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A Hands-On PID Control Education Program Combining LEGO-based Hardware and Scilab-based Simulation

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ABSTRACT
Proportional integral derivative (PID) control is a fundamental topic in control engineering; however, students often have difficulty understanding the relationship between controller gains and system behavior through mathematical lectures or simulations alone. Therefore, the objective of this study is to develop a hands-on education program that enables students to understand feedback control behavior and acquire practical PID gain-tuning skills by directly comparing the responses of an actual motor-angle control system with those obtained from computer simulation. This study proposes a hands-on education program for introductory feedback control education that integrates both physical experiments using LEGO EV3 hardware and computer simulation using Scilab/Xcos. The developed program focuses on PID control of motor angle and is designed to help students acquire both conceptual understanding of feedback control and practical PID gain-tuning skills. Through experiments involving P, PI, PD, and PID control, students investigate the effects of gain parameters on transient response characteristics and compare the differences between real hardware behavior and simulation results. The proposed education program was implemented for 34 undergraduate mechanical engineering students. To evaluate its educational effectiveness, a self-assessment questionnaire consisting of five learning-outcome-based items was administered after the experiment. The results showed that more than half of the students reported being able to explain PID control behavior and tune PID gains appropriately after completing the program. In addition, the combined use of LEGO-based experiments and Scilab-based simulation was found to support students' understanding of both theoretical and practical aspects of feedback control. These results suggest that the proposed education program is effective in developing foundational PID control knowledge and gain-tuning skills for introductory control engineering education.

General Terms
Education, Student, Experiment, Simulation, Control Engineering, Feedback Control.

Keywords
Control Engineering, PID Control, P Control, PI Control, PD Control, Motor Control, Motor Angle, Encoder, LEGO, Scilab, Xcos, PID gain-tuning, Mechanical Engineering Student.

1. INTRODUCTION
Control engineering is an essential subject in mechanical engineering education, and proportional integral derivative (PID) control is one of the most fundamental topics in introductory control courses. Through PID control, students learn the basic concepts of feedback systems, including transient response characteristics, stability, and the influence of controller gains on system behavior. Because of its practical importance and wide industrial application, PID control is commonly included in both lectures and laboratory-based engineering education [1], [2], [3].

However, students often have trouble understanding the relationship between controller gains and actual system behavior. In conventional lecture-based education, PID control is frequently explained mathematically using transfer functions and differential equations, making it difficult for beginners to connect theoretical concepts with physical system responses [4], [5]. Although computer simulations allow students to visualize control responses, simulation-only approaches may not sufficiently demonstrate the differences between ideal models and real hardware systems. Consequently, students may understand PID control theoretically while lacking practical understanding of how gain parameters affect actual control performance.

To improve students' understanding of feedback control, hands-on educational approaches using experimental hardware have attracted considerable attention [6], [7], [8], [9], [10]. Experimental learning environments enable students to directly observe the influence of controller gains on physical systems and therefore help bridge the gap between theory and practice. In particular, LEGO-based educational hardware has been widely utilized in engineering education because of its safety, flexibility, and ease of implementation [6], [7], [8], [9], [10], [11], [12]. Such systems are suitable for introductory control education where students are expected to acquire practical experience through experimentation.

At the same time, computer simulation environments are also important for control engineering education because they allow students to efficiently analyze system responses under various control conditions. Scilab/Xcos is an open-source simulation environment that provides graphical modeling functions suitable for introductory control education [13], [14], [15], [16]. By combining physical experiments with simulation-based learning, students can compare the behavior of actual systems with simulation results and thereby gain deeper understanding of both feedback control theory and practical system characteristics.

Based on this background, the objective of this study is to develop and evaluate a hands-on PID control education program that combines LEGO EV3-based hardware experiments with Scilab/Xcos-based simulations. The

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proposed program is intended to help students acquire both conceptual understanding of feedback control and practical PID gain-tuning skills through direct comparison between experimental results and simulation responses. In the program, students conduct motor-angle control experiments using P, PI, PD, and PID control while adjusting controller gains and observing their effects on transient response characteristics. In addition, students compare the responses of the actual motor system with those obtained from computer simulation to understand the differences between real and idealized systems.

In this study, to evaluate the educational effectiveness of the proposed program, the developed educational materials and experimental activities were implemented for undergraduate mechanical engineering students. A self-assessment questionnaire based on the intended learning outcomes was administered after the experiment to evaluate students' perceived understanding of PID control and gain-tuning skills.

