International Journal of Innovative
Computing, Information and Control
Volume **15**, Number **3**, June **2019**

ICIC International ©2019 ISSN 1349-4198
pp. 997–1007

EMBEDDED CONTROLLER BASED LEARNING SYSTEM FOR DC MOTOR CONTROL

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Received July 2018; revised November 2018

Abstract. *In recent years, the importance of electrical energy such as a motors' power source has become more and more in resolving global environmental problems. Thus, electrical motors are going to be widely used in not only industrial fields but also sources of motive force in electric cars. Despite this social environment, there are just a few changings in educational methods of electrical engineering about motors in university lectures. Since students learn motors control theory and technique with a textbook, it is difficult for them to understand a difference between the control method they learn in class and the control method experienced in practice after employment. Therefore, we are researching and developing an educational teaching material system that allows students to experience motor control based on motor control by the embedded system. This educational teaching material system aims to become a bridge between knowledge that can be learned by university lecture and learning of motors used in embedded systems/electronics/mechatronics equipment.*
Keywords: Embedded system, DC motor, Electrical education, Motor control theory, Motor control experiment system

1. **Introduction.** Embedded system is a computer system that is designed for a specific system and embedded in electronics systems. Embedded systems are usually invisible to users and perform the service in a variety of applications and devices, such as medical equipment, washing machines, airplanes, automobiles, refrigerators, televisions, set-top boxes, routers, and mobile phones. Mostly, embedded systems are designed specially adapted to a target system. An optimized, mixed hardware-software implementation is selected for cost reasons. This mixed design achieves the high flexibility of software with the performance of the hardware.

Embedded system engineers have to know the whole electric, electronic and information fields; in addition to this, they should see the interrelation of these technologies. However, the number of these engineers is not enough in industries. Therefore, companies which are developing and selling embedded systems are designed and researching not only their

DOI: 10.24507/ijicic.15.03.997

engineers but also using an outsourcing engineer. On the other hand, in advanced engineering educations in university, this engineering knowledge is lectured as an independent class, so these are not sufficient to teach many technology fields as one interrelation technologies. We think that the shortage of these engineers will not be solved with these current university educational programs [6]. Thus, it is going to desire educational teaching material system for embedded engineers in university education. Therefore, there are many educational experiment systems researched in recent years, and used in laboratory education. These researches target to develop a learning system of PID control system [1,2,4], and develop laboratory education system using the embedded computer [5,7].

These educational experiments systems using a DC motor had been researched in many approaches. The mechanisms of the DC motor speed-control is straightforward because it depends on changing the power supply voltage. However, the control theory of the DC motor is complicated, because there are many motors controllers (P, PI, PID). These researches of educational experiments systems are using various embedded computers such as PIC [1], the Arduino Uno [2], the Raspberry Pi [7] in recent years.

The educational experiments system should have a control target and user interfaces which are easy to understand for the students because students use this system in their lectures. Therefore, a commercial robot and a commercial DC Motor Kit are used as low-cost laboratory systems and used as a motor control target [5]. There is another approach to achieve an inexpensive laboratory system, and an affordable and portable laboratory kit was designed [7]. In addition to this, to improve the user interfaces, these educational systems use MATLAB/Simulink [7] and LabView [2].

By contrast, our educational teaching material system has richer components such as a large capacity motor driver and high-resolution encoder, because of our system targets comparisons between theory and practice, and observations of analog control which is easy to visualize. However, our educational teaching material system does not have smart user interfaces; this is one of future works.

The purpose of this study is to develop and research educational teaching material system which can experiment in electric, electronic, computer information and machine technologies which are required for embedded engineers. This educational teaching material system is based on an embedded computer system, and students can understand the embedded system and experiment motor control theory. Using this educational teaching material system will support to learn machine technologies which are insufficient in the department of electrical and electronic engineering. Using this educational teaching material system aims that students will be studying based on a primary embedded computer system and getting more knowledge of embedded system engineering. This paper is organized as follows.

