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Applying Project-Based Learning and an Integrated Laboratory Platform to Teach Internet of Things*

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With Internet of Things (IoT) becoming ubiquitous, there is an enormous need to train IoT engineers. Owing to multidisciplinary nature of IoT, it is a big challenge to expose engineering students to both theoretical knowledge and practical applications. Firstly, this paper presents an integrated IoT laboratory platform, which allows students to explore all aspects of IoT technology, such as embedded systems, 4G communication, wireless sensor networks (WSNs) and RFID. Then, by combining project-based learning (PBL) with three-phase pedagogy, a three-phase project-based learning (TPPBL) method is proposed to offer students a progressive learning path from understanding IoT knowledge through lectures, to practicing IoT knowledge through experiments, and to creating IoT knowledge based on their own ideas. Since autumn 2020, the proposed TPPBL method using the integrated platform has been implemented at an IoT course in Central China Normal University. Evaluations of educational results for pre-test (using traditional method) and post-test (using TPPBL) show that the proposed TPPBL has significantly improved students' final grades and self-efficacy, which prepares them for becoming future IoT professionals.

Keywords: Internet of Things (IoT); three-phase pedagogy; project-based learning (PBL); laboratory platform; multidisciplinary; engineering education

1. Introduction

The Internet of Things (IoT) is gaining global attention. Technologies like 4G/5G mobile communications, RFID, embedded systems, wireless sensor networks (WSNs) and GPS are making IoT a reality, which will have a transformative effect on our society and life [1–5]. Therefore, there is an enormous need to cultivate the coming generation of engineers in the field of IoT [6, 7]. However, the multidisciplinary nature of IoT makes it difficult to expose engineering students to both theoretical knowledge and practical applications [8].

In response to this challenge, universities and institutions all over the world are exploring all kinds of teaching methodologies for training IoT students [9, 10]. However, most of existing literatures focus either on designing new pedagogical model or developing applicable laboratory platform, few of them investigate both pedagogical method and the design of experimental platform. According to these two aspects, Table 1 summarizes and compares typical literatures on IoT education, and explains them in what follows.

Guo et al. [11] developed a small-scale IoT testbed for studying security and smart manufacturing, and reported two industrial IoT case studies using this testbed. However, their pedagogy is not given in detail.

Akbar et al. [12] proposed a low-cost technology-based learning system for undergraduates and postgraduates to learn IoT, which enables students to implement industrial standard IoT application. Unfortunately, the evaluation of their educational results is somehow ignored.

By using IBM Cloud and Raspberry Pi, Nykyri et al. [13] presented an IoT demonstration platform, called Cafe IoT, for education and research. Hands-on experience with this platform brings students definite advantages that may be difficult to achieve. Nevertheless, it seems that this platform is mainly used for IoT research rather than IoT education.

Ishihara et al. [14] proposed an educational curriculum to construct an IoT prototype system that can be achieved even by liberal arts students. However, this curriculum only involves the knowledge and technologies of perception layer in IoT architecture.

Byrne et al. [15] described a four-day wearables and IoT hackathon for encouraging pre-university teenagers to pursue careers in STEM (Science, Technology, Engineering, and Mathematics), which can be effective in motivating the self-efficacy

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Table 1. Comparison of typical literature on IoT education

	Pedagogical model				**Laboratory platform**			
	Contains project-based learning?	**Is the pedagogical method progressive?**	**Combination of theory and practice**	**Evaluation of the educational results**	**Covers all aspects of IoT technology?**	**Easy to use**	**Offers corresponding software resources?**	**Supports many different interfaces?**
Guo et al. [9]	No	No	Yes	Without	No	Maybe	NA	NA
Akbar et al. [10]	Yes	Yes	Yes	Without	Yes	NA	Maybe	No
Nykyri et al. [11]	Maybe	No	Yes	Without	Yes	Yes	Maybe	Yes
Ishihara et al. [12]	No	Yes	Yes	Without	No	Yes	NA	No
Byrne et al. [13]	No	Yes	Yes	Inadequate	No	NA	NA	NA
Hussein et al. [14]	No	Yes	Maybe	Without	NA	Yes	Yes	No
Shi et al. [15]	NA	NA	Yes	Without	Yes	Yes	Yes	Yes
Raikar et al. [16]	Yes	Maybe	NA	Inadequate	NA	NA	NA	NA
Bistak et al. [17]	Yes	Yes	Yes	Inadequate	Yes	Yes	Yes	Maybe
Karvinen et al. [18]	Yes	Yes	Yes	Limited	Yes	Yes	Yes	No
The proposed TPPBL	**Yes**	**Yes**	**Yes**	**Adequate**	**Yes**	**Yes**	**Yes**	**Yes**

of adolescents. However, this hackathon is based on 21st-century learning model, not project-based learning (PBL).

By using an online OLYMPUS platform, Hussein et al. [16] developed a crowdsourced peer learning activity to guide learners to think more deeply about IoT products and their design decisions. But this learning method should be extended to university level to support more formal IoT education.

Shi et al. [17] explored and discussed the IoT MOOC (Massive Open Online Course) education, namely "DIY Smart House", implemented at Zhejiang University, which establishes a good bridge between theoretical knowledge and practical applications for IoT learners. However, literature [17] mainly focuses on the arrangement of IoT MOOC and the hardware design of DIY products, while lack of the description of its pedagogical method.

Raikar et al. [18] shared the experience of teaching IoT as an elective course and proposed a framework for including IoT as a regular course in the undergraduate curriculum. The proposed framework prepares students for industry needs according to recent trends and enhances the quality of engineering education at the undergraduate level. Nevertheless, no laboratory platform is used in [18], which may bring difficulty for students to apply theoretical knowledge to practical projects.

Bistak et al. [19] introduced and evaluated an IoT course using a Raspberry Pi based remote-controlled car. This IoT course is an interesting example that adopts PBL approach to make students understand the basics of IoT and implement a simple IoT project. Regrettably, it is not clear that to what extent the course can improve students' IoT skill, because the comparison of students' grades before and after using the course is missing.

Karvinen et al. [20] presented a setup for rapid IoT prototyping by using an Arduino Uno development board and a computer, which accelerates the learning cycle of IoT prototyping skills for novice students. However, the Arduino Uno only offers USB and GPIO interfaces, which may restrict the exploration of hardware aspects. Besides, the analysis of educational results for their proposal is limited.

