instructor to help students review the related theories of electronic/optoelectronic components, circuit design/implementation, and system integration [15]–[18]. Also, the remaining parts of the course are driven by the project tasks in the following 14 weeks. In particular, the theoretical review plays a role in filling the gap between the knowledge needed in the project and that from the prerequisite courses. The concepts required for the project are illustrated in Fig. 2. They offer knowledge integration with the prerequisite courses to enable students to gain insight into the course objectives.

A need to enable students to face practical, real-world problems and to enhance their knowledge and skills can be approached through this course. This fact motivates the course, Applied Electronics, to employ PBL. Furthermore, with the advance of photonics technologies, the introduction of an authentic project relating to such fields would be beneficial to helping students learn and develop skills required by students in a future professional capacity. Also, student teams are expected to develop skills, such as autonomous learning, critical thinking, and collaboration.

A. *PBL Planning*

To let the learning activity proceed effectively, instructors should make more efforts on the PBL planning. For example, they should prepare instruction materials, specify requirements of the system and electronic circuits, explore issues, define tasks, and develop essential techniques to support the learning activity. A key idea behind PBL is to design constructive tasks for students. During the learning, students begin with what they have learned and then extend gradually to new knowledge and skills with the guiding tasks.

To achieve the educational objectives, the project goal includes the specifications of the overall system and the electronic circuits, which reflect the requirements of related industries (Table I). Instructors are to study the feasibility of the project and to organize the project tasks. For instance, instructors may request, in advance, teaching assistants (TAs) to build up a prototype of the proposed system for the PBL. Then, from this development experience, the system component characteristics

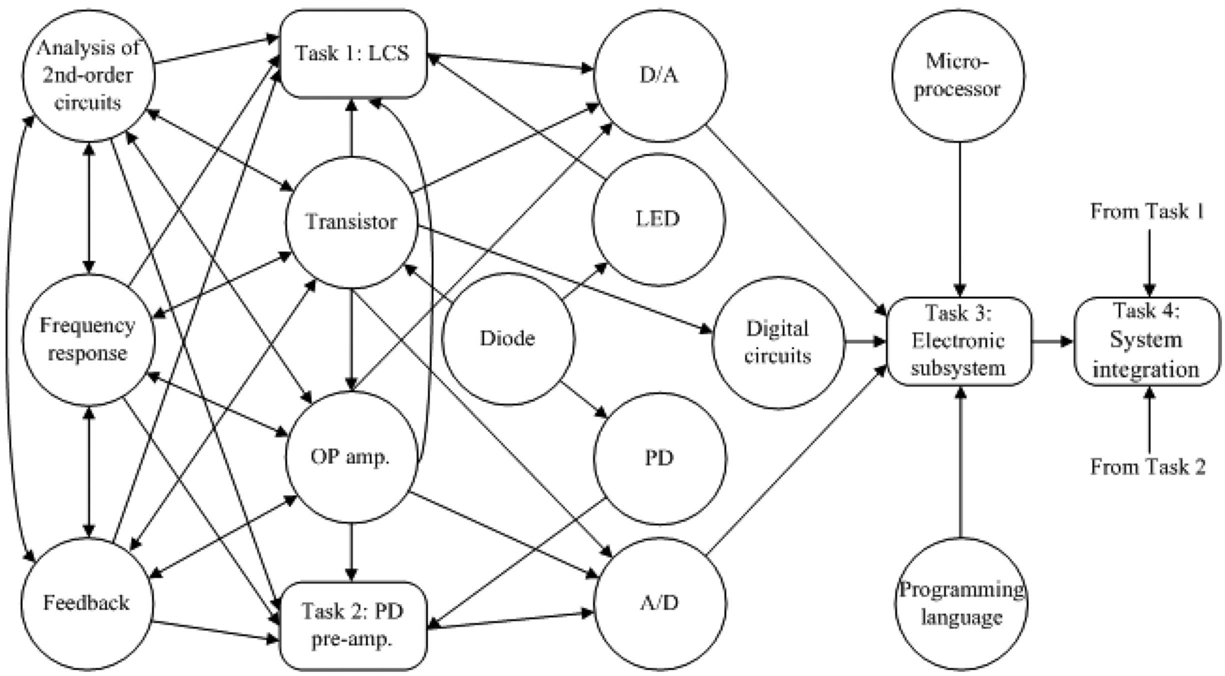

Fig. 2. Concept map for the project.

TABLE I
THE REQUIREMENTS, ISSUES, AND PROPOSALS OF ELECTRONIC-CIRCUIT DESIGN FOR THE OPTOELECTRONIC SENSING PROJECT

Requirement	No.	Issue	Proposal
Proper operation and stabilization for the light sources (or devices under test, DUTs)	1-1	How to design a driving circuit to avoid large in-rush current, so that the light source can be operated properly	Light-source driver circuit with soft start
	1-2	How to enhance the circuit to meet various current specifications of the DUTs and to remove noise in the circuit	Current regulation and noise suppression
	1-3	Protection of the DUTs from working at over-rating current	Over-current protection
Stable, accurate and fast response for the PD detector	2-1	How to use an op amp to convert a tiny photocurrent to a measurable voltage	Using an op amp as a TIA
	2-2	How to increase the system stability	Removing the gain peaking of the PD amplifier
	2-3	Protection of the photocurrent from the contamination because of the leakage current of the circuit board	Using the guard ring technique
	2-4	Is the performance of a two-stage amplifier better than that of the one-stage PD amplifier so that the system requirement is met	Investigating their system stability and bandwidth (or the rise time of a unit-step response)

(e.g., that of calibrating lamps), and the electronic-circuit design requirements, instructors can raise technical issues and lead students to propose their designs. Table I indicates a realization for such a learning activity. More detailed specifications can be finalized in accordance with the real situations in the learning activity. To further support the learning activity, construction of the project website is helpful, where the course materials and some links for self-reviewing the related courses are given to students [20]. Also, students are encouraged to create an online forum and e-mail links to provide a discussion environment.