In this paper, we first discuss the aims and details of the educational teaching material system. Section 3 describes the technical way of DC motor control. Next, Section 4 illustrates the components of the educational teaching material system. Evaluations of the educational teaching material system are presented in Section 5. Finally, Section 6 concludes this paper.

2. The Aim of the Educational Teaching Material System.

This educational teaching material system aims that the students can easily observe the difference in motor responses when different control methods are used. Moreover, make students understand the correspondence between the theory and the phenomena using motors control system and also find merits of using embedded systems.

In lectures, when students are learning motors control methods they only learn the theory of it, and they do not use actual motors experiment system. Thus, it is difficult for students to understand the difference of response and performance of motors controllers (P, PI, PID). In theory, changing the controller's parameters may improve the performance significantly. However, it is difficult for students to imagine the effect of changing the settings. Usually, the software simulators such as the MATLAB or others are used, when students study the motor control theory in the lecture [9,10]. However, these simulators only show the result that the effects are caused by changing parameters, students find it difficult to understand that how it will affect the actual system. Therefore, it is difficult for students to intuitively understand that why the motor speed does not reach target speed using the P controller when students are studying the P control method.

Thus, we believe that an actual educational teaching material system is needed to help the students understand the motor control theory. Therefore, we are researching and developing an educational teaching material system for DC motor control system, which system drives an actual motor by motor theories (P, PI, PID) and realizes to students the phenomenon of the actual motors.

This educational teaching material system can observe different motor response changing by how is changing the parameter of motor control theory because it is difficult for students to understand the difference of motor control theory (P, PI, PID) only university lectures. Students can experiment with the motor system, and feel and experience the movement of the motor and the actual motor's response by using this educational teaching material system. For example, when a motor is slowly rotating, student grips a shaft of the motor and try to stop the motor. If the motor is controlled by P control, the motor will stop. However, if the motor is controlled by PI control, in case trying to stop rotation, rotational power will increase, and the motor will not stop. Thus, using this educational teaching material system, students will be able to intuitively understand motor theory easily by their experiences using an actual motor.

3. **DC Motor Control Using Embedded System.**

3.1. **Characteristics of DC motor.**

The DC motor is an electric engine that converts electrical direct current into mechanical energy [3]. The DC motor speeds can be controlled smoothly by changing power supply voltage, and in addition to this, the direction of motion can be reversed by changing the power supply direction. Thus, DC motors are used in many mechatronics applications, because of their ease of use and their torque properties. Figure 1 shows a DC motor's characteristic chart. DC motor has specific characteristics, which are starting torque is large, linear rotation speed response by the input voltage and linear torque output by input current. Also, DC motor has a problem which stalled current is quite large when the motor stalls.

3.2. **Speed control method of DC motor.**

As mentioned above, the DC motor's speed is controlled by its input voltage. Thus, to control DC motor, it is needed of ways to change DC motor input voltage. However, the embedded computer cannot connect DC motor directly, because the embedded computer output pins' current is limited and output voltage also is not varying. Therefore, the embedded computer uses the motor driver as an electric power device that drives motor. A motor driver is an electronic circuit which consists of power ICs or power transistors [13]. A motor driver receives on/off signal from an embedded computer, and it drives motor. A motor driver is widely used in electronic and robotics as power converters.

A DC motor driver can turn on/off a DC motor, but a DC motor driver does not have a function of a speed control way. Therefore, the embedded computer quickly turns

