The Design and Implementation of a Remote Automatic Control Laboratory: Using PID Control as an Example

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Abstract

As automatic control systems are widely used in industry, the study of them is one of the most important introductory courses offered in college-level curricula. In this paper, we propose a networked learning model for automatic remote control PID experiments, including a platform and a networked learning system designed according to competence-based education methods. The online system offers a new approach to practical learning in a virtual laboratory. To evaluate the efficacy of the system, we conducted an experimental study using students enrolled in the automatic control course at Tungnan University in Taiwan.

We consider three instructional methods in this paper: a traditional method, a remote learning system method, and a competence-based networked learning method. The effects of students' academic performance prior to taking the course on their achievements with regard to PID control learning are also discussed. Thirty students were randomly divided into three groups, and one instructional method was implemented for each group. The students were also divided into two groups (high and low) according to their GPA scores in the previous school year. The data were subjected to two-way ANOVA analysis, and the interaction effect between two independent variables, i.e., one of the instructional methods and the student's performance prior to taking the course, was observed. We found that both variables have a significant effect on a student's learning outcomes. The results show that our competence-based networked learning system is as effective as the traditional instructional method.

***Key Words*:** PID Controller, E-Learning, Virtual Laboratory, ANOVA, Competence-Based Education

1. Introduction

Automatic control systems comprise a very important introductory course in the field of electrical and mechanical engineering. The study and design of automatic control systems, a field known as control engineering, is a large and expansive area [1,2]. From the cruising function in cars to complex machines like space shuttles, control engineering is a part of everyday life.

The Proportional-Integral-Derivative (PID) controller is one of the control algorithms widely used in industrial systems [3,4]. Such algorithms perform well for a wide class of processes. Furthermore, they are easy to implement using analogue or digital hardware and they are familiar to engineers. The PID controller has been incorporated into the design of a number of systems, e.g., process control systems [5], power systems [6], and marine control systems [7], thus showing the controller's importance in academic circles.

With the rapid development of computer multimedia and the Internet, web-based learning is becoming a major trend in education that is transforming the traditional classroom into a virtual learning environment. One of the best features of the Internet is that it allows students

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to learn anytime, anywhere. Moreover, students can choose the materials they need or start a discussion about a topic with other classmates. Designing a good e-learning platform would create a new environment that could be better than traditional instructional methods [8]. However, the application of information technology in education has not reached expectations because of continuous advances in technology. The result of this favors traditional learning systems, since the materials used in distance learning are limited to traditional contents that are merely changed into hyperlinks. Although most current teaching strategies are not efficient in terms of using online materials, there are some relatively new instructional strategies that are noteworthy, e.g., social constructivist learning theory [8], scaffolding teaching [9], competence-based education [10,11], and collaborative learning [12].

This paper integrates the 4Cs — content, communication, computers, and control — to design a networked learning system for an automatic control laboratory. We have designed a networked learning system according to competence-based education techniques, and a remote automatic control experiment platform for a college-level automatic control course. An experimental study was also conducted using a class of students as subjects to analyze their academic achievement in the course under our designed system. Our goal is to establish a competence-based networked instructional method that can be extended to other subjects of study or laboratory courses. We hope the proposed method will improve the teaching and learning effectiveness of vocational education.

The characteristics of our networked learning system are as follows:

(1) The design incorporates a remote desktop system and establishes a virtual control laboratory

Although there are many remote control experiment designs on the market [13–15], our remote control experiment platform, called the remote learning system (RLS), gives students easy access to equipment in a laboratory. The user client can also observe the operation in the laboratory in real-time via a surveillance camera [16].

(2) To promote learning effectiveness, the online learning environment is designed and implemented according to the theory of competence-based education

Competence-based education is a systemic and efficient teaching and learning approach, as it trains students to achieve a "presupposed ability". Prior studies have shown that competence-based education improves learning effectiveness [10,11]. We applied competence-based education in the design of an asynchronous online learning system for automatic control experiments.

