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PAPER

Learning-by-Doing Approach to Teach Microcontroller Course with Portable Training Board

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ABSTRACT

Microcontroller education is attracting increasing attention owing to the widespread application of microcontroller-based systems. This study proposes the learning-by-doing approach. Rather than emphasizing a deep understanding of datasheets and register-level programming, the new teaching model focuses on microcontroller-based applications. During the pre-class, in-class, and post-class phases, students were instructed to practice writing subroutines or building circuits to interface external devices with a training board. A typical case study is presented to illustrate the detailed process of the proposed model. Feedback from students and teaching supervisors in the recent years has shown that the teaching approach coupled with the training board provides students with more opportunities to work on real equipment, which benefits both the grasp of the theoretical knowledge and improvement of practical skills.

KEYWORDS

microcontroller course, teaching approach, learning-by-doing, training board

1 INTRODUCTION

Microcontrollers have become increasingly prominent in various aspects of life. They are widely adopted as fundamental components in many contemporary electronic devices and can be found in a range of household, industrial, and commercial products, such as automobiles, robotics, washing machines, microwave ovens, and toys. According to almost all reports, the global microcontroller market is expected to expand at a high compound annual growth rate in the coming years. The increasing demand for microcontroller engineers in the job market serves as a catalyst for increased enrollment in microcontroller courses. These students require a microcontroller and, therefore, it is necessary to make significant efforts to improve the teaching quality of microcontroller courses [1].

The project-based learning (PBL) approach, which has been in use for several years, has often been employed in microcontroller teaching because of its ability to engage students in developing self-directed learning skills. Using real-world projects, students

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gain theoretical knowledge and practical skills related to microcontrollers during their designated project periods [2]. Metri et al. introduced a PBL-based model for microcontroller laboratory applications. Students were divided into groups and required to complete mini design projects using 8051 or other open-source hardware. Course evaluations by students, staff, and external examiners have shown that this teaching model benefited the development of students' design and technical skills [3]. By implementing smart parking, gardens, homes, and cities, students at L. N. Gumilyov's Eurasian National University learned to solve real-world problems [4]. It is widely believed that a microcontroller classroom in PBL helps students gain a deeper understanding of the background and applications of microcontrollers [5, 6].

Another teaching strategy that has attracted attention in the field of microcontroller teaching is the flipped classroom [7]. For example, Wu redesigned an embedded systems course using this new approach. Students completed preparatory tasks using short video lectures or other content-rich materials before coming to class and then participated in discussions, exercises, or projects during the onsite class session. Preliminary implementation showed that flipped classrooms provide effective ways to facilitate critical thinking in active learning in the classroom [8]. The microprocessor course at East Carolina University is taught using a flipped classroom approach. Students have more opportunities to ask questions and complete learning activities. The instructors reported that, besides the course concepts, the leadership of the students involved had been improved by preparing the class, helping other students learn, and asking questions [9]. Many student surveys and interview data have revealed that the flipped classroom format improves students' learning performance and increases their cognitive and affective engagement in classes [7, 10].

Over the past few years, teaching styles have undergone a paradigm shift because of the COVID-19 outbreak [11]. Educational institutions have had to transform all existing courses, including the microcontroller course, into a fully online format [12, 13]. Online learning techniques have contributed significantly to maintain continuity in education [14]. In addition, online education has been reported to be attractive because of the reduction in transport and accommodation costs, and the flexibility of acquiring education. This also provides a solution to the problem of physical infrastructure limitations [15]. However, unlike many other courses, a microcontroller course typically involves theoretical and practical training. Students are expected to not only acquire the theoretical knowledge of microcontrollers but also gain many practical skills that are usually taught with development boards in hardware laboratories. However, during the COVID-19 pandemic, it was difficult for universities to provide access to such laboratories owing to the lockdown rules.