The remainder of this paper is organized as follows. Section 2 describes the proposed education program, including the developed educational materials and experimental setup. In addition, this section explains the educational implementation and the evaluation method used to assess the effectiveness of the program and materials. Section 3 presents the evaluation results obtained from the student questionnaire. Section 4 discusses the effectiveness and educational implications of the proposed program and materials based on the evaluation results. Finally, Section 5 concludes the paper and summarizes the findings of this study.

2. METHOD

2.1 Proposed Education Program

First, the program introduces fundamental knowledge of P, PI, PD, and PID control. In addition, students learn the principles of feedback control for motor angle control using a PID controller and an encoder. Figure 1 shows a block diagram of the motor angle control system. In Figure 1, s denotes the Laplace variable in the frequency domain representation. The parameters K_p, K_i, and K_d represent the proportional gain, integral gain, and derivative gain, respectively, which determine the behavior of the PID controller.

Second, students implement and operate a motor angle controller using LEGO EV3 and the LEGO MINDSTORMS Module for LabVIEW. LEGO EV3 is adopted in this program because it is cost-effective, easy to use for beginners, and suitable for visualizing control behavior in real time. Figure 2 shows an overview of the motor angle control system based on LEGO EV3 in the proposed program. Using this system, students perform P, PI, PD, and PID control of motor angle. Figure 3 shows an example of the time response of the motor angle in the LEGO EV3-based controller (PID control). Note that advanced materials such as inverted pendulum and balance robot were not used for this education program because PID control with these materials was difficult for inexperienced students. Through these activities, students can observe actual motor responses for each control method (P, PI, PD, and PID), facilitating intuitive understanding through comparison among different control strategies.

Third, students implement a computational simulation of the motor angle controller using Scilab/Xcos. In this step, students investigate the effects of PID gains on system response and control errors. Figure 4 shows an example of the time response of the motor angle in the computational simulation (PID control). The simulation allows students to explore a wide range of PID gain combinations efficiently and supports trial-and-error exploration without hardware constraints.

Through these procedures, students can acquire both fundamental theoretical knowledge and practical skills related to feedback control and PID control. Furthermore, by integrating hands-on experiments and simulation-based exploration, the proposed program enables students to iteratively refine their understanding and develop effective gain-tuning skills.