(3) Continuous evaluation of learning effectiveness

A student-oriented e-learning system needs continuous evaluation and revision so that instructors can realize its advantages and disadvantages. Prior studies have used ANOVA analysis to determine learning effectiveness [17]. In this paper, we conducted an experimental study, using students as subjects, to evaluate the differences in students' performance under three types of instructional methods, namely the traditional method, the remote learning system method, and the competence-based networked learning method. Each method and the students' academic performance prior to taking the course are treated as independent variables, and subjected to two-way ANOVA analysis to determine their effects on students' achievements in the automatic control course.

The remainder of this paper is organized as follows. Section 2, we explain the principles of the PID controller and the traditional automatic control laboratory curriculum. Section 3 contains a detailed discussion of our remote control program, including its application in remote PID control experiments. Section 4 describes how we apply the theory of competence-based education in the design of an online learning environment. In Section 5, we discuss the experimental study, and the results regarding student's learning effectiveness are concluded.

2. PID Controller Laboratory Course: the Traditional Method

2.1 PID Controller Theory

Traditionally, students have gained practical experience in the use of automatic control systems in laboratories, where they can use software, such as VisSim and Matlab, to control equipment with designed algorithms. In this paper, we propose a PID controller for a networked "D.C. servo motor position control" laboratory course.

Control engineering is based on control theory, and integrates electronics, computer, and sensor technology, for the purpose of control. The main objectives of control system analysis and design are as follows: (1) to achieve stability, (2) to reduce the steady state error, and (3) to produce the desired transient response. Generally, time-domain analysis can be employed to study the functions of transient responses, such as maximum overshoot, rise time, delay time, and settling time.

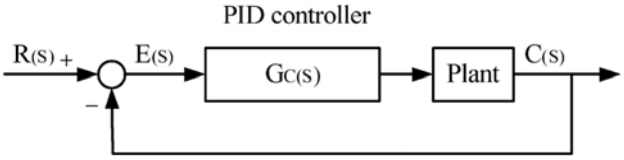

Figure 1. Block diagram of a closed loop PID control system; R(S): reference input, E(S): error signal, C(S): controlled variable, Gc(S): transfer function.

The PID controller is a combination of proportional, integral, and derivative control actions, which means it has to adjust three parameters. "P" denotes proportional control, which tries to increase the system's response time and reduce the rise time; "I" denotes integral control, which tries to reduce the system's steady state error; and "D" denotes derivative control, which tries to prevent instantaneous changes in the system and improve the percentage overshoot. A great deal of research has been conducted on how to tune the PID controller to achieve the optimal response [3,4]. Related information regarding the PID controller experiment course can be accessed from the e-learning webpage of the Tungnan University (http://e-learn.tnit.edu.tw/). Students enrolled in the course are given a username and password, while guests can log in using "guest-pid" as both the username and password.

Figure 1 shows a block diagram of a closed loop PID controller. The transfer function Gc(s) is as follows:

$$Gc(s) = K_P + \frac{K_I}{S} + K_D \cdot s$$

where K_P is the proportional gain, K_I is the integral gain, and K_D is the derivative gain.

2.2 Introduction to PID Controller Laboratory Equipment

In this study, we used the Feedback 33−100 Servo Motor Mechanical unit shown in Figure 2 as the controller. The tachgenerator was used as the speed sensor, and the reference input signal was the input command signal produced by the VisSim/Matlab signal generator. How we establish a real-time DC servo motor control system will be explained later.

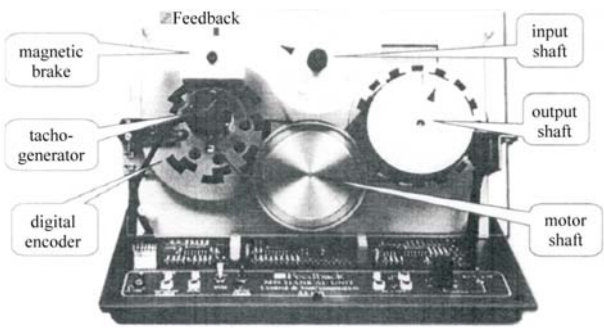

Figure 2. Feedback 33−100 mechanical unit for PID control.

2.3 PID Controller Experiment

Figure 3 shows a block diagram of the DC motor position control system. First, we used the tachogenerator as the speed sensor and the output potentiometer as the position sensor; then we used the input command signal produced by the VisSim signal generator.