This paper proposes a three-phase project-based learning (TPPBL) method for IoT education using an integrated laboratory platform, that allows students to understand the whole structure of IoT, to experiment with all sorts of hardware and software of IoT, to practice IoT projects and to create IoT prototypes. Our main contributions are:

1. We design and implement an integrated IoT experimental platform which has the following advantages: (a) easy-to-use; (b) offers many different interfaces to connect peripheral devices or Internet; and (c) allows engineering students to explore all aspects of IoT technology such as embedded systems, 4G mobile communication, WSNs and RFID;
2. We develop corresponding open-source software resources for all hardware parts of the proposed platform, which provide students with the availability to develop their innovative programs and imitate various real-world IoT systems;
3. By combining PBL method with a progressive three-phase pedagogical model [21], we propose a TPPBL method and design a TPPBL IoT course, which enables students to make progress gradually from understanding IoT knowledge through lectures, to practicing IoT knowledge through experiments, and to creating IoT knowledge based on their own ideas.

The rest of the paper is organized as follows. Section 2 describes the system architecture of the proposed experimental platform. Section 3 introduces the design of the TPPBL IoT course at Central China Normal University (CCNU). Section 4 demonstrates some teaching cases in the IoT course. Section 5 discusses the educational results. Finally, Section 6 concludes the paper and presents our future work.

2. System Architecture of the Proposed Integrated Platform

2.1 Overview

Generally speaking, IoT is one type of Network of Things (NoT), with its "things" connected to the Internet by some sensors. So it is difficult to be bounded because it is changing constantly. People and organizations would like to build NoTs that solve their specific problems or interests rather than discuss primitives and elements of IoT. Based on the understanding of IoT and pedagogical thought, an integrated IoT experimental platform is designed and its system architecture is shown in Fig. 1.

Pioneered by [22], Table 2 categorizes many components of the platform into five IoT primitives: sensor, aggregator, communication channel, external utility and decision trigger. Usually, sensors feed aggregators, and aggregators execute on various external utilities (such as phone, tablet and PC), then communication channels, such as wireless

Table 2. Components category of the proposed integrated platform

Category	Components	Description
Sensor	SHT11 Sensor	Collecting temperature and humidity data
	Gas Sensor	Acquiring air quality data
	. . .	. . .
	RFID Module	Reading and writing IC/ID Card
	GPS Module	Getting location information
Aggregator	ZigBee Nodes	Transforming raw data from sensor into an intermediate form
	ZigBee Coordinator	Coordinating all ZigBee Nodes by establishing a WSN
Communication channel	4G Module	Using LTE technology to realize 4G mobile communication
	Router	Connecting ARM board with the Internet
	Serial and Ethernet Cable	Wired channel between different components
	2.4G Wireless Communication	Wireless channel between ZigBee Nodes and ZigBee Coordinator
	WiFi/Bluetooth Module	Communicating with Router or nearby Bluetooth devices
External utility	PC/Phone	Hosting various logical IoT components
	CC-CCNU	Knowledge sharing, collaboration and discussion forums
	Database/Server	Storing educational big data for further analyzing and processing
Decision trigger	ARM board	Making a final decision to meet an IoT's need

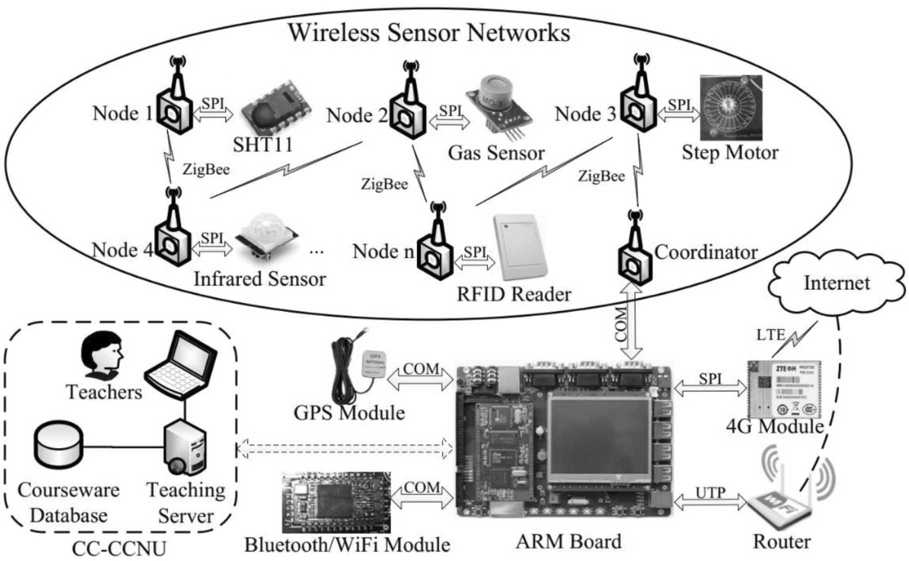


Fig. 1. System architecture of the proposed integrated platform.

or wired, are the veins and arteries that connect sensors, aggregators, external utilities, and decision trigger with the dataflow between them. Lastly, the decision trigger creates the result to satisfy an IoT's purpose and requirements. The descriptions for main components follow.

2.2 ARM Embedded System

The brain of the proposed platform is an ARM embedded development board, which is designed as a flexible structure of daughter-mother-board. Therefore, it is easy and fast to upgrade. The daughterboard features a Samsung's S5PV210 Cortex-A8 processor with 8*1GBytes DDR2 SDRAM and 4GBytes NAND Flash. And the motherboard offers 7 serial ports (including 3 RS232 and 4 TTL), 3 USB Host and 1 USB OTG, 1 Ethernet port, CAN, RS485, HDMI, LCD touch screen, Audio, Camera, ADC and more other peripherals.

Furthermore, the ARM board is a ready-to-run platform, which supports for various popular operating systems such as Linux, Android and WinCE.

2.3 Communication Channels

The proposed platform integrates a variety of wired and wireless communication channels, which ensure all kinds of data can securely and reliably transmit, process, and implement in an IoT. On the one hand, wired channels involve USB cable, serial wire, Ethernet cable and so on, which use to connect ARM board with ZigBee coordinator, PC and router. On the other hand, wireless channels contain WiFi/Bluetooth module, 4G module, GPS etc. WiFi/Bluetooth module is used for communication with router or nearby Bluetooth devices. And 4G module realizes 4G mobile communication by using LTE technology. In addition, GPS antenna provides comparative precise geographic information by receiving coordinate signals from four GPS satellites.

Therefore, the stable communication among all components of the platform is guaranteed, which allows students to imitate all operations of an IoT system, for example, remote control, and real-time location and so on.

2.4 WSNs & RFID

A WSN involves a lot of ZigBee nodes with various sensors (such as SHT11, HC-SR501 and MQ-3) or actuators (such as USB fan, step motor and DC motor), which can design some independent WSN systems.