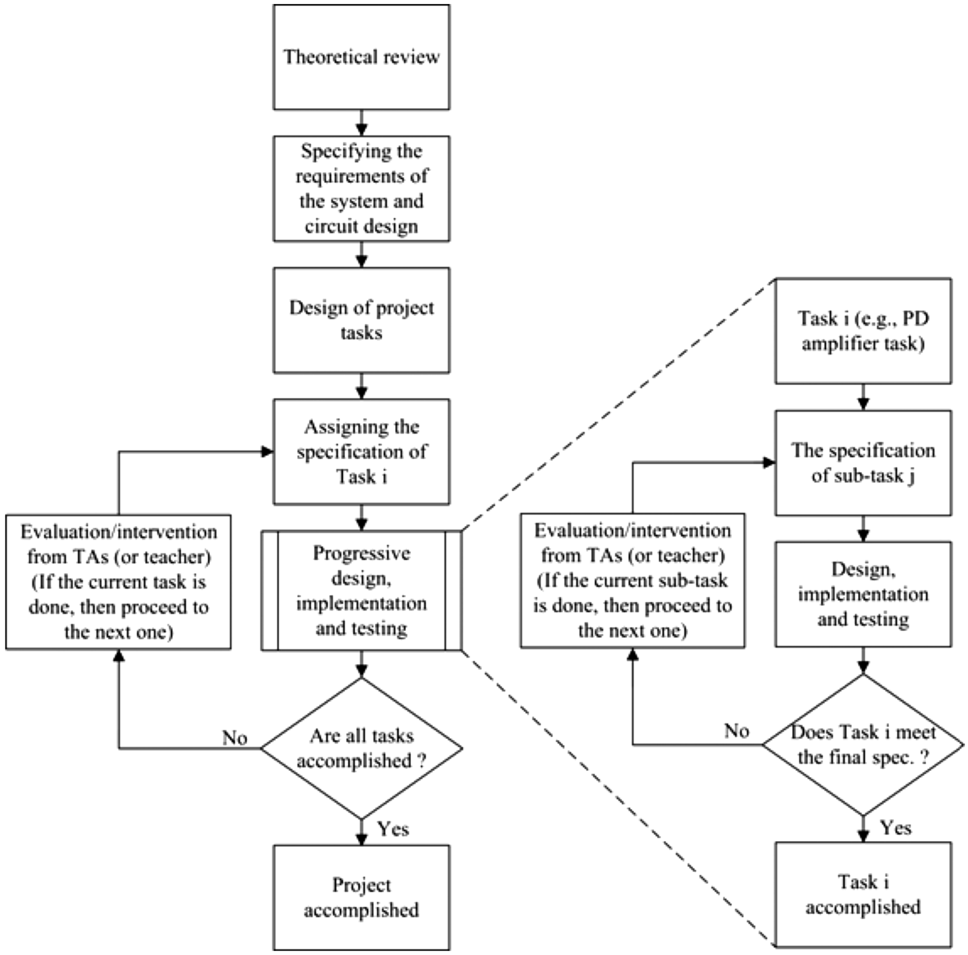

Fig. 3. Progressive design flow diagram.

B. *Progressive Design to PBL*

During the learning, how to reduce the complexity of such a project is regarded as an essential in the process of PBL. From the teaching experiences [12], [13], students tend to have difficulties in the 1) process of inquiry; 2) inefficiency when working with technology; 3) troubleshooting their work; and 4) managing time. In this paper, these are named Difficulties 1–4, respectively. With the help of a systematic, pedagogical design, one can see that such a project becomes easy-to-develop. Thus, the effectiveness of PBL is enhanced [11]. To manage the proceeding of the project efficiently, a divide-and-conquer concept is adopted to guide students progressively to accomplish their system. In the optoelectronic sensing project, the overall system is divided into optomechanical and electronic subsystems. Based on the complexity of the electronic subsystem 1) the light-source current stabilization; 2) the photoelectric detection and amplification; and 3) the acquisition, digitalization, and manipulation of the optical signal are formed as three tasks, called Tasks 1–3, respectively. The integration, testing, calibration, and verification of the overall system (including the optomechanical subsystem) are assigned as the fourth task, Task 4. The detailed descriptions for these tasks are given in Section III.

In this project, beginning with simple-as-possible examples (or templates), the tasks are designed, built, and troubleshooted in a progressive way, respectively. The design specification is progressive in that each required task is added to the overall design without impinging on the previously completed tasks' functionality. Specifically, the function requirements in a previous task must be met before the latter task proceeds. As a result, students can explore the cause and effect for the proceeding of the tasks.

To solve the practical problems in each task, instructors are recommended to guide students with progressive learning from simple to in-depth subtasks. Fig. 3 shows the progressive design flow. Regarding Difficulty 1, taking Tasks 1 and 2 as examples, the authors raised the issues, and then students are guided to propose their solutions, as listed in Table I. To deal with Difficulty 2, Proposal 1-1 to 2-4 individually refer to the corresponding subtasks (or modules offering specific functions, Table II).

In the progressive design, students are guided to add testing points (TPs) to each task without impinging on the previous subtasks' functionality. Proper design of the TPs can assist students in troubleshooting, as described in Difficulty 3. Specifically, through the addition of the TPs, the function requirements in a previous subtask must be met before the latter subtask proceeds. Consequently, they can explore the cause and effect for the proceeding of the subtasks. To help students to overcome Difficulty 4, the evaluation and intervention from TAs or the teacher are required (Fig. 3). As indicated in Table II, a guideline with the task aims is provided to lead students to go through the progressive learning activities.

TABLE II
GUIDELINE OF PROGRESSIVE LEARNING ACTIVITIES AND THE TASK AIMS (TASKS 1 AND 2 ARE PERFORMED SIMULTANEOUSLY)

P/ST* (W)	Task aims (Students are requested to be able to ….)
Task 0: Theoretical review	
4Ws	Understand the design and development concepts for analog/digital components and systems.
Task 1: Light-source current stabilizer (LCS)	
P1-1 (2Ws)	(1) Identify and formulate the problem of how to design a soft start circuit by use of a bipolar junction transistor, BJT, as a switch. (2) Design the circuit and add testing points (e.g., TP 1-1); to verify efficiently the circuit performance, adding testing points is important in the progressive design. (3) Simulate and implement the circuit; let students be familiar with a modern circuit simulation tool (e.g., PSpice). (4) Incorporate the soft start with a BJT to drive the light source (e.g., a THL) and implement the driver to avoid in-rush current. (5) Generate a noise source (e.g., ripple noise generated by use of a power transformer, a full-wave rectifier, and a rectifier filter) and incorporate the noise into the driver; the noise generation is used to emulate realistic situations in the circuit, e.g., temperature variation. (6) Investigate the noise effect on the variation of the light-source current.
P1-2 (2Ws)	(1) Identify and formulate the problem of how to regulate the light-source current and to suppress noise; this problem is similar to that of voltage regulation (with a negative feedback) in a power supply. (2) Solve this problem by enhancing the driver circuit with a negative feedback technique, which consists of a sensor (using a resistor), a transducer and a controller (using op amps); also, add a testing point TP 1-2 to the enhanced circuit. (3) Simulate the enhanced circuit, determine its parameters (e.g., resistance), and implement the circuit and verify its performance.
P1-3 (2Ws)	(1) Identify and formulate the problem of how to design an over-current (or overload) protection circuit by use of a BJT, according to the relationship between the slopes of the load line and the output characteristic $i_C - v_{CE}$ curves (with respect to different base currents i_B). (2) Design the protection circuit and add a testing point TP 1-3. (3) Simulate, analyze, and implement the circuit, and verify its performance; this step enables students to learn a modern circuit layout tool (e.g., Protel). (4) Interpret the experimental results; this step also enables students to be familiar with the operating principle of BJTs. (5) Build the LCS with the circuits developed from Tasks 1-1 and 1-3, and verify its performance.
Task 2: PD amplifier	
P2-1 (2Ws)	(1) Learn PDs from diodes and tell the difference between the two kinds of devices; specifically, read the data sheets and analyze the PD equivalent circuit. (2) Use an appropriate op amp (e.g., CA3130 with a MOSFET input stage having extremely small input bias currents) with a feedback resistor to design a TIA to convert a tiny photocurrent to a measurable voltage and add a testing point TP 2-1 (Fig. 10a) to the PD amplifier for adjusting the voltage gain. (3) Simulate the amplifier and analyze the step response. Since the op amp is bandwidth-limited, the amplifier may be approximated as a first-order circuit (specifically, a low-pass amp. [18, pp. 114-115]). As a result, the amplifier (involving the PD junction capacitance) can be treated as a second-order circuit. (4) Implement the amplifier and investigate to see if experimental results are consistent with the simulation ones; students can find the underdamping or gain-peaking phenomenon.
P2-2 (1W)	(1) Derive the transfer function of the second-order circuit (i.e., the amplifier) according to the PD and op amp data sheets and sketch the Bode plot; this step explains the reason the gain-peaking occurs. (2) Simulate the amplifier frequency response using PSpice; perform the experiment using LabView (or other programs); and investigate if the experimental result is consistent with the simulation one. (3) Find a method to remove the gain peaking and to make the system bandwidth maximum; students are encouraged to solve this problem with the concept of transfer functions. One can see that adding a feedback capacitor to the amplifier as a phase compensation for the problem is a convenient method. Also, adding a testing point TP 2-2 helps students observe the effectiveness.
P2-3 (1W)	(1) Understand the reason for the presence of the leakage current by performing real measurements; in practice, the photocurrent is contaminated by offset current or leakage current through the investigation of PD sensing characteristics. (2) Use guarding ring to solve this problem; also, adding a testing point TP 2-3 helps students understand the severity of the leakage current.
P2-4 (2Ws)	(1) Investigate the factor that influences the rise time (or the dominant time constant $R_f C_j$) of the output voltage; obviously, changing the values of the feedback resistor may be a convenient way. However, this change affects the voltage gain. Specifically, a lower value of the resistor resulting in a smaller gain yields a faster response. (2) Find another way through reverse biasing a PD to decrease its junction capacitance; adding a testing point TP 2-4 enables students to understand the effect of the biasing. (3) Under the condition of no gain peaking and maximum bandwidth, apply one more op amp to further increase the response speed, in addition to the reverse biasing; adding testing points (TPs 2-5a and 2-5b) helps students to investigate the effectiveness. (4) Compare the performance of the two-stage amplifier with that of the one-stage one. Furthermore, have a discussion on the PD amplifier designs regarding the specification of different op amps (e.g., GBW product).
Task 3: Hardware and software development	
ST3-1 (3Ws)	Develop an 89C51 system that includes basic hardware/software and I/O devices, such as A/D, D/A, stepping motor and RS232 interface, and write a GUI on a PC to handle events. Also, implement a computer averaging (e.g., averaging the measured data) to reduce noise, by means of increasing the number of the acquisitions (or measurement times) at each rotation angle.
ST3-2 (1W)	Integrate the electronic sub-system with the current stabilizer and the PD amplifier.
Task 4: Overall system integration, calibration and verification	
ST4-1 (2Ws)	Build and test the optomechanical sub-system.
ST4-2 (2Ws)	(1) Integrate the overall system. (2) Calibrate the system for spatial radiance characterization of LEDs; specifically, perform the compensation for A/D nonlinearity and computation for the deviation from the intensity formula. (3) Discuss the selection of the one-stage or two-stage amplifier for the system, according to the progressive modifications in the amplifier design.

