Freewheeling Electronic Laboratory Learning with Pocket Instruments

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***Abstract—Work in Progress*: This Innovative Practice Work-in-Progress Paper presents how a portable laboratory kit named *Pocket Instruments* has facilitated electronic laboratory learning in the undergraduate engineering programs. Traditionally, owing to the lack of necessary instruments at hand, students could only think abstractly and design on paper during pre-lab and post-lab time but could not physically work on their circuits outside the laboratories. Through the corresponding virtual instrument application software deployed on a laptop, the Pocket Instruments can act as a portable signal generator, an oscilloscope, a digital analyzer, and a spectrum analyzer, which makes it possible for students to experiment with electronic circuits freely outside the allocated laboratory time. The teaching practices in the engineering program of Tsinghua University for seven years have shown that such an always-available lab kit can achieve a measurable increase in students' engagement and achievement in experimental exploration. With the growing needs in online learning, the Pocket Instruments can also provide an effective means for distance learning of laboratory skill training.**

Keywords—portable lab kit, electronic circuit, laboratory learning, signal generator, oscilloscope

I. Introduction

As an indispensable part of undergraduate programs of electrical and computer engineering as well as other related engineering areas, electronic circuit laboratory is a critically important learning element to improve students' hands-on skills on circuit design, troubleshooting, and problem-solving. Up to now, most undergraduates experiment with circuits within the designated area of laboratories during preassigned time slots, where such general-purpose electronic instruments as a waveform generator, an oscilloscope, and a logic analyzer are ready for use in their turns. When leaving the laboratory with unfinished tasks and unsolved puzzles, students tend to feel frustrated and then desire to learn and try more. Owing to the lack of necessary instruments at hand, they could only think abstractly and design on paper but could not physically work on their circuits outside the laboratories during pre-lab and post-lab time.

By integrating the main functionalities of frequently-used electronic instruments, a portable lab kit named Pocket Instruments has been developed and refined in several editions since 2009. The motivation was to provide every student in our course with a low-cost portable electronics lab kit for their hands-on learning. Powered by the USB interface, the Pocket Instruments supplies several fixed powers and one programmable power for electronic circuits. Through the corresponding virtual instrument application software deployed on a laptop, the Pocket Instruments can act as a portable waveform generator, an oscilloscope, a digital analyzer, and a spectrum analyzer. With this portable kit, it becomes possible for students to carry out some tests and measurements on their circuits anytime and anywhere.

The Pocket Instruments has been put into practice in multiple courses at Tsinghua University since 2013. By distributing a set of Pocket Instruments to each student, laboratory learning is no longer limited by space and time. Through this teaching model, along with a measurable increase in students' interest and engagement in circuit experiments, enhanced hands-on skill and problem-solving abilities have been achieved.

Related work on similar portable lab kits can be found in [1]. The Georgia Institute of Technology has introduced experiment-based active learning into lecture-based courses, which allows students to do experiments at home or in the classroom. Effectiveness in enhancing the learning of fundamental concepts and in inspiring the students in the topics being taught was assessed. The Analog Discovery kit developed by Digilent Inc. has facilitated the teaching of analog circuit courses and the development of Hackster projects [2]. In [3], the model and approach of Lab@home for analog electronic circuit laboratory was introduced, which helps students develop the knowledge and competence on the subject, allowing them to develop their autonomy, creativity, and ability to innovate.

In designing such a portable lab kit, one of the key considerations is that it should be strongly related to course teaching. Both the functionalities and usage model should be suitable for students. Compared to other recent teaching practices using industrial products, a unique aspect of the Pocket Instruments is that the design and development was a joint work by instructors and students who are familiar with electronics laboratory teaching and learning. Dozens of undergraduates have benefited from an evolving series of projects centered around the Pocket Instruments. Second, based on the design experience accumulated over the years and editions, the overall and modular design of the Pocket Instruments was adopted as real-world case studies in multiple courses on digital and analog circuits. Third, open projects were proposed for students to enrich functionalities or improve the performance of Pocket Instruments. As an example, some students implemented an automatic data recorder as an extension to the intrinsic oscilloscope module. Laboratory training embodied in these projects has significantly stimulated the innovation and creativity of undergraduate students.