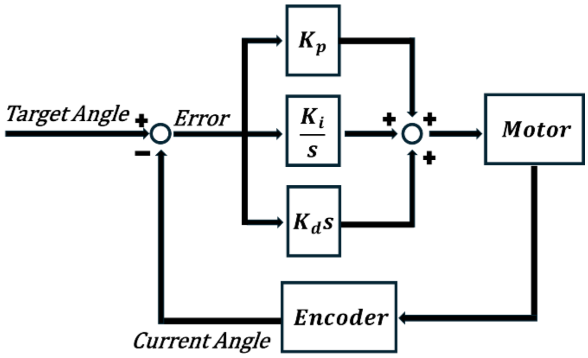

Fig 1: Block diagram of the motor angle control system

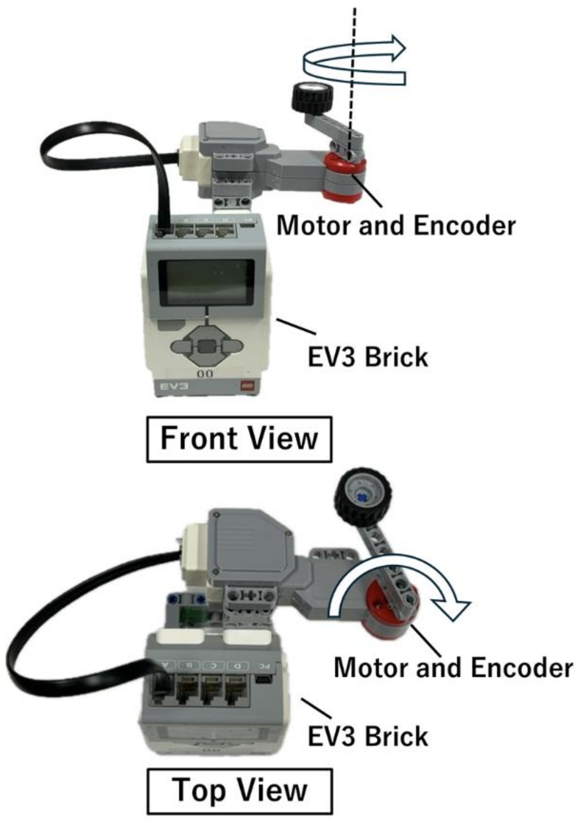

Fig 2: Overview of the LEGO EV3-based control system for motor angle control

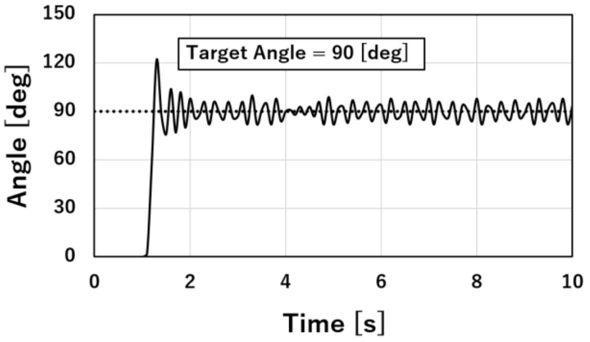

Fig 3: Example of time response of the motor angle in LEGO EV3-based control system (PID control)

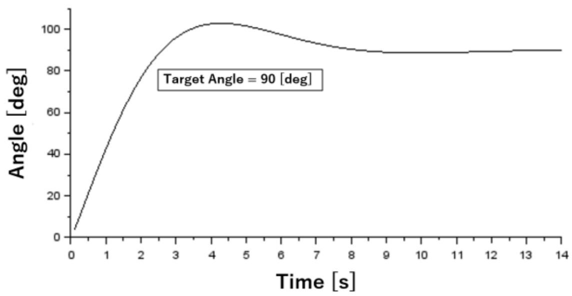

Fig 4: Example of time response of the motor angle in Scilab/Xcos -based simulated controller (PID control)

2.2 Evaluation of Education Program

To evaluate the effectiveness of the proposed education program and instructional materials, a self-assessment questionnaire was administered to students after completing the PID control experiment. The evaluation targeted a total of 34 undergraduate students in mechanical engineering, who participated in the program in small groups consisting of five to six students. This group-based format was adopted to facilitate collaborative learning and hands-on activities.

The evaluation aimed to assess students' perceived learning outcomes, particularly in relation to both conceptual understanding and practical skills in feedback control and PID control.

The questionnaire consisted of five items derived directly from the learning objectives of the experiment (Table 1). Each item was formulated as a self-efficacy statement beginning with "I can," allowing students to report their perceived level of competence in specific tasks related to the program.

Responses were collected using a five-point Likert scale (Table 2), ranging from 1 (cannot perform even with guidance) to 5 (can perform independently without assistance). This scale was designed to reflect different levels of instructional support, thereby capturing not only task completion but also the degree of learner autonomy developed through the program.

The questionnaire items covered three main competency areas: (1) planning and execution, (2) equipment preparation and operation, and (3) results analysis and interpretation. These areas correspond to the key stages of the proposed program, including hands-on experiments using LEGO EV3 and simulation-based analysis using Scilab/Xcos. This structure enabled a comprehensive assessment of both procedural skills and conceptual understanding in control engineering.

Furthermore, the inclusion of both experimental and simulation activities in the program allowed students to engage in comparison-based learning and trial-and-error exploration, particularly in relation to PID gain-tuning. Therefore, the questionnaire was designed to capture learning outcomes associated with these educational features.

The questionnaire items were constructed to align with the intended learning outcomes of the program, ensuring content validity. Through this evaluation method, the effectiveness of the proposed program in enhancing students' understanding of feedback control and their gain-tuning skills was systematically assessed.

Table 1. Self-assessment questionnaire items

Item	Statement
Q1	I can set the target angle for motor control and carry out the experiment according to the manual.
Q2	I can set the gain values (P, PI, PD, and PID) in the control device or simulator according to the manual.
Q3	I can summarize the time response of motor angle under P, PI, PD, and PID control and explain the differences based on observed trends.
Q4	I can explain the differences between the control device and the computer simulation based on experimental results.
Q5	I can explain the effects of gain on control behavior based on experimental results.

Table 2. Rating scale used in the self-assessment questionnaire

Level	Description
Level 1	Cannot perform even with guidance.
Level 2	Can perform with detailed guidance.
Level 3	Can perform with general guidance.
Level 4	Can perform with minimal guidance.
Level 5	Can perform independently without assistance.

3. RESULTS

Figure 5 shows the results of the self-assessment questionnaire for Q1–Q5, presented as five pie charts. Overall, the results indicate that most students evaluated their performance at Level 4 ("with minimal guidance") or Level 5 ("without guidance") across all questionnaire items. Responses at Level

5 accounted for more than half of the students in each question, demonstrating a high level of self-reported competence.

Notably, no responses were observed at Level 1 (“cannot perform even with guidance”) or Level 2 (“can perform only with detailed guidance”) for any of the questions. This result suggests that all students were able to perform the required tasks without the need for detailed instructional support.