*: Proposal (P), sub-tasks (STs), and week (W)

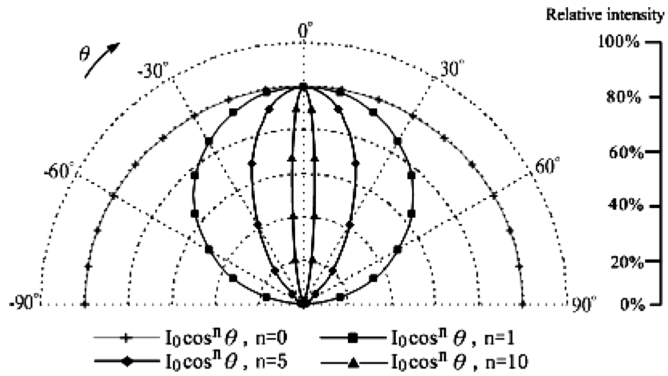

Fig. 4. System requirement for measuring the spatial radiance distribution of light sources at the rotation resolution of one degree and in a total of 30 seconds.

C. Implementation and Management of the Enhanced PBL

In the beginning, the project implementation is to arrange project teams, each consisting of two students. The grouping policy ensures that each team has at least a member familiar with a microprocessor, so that the tasks would not be too difficult for the teams. This policy mimics the project groups in industries. The background diversity fosters the necessary of knowledge sharing with the team members and their communication skills can thus be improved. Also, in the evaluation of the learning outcomes, the project members are asked to exchange the role of oral presentation for the individual work of their member, to encourage their collaboration.

According to the guideline, students are guided progressively by the tasks to build up the system. Before the proceeding of the project, an overview of design methodology is provided for students, and the project design process shown in Fig. 3 is presented. They are asked to declare their individual scopes of work and to meet the requirement of each task. Students are expected not only to develop related skills from the project, but also to build their ability to analyze and solve problems.

D. System Architecture

The system requirement is depicted in Fig. 4, for measuring the spatial radiance distribution of various light sources (e.g., LEDs) [15] at the rotation resolution of one degree and in a total of 30 seconds. Also, students are expected to develop their systems with measurement error less than 5%. Specifically, the measurement error can be obtained from computing the deviation of the measured spatial radiance of a calibrating lamp (described in Section III-D) from the ideal spatial radiance. To achieve the system requirement, this system consists of the electronic and optomechanical subsystems (Fig. 5). In the electronic subsystem, the light emitted from a light source under test is detected by a photoelectric sensor that transforms the optical signal into an electric one. This signal is then amplified by an amplifier, and converted to a digital form by an analog-to-digital (A/D) converter. A microcontroller is applied to pick up and interpret the digital signal. Furthermore, this device can transmit the measured data to a PC to display information. In the optomechanical subsystem, the photoelectric detector is mounted on a rotary stage driven by a stepping motor, and the microcontroller can perform rotation control through sending control signals to the motor driver.

III. Project Tasks

The project tasks are listed in Table II. Through the learning activity, the tasks are designed to achieve the educational objectives and the system requirement. Task 1 mainly deals with a light-source current stabilizer (LCS) and contains some functions that help students to identify, formulate, and solve the problems which arise from the issues in Table I. In Task 2, through the progressive modifications in the design of the PD amplifier, students are guided to handle the case studies from basic to advanced ones, and further to achieve industrial application goals. Task 3 gives students the experience of hardware and software development, through the integration of the electronic subsystem with a single-chip 89C51 and its peripherals. Finally, in Task 4, students are guided to build the optomechanical subsystem, and then to integrate, test, calibrate the overall system, and verify the system performance.

A. Task 1: Development of the LCS

To stabilize the illumination of the light source under test, a current stabilizer is developed, called LCS. The design aim is to regulate the current to a desired value, and to suppress noise which contaminates the system voltage source. In addition, for the calibration of the spatial radiance measurement, a tungsten halogen lamp (THL) has been regarded as an economical and reliable choice. However, such a lamp usually suffers from the damage of inrush current [15, pp. 91-93]. To extend the lifetime of this kind of light sources, a soft-start circuit is implemented in the LCS. Also, a protection circuit is added to protect the stabilizer from the risk of overcurrent operation. Fig. 6 displays a function block diagram of feedback control for the current regulation and noise suppression. In Fig. 7(a), the soft-start circuit is associated with a power transistor directly driving the light source without feedback control. The circuit with feedback control is illustrated in Fig. 7(b). With the help of TPs 1-1 to 1-3, the LCS is then progressively developed with the techniques of the soft-start, feedback control, and overcurrent protection, as shown in Fig. 8. One can see that troubleshooting the LCS becomes easy. Fig. 9(a) and (b) display the comparisons for the simulation and experimental results of noise suppression, with and without feedback control, respectively. In the experiment, to demonstrate the effectiveness of the noise suppression, the voltage variation (or ripple) generated by use of a power transformer, a full-wave rectifier, and a rectifier filter may be employed to emulate a noise source in realistic situations in the circuit, e.g., temperature variation. In this task, students are required to enhance their ability to identify, formulate, and solve the problems from the stabilizer circuit design.