An ideal solution to this issue is to use remote online laboratories. Using a computer website, students can remotely access real hardware anywhere at universities [16]. Raczyński implemented a workstation for remote laboratory classes in the fields of microcontroller programming and electronic circuits. The workstation enables students to access the existing equipment at universities. Students can conduct the required classes on the workstation, in addition to using it as a supplementary way to improve their programming skills outside of class [17]. Mahmood et al. proposed an AT89C51-based training kit designed to work with real components. All students, even in remote rural areas, can conduct IoT projects electronically anywhere and at any time [18]. Svatos introduced STM32-microcontrollers-based improvised instruments (SDI) that cannot provide measurements with top-class parameters but are sufficient for electronics classes at universities. Students conduct circuit experiments on a breadboard and present the results to lecturers using an SDI screen. With SDI, lecturers can understand the experimental procedure and provide effective instruction to students [19].

All the abovementioned studies have contributed significantly to the teaching of microcontroller classes and are beneficial to students' learning; however, most studies divide the teaching of microcontrollers into two stages. That is, students first take the theoretical classes and then conduct experiments in the laboratory or online. Considering the practical and experimental nature of microcontrollers, a better method would be to teach courses in a learning-by-doing way [20]. It is widely believed that the learning-by-doing strategy helps the students better understand the microcontrollers [11]. The most challenging situation in this approach is conducting experiments on actual hardware. To address this problem, some instructors resort to the simulation software like Proteus [21, 22]. In this study, we introduced a portable development board that is inexpensive and empowers all the students. Using this board, students can conduct experiments anywhere and at any time. Another contribution of this work is that pedagogy combined with the development board ensures that course learning outcomes are not affected by situations such as COVID-19, when students cannot attend the university.

The remainder of this paper is organized as follows. Section 2 provides the general design of the development board, and Section 3 describes the detailed teaching strategy. In Section 4, a typical case is provided, followed by Section 5, which illustrates the feedback from the students and teaching supervisors. Finally, Section 6 concludes the study.

2 DESCRIPTION OF MICROCONTROLLER TRAINING BOARD

Various microcontroller training kits are available in China; however, most of these methods are complex, bulky, and expensive. Most students cannot afford them, which limits their pre-class and post-class activities on these kits. Additionally, these training kits were not suitable for online teaching during the COVID-19 pandemic.

Therefore, we designed a training board to address these limitations, as shown in Figure 1.

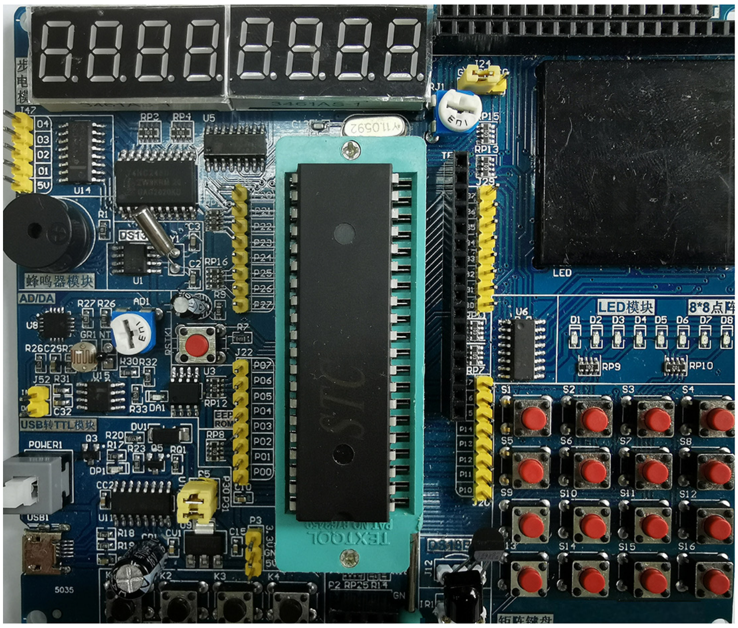


Fig. 1. Image of microcontroller training board

The board provides sufficient resources for students to learn, such as digital input and output ports, serial interfaces (SPI, I2C, UART, and USB), motor control (stepper motor, brush motor, and RC servo), and external sensor circuits. Table 1 presents the board's resources in detail. It allows for easy storage in the laboratory and portability. Power is supplied by a USB connection, which is also used for onboard programming. Input/output (I/O) pins are connected to the terminals such that the expansion function is easy to realize. The training board can be used to complete assignments in addition to conduct experiments for other individual projects.

