

Designing a Project-based Plant to Enhance Mechatronics Students for Self-learning Embedded Control System

Chaiyaporn SILAWATCHANANAI^{a*} & Piyanun RUANGURAI^b

^a*Department of Teacher Training in Mechanical Engineering, Faculty of Technical Education King Mongkut's University of Technology North Bangkok, Thailand*

^b*Department of Mechanical Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Thailand*

*chaiyaporn.s@fte.kmutnb.ac.th

Abstract: The feedback control system laboratory is required to enhance the knowledge of enrolled students. However, the apparatus provided by educational company usually is high cost, needs a high-performance computer and the professional instructor to conduct the experiment. In this paper, the designing of project-based learning for self-learning embedded control system is proposed. The low-cost experiment kits for microcontroller-based control can be alternately solution instead of using virtual or remotely experiment. In this work, two different types of plant systems: air levitation system and serial elastic actuator are presented. Both are easy to construct and able to implement the controller with any microcontroller. The real-time operation system for embedded system is also introduced which required for industrial control. Based on project-based approach, there are four stages guiding students and teacher to follow up the content and assessment so that the objective of embedded control learning can be achieved within 16 weeks.

Keywords: Hands-on experience, engineering education

1. Introduction

Control theory or Feedback control system course is one of the important subjects for undergraduate students in robotics or mechatronic field of studies. Closed-loop control of position or velocity of electrical motors is the fundamental of servomechanism that found in mostly industrial robot and automation system. The knowledge related to temperature, water level or flow rate control can be applied in industrial process control and smart agriculture.

However, the contents (Ogata, 2010) and (Nise, 2011) in this subject usually is described with mathematical model, open-loop and closed-loop transfer function. The physical systems such as electrical, mechanical, pneumatic, hydraulics and heat transfer systems can be expressed in either differential equations or Laplace domain. Teaching the core of system dynamics and control topics such as time and frequency response, poles and zeros, stability and compensator design based on mathematical foundation can be abstracted for students and lead to misconception how system in real world work. The experiment with the real hardware is necessary for enrolled students of system dynamics and control. The traditional feedback and control laboratories have limitations (Durfee, Li, & Waletzko, 2005). It requires high-performance computer, plants, expert control faculty and instructors for high quality laboratory. Moreover, commercial experiment kits also are high cost resulting the number of lab stations less than the number of students. Even though several works introduced virtual (Bhutta, Mansoor, & Tariq, 2016) or remote laboratories via internet to solve problem, it does not give the feeling of working with a physical system.

Many courses in school and university deployed Project-based Learning (PBL) to their students to improve the solving skills, inquiry, collaborative among members and encourage for subjects. Due to low cost and high performance, embedded system-based microcontroller becomes more popular for high school students and undergraduate students. Arduino[©] is one of the most used open-source electronics platforms because it is easy-to-use for different backgrounds, plenty libraries, and

communities to support. Thus, there are varied types of Arduino boards as a tool in microcontroller course, Capstone projects in high school, vocational and university in Thailand. For feedback control system, using microcontroller as a main controller has more convenient than analog controller based on electronic circuit.

This work introduces the project-based plants for enhancing self-learning in embedded control system. Two different types of plants for mechanical engineering: air levitation and mass spring system are addressed.

2. Literature Review

2.1 Practical Laboratory Model

The hands-on activity in Feedback Control Laboratory provides the student with the knowledge and experience. Unfortunately, commercial test bed sets usually are high cost, requires high performance computers so that some schools or universities may lack the budget to utilize some of equipment and software licenses. Instead of using computer simulation, several works proposed the low-cost alternatives for students, thus they are able to learn some topics by taking-home experiments. The work in (Durfee et al., 2005) proposed the distributed labs approach to giving students hands-on experience. Their projects consist of three parts: a fourth-order mass spring damper, the controller board, Window based interfacing software for visual display and other supervisory control. The work in (Çatalbaş & Uyanık, 2017) proposed a low cost DC motor kit to conduct the frequency domain characteristic with MATLAB software. (Jahnvi & Sivraj, 2018) proposed the design and development of five-degree of freedom (DOF) robot arm working with Graphic User Interface (GUI) in MATLAB. This work also implements serial link kinematics in order to compare the position of robot tip obtained by joint sensor and the end-effector. (McPherson, Legris, Flynn, Bradley, & Daniels, 2016) proposed the low-cost two-degree-of freedom mass-spring cart system for system identification laboratory exercise. The input-output data obtained from data logger, the mathematical model of mechanical systems can be identified.