B. Task 2: Development of the PD Amplifier

According to the system requirement, the idea behind Task 2 is to guide students to design PD amplifiers progressively from basic to advanced ones, and further to achieve the goals of optoelectronic sensing in the practical applications (Fig. 1). Task 2 contains four subtasks corresponding to Proposals 2-1 to 2-4,

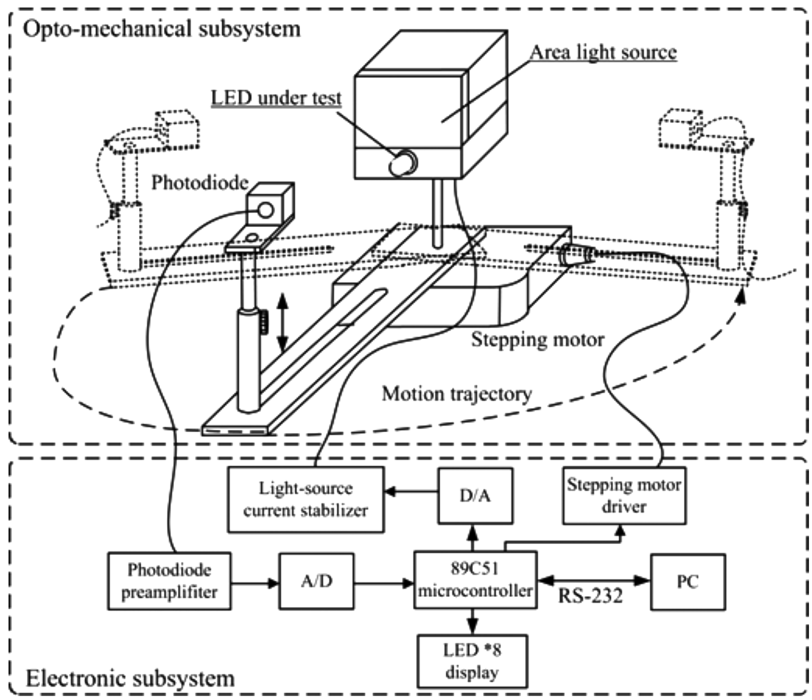

Fig. 5. System function block diagram.

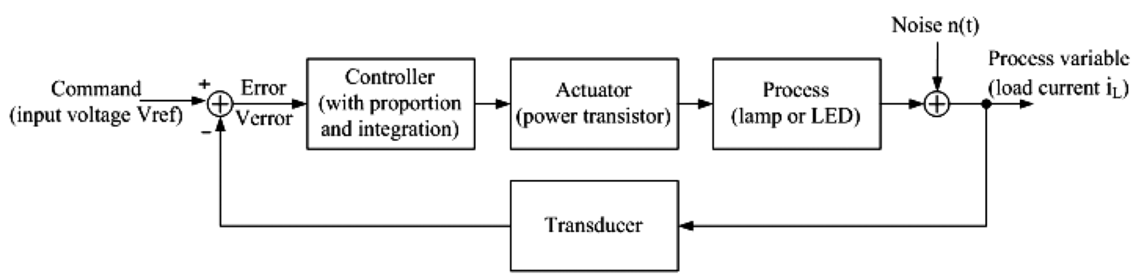

Fig. 6. Feedback control diagram for the light-source current stabilizer.

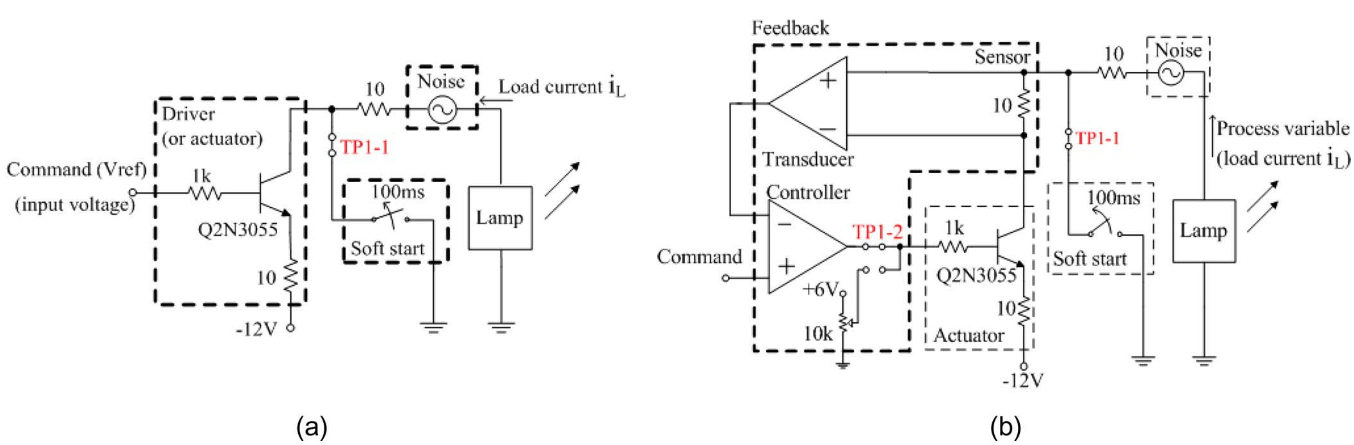

Fig. 7. Illustrative circuits for (a) the soft start and (b) the feedback control.

as shown in Table II. All of the subtasks are designed to motivate students to learn the related technical materials actively. Through the use of TPs 2-1 to 2-5, students are progressively guided to solve a series of inevitable problems as simply as possible, to achieve the task aims, as indicated in Table II.

Subtask 2-1 motivates them in how to design an electronic circuit to convert a tiny photocurrent (about 10^{-11} to 10^{-9} ampere per lux) to a measurable voltage. Specifically, the aim of this subtask is to simply design an operational amplifier (op amp) with some peripheral components (e.g., a feedback resistor R_f) for a PD. In this task, a commercially available silicon PD (model No. S2386 [19], Hamamatsu, Japan) is employed to detect the incoming light. The TIA is referenced to as the PD amplifier [Fig. 10(a)].

In general, the equivalent model of a PD mainly contains a photocurrent source, junction capacitance C_j, a shunt resistance, and a series resistance [16]. Also, an op amp usually has input capacitance. The presence of the two irreducible capacitances causes the PD associated with its amplifier to be a second-order circuit. Obviously, the circuit stability is affected