II. Pocket Instruments and Its Development

A. *The Usage Model of the Pocket Instruments*

In traditional electronic circuit lab teaching, the frequently used instruments for students to carry out their experiments include a DC power, a signal generator, and an oscilloscope. The DC power supply is the source of power for an electronic circuit, the signal generator generates and feeds signal of the prescribed waveform into the circuit for a particular experiment, and the oscilloscope is used to measure and display signals at different test points of the circuit.

The traditional duty models of these instruments are restricted to in-lab use only. To establish an always-available portable lab environment for students to do experiments anytime and anywhere, the proposed Pocket Instruments integrates instruments including the above three into one portable lab kit. The functionalities of the signal generator and oscilloscope are implemented through the interaction with a virtual instrument software on a laptop.

Fig. 1 illustrates the exterior design of the latest version of Pocket Instruments and its usage model. On the right-hand side of Fig. 1 (a), the USB port near the middle is used to communicate with the virtual instrument software on a laptop, and the left one is used for auxiliary power supply. The waveform of the signal generator is output from the “AO1” and “AO2” pin located in the left socket, and signals at test points are measured through connecting to the pins “AI1” and “AI2”.

When working with a specially designed breadboard, Pocket Instruments can be plugged into the right socket of the breadboard. First, students build a circuit on the breadboard. Second, they obtain the power supply from the DC output terminal of the breadboard. Third, by using the control panel of the virtual instrument software on the laptop, they can start the signal generator of Pocket Instruments and feed signal to the circuit through the “AO1” or “AO2” terminal. Finally, students use the embedded oscilloscope to measure signals of the circuit and display waveforms on the control panel.

The control panel of the signal generator and oscilloscope is also shown in Fig. 1. Parameters of these two virtual instruments can be input or altered through the text boxes, buttons, and knobs. The captured signal is displayed in the left waveform chart area of the oscilloscope control panel.

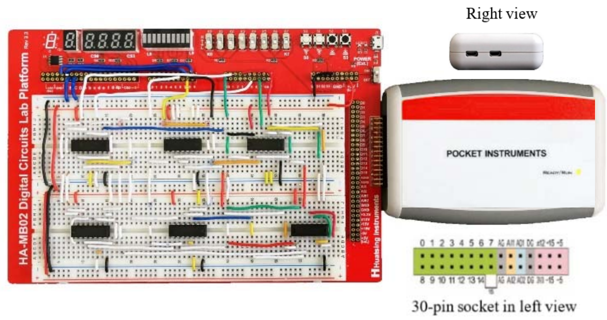
B. The Architecture of the Pocket Instruments

Fig. 2 shows the architecture of the first version of Pocket Instrument, illustrating the roles of the digital modules and analog circuits as well as the interactions between them. As shown in Fig. 2, the analog circuits and digital modules such as Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC) work together to implement functions of the Pocket Instrument.

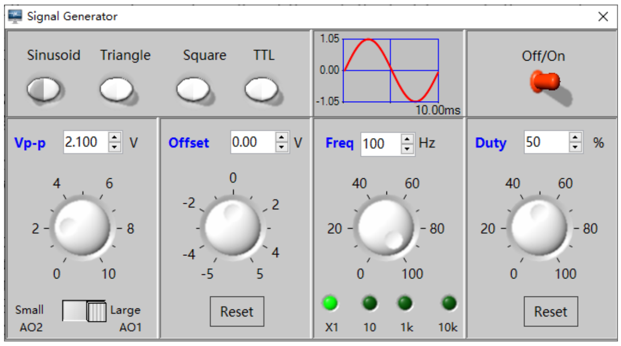
When the Pocket Instrument functions as an oscilloscope, the ADC first samples the input signal amplified by a Programmable Gain Amplifier (PGA). Then the sampled data is passed to an FPGA (Field Programmable Gate Array) for digital processing. After that, the processed data go through a USB interface, and the waveform of the input signal is plotted on the control panel of the virtual instrument software.

When the Pocket Instruments functions as a waveform generator, the user-defined waveform parameters are first passed from a virtual instrument software to FPGA through the USB interface. Then the FPGA-based digital processing module generates a series of waveform data according to these parameters and passes them to the DAC. The DAC converts the data into an analog signal, which is then output through an amplifier.