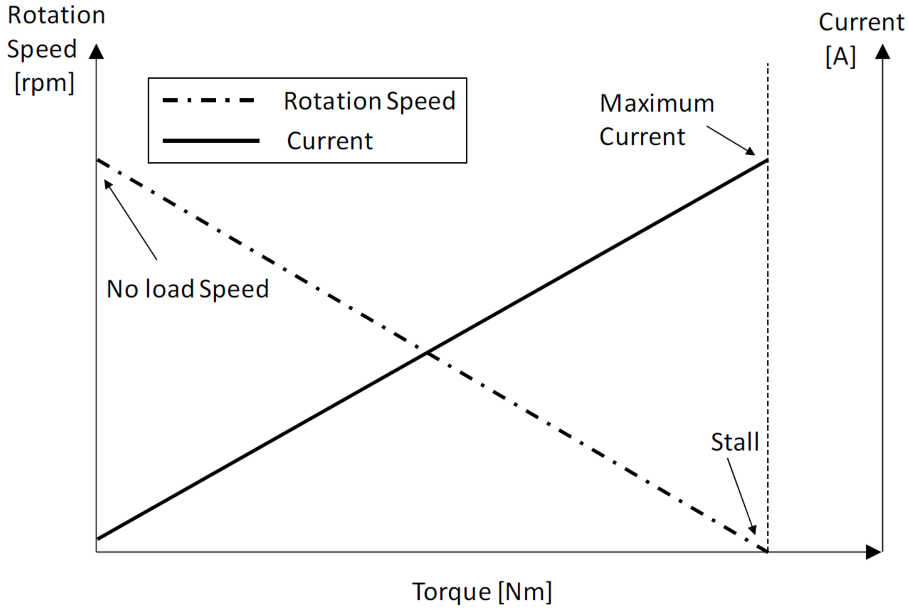

Figure 1. DC motor characteristic chart

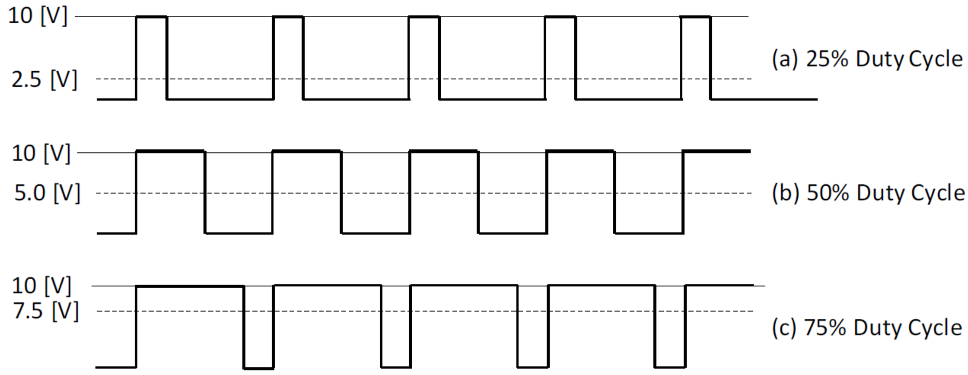

Figure 2. PWM signals of varying duty cycles

on/off these switches with Pulse Width Modulation (PWM) and controls motor speed by changing the PWM ratio. PWM is a method of modulating a signal by varying the duty ratio of pulses at a constant carrier signal frequency (period) and pulse amplitude. The embedded computer uses digital output pin with the PWM mode as controlling peripherals.

Figure 2 shows three different PWM signals. Figure 2(a) shows a PWM output at a 25% duty ratio. In this case, the output signal is turned on for 25% of one cycle and off the other 75%, so that the output voltage becomes 2.5 [V]. Figures 2(b) and 2(c) show PWM outputs at 50% and 75% duty ratio, and these output voltages become 5.0 [V] and 7.5 [V]. Thus, the embedded computer could control the DC motor by using the PWM signal.

3.3. **Motor speed calculated method.** In order to calculate motor speed, a rotary encoder is used. Rotary encoders are used to measure the motor rotational speed and direction. Figure 3 shows the typical components of a rotary encoder. A rotary encoder consists of a light source (LED), a light sensor, and a disk which is attached to a shaft. The disk has many slits which pass light. When the disk rotates, the light from a light