After completing the configuration of the input/output channel, a PID control block diagram can be drawn, as shown in circle A of Figure 4. We used a square function with 0.1 Hz, +/-5 V as the reference signal. In addition, we set the proportion gain Kp to 65, and Ki and Kd to 0, using only the proportion controller to control the system. We discuss the behavior of the proportion controller in terms of the reference signal and position response. The result is shown in circle B of Figure 4, where the position response shows apparent oscillations. Next, we set the Kd to 2. The resulting position output met our control objective.

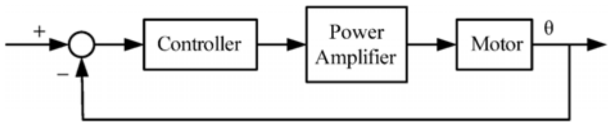

Figure 3. Block diagram of the DC motor position control system.

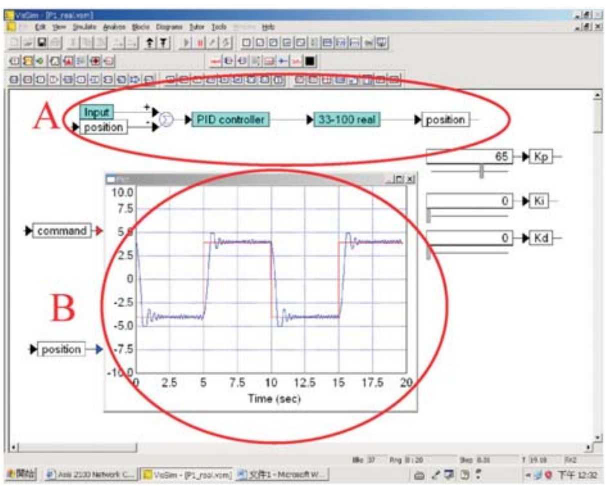

Figure 4. Real-time response of the proportion position controller (Kp = 65, Ki = 0 and Kd = 0).

3. The Design of a Remote Learning System and the Establishment of a Virtual Control Laboratory

3.1 The Design of a Remote Learning System

3.1.1 Introduction to a Virtual Laboratory

In this study, we transform the traditional automatic control laboratory into a virtual laboratory by taking advantage of the convenience of the Internet. The system is designed to allow students to log into the main server located in the laboratory from remote locations. Students can design and execute automatic control experiments and observe the results in real-time. We designed a Windows-based application similar to a Windows operating system remote control application. This virtual laboratory runs 24/7 so that students can practice and gain hands-on experience of automatic control systems anytime, anywhere.

A great deal of research has been conducted on virtual laboratories, distance learning, and evaluation and learning methods; however, each study serves only one purpose. For example, Swamy, Kuljaca, & Lewis [18] use NetMeeting to construct a remote control system, but the NetMeeting function cannot be integrated effectively, so the system is not ideal. Hodge, Hinton, & Lightner [19] provides a good electronics circuit simulation environment, but it does not integrate with the Internet effectively, so it is only a software application that probably cannot be used as a remote control system by instructors and students.

The main features of our remote learning system (RLS) are as follows:

(1) On-line information search, reservation, and management system

We call this the class management center. Students can log into the Web-based system in the laboratory via the Internet, check the equipment usage status in the laboratory, and reserve a time slot to operate the system remotely. If a time slot is already taken, the student is put on the waiting list. Each time slot allows one hour of operating time, and the session will be cancelled if the student fails to login within 10 minutes of the start of the reserved slot.

(2) Remote desktop system design

We developed a software application similar to Symantec PcAnywhere. It allows the PID controller to work on the Internet without changing previously-developed PID control on-screen graphics. This application lets users see the screen of the control experiment remotely, as if the user is actually sitting in front of the computer in the laboratory. Apart from the remote control function, the system also connects to the PID Class Management system and checks the user's license status to prevent the equipment being damaged by remote users.

(3) Remote video monitoring system

When students finish the PID control diagram and start executing the experiment, they have the option to open a pop-up video window. A video image of the equipment screen will be transmitted to the user's computer over the Internet. Users can actually see the execution results by monitoring the status of the real-time operation in the laboratory via the screen.