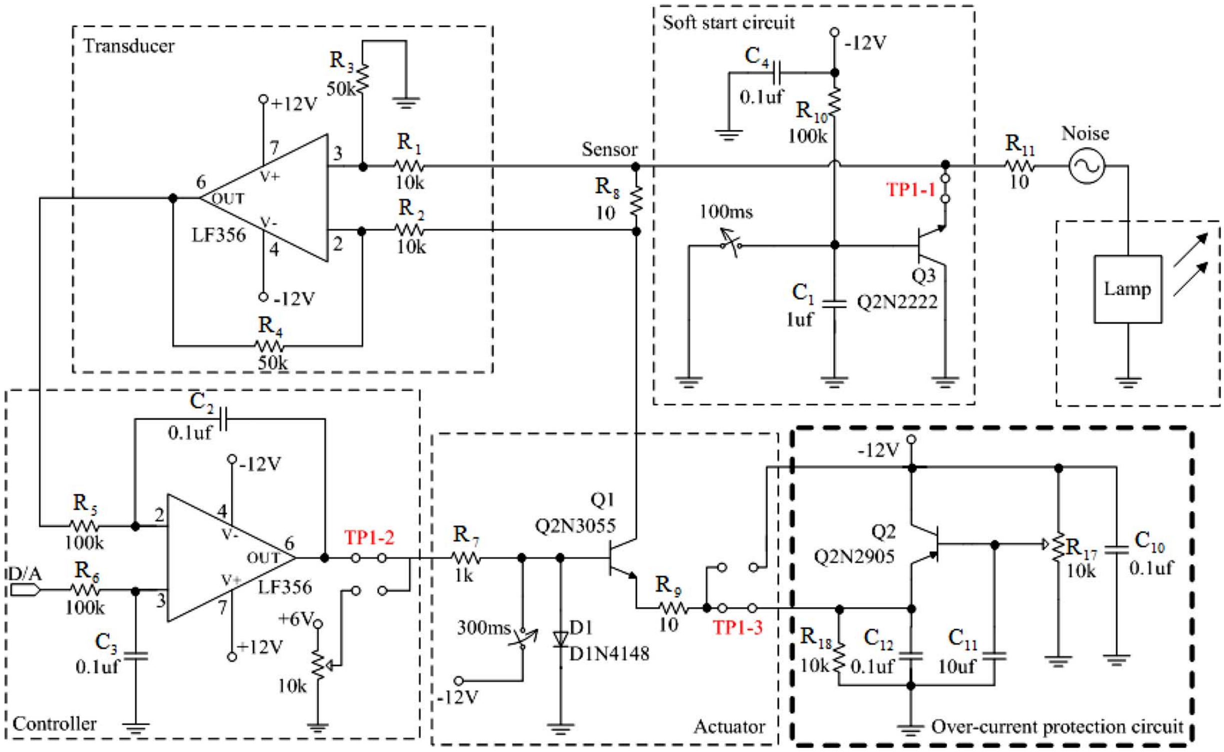

Fig. 8. Schematic for the LCS.

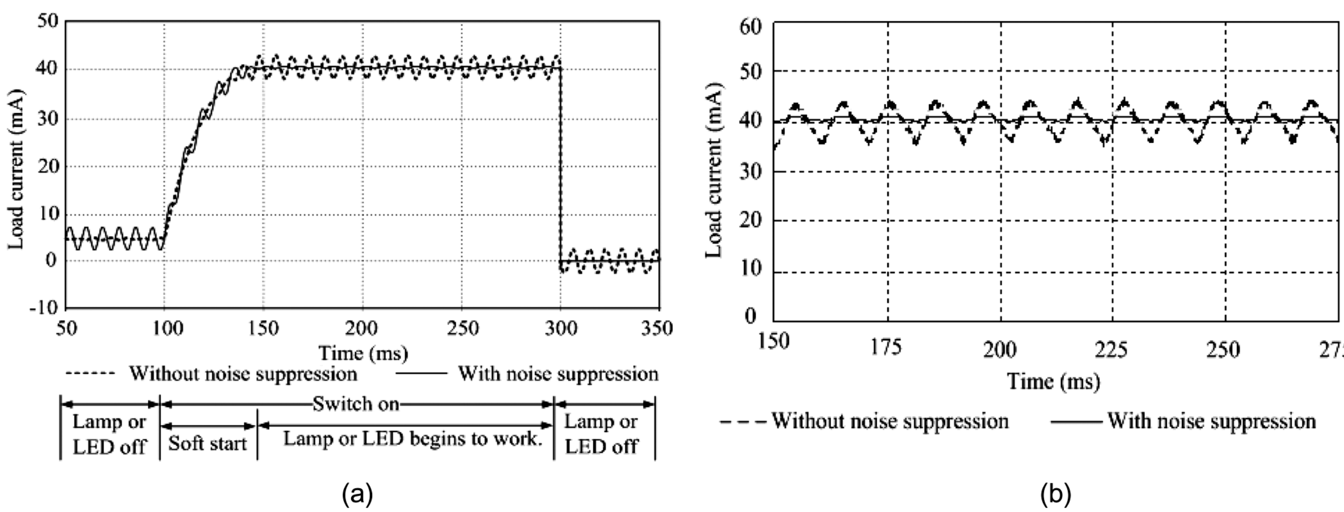

Fig. 9. (a) Simulation results and (b) experimental results for the LCS.

by the two capacitances. Fig. 10(b) shows the underdamping (or gain peaking) of the amplifier in response to the input optical pulse [17]. The aim of Subtask 2-2 is to stabilize the amplifier. One can see that the gain peaking can be reduced or eliminated by adding a feedback capacitor C_{f}, as circled in Fig. 10(a). Fig. 10(b), (c), and (e) show the effectiveness of the reduction for gain peaking in the time and frequency domains, respectively.

In addition, leakage current exists on the circuit board. To overcome this difficulty, in Subtask 2-3, the guard ring technique is used to shield the photocurrent from the leakage current. The effectiveness of this technique is shown in Fig. 10(c). Subtask 2-4 focuses on dealing with the bandwidth of the PD amplifier, to meet the system requirement. A sufficiently wide bandwidth is needed in response to the light with high-frequency modulation, which results from the relative motion between the PD and the light source under test.

In Subtask 2-4, when confronted with the requirement to greatly boost the amplification of an input signal in a one-stage amplifier, one may choose to use a very large value of R_{f} (about several Mega ohms). In practice, a larger value of the PD junction capacitance is a result of the need of a wider active area or larger photocurrent [16]. The effect of the presence of C_{j} associated with the large value of R_{f} gives rise to a longer time constant. Thus, the system bandwidth decreases. To tackle this problem effectively, one can apply reverse-biased voltage