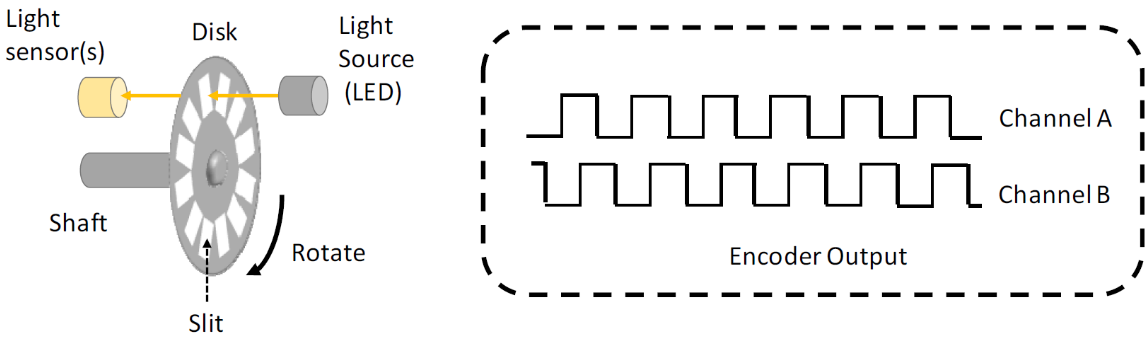

FIGURE 3. Structure of rotary encoders and encoder output (pulse)

source passes by slits, and a light sensor detects light intermittently and generates encoder output pulses. The frequency of this encoder output pulse means motor rotation speed.

The rotary encoder outputs two pulses from channels A and B when the disk rotates. The direction of motor rotation can detect by using two channels of encoder output. The number of pulses which are generated per complete turn of the motor depends on encoder's resolutions. If the rotary encoder has high resolutions, it can detect a high-precision motor moving. The embedded computer can calculate motor speed using its internal counter and rotary encoder.

4. Components of the Educational Teaching Material System.

4.1. System components. The basic configuration of this educational teaching material system and the outline of the whole system are shown in Figure 4. This educational teaching material system consists of (1) computer section, (2) embedded processor section, (3) motor driver section, and (4) control target section (DC motor). Figure 5 shows the educational teaching material system which we are researching and developing using an embedded computer.

In the PC section, we use the personal computer for various operations such as control system commands generation, and data display. In the embedded CPU section, the