Owing to the portability of the training board, students can carry it anywhere. In addition, the experiments can be conducted by connecting them to a personal computer, and no additional equipment is required. Therefore, the board satisfies the requirements for easy access. It allows the students to verify their understanding and improve their skills in actual hardware components at various stages of pre-class, in-class, and post-class learning. It is noteworthy that during a lockdown, the training board can prevent the students from being affected, even when they are isolated in dormitory rooms or at home in remote rural areas.

Table 1. Training board resources

Resources	Specifications
System power	Powered by external components through the voltage input pin or computer through the USB connector. One power switch to select 3V or 5V voltage for microcontroller. No additional power is needed for onboard devices to operate
Microcontroller	Placed on a 40-pin socket, to ease the changing of the microcontroller. Support AT89S52/AVR/STM serial microcontrollers
Reset circuit	Designed for 8051-based microcontroller and compatible with AVR series microcontrollers
In-circuit serial programmer (ISP) interface circuit	Download program to flash ROM of microcontroller
Push buttons	8 user programmable push buttons
Keypad	4 × 4 matrix keypad
LED indicator	10*1 independent LED, which can be used for experiments of water lamp or traffic light
Led matrix	16*16 single color LED, which can be used to display number, character, or graph
Graphic LCD	Support LCD9648, MiniLCD12864, or TFT LCD panel
Character LCD	Support LCD1602 or LCD9648
7-segment displays	Two 4-bit 7-segment display driven by 74HC245
External EEPROM	AT24C02, 2048 bits serial EEPROM with SPI interface
Infrared (IR) transmitter and receiver	Standard 38 kHz transmitter and receiver for IR remote control system
Real-time clock	DS1302 with battery backup using coin cell battery
Digital sensors	DS18B02 or DHT11 for experiments on temperature or humidity measurement
ADC/DAC convertor	Including XPT2046, LM358, etc., for sampling analog voltage

(Continued)

Table 1. Training board resources *(Continued)*

Resources	Specifications
UART communication	9-pin D-type connector, a direct connection to computer/laptop with MAX232 for communication
USB communication	Connect the board to PC via USB port using CH340, a small USB to TTL adapter
Wireless communication	NRF24L01 providing the cheapest wireless communication
Extensive communications	Providing interface to extensive peripherals including WiFi module, Bluetooth module, or GPS module
Buzzer	One programmable buzzer as sound indicator
Relay output	One 5 V, 1 A relay output
Stepper motor	One stepper motor, unipolar, 1.8 degrees per step
DC motor driver	One DC motor, 5 V operated, rated current: 40 mA, rated Speed: 80 RPM

3 TEACHING MICROCONTROLLERS USING LEARNING-BY-DOING APPROACH

3.1 Teaching approach

A flipped classroom, which is a state-of-the-art teaching method, is applied in the microcontroller course [8, 10]. The class is composed of three main phases: pre-class, in-class, and post-class. In every phase, students' learning is embedded in the activities involved with the training board so that they can develop knowledge and skills through hands-on experience. Then the performance of "learning-by-doing" is achieved.

Figure 2 depicts the teaching process of the approach employed to teach the microcontrollers course at Shaoxing University.