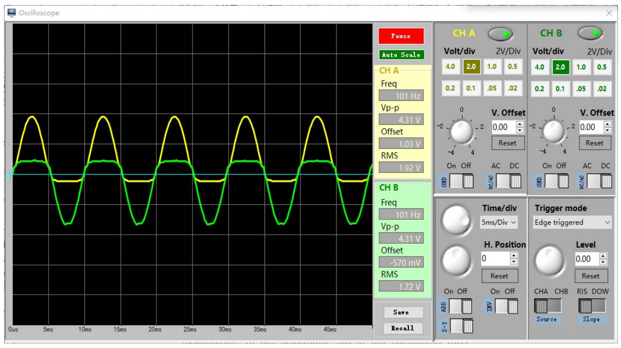
The above architecture was used as an application case study in the teaching of a digital electronics course at Tsinghua University. It helps students get an overall understanding of how a hybrid digital and analog electronic system performs and interacts. After the fundamental theory of ADC and DAC was taught in this course, the real ADC and DAC chips used in the Pocket Instruments were introduced in the class. Both external interfaces and internal modules were analyzed into detail, which helps students gain a better understanding of how a real ADC or DAC is implemented with up-to-date technology and how it is used in a real application.



(a) The Pocket Instruments connected with a breadboard



(b) The control panel of the signal generator



(c) The control panel of the oscilloscope

Fig.1. The Usage model of the Pocket Instruments.

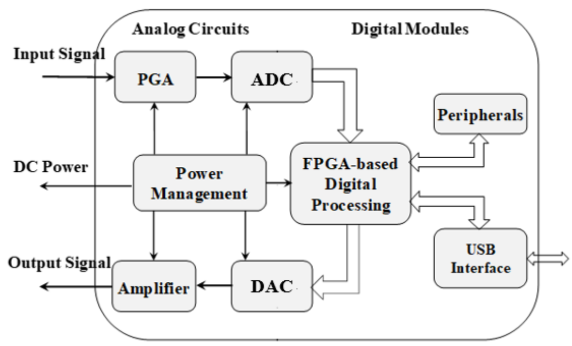


Fig. 2. The architecture of the Pocket Instruments.

C. *The Development of the Pocket Instruments*

The design and development of the Pocket Instruments itself was a continuous laboratory training project which had accumulatively involved dozens of undergraduates. Through their participation in this project, these students had got an opportunity to practice what they have just learned from the electronic courses.

The initial motivation came from the students' feedback on an electronic circuit laboratory course in 2009. As written by some of the students, it would be exceedingly desirable and helpful if they could have a portable lab kit to experiment with circuits whenever they wanted to. Based on this background, the Pocket Instruments was designed to cover the learning requirements of several electronic lab courses at Tsinghua University. Instead of pure pursuit for high performance, the specifications were designed to facilitate the related course teaching. The current Pocket Instruments is not designed for the test of the high-frequency circuit, although the practices and experiences developed through Pocket Instruments can be extended to developing a high-frequency version should there be a broad need in teaching and learning on such material.

At first, the instructor published an Undergraduate Student Research Training project on developing a virtual oscilloscope at Tsinghua University. Resonated by the same needs in electronic laboratory learning, student Yarui Peng joined the project and developed an FPGA-based virtual oscilloscope application [4]. We used an FPGA instead of a microcontroller so that we could implement a compact FPGA development board together with the Pocket Instruments. FPGA has become broadly adopted in digital electronics education in recent years. A development board with FPGA chip and necessary peripherals makes it easy for students to exercise FPGA-based digital system design. Based on this work, another student, Guangwei Tu, built an FPGA-based hardware platform in his graduation project in 2012 [5]. Based on this platform, the software part was fulfilled by Yifan Wu in 2013 [6]. As the real end-users of the Pocket Instruments, the students were competent to add some unique features to the software.

Today, students in multiple lab courses are encouraged to build new functionalities for the Pocket Instruments. Also, the submodules of the FPGA-based digital processing system are extracted as practical training exercises. Through such kind of exercises, students have an opportunity to practice what they have just learned from the electronics course. The performance of different implementations from students is evaluated and ranked. Motivated by the desire to surpass the existing implementation of the Pocket Instruments, students show high engagement in this practical training.