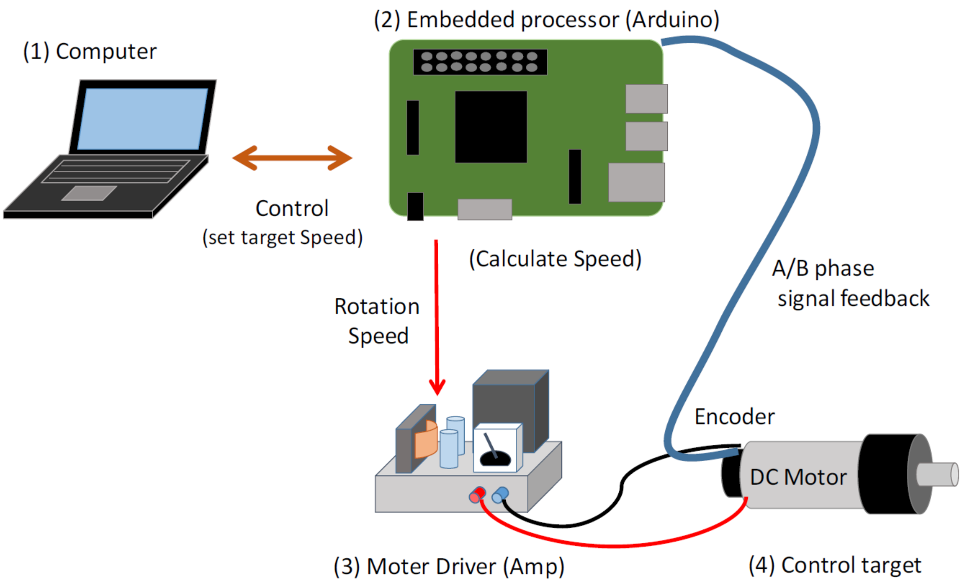

FIGURE 4. System diagram

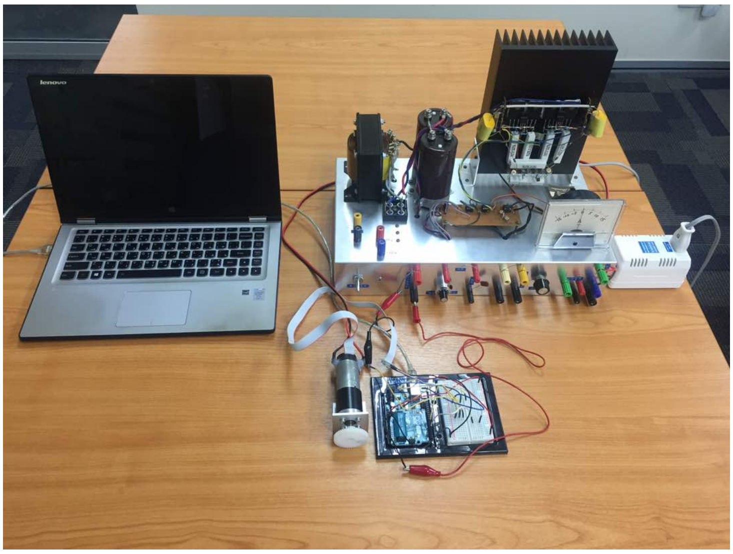

FIGURE 5. Educational teaching material system

Arduino Uno is used for the motor control execution [8]. We implemented the control system of the motor using C language to the Arduino Uno. In the motor driver section, we use the motor driver as a power supply for the motor, and a DC linear amplifier is used in this system. In the control target section, we had selected a DC motor (made by Maxon) incorporating an optical rotary encoder. The Arduino Uno calculates the motor rotation speed by using the Maxon motor's encoder output. We implemented a motor control program based on motor theories (P, PI, PID) to the Arduino Uno.

This system aims at students studying embedded computer systems. Therefore, we had selected the Arduino Uno as a low-cost embedded computer, whose price is $22. However, this system needs a large power supply capacity and some functions for experiments, and commercial ready-made motor drivers are not suitable for this system. Therefore, this motor driver is assembled from parts such as transistors, trans, and capacitor, and the motor driver cost is about $500. Also, the motor requires a high-resolution encoder; thus, the motor cost is about $400. As a result, the total system cost is about $1000.

4.2. **Control target.** This educational teaching material system uses Maxon DC Motor as a target motor [11,12]. It consists of a planetary gearhead, Re-max graphite brushed motor and a 3 channels encoder sensor with line driver. An essential point of motor selection is encoder's resolutions. If encoder's resolutions are not enough to calculate motor speed, one cycle time of motor control takes a long time, and motor control response becomes poor. Therefore, we had selected this Maxon motor because of its reasonable price, high speed and high encoder pulse count per rotation (1000 pulses per rotation). Figure 6 shows the Maxon motor which we are using.

This educational teaching material system aims that students understand motors theory and experiment motors control. Thus, this educational teaching material system's motor driver has a large power supply capacity, because it is to understand the phenomenon that motor current will be excessive when the motor is stalled. In addition to this, this educational teaching material system targets not only motor control by digital control, but also comparisons between theory and practice, and observations of analog control which is easy to visualize. Thus, this motor driver has many peripheral ports which support to observe signals. Figure 7 shows the motor driver that we are using in this educational

FIGURE 6. Maxon motor

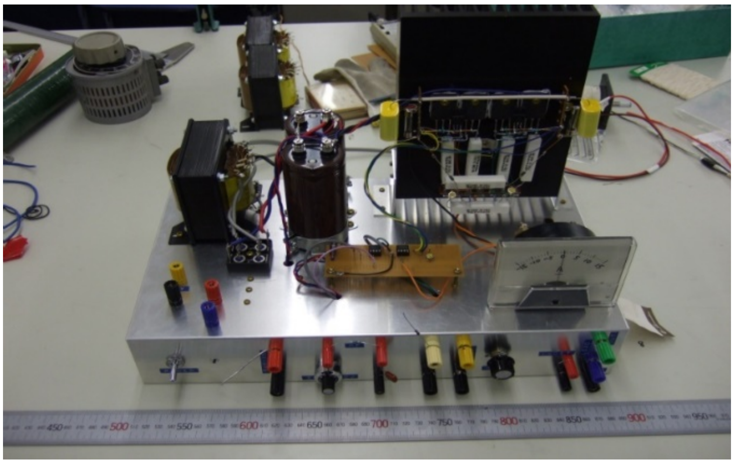

FIGURE 7. Motor driver

teaching material system. To prevent thermal runaway caused by the bipolar transistor for current amplification, the motor driver has a large heat sink.