In summary, the low-cost experiment sets become more popular in control engineering education to enhance the knowledge of students. Since the model consist of mainly three components: hardware, microcontroller and computer software, they can be reproduced.

2.2 Real-time Operation System

Real time system is the key of industrial automation applications. According to program developed by Arduino platform, it has two functions: setup function to configure the peripheral and main function in which the developed program is executed that repeat over and over. In a digital closed-loop control system as shown in Figure 1, the controller executes to read the set point and sensor data, and then use these numbers to calculate the controller output which is sent to the actuator. The digital or discrete control system observes the input signal at a certain time, then calculates the control input signal for actuator driven.

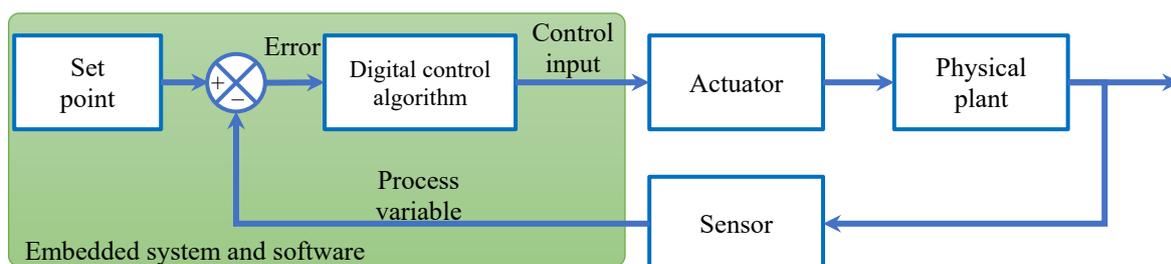


Figure 1. Block diagram of digital control system.

To execute the loop control in precise time, Real-Time Operation System (RTOS) including the feature multi-tasking with multiple threads and inter-task communication and synchronization mechanisms should be considered when implementing digital control and state-space control (Gambier,

2004). For embedded control system, there are many platforms supporting real-time application such as PIC, ARM and Arduino. The survey of available RTOS (He & Huang, 2014) showed that FreeRTOS is free license, portable to a large number of MCUs, well-document and then supports most common MCUs. Microcontroller used in student's project has one processor core, only one task can be executing at any one time. By using FreeRTOS scheduling mechanism, it makes the decision which each tasks should be execute at a time. As shown in Figure 2, the controller can be performed every period T_s by using a single task model.

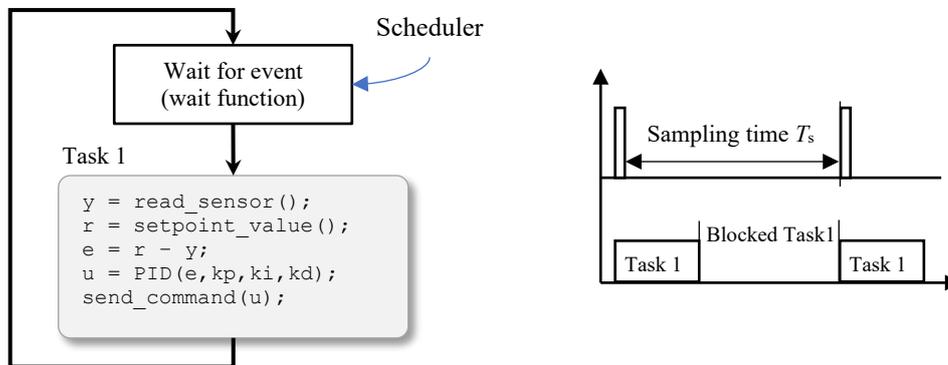


Figure 2. Controller implemented with real-time periodic task.

3. Methodology

3.1 Design Learning Activities

This section, the learning activities of project-based embedded control system course are proposed. There are four stages that beginning from proposed topics until evaluate the performance of controller result. All activities can be conducted for one semester or 16 weeks. According to Figure 3, Firstly, the teacher asks the students propose the topic of plant system for project-based and discussion how student's topics relating to the real applications. The second stage, the components of loop of automatic control are identified by describing the physical working principle. In the third stage, the students design and implement digital control such as PID or Fuzzy logic controller in microcontroller. Lastly, the students evaluate the performance of controller by using the date sent from the embedded system. This data can be visual in terminal program such as Teraterm or Hyper-Terminal. Moverover, some program such as Serial monitor or Serial plot in Arduino IDE can read .csv data format and plot the time response result in real-time. Thus, the student is able to relate the response in graph to the real physical system easier. Note that assessment of student project is conducted in the transition between each state.