3.1.2 System Architecture of the Virtual Laboratory

An overview of the RLS virtual laboratory is shown in Figure 5. The system is divided into two parts: the server on the left-hand side and the user/client on the right-hand side. The two sides are connected via the Internet. The server side consists of a control server and a class management server. The DC server motor and the monitoring camera are connected to the control server.

3.1.3 Class Management Center

The web-based management system is not a traditional Windows application, but an instance that can be activated by the web server. Taking account of compatibility and efficiency, we use CGI to connect the client and the management server. C programming language is used to implement CGI on the Apache web server.

When a student logs into the system, a window will display the equipment list and usage status. The student can then select a time slot to make a reservation for the equipment. In addition to the interactions with the ses-

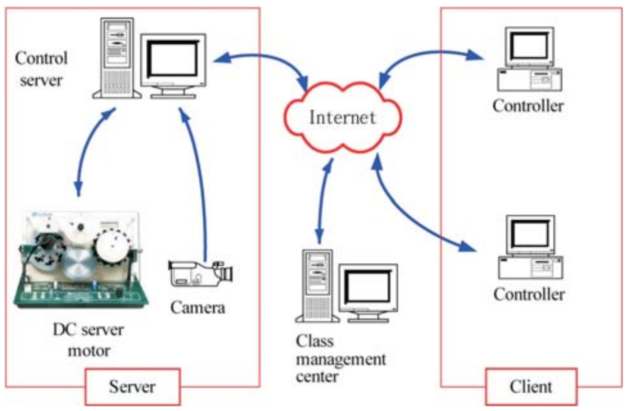

Figure 5. A system overview of the RLS.

sion management server, the control server can also communicate with the management system. Before a student starts a laboratory operation, the control server connects to management system and checks that the student has permission to operate the equipment. The system also checks the time limitations and then establishes a real-time connection for the operation. The reservation process for the virtual laboratory is shown in Figure 6. The URL of the homepage of the class management center is http://140.129.122.1.

3.1.4 The Design of the Remote Desktop Program

Our software is designed to connect to the management system through TCP, as it will activate the PID controller and transmit the screen to the user's desktop over the Internet. It also transfers keyboard and mouse events to the PID control server.

The program is compatible with all kinds of controllers; hence, we do not have to spend time redesigning existing control diagrams to suit our needs. Moreover, since the operation of the remote system is the same as the system in the laboratory, students do not need to learn a foreign interface. This makes the operation simple, so students can focus on learning PID controller design skills. This seemingly simple concept allows us to make an efficient transmission between the display window on the control side and the client end. Most of today's PID controller screens are monotone; therefore, a run length coding scheme and Huffman coding scheme are used for spatial and temporal compression operations.

Transmissions from the control server to the client are in video format. However, transmissions from the client to the control server are events or commands, such as mouse tracks, mouse clicks and keyboard commands, input by students. Since only moderate bandwidth is required, there is no need to compress the data.

3.2 Using the RLS for On-Line Practice

3.2.1 On-line Materials

Students need to understand related information regarding the PID control experiment, such as the theory, and the experimental method and procedure, before using the laboratory. The information can be accessed through the e-learning webpage at Tungnan University (http://e-learn.tnit.edu.tw/). Students enrolled in the course have their own username and password. Guests can log in using "guest-pid" as the username and password. Students can interact with each other by clicking on Course Discussion, On-line Discussion, Group Discussion, or Topic Discussion.

3.2.2 Remote Execution of the PID Controller

After the student has reviewed the on-line materials and understood all the related information about the PID controller laboratory course. Students log into the server to execute the RLS system; then, they can design the PID control diagram and run the PID controller. At the same time, they can also monitor the laboratory equipment and its operational status remotely via the video feed from the surveillance camera.