III. TEACHING PRACTICE

A. *Courses and Lab Items*

Since 2013, more than ten pilot runs have been done in some digital and analog electronics courses by delivering a set of Pocket Instruments to every student. Instead of having to do experiments in the electronics lab at the designated time, students can work on their lab assignments anytime.

Table I lists some of the lab items successfully performed via the Pocket Instruments, with the corresponding functions ticked. The first four experiments are with a digital electronics course and the rest with an analog one.

TABLE I. LAB ITEMS PERFORMED VIA POCKET INSTRUMENTS

Item Name	**Functions Used**		
	DC Power	*Signal Generator*	*Oscillo-scope*
Voltage Transfer Characteristics of NAND Gate	√	√	√
Propagation Delay of NAND Gate	√	√	√
Instantaneous Short-circuit Power Dissipation of NAND Gate	√	√	√
2-bit Binary Adder Circuit	√	√	√
DC Operating Point Configuration of Common Emitter BJT Amplifier	√		√
AC Characteristics of Common Emitter BJT Amplifier	√	√	√
Two-stage Amplifier	√	√	√
Negative Feedback Amplifier	√	√	√
Waveform Generator Circuit	√		√

For example, the four experiments with the digital electronics course are designed for an experimental measurement on the electrical characteristics of the NAND gate and binary adder circuit. Circuits are built on the breadboard and powered by the Pocket Instruments. The functionalities of the signal generator and oscilloscope are used to facilitate the measurement.

For the analog circuit course, the Pocket Instruments was used throughout the semester. After students built the analog circuit on the breadboard using the transistors, resistors, capacitors, and operational amplifiers, they could immediately test and verify it. Owing to the more flexible learning environment, they tend to do more from the experiments by self-exploration. For example, when working with the sinusoidal waveform generator circuit, one student found that the oscillation frequency of the waveform decrease with the increase of the output amplitude. Through a thorough measurement and theoretical analysis, he realized that it was due to the slew rate of the operational amplifier. Although the instructor did not assign the test of the frequency value corresponding to each output magnitude, the student put in extra effort and gained valuable insights first-hand.

Before the adoption of the Pocket Instruments, due to the limitations of in-lab learning time for each student, the instructors could only assign a small set of lab items for each course. With the aid of the Pocket Instruments, more lab items were added into the course, and in each lab item, more interesting elective experiments were designed other than the mandatory ones.

B. *Outcome*

With such a portable lab kit at hand, students are more active in doing experiments. During the pre-lab and post-lab time, when they have some thoughts on the tasks, it is convenient for them to test and verify instantly. Because they are no longer restricted to finish preassigned tasks in the limited in-lab hours, many students feel that hardware experiments become more exciting and attractive, and they are willing to explore more.

As the statistics for a digital electronics course shown in Table II, there has been a distinct increase since 2013 in students' extra effort on hardware exercises. For each experiment listed in Table II, students are required to complete the mandatory part and are encouraged to do further exploration in the elective part. In 2012 when students could only do experiments in preassigned in-lab sessions, on average, less than 20% of the 39 students made extra efforts

TABLE II. STATISTICS OF STUDENTS' EXTRA EFFORT IN DOING EXPERIMENTS

Year	Total Students Number	Extra Effort in Doing Elective Experiments				Average % of students who put extra effort	Average extra items per enrolled student	Notes
		NAND Gate Test		*Binary Adder*				
		Students	*Items*	*Students*	*Items*			
2012	39	7	7	8	8	19%	0.38	a, c
2013	42	9	9	21	31	36%	1.02	b, c
2014	37	12	12	14	21	35%	0.89	b, c
2015	32	22	54	23	34	70%	2.75	b, c
2016	118	76	124	79	130	66%	2.15	b, d
2017	98	78	151	80	142	81%	2.99	b, d
2018	135	124	238	120	232	90%	3.48	b, d
2019	155	140	270	135	260	89%	3.42	b, d

[a.] The Pocket Instruments were not available. [b.] The Pocket Instruments were available. [c.] Students from one digital electronics course. [d.] Students from two digital electronics courses.

on these experiments. A significant reason for the low participation of the elective experiments is that the two experiments were strongly dependent on the use of lab instruments, which had limited availability to students back in 2012 before the design of the Pocket Instruments.