4.3. **Motor control system on the embedded computer.** In this educational teaching material system, the Arduino Uno is used as the embedded computer. The Arduino Uno is connected to the motor driver's controlling pins that control the rotation speed by PWM signal. A motor control system which is a PID controller is implemented to the Arduino Uno by C Language, and the Arduino Uno controls the motor using motor driver by user operations input. The motor control system is implemented using a closed-loop feedback system on the Arduino Uno. Figure 8 shows the motor control system diagram, which is indicating the software part of the embedded computer (the Arduino Uno) with a dashed line.

In this motor control system, the Arduino Uno is aware of the current motor speed and state and controls motor speed. The Arduino Uno receives user operation input orders and encoder pulses from the motor encoder and sends control signals to the motor driver. The user operation input orders are a target motor speed [RPM], control modes (P/PI/PID) and control parameters (K_p, K_i, K_d). The Arduino Uno receives encoders pulses from the optical rotary encoder and then counts the number of encoders pulses. Using the encoders pulse counter, the Arduino Uno calculates the motor speed every 10 ms.

The Arduino Uno counts when the encoder pulse was rising and checking how many count number every 10 ms period, which means how much degree motor rotates. The Arduino Uno uses the current value of the counter and previous (in 10 ms before) value of the counter and calculates motor speed. (Enc_{new} is a value of the counter, and Enc_{old}

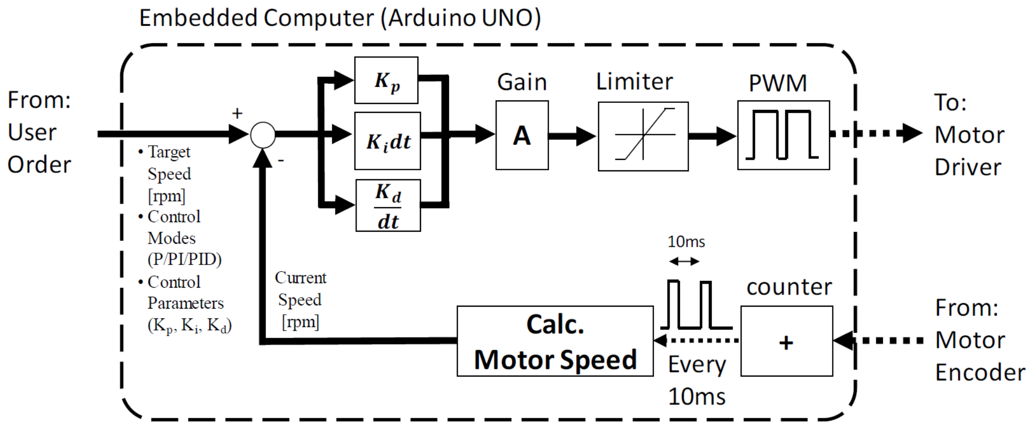

FIGURE 8. Motor control system diagram

is a value of the counter in 10 ms before.) The motor speed is calculated by how much degree rotates every 10 ms using Equation (1).

$$\text{“Motor Speed”} = \frac{Enc_{new} - Enc_{old}}{1000} \times 100 \times 60 = (Enc_{new} - Enc_{old}) \times 6 \qquad (1)$$

The embedded computer calculates motor speed every 10 ms. The speed is multiplied by 100 to convert it from milliseconds to seconds. Then it is multiplied by 60 to convert it from revolution per second to revolution per minute (RPM). “1000” indicates encoder's resolutions of the Maxon motor, which is counts of encoder pulses for one motor rotation.