3.2.3 Execution Results of the PID Controller

The response interface of the RLS for students using the remote networking PID control system is shown in Figure 7. The parameters are Kp = 65, Ki = 0, Kd = 0. The frame shows the remote experiment window for the

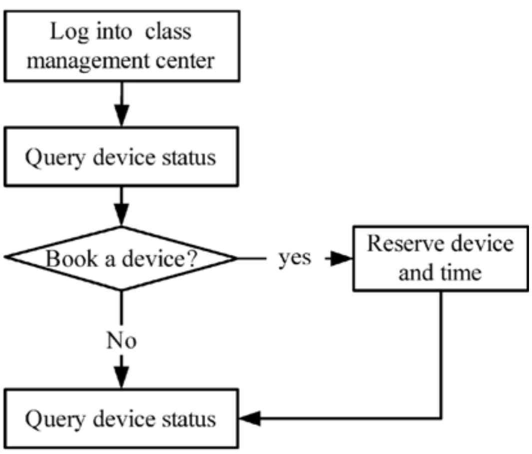

Figure 6. The RLS search/reserve flow chart.

Figure 7. Response interface of PID position control for the RLS (Kp = 65, Ki = 0 and Kd = 0).

PID control system in the laboratory. When compared, the remote control practice (Figure 7) has the same outcome as the actual laboratory practice (Figure 4) in terms of PID position control response. This demonstrates that our remote control program is well designed. In addition to the remote desktop control function, our RLS allows students to monitor both visual and audio equipment in the laboratory, as shown in the bottom right-hand corner of Figure 7.

4. Competence-Based Networked Learning System

4.1 Introduction to Competence-Based Education

In this paper, we adopt competence-based education (CBE) theory as the foundation to integrate the networked learning platform and RLS. Our goal is to design a competence-based networked learning system (RLS+ CBE). An instructional method based on this system differs from the RLS mentioned in Section 3. Apart from providing on-line materials and a remote learning system for students to use by themselves, instructors are involved in the learning process to guide students according to their progress and level of understanding.

Competence-based education evolved from the American system of vocational education, which in turn developed from normal educational methods. It was successfully expanded to vocational education in other countries, and has been applied in college curricula and in industry [10,11]. Competence-based education is a systematic yet flexible approach to organizing instruction. This approach focuses on defining, in measurable terms, what students are to learn and evaluate how well they can perform designated tasks after instruction. Expected behavior or tasks, conditions for their performance, and acceptable standards are explained to students prior to instruction.

The main objectives of competence-based education are as follows. First, its purpose is to motivate learners to achieve a preset goal. The individual learner's behavior in the learning process is taken into consideration when presetting the goal. Second, its evaluation is criterion-referenced. This can be easily realized on the Internet, because such an environment permits learners to determine their own learning pace and learning sequence.

Instead of simply being a course provider, the teacher plays a dual role: administrator of the material and motivator for learning. It has been shown that the intervention of instructors improves students' academic outcomes [17]. Students themselves are the core of the learning process and the teacher helps make this process run smoothly. Students can select their own learning materials based on their needs. They can also interact with one another by participating in various kinds of online discussions, in groups or by topics. Our system can also to record each student's learning process.

4.2 Implementation of Competence-Based Education in a Networked Learning System

Our on-line learning system is designed according to competence-based education theory. It offers a system for PID control experiments, provides proper materials, and records students' learning progress. First, the students study PID control theory, after which they are able to use the RLS and access the laboratory equipment on-line as if they are actually operating the system in the laboratory.

Students are evaluated when they enter each study unit. Students are to follow the study process described in the following:

(1) Possess all the required skills

When a student enters a learning unit, he can take the performance evaluation if he thinks he has all the required skills for that particular unit; otherwise, he will need to complete all the lessons in that unit.

(2) Learn all the skills

After the student has completed all the lessons in the unit, he can then take the performance evaluation; he will need to finish all the lessons to do so.

(3) Instructor evaluation

The student's performance evaluation is uploaded to the instructor who decides whether the student has achieved the pre-set learning outcome. If the student passes, his work will be shared among other students; if not, he will need to re-learn the unit until he passes.

5. Analysis of the Instruction Outcomes

5.1 Experiment Design

In addition to designing a competence-based networked learning system for students to utilize online materials and practise remote control learning, we investigated the effects of the different instructional methods on the students' performance. We used two independent variables in our experimental study, which was based on 30 undergraduate students enrolled in an automatic control course at Tungnan University. After completing the PID controller learning unit, the students' data was subjected to two-way ANOVA analysis using the SPSS statistical analysis software [20,21]. The interaction effect between the variables was also taken into account.