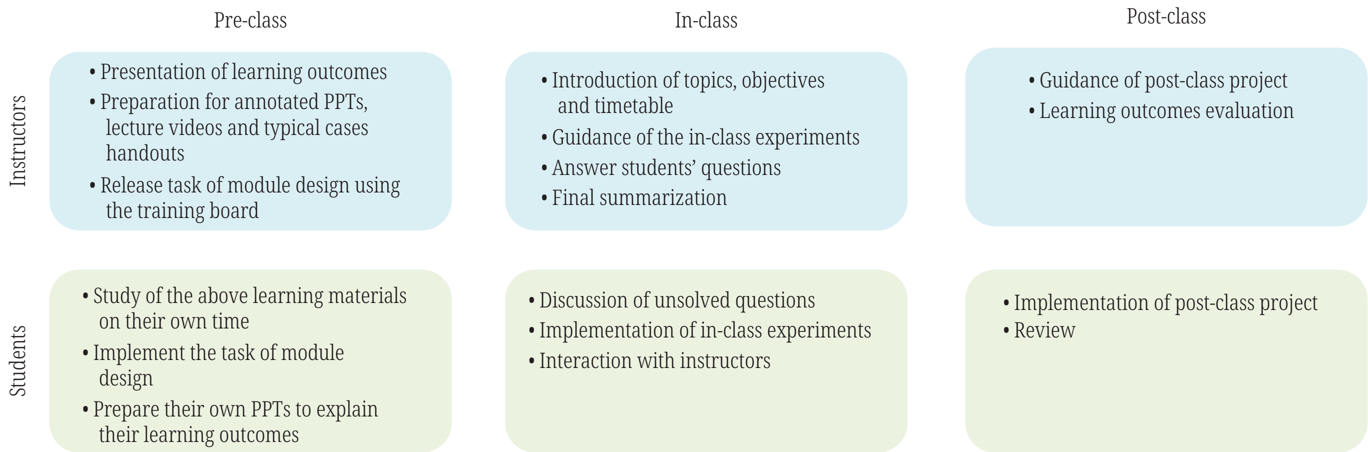


Fig. 2. Graphical illustration of teaching process

In the pre-class section (approximately one week before class), instructors released the learning outcomes of the chapter, provided study materials, and assigned the module design task through the Chaoxing Learning App (developed by

Beijing Chaoxing Digital Library Information Technology Co., Ltd., China). The materials included annotated PowerPoints (PPTs), lecture videos, and typical handouts. Students were required to study the study materials on their own and implement the pre-class labs with the training board, which mainly involved the knowledge and skills that appeared in the previous chapters but were essential for the next chapter.

One difficulty in teaching microcontrollers using this approach is that some students are unable to learn the content effectively on their own because of their poor self-regulatory skills. Teachers should focus on pre-class student preparation. If students do not perform pre-class work, the entire plan of this approach fails [23]. Therefore, students' learning statuses should be monitored using the Chaoxing Learning App. In addition, teachers should remind, record, and encourage students who lag behind in completing their learning tasks by the deadline.

During the class session, the instructor provided a brief outline of the lecture. Students were asked to present and discuss their own PPTs within the pre-assigned groups. Students then collaborate in groups to implement the in-class labs under the guidance of teachers. The training board is the main equipment in the in-class labs so that the students can practice the theoretical knowledge they mastered in the pre-class section. Because the students have completed pre-class labs that involve knowledge of previous chapters, they can only concentrate on the knowledge of the current chapter during the in-class activities. Over the past three years, teaching practices have demonstrated that this teaching process is effective in improving the in-class learning efficiency.

During the in-class phase, the interaction between the teacher and students is vital to learning. If students face problems, they should notify their teachers immediately, who would then clarify their doubts. Teachers should guide the students from other groups in solving this problem.

In the classroom, teachers are responsible for helping students rather than delivering information. Students must govern their learning pace by conducting hands-on labs, rather than by consuming the material presented to them in a more passive manner.

In the post-class stage, independent laboratories were assigned to provide students with an agile way to be creative and responsive to the complexity of real engineering problems. To complete these independent laboratories, students must apply their knowledge of theoretical concepts to the design scheme, construct a circuit system using a training board, and program a microcontroller. After completing these labs, students were required to submit their experimental results, including the circuit schemes, C language programs, and videos depicting the procedure of the experiments, to the Chaoxing Learning App.

For students with excellent results, senior design projects are assigned as additional practices that help them conceive, design, and develop microcontroller-based projects. These senior design projects are inherently interdisciplinary and may involve motor control, the Internet of Things, robots, and power conversion. After completing these projects, students received a reward for their final exam scores. The advantage of this arrangement is that it enhances learner engagement and improves learning outcomes.

3.2 Illustrative example

In this section, the proposed teaching approach is illustrated using a typical microcontroller module consisting of timers and counters.

The 8051 microcontroller provides two 16-bit timers called Timers 0 and 1, which can be used as timers and counters, respectively. The learning outcomes were as follows.