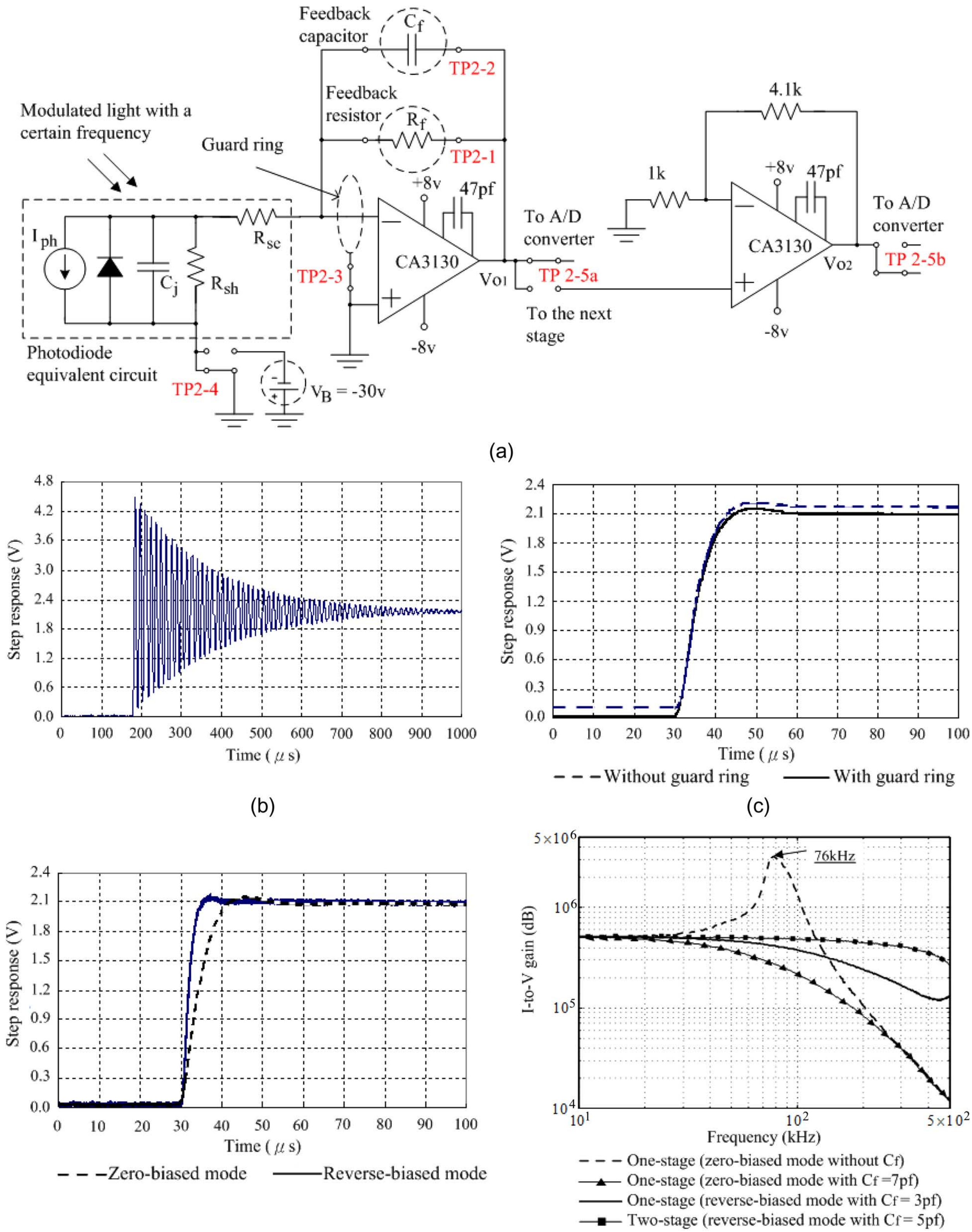

Fig. 10. (a) Schematic for the one-stage/two-stage PD amplifier. (b) Step response of the one-stage amplifier for the zero-biased mode ($R_f = 510$ k, no feedback capacitor). (c) Responses of the one-stage amplifier with and without guard ring for the zero-biased mode ($R_f = 510$ k, $C_f = 7$ pf). (d) Comparison between the response of the one-stage amplifier for the reverse-biased mode ($V_B = -30$ V, $R_f = 510$ k, $C_f = 3$ pf) and that for the zero-biased mode (with guard ring). (e) Comparison between the frequency responses of the one-stage amplifiers in different modes and that of the two-stage one for the reverse-biased mode ($V_B = -30$ V, $R_f = 100$ k, $C_f = 5$ pf).

V_B to the PD to reduce this capacitance, and use a lower value of the feedback resistance R_f. In principle, a higher value of V_B results in a smaller value of C_j. Fig. 10(d) demonstrates the rise time in the reverse-biased mode which is faster than that in the zero-biased mode. Students are asked to increase the system bandwidth further by adding one more op amp to form a two-stage amplifier [Fig. 10(a)], and then to compare the experimental results. Fig. 10(e) shows a comparison for the system bandwidths of the one-stage and two-stage amplifiers. Therefore, this subtask offers a way to help students to determine an appropriate bandwidth that meets the requirements of various optoelectronic sensing systems.

C. Task 3: Hardware/Software Development and Electronic Subsystem Integration

The aim of Task 3 is to integrate the LCS, PD amplifier, and an 89C51 microcontroller into the electronic subsystem. This task contains two subtasks, as shown in Table II. First, students are asked to develop the basic 89C51 hardware/software to control input and output (I/O) devices and communicate with these devices. For example, the optomechanical subsystem is driven by a stepping motor that is controlled by the microcontroller. Also, the measurement results are acquired by the microcontroller, and they are transmitted to a PC via a RS232 interface [20]. Second, the LCS and PD amplifier modules are connected to the microcontroller with adequate peripherals, such as A/D and D/A. The program of the single chip 89C51 is designed to acquire and transmit the measurement results to a PC (Fig. 11). Students have to design a graphic user interface (GUI) to display and manipulate the measurement results and to communicate with the microcontroller (Fig. 12). In addition, to reduce noise in the optoelectronic sensing process, students are asked to implement a computer averaging (e.g., averaging the measured data), by means of increasing the number of the acquisitions (or measurement times) at each rotation angle [21].

D. Task 4: Overall System Integration, Testing, Calibration, and Verification

The optomechanical subsystem is built according to the design drawings and mechanical component specifications provided to the students. Subsequently, this subsystem is incorporated with the electronic subsystem to form the overall system. Fig. 13 displays a photograph of the proposed system. After finishing the system integration, students are guided to prepare for the calibration of the spatial radiance measurement system. Since the characteristics of PDs are fairly linear in response to the illumination of light sources, the measurement errors mainly arise from the nonlinearity of the A/D converter [18]. The use of neutral density filters (Wratten No. 96, Kodak Inc., Rochester, NY) with different optical densities is required to characterize the overall response (or the deviation from linearity) of the PD, amplifier, and A/D converter.

To guide students to survey a better solution to the optoelectronic sensing design, they are asked to compare the measurement results in the progressive way. As a calibrating lamp, a THL (model No. 01110, Welch-Allyn Inc., Skaneateles Falls, NY) with a commercially-available acrylic diffuser is used to form an area light source. Students were required to test their systems with such a lamp having the characteristic of Lambertian cosine (Fig. 4). In this figure, the radiation patterns of common light sources can be generally expressed by the luminous intensity $I_\theta = I_0 \cos^n \theta$, where the intensity in the surface

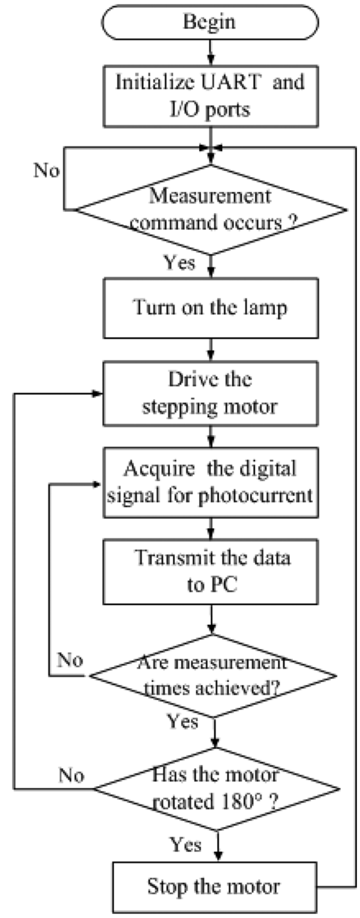

Fig. 11. Flow chart of the measurement system.

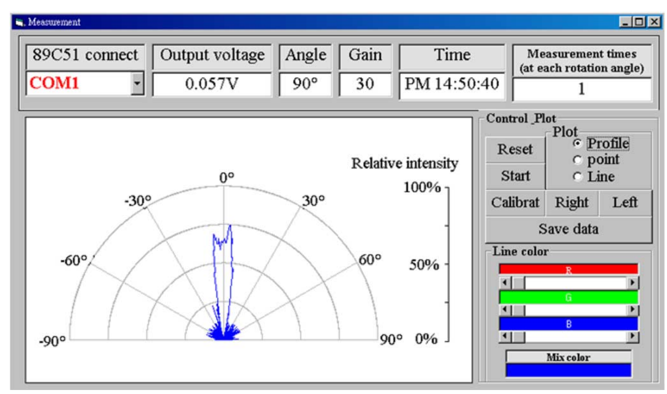

Fig. 12. GUI for the system.

normal is denoted as I_0, θ is the angle of a certain direction making with the normal, and n signifies the radiation pattern exponent. In the case of $n = 1$, when light is directed through a diffusing transparent material, the type of profile is generated according to the so-called Lambert's cosine law, $I_\theta = I_0 \cos \theta$.