These findings indicate that the students successfully acquired both fundamental knowledge and practical skills in PID control through the proposed education program. In particular, the high proportion of Level 5 responses implies that students were able to independently perform key tasks, including gain-tuning and analysis of control responses.

Furthermore, the absence of lower-level responses suggests that the combination of hands-on experiments using LEGO EV3 and computational simulation using Scilab/Xcos effectively supported students in developing sufficient understanding and operational skills. This outcome highlights the effectiveness of the proposed program in promoting autonomous learning and practical competency in control engineering.

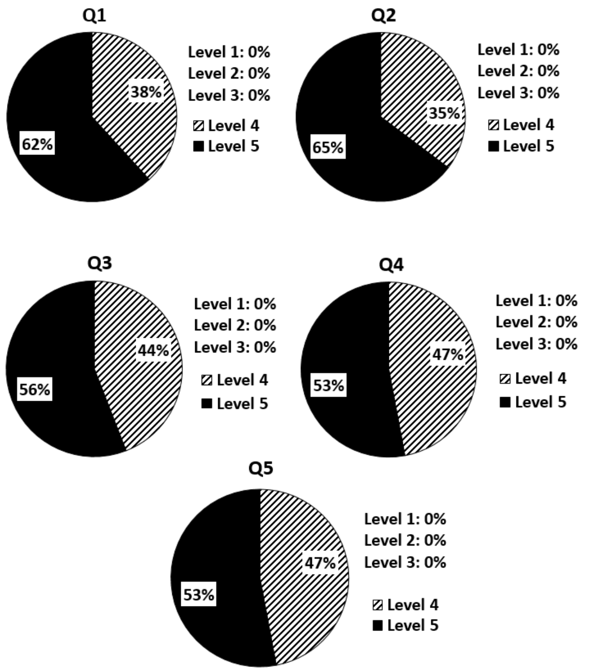

Fig 5: Results of the self-assessment questionnaire

4. DISCUSSION

The results of the self-assessment questionnaire indicate that the proposed education program is effective in enhancing students’ understanding and skills in PID control. The high proportion of Level 4 (“with minimal guidance”) and Level 5 (“without guidance”) responses across all questionnaire items suggests that students were able to perform the required tasks with a high degree of independence. In particular, the fact that more than half of the students selected Level 5 for each question demonstrates that the program successfully fostered autonomous learning and practical competency.

Furthermore, the absence of Level 1 and Level 2 responses indicates that all students were able to complete the tasks without detailed instructional support. This result suggests that the combination of hands-on experiments using LEGO EV3 and computational simulation using Scilab/Xcos effectively supported students in acquiring both conceptual understanding and practical skills. In particular, the program appears to have contributed to the development of gain-tuning skills, as students were able to explore and adjust PID gains through both experimental observation and simulation-based trial-and-error processes.

These findings highlight the educational value of integrating physical experimentation and computational tools in control engineering education. The use of LEGO EV3 enabled students to visualize system behavior in real time, while the simulation environment allowed efficient exploration of parameter settings. This dual approach likely facilitated comparison-based learning and iterative refinement of understanding, leading to improved learning outcomes.

However, this study has some limitations. The evaluation of the program was based solely on students’ self-assessment, which reflects their perceived competence rather than their actual performance. Therefore, the results do not provide direct evidence of the extent to which students acquired specific knowledge and skills in PID control. Future work should incorporate objective evaluation methods, such as performance-based assessments, tests, or analysis of experimental results, to more rigorously validate the effectiveness of the program. Another limitation of this study is that the evaluation was conducted with a single cohort of 34 mechanical engineering students at one institution. Future studies should investigate the applicability of the proposed program to students from different disciplines, educational levels, and institutions in order to verify its generalizability.

5. CONCLUSION

This study proposed an education program for teaching PID control that integrates fundamental theory, hands-on experiments using LEGO EV3, and computational simulation using Scilab/Xcos. The program was designed to promote both conceptual understanding and practical skills, particularly in relation to feedback control and PID gain-tuning.

The results of the self-assessment questionnaire indicated that most students were able to perform the required tasks with minimal or no guidance, demonstrating a high level of autonomy. In particular, the high proportion of responses at Level 5 suggests that the program effectively supported students in independently applying PID control techniques.

These findings suggest that the combination of physical experimentation and simulation-based learning is effective for enhancing students’ understanding and skills in control engineering. The proposed program provides an accessible and practical approach to teaching PID control.

However, the evaluation in this study was based solely on students’ self-assessment, and therefore does not directly measure their actual performance. Future work will focus on incorporating objective evaluation methods to more rigorously assess learning outcomes and further improve the effectiveness of the program.

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