- Understanding the operation of timers run and configuration of special function registers in the Timer module.
- Writing subroutines in C language to operate Timers for the given function.
- Gain hands-on experience of applying Timers in common engineering projects.

To achieve the above-mentioned learning outcomes, laboratories for the three different phases were designed, as listed in Table 2.

Table 2. Labs using the training board for 8051 timer

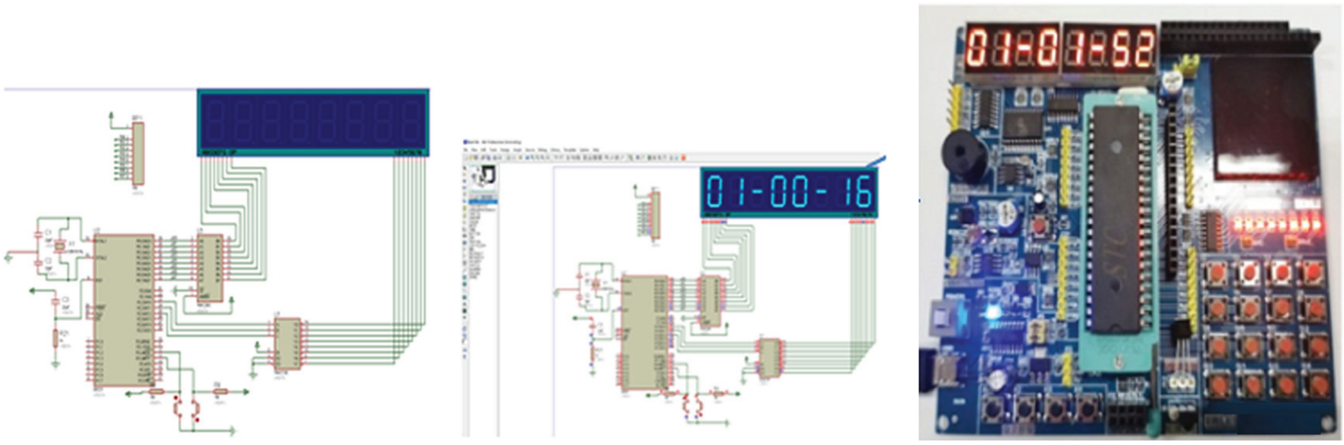
Type	Description
Pre-class labs	Manual control of water lamp using keys
	Seven segment LED display
In-class labs	Automated control of water lamp using Timer
	Count the external pulses
Independent labs	Traffic light control using Timer
Senior design projects	Real time clock using hardware Timer on 8051

The main purpose of the pre-class labs was to help the students review the essential knowledge of the previous chapters for the next class. In this section, the knowledge and application of the input/output ports are reviewed, because the value of the Timer registers needs to be demonstrated through LED or seven-segment LED, and external pulses are needed to conduct the 8051 counter labs. Therefore, we designed two pre-classification laboratories. Students were required to implement a water lamp manually controlled by keys and display numbers on the seven-segment LEDs. These two pre-class labs provide solid foundations for students to conduct subsequent labs during the in-class and post-class phases.

The in-class labs are mainly intended to help students understand the 8051 timer operation, learn to configure the special function registers regarding the 8051 timer, and gain the skills to write a C program to complete the given tasks. To achieve this goal, we guided the students to implement a water lamp controlled by an 8051 timer interrupt using the training board. In addition, we instructed the students to conduct a counter laboratory, in which the 8051 timer counted the number of external pulses. Students were expected to construct an understanding of both the timer and counter modes of the 8051 timers.

The independent lab in the post-class stage controls traffic lights using a timer interrupt. Students with excellent results are assigned to an additional lab of real-time clock design as a senior design project. The purpose of these laboratories is to help the students apply their learnings to address practical problems.