Every ZigBee node integrates a TI's CC2530 microprocessor with 256KB Flash and 8KB SRAM, and is available for online debugging. So it is really helpful for students to train their programming skills and problem-solving abilities.

In addition, a RFID Card Reader for both 125KHz ID and 13.56MHz IC is placed in WSN area of the platform, which works under two alternative modes (Wiegand 26/34) with a 9–15V power supply range, and has a short reading/writing delay. Thus, students can perform RFID-based entrance guard experiments and apply RFID technology to practical applications like car anti-theft system, library management and so on.

2.5 Cloud Classroom

Based on dual coding and flipped classroom theories, advanced technologies like cloud computing, big data and P2P streaming media are utilized to create a flexible user cloud port, namely the cloud classroom of Central China Normal University (CC-CCNU [23, 24]) for knowledge sharing, teacher-student interaction and discussion forums. Hence, it helps students communicate with teammates, get support from instructors, share and demonstrate laboratory results with others.

3. Design of the TPPBL IoT Course

PBL (project-based learning) is an effective student-centered teaching method that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem [25, 26]. By combining three-phase pedagogy with PBL approach, we propose a TPPBL method and design a TPPBL IoT course based on the integrated laboratory platform for electronics and information engineering students at CCNU.

3.1 Teaching Objectives

The aim of this TPPBL IoT course is to encourage students to acquire [27]:

(1) *Domain knowledge* – ability to understand and design IoT systems;
(2) *Technical skills* – hardware design, software frameworks, programming languages and protocols;
(3) *Soft skills* – communication, team cooperation and management abilities.

In order to achieve above teaching objectives, a progressive learning path of the IoT course is conceived, which enables students to make progress gradually from transferring IoT knowledge, to practicing IoT knowledge, and to creating IoT knowledge, as shown in Fig. 2. Based on this step-by-step learning path, we design a TPPBL pedagogical model for the IoT course, with its pedagogical goals and sample topics summarized in Table 3.

Table 3. A TPPBL pedagogical model for the IoT course

Phase	Pedagogical Goals	Sample Topics
Phase 1: Transferring IoT Knowledge	• Ramp-up time and fundamental knowledge review; • Understanding IoT architecture; • Preparing students for experiments.	• Review circuits and programming knowledge; • Introduction of Internet of Things; • Installing development environments.
Phase 2: Practicing IoT Knowledge	• Teaching factual knowledge and practicing knowledge; • Cultivating hands-on and independent thinking abilities.	• Single-node flow-water LEDs experiment; • Construct a WSN system using several ZigBee nodes; • Design a simple temperature-adaptive IoT system.
Phase 3: Creating IoT Knowledge	• Developing and creating innovative projects; • Collaborative design and sharing knowledge.	• Design a basic embedded system; • Develop a friendly GUI; • Create a DIY IoT system.

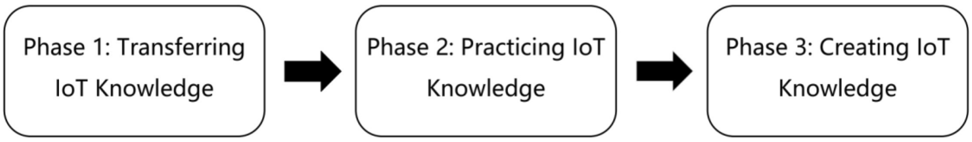


Fig. 2. Learning path of the IoT course.

Table 4. Couse content of the IoT course

Phase	Week	Task
1	1–3	1. Introduction of Internet of Things 1.1 The overview of IoT 1.2 The architecture of IoT 1.3 The core technologies of IoT 2. Review basic knowledge 2.1 Analog and digital electronic technology 2.2 C/C++ programming 3. Install development environments 3.1 IAR Embedded Workbench 3.2 TI Stack & Debugger driver 3.3 SmartRF Flash Programmer 3.4 SecureCRT & VMware Workstation 3.5 Altium Designer 3.6 Qt Creator
2	4–7	4. Single ZigBee node experiments 4.1 Flowing-water LEDs 4.2 Keyboard scanning 4.3 External interrupt 5. Wireless Sensor Networks experiments 5.1 Measurement of temperature and humidity 5.2 Body heat releasing infrared ray detection 5.3 Gas/Flame/Rain sensor demo 5.4 Wireless measurement of vibration 5.5 Wireless control of digital tube and buzzer 5.6 Wireless control of relay and fan 5.7 Wireless control of stepper motor 6. Design a simple IoT system based on the platform 6.1 Design a temperature adaptive IoT system 6.2 Design a RFID-based entrance guard IoT system 6.3 Design a GPS-based location tracking IoT system
3	8–12	7. Design a basic embedded system 7.1 Transplanting u-boot 7.2 Tailoring Linux kernel 7.3 Building root file system 8. Develop a friendly GUI 8.1 Cross-platform GUI design 8.2 Qt-based network programming 9. Create a DIY IoT project 9.1 Smart home 9.2 Green agriculture 9.3 Energy-saving lighting

3.2 Course Content

According to the TPPBL pedagogical model described above, the contents of the IoT course are well-organized, as shown in Table 4.

Phase 1 aims at warming students up, reviewing fundamental knowledge and understanding architecture of IoT systems. Hence, during week 1–3, teaching tasks are: (a) finish the introduction of IoT by lecturing IoT overview, IoT architecture, IoT core technologies and typical applications; (b) review basic circuits and programming knowledge; (c) configure necessary development environments such as IAR Embedded Workbench, Qt Creator and Altium Designer; and (d) teach students how to operate the proposed integrated platform correctly.

Phase 2 asks students to practice IoT knowledge gained in Phase 1, intended to cultivate their hands-on and independent thinking abilities. Therefore, during week 4–7, teaching tasks mainly include: (a) guide students to perform single ZigBee node experiments using lab manuals; (b) ask students to perform WSNs experiments by themselves using several ZigBee nodes; and (c) ask students to independently design a simple IoT system based on the platform.

Phase 3 encourages students to create their innovative IoT systems by collaborative design and sharing knowledge in groups of five or six classmates. During week 8–12, they should: (a) design a basic embedded system; (b) program a friendly GUI; and (c) develop some practical DIY IoT projects, such as smart home, green agriculture, energy-saving lighting and so on.