Fig. 14(a)–(d) show the experimental results from the system with the different optoelectronic sensing circuits. Fig. 14(a) and (b) display the measured spatial radiation patterns of the calibrating lamp, from the one-stage PD amplifiers (using an op amp CA3130), with and without gain peaking, respectively. The latter comes from the amplifier under the

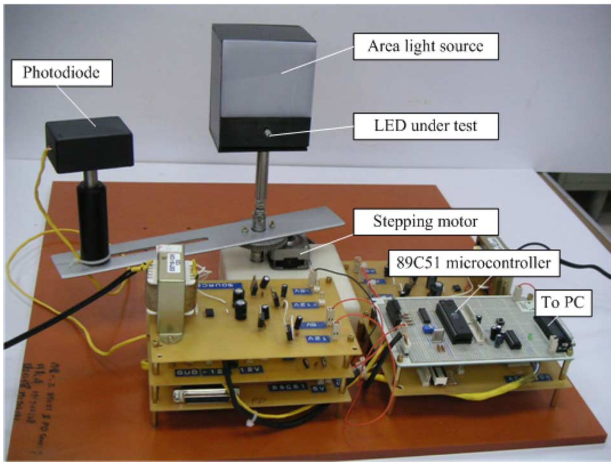

Fig. 13. Photograph of the proposed system.

condition of a higher stability and a maximum bandwidth (i.e., damping ratio equal to 0.707 [17]). As progressive modifications in the design of the amplifier are made to yield wider circuit bandwidths, one can see that noise is gradually introduced. As shown in Fig. 14(c) and (d), the spatial radiation patterns appear more and more noisy, while they are measured from the one-stage amplifier and the two-stage one, both under the same condition of the reverse-biased mode and the damping ratio.

To reduce the noise effect as a result of the increase in the circuit bandwidth, students are guided simply to make use of the technique of computer averaging, as mentioned in Section III-C. Fig. 14(e) and (f) show the 10-times averaged results of the radiation patterns measured from the one-stage amplifier (zero-biased mode) and the two-stage amplifier, respectively. Table III compares the noise-reduction performance for the various designs of the PD amplifiers. Obviously, in the optoelectronic sensing project, the radiation pattern measured from the one-stage amplifier [using an op amp with sufficiently high gain-bandwidth (GBW) product, such as CA3130] with zero-biased mode is closer to the ideal one of the calibrating lamp than those from the others, which have wider bandwidths, and thus suffer from the contamination of more noise.

One can see that the measured data from the optoelectronic sensing circuit with the compensation for the nonlinearity mainly arising from the A/D converter gives a satisfactory result [Fig. 14(g)]. Finally, after the system calibration, students can find that the spatial radiance distribution of a LED is quite close to the system requirement [Fig. 14(h)]. Indeed, this radiation pattern reveals the characteristic of an exponential intensity source (Fig. 4). In this project, the student teams were required to use different kinds of op amps (with various specifications, e.g., GBW product) to design one-stage and two-stage PD amplifiers, and then to discuss which solution yields a satisfactory result.

IV. Assessment and Discussion

This project has been used for a semester with 46 students. Each project team consists of two students. The assessment procedures contain the scoring on project achievement, the quantitative evaluation through questionnaires, and the assessment from focus groups. Following, the assessment results are also discussed.

A. Assessment

1) Scoring on Project Achievement: To evaluate various students' learning performances, Table IV indicates the scoring rule, which includes not only their task achievements but also their improvements in reports, presentation skills, and collaborations with team members. In this table, the formative evaluation is focused on the first three terms, i.e., the quiz, task functionality and team reports, and peer evaluation.

The quiz for the theoretical lecture can motivate students reviewing the related knowledge (Fig. 2). Each student team was asked to provide oral and written reports for each task. Their written reports included the technical achievements for individual tasks, the team citizenship, and the participation of their members. Specifically, each member had to state his or her questions and contributions within the tasks. At the end of each task, the instructors provided written feedback on where or how the teams improved the work. Students were also encouraged to provide suggestions to improve the remainder of the course or the course content in the future. The authors found that many suggestions from them were feasible and beneficial to the assessment process. In addition to the instructors' evaluation, the peer evaluation was required to reflect quantitatively the citizenship and the participation.

In the last term of Table IV, the effectiveness of the learning activities is partly revealed in their scores since the achievement of the final works is regarded as an objective indication. Twenty-one of the 23 teams successfully completed their projects by the due date. Two teams failed to meet the requirement of the overall systems, but the functionalities of Tasks 1 and 2 in their individual work were satisfactory.

2) Quantitative Evaluation: Students' opinions on their learning and the development of the project were collected at the end of the course. The anonymous questionnaires contain the quantitative ratings to the achievement of the educational objectives, the qualitative explanations about the ratings, and additional comments. The quantitative results are indicated in Table V. In Item 4, students feel that the progressive learning activity guideline and course materials are satisfactory. Items 6 and 7 indicate that most of the students think the progressive design learning in the project increases their theoretical understanding and skills in electronics. Also, many of them think this project is difficult but interesting, since the average scores for items 8 and 9 are 7.2 and 8.2 points, respectively. These opinions reveal the effectiveness of the progressive design learning.

In the qualitative opinions, most of the students feel that this course is really interesting, but some of them think that the work load is quite heavy. Several students in this course reveal more interests in learning circuit design. Also, most of the students have never thought of using a PD. In this course, they have the opportunity to make use of such an optoelectronic device.

3) Focus Groups: To further assess students' learning gains for the educational goals of this course, two focus groups were