After calculating motor speed, the Arduino Uno updates directive of speed control by comparing the target motor speed with current motor speed. Then, comparing the current speed with the target speed, the PID controller is implemented using the control parameters K_p, K_i and K_d to control the PWM parameter driven to the motor driver. Then, the new speed-order has multiplied the gain which is a parameter called “A”. The parameter “A” is treated as a system gain parameter. After that, the new multiplied speed-order is limited by the allowance of the system input depending on the motor driver interface. Finally, the embedded computer sets new PWM parameter by the limited multiplied new speed-order resulting in changing the motor speed by the new speed-order.

In this educational teaching material system, the Arduino Uno records the motor speed data every 10 ms. When the target speed is reached, or test time is passed, the log file will be used to produce the response graph of the system. The graph can be used to study the transient response and steady-state response of the system. By using different types of controllers such as P, PI, and PID, the result can be compared to the theory.

5. **Evaluation.** We evaluated the educational teaching material system using four different PID control methods: P, PI, PD, and PID; all evaluations have been tested with no load. For P and PI controls, the parameters (K_p, K_i) mean to turn on/off P or I control. Thus, we only evaluate the effect of changing the gain parameter “A” tested on the system. For PD and PID controls, the effect of changing the derivative parameter (K_d) is tested on the system. In this evaluation, K_d parameter is very small because the derivative parameter (K_d) is very sensitive and it is difficult to find suitable parameters. If the K_d parameter sets 1, the motor vibrates and is not stable.

We set the target speed to 150 [RPM] in all evaluations, and observed the motor response. Figure 9 shows a comparison between the four control methods (P/PI/PD/PID) used in the educational teaching material system. In this comparison, the parameters are as below. The P control is “$K_p = 1$, $A = 2$”. The PI control is “$K_p = 1$, $K_i = 1$,