3.3 Evaluation Criteria

This TPPBL IoT course intends to help students appreciate the fundamental theory taught in the classroom and gain the knowledge and experience in practical applications. Hence, the *Project* in Phase 3 is a very significant part of the whole IoT course, determining 50% of the final grade. At the end of the semester, except for the final examination, all groups must give a presentation to introduce their system design, unique features and work division. Then, all group members will attend a quiz and defense their understandings of the respective works. And a brief demonstration of the designed system is required to show its basic functionality and extra features. Finally, individual students have to submit a course report to describe their products and summary their contributions.

The final grade is a numeric score, from 0 to 100 (60 or above is a passing grade), calculated by summing weighted percentages, as follows.

- 30% – The overall functionality of the design (Part 1).
- 20% – The robustness of the IoT system and the accuracy of its performance (Part 2).
- 25% – Final examination (Part 3).
- 15% – Oral presentation (Part 4).
- 10% – Course report (Part 5).

4. Teaching Cases in the IoT Course

In this section, some teaching cases are selected to offer the details of the proposed TPPBL IoT course that allows students to understand IoT knowledge, to practice IoT knowledge and to create IoT knowledge.

4.1 Phase 1: Understanding IoT Architecture and Operating the Proposed Platform

At this teaching case of Phase 1, teaching objectives are: (a) understand IoT architecture; (b) get familiar with the proposed laboratory platform; and (c) configure IoT development environments.

In order to help students better understand IoT, an auxiliary textbook, written and published by our team in 2017 [28], is used for this course. With the help of this textbook, students can clearly understand that general IoT architecture usually consists of three layers:

1. Sensing Layer – using technologies like RFID, Sensor Networks and image recognition to realize information collection, event capture and identification of "things".
2. Network Layer – a bridge between Sensing Layer and Network Layer, which is responsible for efficiently, stably, real-time and securely transmit upper or lower layer data.
3. Application Layer – consists of Application Support Sublayer (ASS) and IoT business applications. ASS mainly includes public middleware, information open platform, cloud computing platform and service support platform, while IoT business applications are involved in many fields, such as green agriculture, smart city, home automation and so on.

4.2 Phase 2: Practicing a Simple IoT System Based on the Platform

At this teaching case of the Phase 2, teaching objectives are: (a) practice single ZigBee module and some sensors; (b) construct a WSNs-based IoT system using several ZigBee modules; and c) use ARM board to display and control different ZigBee modules.

This case began with single-module experiments, such as flowing-water LEDs, keyboard scanning and external interrupt, which served as foundations of the following WSNs experiments. After that, students managed to build a simple constant-tem-

Fig. 3. Prototype of the constant-temperature control IoT system using the proposed integrated laboratory platform.

perature control IoT system by using an ARM board and five different ZigBee modules (① temperature-humidity module; ② digital tube module; ③ relay module; ④ step motor module; ⑤ coordinator module), as shown in Fig. 3.

Fig. 4 shows the software flowchart of the constant-temperature IoT system. Firstly, temperature-humidity module measures temperature data and sends them to coordinator module. Then, coordinator module transmits the temperature packets to 7-segment digital tube module for real-time display. At the same time, coordinator module will decide whether to adjust temperature or not. For instance, if the temperature is higher than 28, in order to reduce the temperature, relay module will be activated to turn on the fan while step motor module will be driven to rotate forward to open the window. And if the temperature is lower than 18, in order to increase the temperature, relay module will be deactivated to turn off the fan and step motor will rotate reversely to close the window. Furthermore, ARM board is used to display and control these sensors or actuators except coordinator.

4.3 Phase 3: Some Examples of Creating IoT Systems

At this teaching case of Phase 3, teaching objectives are: (a) develop the creativity of designing new IoT projects and (b) cultivate soft skills such as teamwork and management ability. Hence, during the Phase 3, students are encouraged to choose their own teammates and distribute individual tasks.

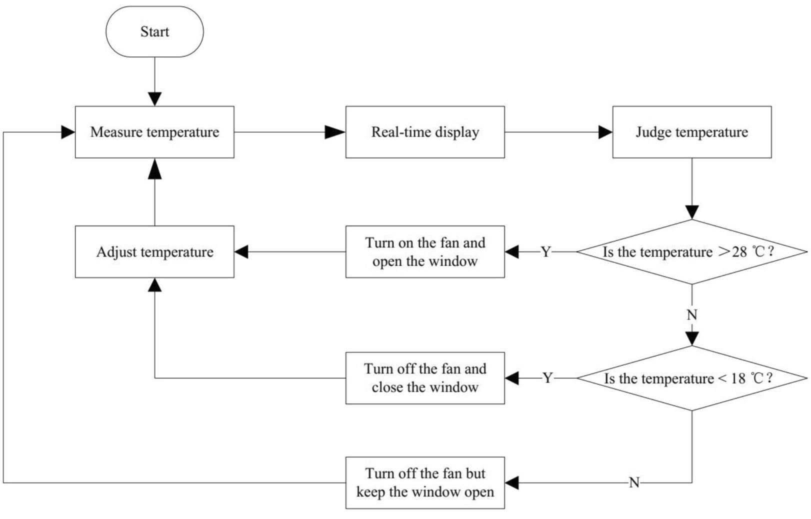


Fig. 4. The software flowchart of the constant-temperature IoT system.

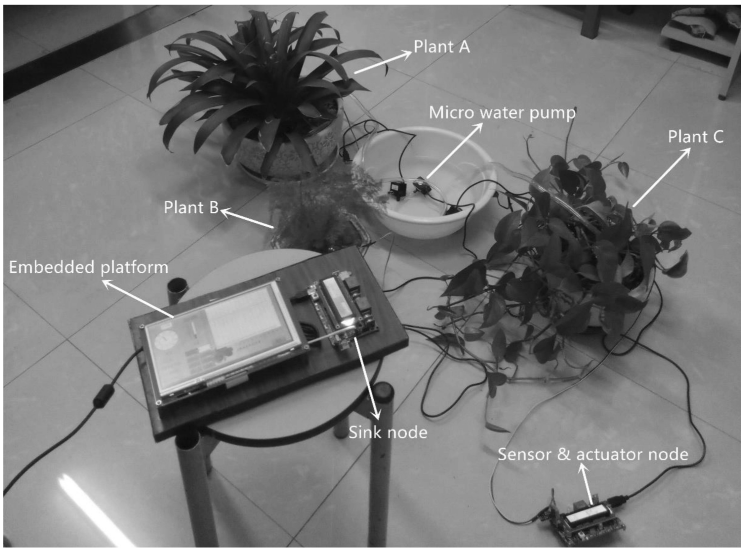


Fig. 5. IoT prototype of Smart Gardener.