The first independent variable was the students' academic performance prior to taking the course (denoted as LEVEL), and was based on their GPA from the previous school year. The students were divided into two groups, high performance and low performance, with 15 people in each group. The second variable was the instructional method (denoted as TEACHING). The 30 students were randomly and evenly divided into three groups, and each group was taught using one of the following instructional methods:

(1) Traditional method (LAB). This involves 3 hours of laboratory work each week. The students learn one laboratory unit each week after the instructor explains related information on the topic. Students are tested after six weeks.
(2) Remote learning system (RLS). This consists of self-instructed online learning, where the students learn related laboratory information on the school e-learning webpage and use the remote learning system to practice remote PID control experiments.
(3) Competence-based networked learning system (RLS+CBE). This is similar to the remote learning system, but instructors guide students by employing competence-based teaching techniques.

5.2 Research Hypotheses

For the purpose of this study, we consider the following research null hypotheses:

(1) no significant interaction in a student's academic achievement between the instructional methods and student's academic performance prior to taking the course
(2) no significant differences in the academic achievements of students classified as high performance and low performance prior to taking the course
(3) no significant differences in students' academic achievements for the three different instructional methods

5.3 Results

5.3.1 Descriptive Statistics

The mean scores, standard deviations, and the number of students (N) for each subgroup are shown in Table 1. TEACHING represents the three instructional methods, i.e. LAB, RLS, and RLS+CBE. LEVEL, i.e., H (high) and L. (low), represents the academic performance achieved by the students prior to taking the course.

5.3.2 Levene's Test of Equality of Error Variances

The results, detailed in Table 2 ($F = 0.509$, $p > 0.05$), show no significant differences between the academic performance variations among the test subjects. We can conclude that we have not violated the homogeneity of variances assumption; thus, we proceed with the analysis.

5.3.3 Interaction Effect

The interaction effect between the variables is shown in Table 3, where the sum of squares between the two variables (TEACHING*LEVEL) is 283.3, with a mean square of 141.6 ($F = 4.79$, $p < 0.05$). This result shows that the interaction effect has a significant effect on the learning outcomes; therefore, null hypothesis 1 is rejected.

5.3.4 Main Effects

Table 3 also shows the results of two-way ANOVA analysis. The sum of squares between the different instructional methods was 773.3, with a mean square of 386.6 ($F = 13.1$, $p < 0.05$). The sum of squares between student's academic performance prior to taking the course

Table 1. Descriptive statistics
Dependent Variable: GRADE

TEACHING	LEVEL	Mean	SD	N
LAB	H	76.0	4.47	5
	L	65.0	3.74	5
	Total	70.5	6.98	10
RLS	H	72.0	7.84	5
	L	50.0	3.39	5
	Total	61.0	12.92	10
RLS+CBE	H	85.4	6.23	5
	L	60.0	5.61	5
	Total	72.7	14.51	10
Total	H	77.8	8.26	15
	L	58.3	7.61	15
	Total	68.1	12.61	30

Table 2. Levene's test of equality of error variances[a]
Dependent Variable: GRADE

F	df1	df2	p
0.509	5	24	0.767

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
[a] Design:
Intercept+LEVEL+TEACHING+LEVEL*TEACHING

Table 3. Summary of two-way ANOVA results

Source	SS	df	MS	F	p
TEACHING	773.3	2	386.6	13.1	< 0.01
LEVEL	2842.1	1	2842.1	96.2	< 0.01
TEACHING*LEVEL	283.3	2	141.6	4.79	0.018
Error	709.2	24	29.6		
Total	4067.9	29			

was 2842.1, with a mean square of 2842.1 ($F = 96.2$, $p < 0.05$). From this result, we can conclude that student's academic performance prior to taking the course had a greater influence on their learning outcomes than the instructional methods. The F-values and p-values also show that both variables indeed have a significant effect on students' learning outcomes; thus, we reject null hypotheses 2 and 3.

5.3.5 Multiple Comparisons

The results of the post-hoc tests are listed in Table 4. Post-hoc comparisons using the Tukey HSD test indicate that the learning outcomes from instructional methods LAB and RLS as well as RLS and RLS+CBE were statistically significant ($p < 0.05$); while LAB and RLS+CBE were not statistically significant ($p > 0.05$). This shows that the competence-based networked learning method and the traditional method are equally effective in terms of students' achievements.