While conducting independent laboratory and senior design projects, students were required to follow the same step-by-step procedures, which are widely employed in real-world projects. First, a project plan is needed, in which the students clarify the project goals, desired outcomes, and main electronic components required. Subsequently, a circuit scheme is designed based on a deep understanding of the project outcomes. Therefore, validation of Proteus is required. The students constructed a circuit and debugged each code in the software. Validation can help students identify the design mistakes and easily implement labs on the hardware. Finally, the students tested their hardware and software designs using the training board. The goal is to ensure that the students gain the skillsets to fulfill the needs of the industry. Figure 3 shows the results of this inter-step; Figure 3a shows the design scheme of the real-time clock; Figure 3b illustrates the validation results for Proteus; and the hardware results are shown in Figure 3c.



a) Designed Scheme **b) Validation Result on Proteus** **c) Hardware Results**

Fig. 3. Inter-step results of senior design project of real-time clock

4 RESULTS OF PRESENTED TEACHING APPROACH

We began teaching a microcontroller course using this learning-by-doing approach in 2020, during the Covid pandemic outbreak. In the spring semester of 2020, 38 students participated in the course. The numbers in 2021 and 2022 were 51 and 37, respectively. At the end of each semester, feedback from the students and teaching supervisors was collected to ensure continuous improvement.

4.1 Feedback by students

At the end of each semester, student feedback and perceptions of the teaching approach were collected using the WeChat software. The questionnaire covered aspects of the teaching approach, training board, and arrangements of learning-by-doing labs. It contains 11 Likert-type items with 5-point scale (5 = strongly agree, 4 = rather agree, 3 = neutral, 2 = rather disagree, 1 = strongly disagree). The questions and average answers are presented in Table 3.

The survey revealed that students had an overall positive attitude towards both the teaching approach and training board. These results were also validated by the students' scores on the final exams. The learning-by-doing approach with the training board significantly increased the students' scores.

It is noteworthy that almost all the students who participated in the questionnaires strongly agreed that the training board provided more possibilities for studying real equipment in the context of online teaching, especially during the Covid-19 pandemic. Another important observation was that the last participant received the worst answer among all the questions. Conversations with some students revealed that senior design projects increased the students' burden. There is a plan to reduce the complexity of each project to make it more aligned with the teaching needs.

Table 3. Student feedback form with corresponding average answers

Questions	Average Answers		
	2020	2021	2022
The teaching model is satisfying as a whole.	4.2	4.2	4.6
The teaching model is suitable for online teaching as well as offline teaching.	4.4	4.6	4.3
The teaching model is helpful to promote learning motivation.	4	4.3	4.5
The training board is of great use in microcontroller training.	4.8	4.8	4.6
The portability of the training board provides more opportunities to study on real equipment for the online teaching.	4.9	5	5
The training board is at a good cost.	4.4	4.5	4.8
The training board and software are user-friendly.	4.5	4.3	4.6
The pre-class labs are helpful for the pre-class preparation.	4.5	4.1	4.2
The in-class labs contribute to the comprehension of knowledge.	4.4	4.7	4.5
The independent labs helps to gain more hands-on expertise.	4.3	4.4	4.4
The senior design projects contribute to improving practical skills.	4.1	4.2	4.1

4.2 Feedback by teaching supervisors

As per the Center for Teaching Quality Assessment requirements, three different teaching supervisors observed the classes and gave feedback at the end of each semester. All the supervisors had a positive attitude towards the teaching approach. Some typical comments were as follows:

- Students have more opportunities to study real equipment rather than working on a simulator or even passively observing.
- Students can carry the training boards with them; therefore, they have flexibility in selecting their learning time. Therefore, each student spends more time on the course.
- The teaching model shows greater advantages in developing the high-level cognitive abilities.

5 CONCLUSION

A learning-by-doing approach for teaching a microcontroller course coupled with a portable training board was proposed in this study to improve the practical skills of students. The course comprised three main phases. In each phase, students conducted hands-on labs or projects on a training board. The training board introduced in this study is portable and inexpensive. It can be distributed to students. Therefore, students have more opportunities to study real equipment even during the COVID-19 pandemic, when access to hardware laboratories on campus is hampered.

The proposed approach has been applied for three years and has received positive feedback from both students and teaching supervisors. This motivated students to spend more time on their learning activities and contributed to a deep comprehension of microcontroller applications.

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