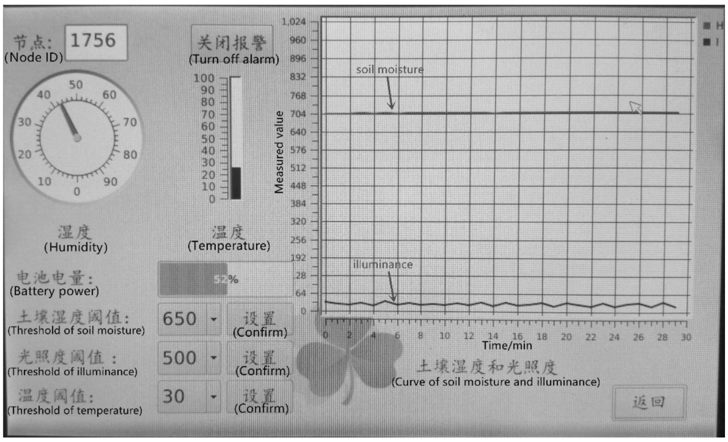


Fig. 6. GUI of embedded platform of Smart Gardener.

Each team is asked to use all sorts of sensors, devices and components from market to create some DIY IoT systems and apply them to practical applications like smart home, green agriculture, energy-saving lighting. There are two representative examples, as follows.

(1) Smart Gardener

In this project, the goal was to create an automatic IoT irrigation system that can help us water our plants at the perfect time and take good care of them when we are unavailable. In response, a team developed an intelligent plant-irrigation IoT system named "Smart Gardener", as shown in Fig. 5. Smart Gardener mainly includes the following functions: (a) collect various ambient parameters such as temperature, humidity, illuminance and soil moisture of each plant; (b) send these collected data to an ARM embedded system through WSNs for further processing and analyzing; (c) use a simple expert control strategy to make a final decision and automatically water the plants when needed.

Fig. 6 shows the GUI of embedded platform of Smart Gardener. It can be found that the intuitive data visualization of different environmental information of plants is successfully achieved. Besides, users can also adopt this friendly GUI to set the threshold value of various ambient parameters as well as know the residual battery power to exchange batteries in advance.

Fig. 7 shows the change of soil moisture of Plant A. According to the growth characteristics of Plant A, the target value is set as 600, while the upper and lower threshold is set as 650 and 550, respectively. We can see from Fig. 7 that soil moisture gradually decreases with time, and once soil moisture is lower than 550, Plant A will be watered automatically.

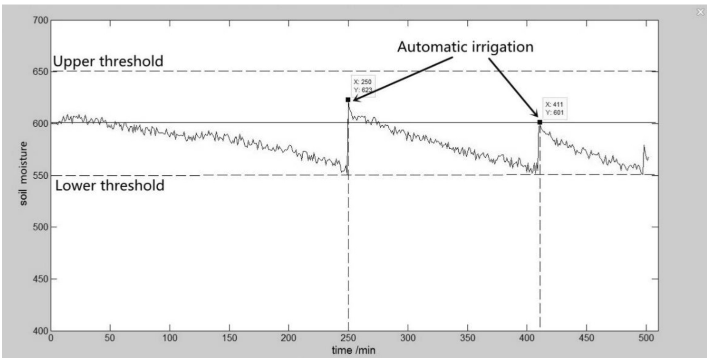


Fig. 7. The change of soil moisture of Plant A.

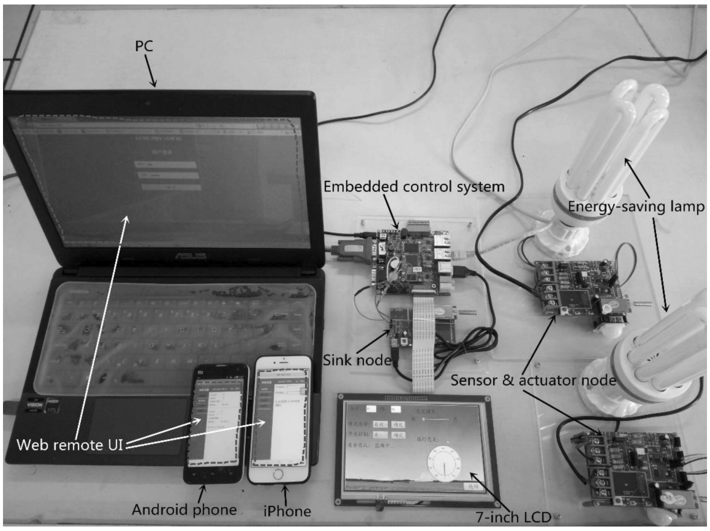


Fig. 8. IoT prototype of Smart Streetlights.

(2) Smart Streetlights

In this project, the goal was to create an energy-saving lighting IoT system that can realize the energy conservation and fault self-diagnosis of lamps. In response, a team designed an intelligent lighting IoT system called "Smart Streetlights". As shown in Fig. 8, Smart Streetlights mainly includes: (a) two sensor & actuator nodes, each equipped with a 85W energy-saving lamp; (b) a sink node that wirelessly communicates with two child nodes by using a SI4463 radio module; (c) an ARM embedded control system with a 7-inch LCD; (d) compatible Web GUI for various operating systems such as Windows, Android, Linux and iOS. Furthermore, the main functions of Smart Streetlights are: (1) to automatically turn on or off the lamps according to ambient parameters (Day or night? Is there someone passing by?); (2) to automatically report the location and the ID number of the broken lamp; (3) to use a variety of devices (such as mobile phone, PC or tablet) to remotely monitor and control the status of a specific streetlight.

Fig. 9 shows a simple Web remote UI of Smart Streetlights on an Android phone. By using an arbitrary Web browser to login the server, clients can conveniently change control mode (including automatic or manual control), monitor the status of two streetlights (see Fig. 9(a)) and adjust the desired illuminance value of each streetlight (see Fig. 9(b)).

Similarly, this UI can also perform on a PC, as shown in Fig. 10. We can see from Fig. 10 that the No. 11 streetlight in group 1 is working normally, with its current illuminance 403. And that the natural luminance of the position this lamp locates is changing along with time. By viewing and analyzing the changing trend of natural luminance within a period, we can timely set reasonable illuminance threshold and adjust control strategy, so as to realize the energy-saving lighting of streetlights.

5. Results and Discussion

The key objective of this TPPBL IoT course is to place at the core of the fourth-year curriculum at

Fig. 9. Web remote monitoring UI of Smart Streetlights on an Android phone: (a) environment monitoring, (b) luminance adjustment.