5.3.6 Discussions

Figure 8 shows the interaction graph of the three types of instructional methods and the students' academic performance prior to taking the course. The differences in learning outcomes are presented in an easily understandable format. In Table 1, the SD values in the H and L groups of RLS/RLS+CBE are relative low, but the SD values in the total groups of these two methods are relative high. The reason for this might be that students with higher academic performance are more adaptive to new instructional methods and learning environments; while students at the other end of the spectrum could not adjust to new instructional methods easily because they are more used to the traditional method. Nevertheless, the small sample size might have contributed to the high SD values. Follow-up studies could use a larger sample size to decrease the potential for aberrant results in an inspection.

The results show that students with higher previous academic achievements performed better under the RLS+

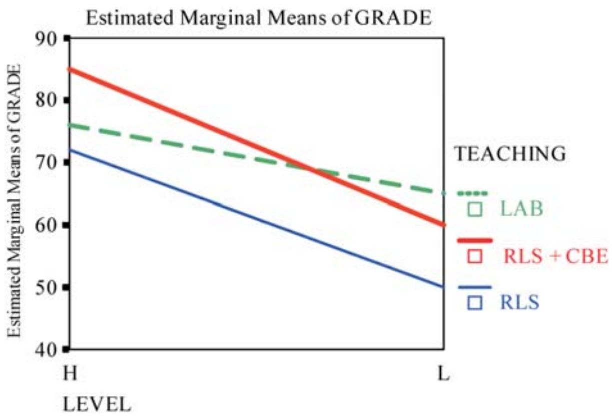

Figure 8. Interaction graph of the three instructional methods and the two kinds of academic performance in an easily understandable format.

Table 4. Multiple comparisons
Dependent Variable: GRADE
Tukey HSD

(I) TEACHING	(J) TEACHING	Mean Difference (I-J)	Std. Error	p	95% Confidence Interval	
					Lower Bound	Upper Bound
LAB	RLS	9.5000*	2.4310	.002	3.4290	15.5710
	RLS+CBE	-2.2000	2.4310	.642	-8.2710	3.8710
RLS	LAB	-9.5000*	2.4310	.002	-15.5710	-3.4290
	RLS+CBE	-11.7000*	2.4310	.000	-17.7710	-5.6290
RLS+CBE	LAB	2.2000	2.4310	.642	-3.8710	8.2710
	RLS	11.7000*	2.4310	.000	5.6290	17.7710

Based on observed means
*The mean difference is significant at the .05 level.

CBE method compared to the other two methods. On the other hand, students with lower previous academic achievements actually performed better under the traditional instructional method (LAB). Students performed worst under the RLS method, regardless of their academic performance prior to taking the course. The reason for this might be the lack of instructor guidance, i.e. without CBE, in the learning behavior using only RLS method, which is a key factor in motivating students to achieve better grades.

6. Conclusion

This paper integrates the 4Cs — content, communication, computers and control — in designing a networked learning system founded on competence-based education. Our study show promising results that could prove useful in designing remote automatic control courses in the future.

By applying the theory of competence-based education to our remote learning system, we provide effective e-learning materials and a new learning environment, which meets the goal of education in continuously improving learning methods to suit the needs of the students. Our proposed remote control software provides an online environment that students can access anytime, anywhere to control or observe equipment in the laboratory. This remote automatic control platform can be implemented in college-level automatic control courses for students and instructors to carry out online laboratory courses. The online learning activities of our system allow students to participate in group discussions, which in turn help students establish good interaction skills and sharing habits. The platform also provides a place for students to collect information, share their learning experiences, and construct their own knowledge banks. To further evaluate the efficacy of our system, we conducted an experimental study and analyzed the outcomes of different instructional methods. We also investigated the effect of students' prior academic performance on their academic achievements in the automatic control course. The results show that our system is as effective as the traditional instructional method; hence, it has practical value in education and can be extended to other subjects of study or laboratory courses. We hope that our findings will help improve the teaching and learning effectiveness of vocational education methods.

Acknowledgement

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