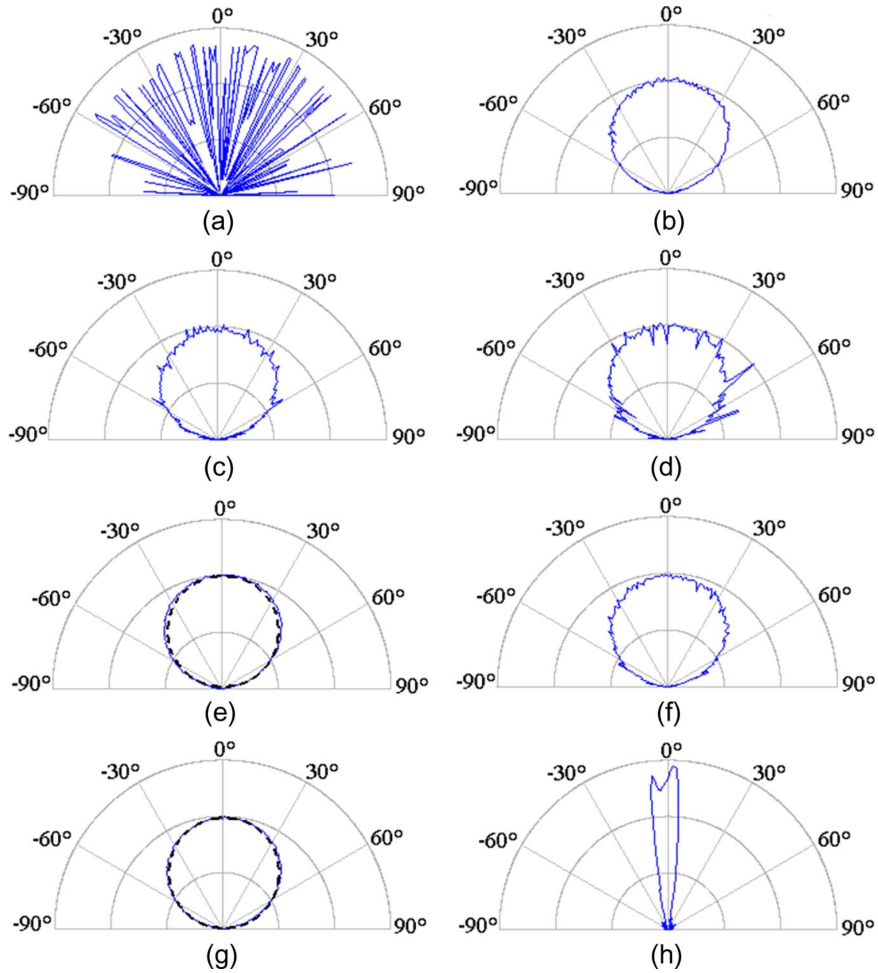

Fig. 14. Measurement results from the system with the different optoelectronic sensing circuits, for the calibrating light source, and a LED under test. (a) One-stage PD amplifier without the feedback capacitor for the zero-biased mode. (b) Capacitor $(\mathrm{Cf} = 7\ \mathrm{pf})$, yielding the condition of no gain peaking and a maximum bandwidth, for the same mode. (c) Capacitor $(\mathrm{Cf} = 3\ \mathrm{pf})$ remaining the same condition for the reverse-biased mode. (d) Two-stage amplifier $(\mathrm{Cf} = 5\ \mathrm{pf})$ under the same condition for the reverse-biased mode. (e) Performing the computer averaging for ten times measurement at each rotational angle, where the dash lines stand for the spatial radiation pattern of an ideal diffuser for the above part (b) condition. (f) Performing the same computer averaging for the above part (d) condition. (g) Having the compensation for the deviation from linearity for the above part (e) condition. (h) Measuring the LED for the above part (g) condition.

TABLE III
COMPARISON OF THE NOISE-REDUCTION PERFORMANCE FOR VARIOUS DESIGNS OF THE PD AMPLIFIERS

No	Design of PD amplifiers	Mean squares errors (MSE) of measurements*	
		One time with respect to (w.r.t) 50 times	10 times w.r.t 50 times
1	The one-stage amplifier with zero-biased mode	0.08154	0.03003
2	The one-stage amplifier with reverse-biased mode	0.13061	0.07152
3	The two-stage amplifier with reverse-biased mode	0.22911	0.09233

* Differences of the measured-data averages from the corresponding ones of the 50 times measurements.

held after this course. Each contained about twenty students who took this course. Both groups were individually coordinated by two members of the Center of Research for Educational Evaluation and Development in the authors' university. The asked questions for the groups are partly listed as follows.

- Do you think that with the help of raising issues, the progressive learning activities are beneficial to discussing with each other, and then to proposing a design?
- Do the learning activities assist you in identifying, formulating, and solving the problems in the project?

TABLE IV
SCORING RULE AND THE GRADES EVALUATED FROM THE FIRST 46 STUDENTS

No.	Methods		Weight	Mean score	Standard deviation
1	Quiz for the theoretical review		10%	80.1	8.4
2	Functionality evaluation and team report for the project tasks (on group basis)	Task 1	15%	86.3	5.3
		Task 2	15%	80.7	6.0
		Task 3	15%	82.1	4.8
		Task 4	15%	81.3	7.5
3	Peer evaluation for participation		10%	88.5	4.1
4	System functionality* (10%) and final report (10%, on group basis, including documentation, written report, oral presentation)		20%	83.6	5.7

** Scoring on the system functionality is focused on the measurement accuracy. Full points are given to the proposed systems with the measurement errors less than 5%.

TABLE V
EVALUATION OF THE OPINIONS FROM THE FIRST 46 STUDENTS

Questions	Average*
1. Do you think you have benefited from the course?	8.6
2. Do you think the knowledge and skills from the course are useful after graduation?	8.3
3. Do you recommend other students take the course?	8.0
4. Do you think the material handed out was adequate and appropriate for the proceeding of the project?	8.5
5. Do you believe the project will be relevant to your future?	8.2
6. Do you think the progressive design learning in the project increased your understanding in electronics?	8.7
7. Do you think the progressive design learning in the project increased your skill in developing electronic circuits?	8.5
8. Overall, how difficult did you feel for the project (the high score means more difficult).	7.2
9. Overall, how interesting did you feel for the project (the high score means more interesting).	8.2
10. Overall, how would you rate this project?	8.1

* Learners evaluate each item in 0–10 points, where 10 is the highest.

- Do you feel that progressively adding testing points in the design process is helpful in efficiently implementing and troubleshooting your work?
- Is the schedule of the guideline appropriate for the progressive approach?
- Does this project enable you to gain insight into optoelectronic sensing techniques?

The first four questions are introduced to investigate whether Difficulities 1–4, as mentioned in Section II-B, are resolved. For instance, some of the students thought their microelectronics backgrounds were weak before they took this course. This course enhanced their knowledge and skills in the design and development of electronic circuits. In addition, many of the students felt that this project gave them a real-world experience in optoelectronic sensing system developments. However, they also felt that the optics-related material should be introduced earlier in the curriculum. As expected, most of their opinions for the previously mentioned questions are quite positive and satisfactory.

B. Discussion

From the previously mentioned assessment results, the instructors felt that the students made significant progress in communication and presentation skills. In particular, the assessment of the focus groups further convinced the instructors that the proposed approach helps students gain knowledge and skills in optoelectronic sensing systems, and give them an industry-related experience. Peer evaluations are combined with instructors' assessment for individual team work to give each student a proper score on his or her performance. In the learning activity, even though Tasks 1 and 2 of the project are performed by individual team members, the achievement of the project belongs to the whole team. This step can make them collaborate with each other. Also, students are encouraged to do so, through peer evaluation of the scoring rule.

The educational objectives have been achieved by the proposed approach and are briefed as follows.

- The tasks progressively guide students from basic principles to practical applications. For example, the task of

developing the PD amplifier helps students to gain more knowledge and skills on improving the circuit stability.
- Students' presentation skills are improved by persistent practice, peer evaluation, and feedbacks.
- The industry-related skills, such as cooperation in a group and project management, are also enhanced.

However, some of the students pointed out that their work load was increased. The instructor tried to reduce the work load by offering proper assistance (e.g., providing design templates and related examples). In the future, to lower the work load further, two teams may collaborate with each other to implement one optomechanical subsystem.

V. Conclusion

In the project, the objectives of this paper have been achieved. The spatial radiance measurement systems from students have been developed through the enhanced PBL. One can see that their knowledge and skills for electronic systems and instrumentation have been enhanced by the progressive design approach. Through this project, students have experienced the processes of electronic hardware/software design, simulation, implementation, system integration, testing, and verification, according to the progressive design. In addition, this project has offered students the opportunity to practice their communication skills, to collaborate in groups, and to do some project management. Furthermore, this approach has been designed to motivate students' learning and develop the required knowledge and skills for a future professional capacity.

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