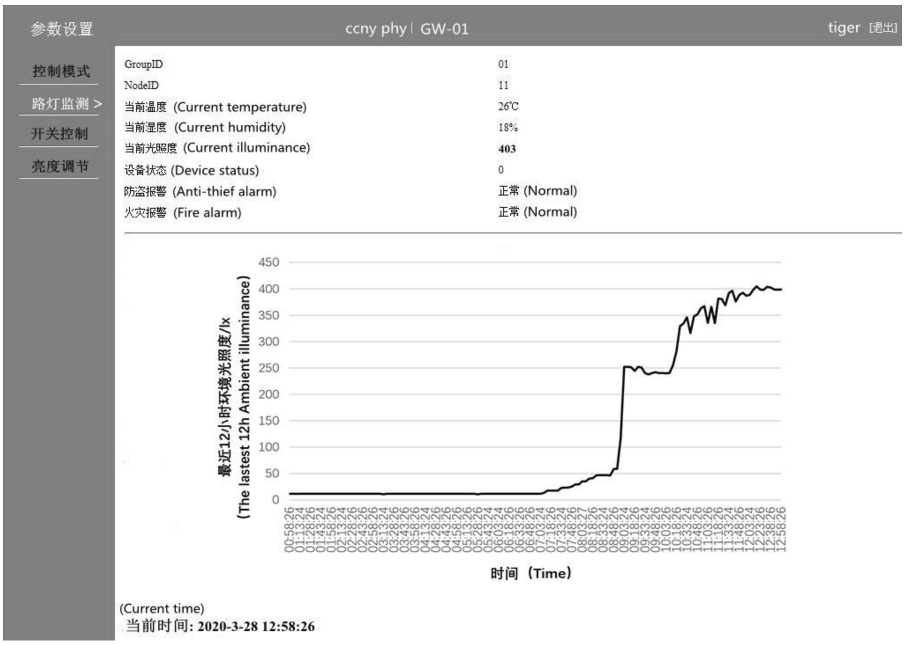


Fig. 10. Web remote monitoring UI of Smart Streetlights on a PC.

the Department of Electronics and Information Engineering of CCNU, and prime senior students to meet the coming challenges in their career. Moreover, this course also teaches undergraduate students at the College of Computer and Information Technology of CTGU (China Three Gorges University). Since autumn 2020, the IoT course has served 220 senior students. In order to analyze the effectiveness of the proposed TPPBL approach, we use pre- and post-test design. For pre-test group (students in 2019), we used traditional lecture and experiment based learning (LEBL) method to train students. While for post-test group (students in 2020 and 2021), we adopted TPPBL method. And we surveyed and analyzed the academic records from the IoT course under two teaching methods, and collected both quantitative and qualitative feedback from senior students in CCNU.

According to the evaluation criteria in subsection 3.3, we compared and analyzed all students' final grades from pre-test group (using LEBL, in 2019) and post-test group (using TPPBL, in 2020 and 2021), respectively, as shown in Fig. 11. The results show that when using LEBL, only 26% of students earn more than 80, but when using TPPBL, at least 70% of them score more than 80. That is to say, students using TPPBL achieved higher final grades, compared with traditional LEBL. Fig. 12 compares students' average final grade and its constituents before and after introducing TPPBL. We can see from Fig. 12 that after introducing TPPBL approach into previous IoT course, final grades significantly increase, with an evident climb of Part 1 and 2, but a humble raise of Part 3–5.

To investigate the impact of students' performance in project on their final grades, we adopted Pearson correlation analysis method. In 2021, the total number of senior students who participated in this course is 117, divided into Class 1 (55 students) and Class 2 (62 students). Fig. 13 shows the correlation between project grades and final grades for two classes. Note that project grades (Part 1+Part 2) earned in Phase 3 were on a range from 0 to 50, while final grades were on a range from 0 to 100. It can be seen from Fig. 13 that the project grades greatly affected their final grades. The Pearson correlation coefficient on these two sets of data for Class 1 and 2 is 0.799 and 0.775, respectively, reflecting a strong positive correlation. Thus, students who perform better in project will confidently get higher final grades.

In order to further explore the advantages and drawbacks of the proposed TPPBL, we designed two questionnaire surveys (namely Questionnaire A and B) and collected students' feedback. Specifically, one is used to validate the effectiveness of TPPBL, another for finding its future improvement points. Table 5 summarizes the quantitative feedback on the IoT course received from the students during 2019-2021. We can see from Table 5 that the percentage of respondents in 2019 (using LEBL), 2020 (using TPPBL) and 2021 (using TPPBL) is

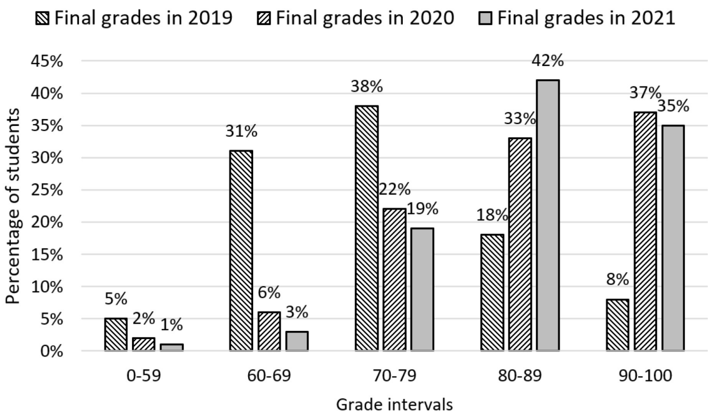


Fig. 11. Comparison of final grades distributions for students using LEBL (in 2019) and TPPBL (in 2020 and 2021).

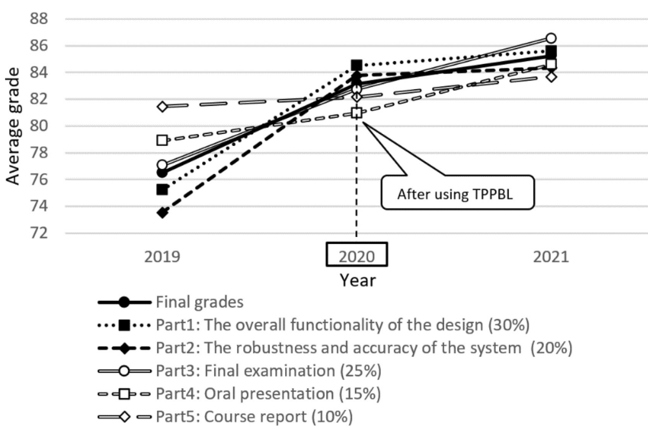
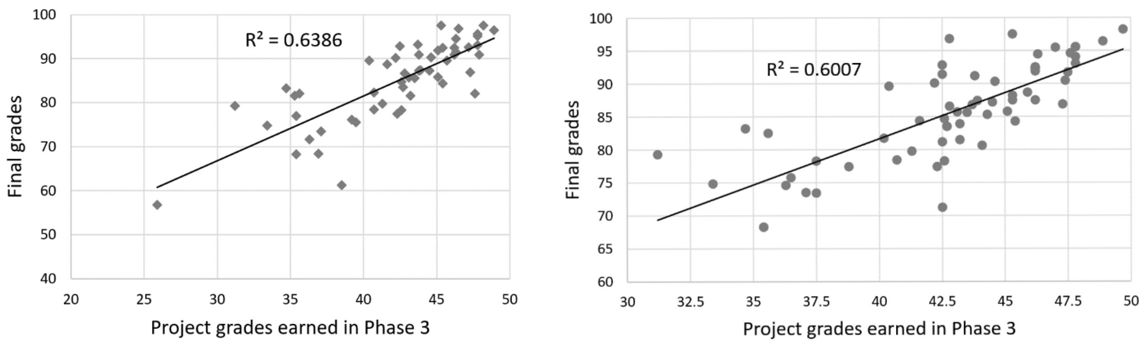