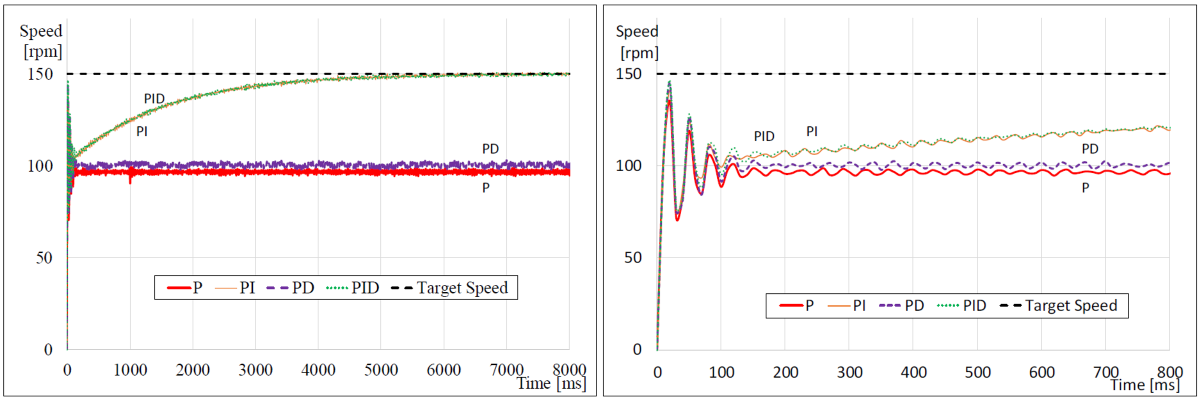

FIGURE 9. PID response comparison

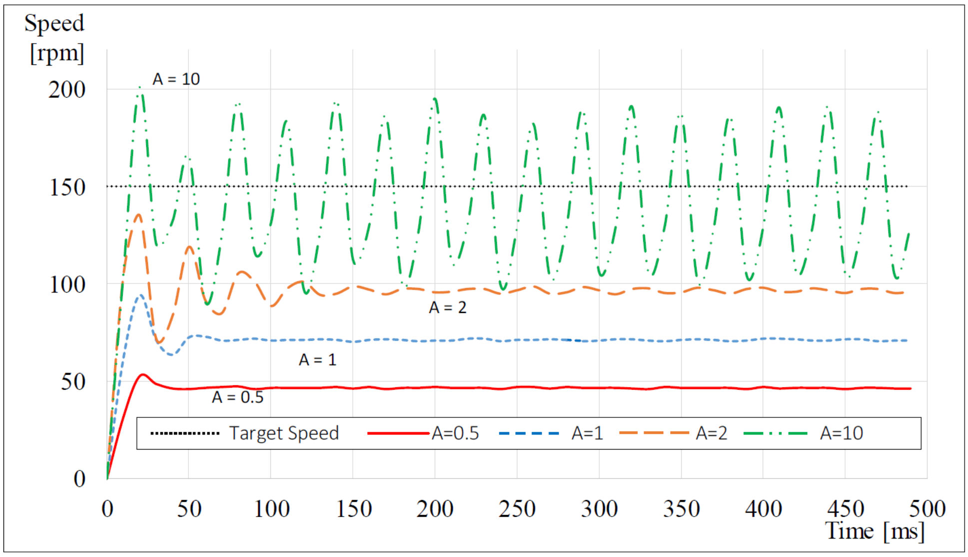

FIGURE 10. Stability of the system (using the P controller)

$A = 2$". The PD control is "$K_p = 1$, $K_d = 0.003$, $A = 2$". The PID control is "$K_p = 1$, $K_i = 1$, $K_d = 0.003$, $A = 2$".

From Figure 9, the P and PD controllers have a very similar transient response. However, in the steady-state responses, the PD control has a smaller steady-state error. Also, the PI and PID have similar transient responses and steady-state responses. The PID control offers smaller overshoot and higher oscillation compared to the PI control which offers higher overshoot and less oscillation. In this evaluation, the effect of the derivative control on the system is unnoticeable since the K_d parameter is very small. If the K_d parameter is set the more large value, the result becomes poor system stability. The derivative control is sensitive in the real-world application. Hopefully, optimizing the parameter, the PID control will have the best response. In this evaluation, however, we did not find a suitable K_d parameter.

Next, we evaluate that whether the educational teaching material system can observe effects to the response of the motor by changing parameter "A". This evaluation is using the P controller, and observes the stability of the system and actual motor rotation state. Figure 10 shows the evaluation result of the P control, which in this evaluation gain parameter "A" is changed from 0.5 to 10.

This evaluation shows that the educational teaching material system can observe effects caused by changing gain parameter "A" using an actual motors system. In addition to this, students can measure a motor rotation speed using a tachometer, when the amplification degree is insufficient by the P control, students can be experienced that there is large steady-state error occurring with the target speed in an actual system. Also, students can observe the system becomes poor system stability, when the amplification degree is excessive. From this, students can observe and understand that the motor will be vibrating when the system becomes poor system stability. Using the educational teaching material system has considerable merit because students cannot experiment the actual motor state when they are simulating the motor in the software.

6. **Conclusion.** In this paper, the educational teaching material system was described. This system was implemented to aim that students can easily observe the difference of motors response by different control methods. From the evaluation, it was confirmed that the difference of motor response controlled by P, PI, PD, and PID control could observe. In addition to this, changing the controller's parameters affecting motor response was also confirmed. Thus, the educational teaching material system can observe the response of the motor by the motor control theory in an actual system. Therefore, students will be able to understand the correspondence between the theory and the phenomena more efficiently and find the merits of using the embedded system.

In this educational teaching material system, students will be able to experience the interrelated technologies of machinery, electricity, electronics and computer technology by using the control by the embedded processor. Moreover, they can experience the functions, roles of motor control, and visualize the effect as a phenomenon. By using this, students will be making it easier to understand the theories by seeing these as actual phenomena through motor control.

In the future work, several functions are needed to be implemented in the educational teaching material system. In addition to this, evaluate using this system in an experiment and checking the reaction of students. The future works are summarized as follows. (1) A smart graphical user interface should be added to the system, and an automatically graph figuring system should be implemented. Using the interface and system, the s-tudents will easily do various experiments by changing parameters and control modes. (2) Implement another control method such as PI-D and I-PD and a function to change motor control cycle time; then students will have a better understanding by observing the system response.

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