Since 2013 that each student became equipped with a set of Pocket Instruments, increasingly more elective items have been taken and explored in depth. Till 2015, the average percentage of students with extra efforts had increased by more than threefold from 19% to 70%, and the average extra items taken by each student has increased by nearly an order of magnitude from 0.38 to 2.75. Based on the consistently positive outcome over three years, the program at Tsinghua University adopted this teaching practice for more students and course sessions since 2016. In 2019, among a total of 155 students in two digital electronics courses, the average percentage of students with extra efforts was 89%, and the average extra items taken by each student was 3.42.

Once students engage more in hardware experiments, their hands-on skill and problem-solving abilities can be substantially enhanced. After the adoption of the Pocket Instruments, students should have an improved mastery of the course content. For the outcome of the Pocket Instruments, data collection and analysis are still in progress. As a preliminary indicator, we have examined in Fig. 3 the trend of students' 100-point average scores of the midterm exam, noting that most of the hardware-related lab tasks are assigned and fulfilled in the first half-semester. Earlier average midterm scores were not available due to different teaching arrangement of the course before 2012.

IV. CONCLUSIONS AND FURTHER DISCUSSIONS

This paper presents a multi-year teaching practice of electronic circuit laboratory using the Pocket Instruments, a newly developed low-cost portable lab kit. It integrates the main functionalities of frequently used devices in doing electronic circuit experiments, which include a DC power, a waveform generator, and an oscilloscope. With Pocket Instruments, instructors can advance electronic laboratory learning beyond the wall of laboratories. Teaching practice at Tsinghua University for seven years has shown that providing students with an always-available lab kit such as the Pocket Instruments can play a substantial role in engineering education, as it helps overcome the traditional facility limit and motivate students to try more hands-on exercises and learn more.

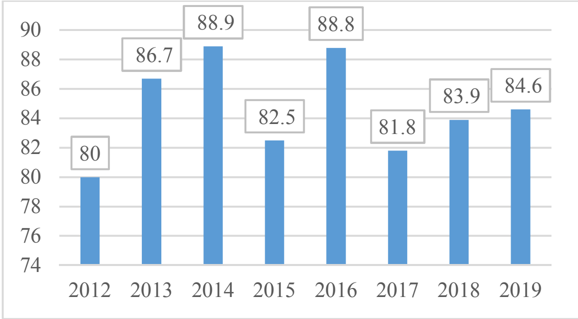


Fig. 3. The change of the average midterm score.

Through this development and teaching practice, as the instructors of the electronic circuit course, we found it essential to care about students' feedback on the course learning. The original motivation came from students' dream of taking electronics lab back home, and the Pocket Instruments makes it possible. By getting students involved, the design and development of the Pocket Instruments is also practical hands-on training. While using such a self-made teaching tool, the instructors show more passion in course teaching, which can further arouse the students' learning and innovation interests.

Pocket Instruments can be extended to more courses in electrical and computer engineering undergraduate programs such as Electric Circuits, Signals and Systems, and Control Theory. These lab courses or theoretical courses with lab units have a common requirement for test and measurement instruments. By keeping a set of Pocket Instruments at hand, experimental training of multiple courses can be continuously covered for undergraduates from freshman to senior.

Going beyond the in-person classroom learning, we see a growing trend of web-based teaching platform widely known as the Massive Open Online Courses (MOOCs) [7], [8]. Since most MOOCs do not have physical classrooms and labs, an affordable portable lab kit can be an attractive solution for worldwide MOOCs students to practice the same experiments as the students of traditional classes. In one MOOC effort of digital electronics developed by Tsinghua University, several lab-teaching videos with the Pocket Instruments have been included [9]. An online analog circuits lab teaching course with the Pocket Instruments is under construction.

On-going teaching activities also suggest that when the labs or universities are closed due to extreme cases such as pandemic and natural disasters, Pocket Instruments can provide an effective means for distance laboratory learning. When the on-going COVID-19 pandemic had prevented undergraduate students from on-campus learning, a set of Pockets Instruments has been mailed to each of the 180 students in the Electronic Circuit courses of this semester. More complete pedagogical data for distance laboratory leaning with Pocket Instruments are in progress.

Some future work includes a survey among students to study the suitability of this lab kit and how they have advanced with the aid of this device. Expanding the use of the Pocket Instruments from in-course teaching to extracurricular research activities is also under consideration.

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