Fig. 12. Comparison of average final grade and its constituents before and after introducing TPPBL.



(a) (b)

Fig. 13. Correlation between project grades and final grades: (a) Class 1, (b) Class 2.

Table 5. Quantitative feedback on the IoT course received from the students during 2019-2021

Course name	**Internet of Things Technology**		
Year	2019	2020	2021
Teaching method	LEBL	TPPBL	TPPBL
Questionnaire used	A	A and B	A and B
Number of students	89	103	117
Number of respondents	58	76	94
Percentage of respondents	65.17%	73.79%	80.34%
Cronbach's Alpha of Questionnaire A	0.774	0.756	0.781

65.17%, 73.79% and 80.34%, respectively. This means most of students have answered the questionnaires, thus guarantee the coverage and fairness of questionnaire results.

Furthermore, in order to validate the reliability and rationality of "Questionnaire A", some statistical analysis regarding Questionnaire A is performed by using IBM SPSS software. The Cronbach's Alpha of Questionnaire A in 2019, 2020 and 2021 is 0.774, 0.756 and 0.78 (see Table 5), respectively, meaning that the designed 11 questions in Questionnaire A have good internal consistency.

According to reference [29], engineering students' self-efficacy related to IoT should be evaluated from five different perspectives: *Algorithms*, *Programming skill*, *System architecture*, *Creative design* and *Collaborative ability*. As a result, "Questionnaire A", composed of 11 statements (e.g., "Basic programming principles can be learned easily" and "I enjoy cooperating with others to finish IoT projects"), was designed and delivered to pre- and post-test group. As shown in Table 6, the answers of Questionnaire A were in the form of a 5-point Likert scale [30], [31]: 5, I completely agree; 4, I mostly agree; 3, I have no idea; 2, I mostly disagree; and 1, I completely disagree. Please note that $\bar{x}$ is mean value and δ is standard deviation.

Obviously, students' perceptions related to programming skill, system architecture and creative design are positive (most of scores regarding Question 3–9 are bigger than 3), while their opinions on algorithms are negative and receive the lowest average score (1.26 in 2019; 1.38 in 2020; and 1.42 in 2021). In order to clearly demonstrate the improvement of students' self-efficacy, we extract and compare the average score (originated from questionnaire results in Table 6) according to above-mentioned five perspectives, as depicted in Fig. 14.

We can observe from Fig. 14 that students' self-efficacy on programming skill, system architecture and creative design increases the most significantly, which means this TPPBL IoT course is an efficient teaching method for helping students better master IoT domain knowledge and cultivate their IoT technical skills. Hence, teaching objective 1 and 2 in subsection 3.1 are well satisfied.

In addition, we can also find that the self-efficacy on collaborative ability achieves a humble raise. In other words, students' soft skills such as teamwork cooperation and management abilities are also somewhat developed, which achieves teaching objective 3 to a certain extent. However, the average score regarding algorithms remains a low level, that is, it is still relatively difficult for students to acquire the ability to understand and design algorithms, because this IoT course mainly focuses on training students' practical abilities while algorithm related knowledge is theory oriented.

In order to further improve the proposed TPPBL method, "Questionnaire B", as listed in Table 7, was designed to evaluate students' impressions and attitudes towards the IoT course using TPPBL (in 2020 and 2021). The questionnaire results are presented in Fig. 15. It can be seen from Fig. 15 (a) that most respondents (around 80%) enjoy the TPPBL pedagogy as well as appreciate the flexibility and easy-to-use of the proposed integrated laboratory

Table 6. Results of Questionnaire A that evaluates students' self-efficacy under LEBL and TPPBL

Course name	**Internet of Things Technology**					
Year	**2019**		**2020**		**2021**	
Teaching methodology	**LEBL**		**TPPBL**		**TPPBL**	
Questions	$\bar{x}$	δ	$\bar{x}$	δ	$\bar{x}$	δ
Questions related to algorithm						
1. Basic algorithm knowledge can be understood	1.39	0.65	1.55	0.64	1.46	0.54
2. I can design algorithms that operate sensor data	1.13	0.61	1.21	0.57	1.38	0.60
Average of $\bar{x}_1$ and $\bar{x}_2$	**1.26**		**1.38**		**1.42**	
Questions related to programming skill						
3. Basic programming principles can be learned easily	3.12	0.70	4.29	0.76	4.17	0.45
4. Software resources are sufficient for performing IoT experiments	3.23	0.73	4.43	0.83	4.38	0.51
5. I can develop networked systems embedded in the physical world	2.97	0.48	4.03	0.50	4.11	0.56
Average of $\bar{x}_3$, $\bar{x}_4$ and $\bar{x}_5$	**3.11**		**4.25**		**4.22**	
Questions related to system architecture						
6. I can clearly understand IoT architecture	3.19	0.59	4.56	0.62	4.69	0.64
7. I can easily distinguish distributed and collaborative IoT systems	3.06	0.64	4.29	0.65	4.35	0.71
Average of $\bar{x}_6$ and $\bar{x}_7$	**3.125**		**4.425**		**4.52**	
Questions related to creative design						
8. I can design innovative programs and PCB	3.27	0.55	4.60	0.75	4.43	0.60
9. I can create practical IoT prototypes to solve real-world problems	3.01	0.68	4.14	0.92	4.36	0.73
Average of $\bar{x}_8$ and $\bar{x}_9$	**3.14**		**4.37**		**4.395**	
Questions related to collaborative ability						
10. I enjoy cooperating with others to finish IoT projects	2.31	0.61	2.95	0.58	3.19	0.57
11. It improves cooperation and communication abilities	2.15	0.65	2.56	0.69	2.77	0.51
Average of $\bar{x}_{10}$ and $\bar{x}_{11}$	**2.23**		**2.755**		**2.98**	

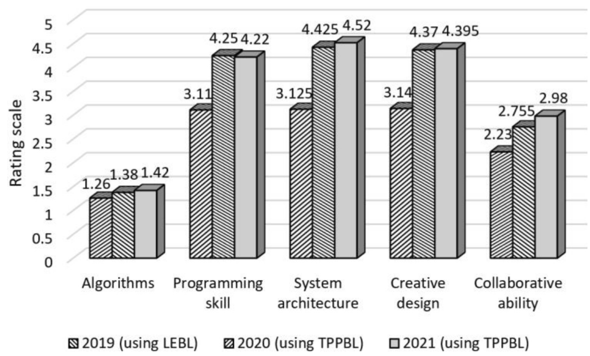


Fig. 14. Differences in students' self-efficacy under LEBL (in 2019) and TPPBL (in 2020 and 2021).

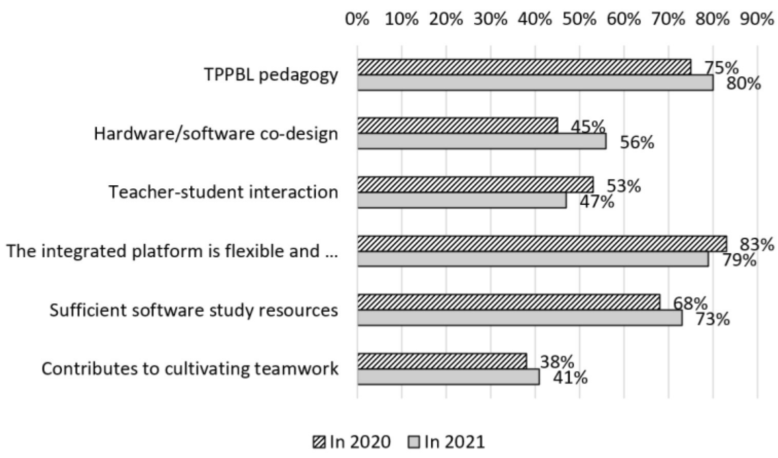
platform. Besides, approximately 70% of respondents believe the sufficiency of software study resources is another strong advantage for working on their IoT projects.

However, more than half of respondents feel that long training hours and the difficulty in debugging programs are two biggest negative factors of the course, as shown in Fig. 15 (b). Hence, next work is to consider properly shortening the training hours to alleviate their study load, and offering more straightforward demos before debugging complicated programs.

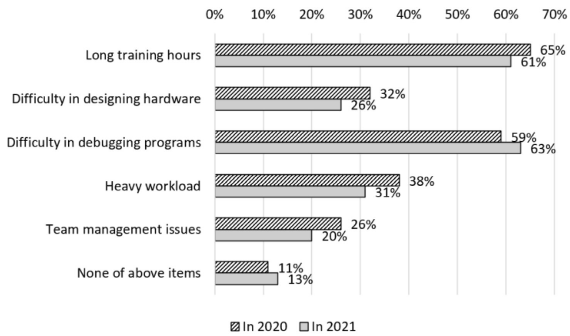
Regarding "Question 3" in Table 7, we received the qualitative feedback on the holistic IoT course based on the proposed TPPBL approach and the integrated lab platform. Most of answers are encouraging, but a minority of that still indicate further improvement could be made. And we randomly select some comments from respondents in different grade intervals, as follows.

Respondent 1 (within 90–100 scores): "This course is perfect. It teaches us a mass of knowledge about IoT and gives us the confidence to become future IoT engineers."

Respondent 2 (within 80–89 scores): "We do learn a lot about IoT, WSNs, RFID and embedded systems."



(a)



(b)

Fig. 15. Students rating of the various factors for the IoT course using TPPBL: (a) positive factors, (b) negative factors.

Table 7. Questionnaire B that evaluates students' impressions and attitudes towards the IoT course under TPPBL

Course name	**Internet of Things Technology**
Questions	**Answers**
1. Which of the following items are the advantages of the IoT course?	**Mark " √ " on below brackets (Multiple choices are allowed)**
A. TPPBL pedagogy	( )
B. Hardware/software co-design	( )
C. Teacher-student interaction	( )
D. The integrated platform is flexible and easy to use	( )
E. Sufficient software study resources	( )
F. Contributes to cultivating teamwork	( )
2. Which of the following items are the disadvantages of the IoT course?	**Mark " √ " on below brackets (Multiple choices are allowed)**
A. Long training hours	( )
B. Difficulty in designing hardware	( )
C. Difficulty in debugging programs	( )
D. Heavy workload	( )
E. Team management issues	( )
F. None of above items	( )
3. What is your overall impression towards the IoT course?	

Respondent 3 (within 70–79 scores): "This is a very amazing course because of the interesting IoT projects."

Respondent 4 (within 60–69 scores): "It provides maximum practical exposure of the IoT concepts and gives us a deeper understanding of IoT."

Respondent 5 (within 60–69 scores): "I feel difficult to understand Linux programing, maybe more embedded systems experiments should be offered to us."

Respondent 6 (within 0–59 scores): "This course is not bad, but I think the training time is very long."

Respondent 7 (within 0–59 scores): "I find it hard to create a DIY IoT system in Phase 3."

Qualitative comments of Respondent 5, 6 and 7 reflect the drawbacks of our proposal. In order to further optimize the proposed TPPBL IoT course, we will appropriately reduce overall training periods, increase the number of embedded systems experiments in Phase 2, and provide more design guidance in Phase 3.

6. Conclusion

This paper first presents an integrated laboratory platform for IoT learners that involves various software/hardware experiments. Then, based on this platform, a three-phase project-based learning (TPPBL) method is designed and implemented at an IoT course, namely TPPBL IoT course. Furthermore, some teaching cases in the IoT course are given to show how to transfer IoT knowledge, to practice IoT knowledge and to create IoT knowledge. Finally, assessments of educational results before and after introducing TPPBL show that students' final grades as well as their self-efficacy related to IoT are significantly enhanced, which means TPPBL can help them better master IoT knowledge and learn how to use IoT technology to solve real-world problems.

In the future, our team will introduce LPWAN technologies such as LoRaWAN and SigFox into the Phase 2 of our IoT course, upgrade the experimental platform, and provide more easy-to-understand demos and open-source projects for IoT students.

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