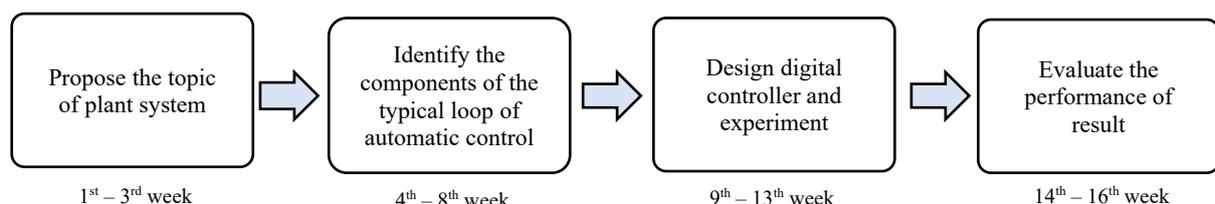


Figure 3. Project stage of control systems area.

3.2 Air Levitation System

The conceptual design of air levitation system kits mainly consists of tube structure, actuator of air flow and displacement sensor. Because it is easy to construct and relates to aerodynamic, several researches proposed ball levitation system as training kit for verifying a novel control algorithm or teaching purpose (Cholodowicz & Prłowski, 2017). As shown in Figure 4, the system has 12VDC fan duct motor

for lifting up the ping pong by generating the air flow through the tube. The ultrasonic sensor is installed on the top of the tube to detect the position of ping pong ball. The height of plant is 1 meter so that the response of position control of ping pong ball be significant.

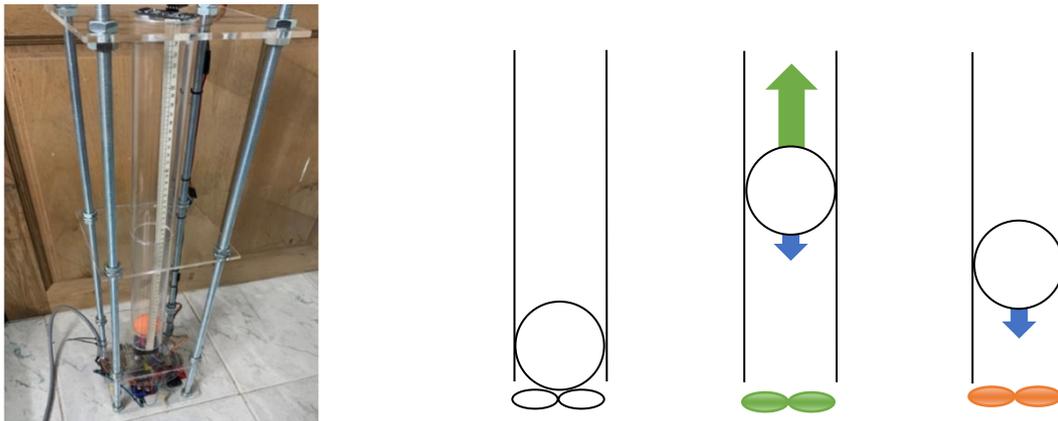


Figure 4. Ball levitation system and its working principle.

According to proposed project stage, learning activities should be

- *Stage 1:* Propose the concept of mechanical design, how to install all components, describing the working principle of air levitation by Newton's law and Bernoulli's principle.
- *Stage 2:* Identifying the component of loop control where ultrasonic sensor is used to detect the ball position with reference to the top. How fan duct motor should work to lift the ball and what is the proper action for moving lower?
- *Stage 3:* Implement the controller by coding with FreeRTOS library. In this stage, teacher should guide how to set task priority and sampling rate for controller task including how to receive the controller parameters and sent data in .csv format.
- *Stage 4:* By doing the experiment, the performance of controller can be observed in real-time. What is the time response graph telling us? What the effect of controller parameter is?

Finally, students should address the problem during work and the future work for this system. Figure 5 shows the screen shot of video presentation file of finished project. It shows the camera view of air levitation system, real-time history plot and explanation by students.

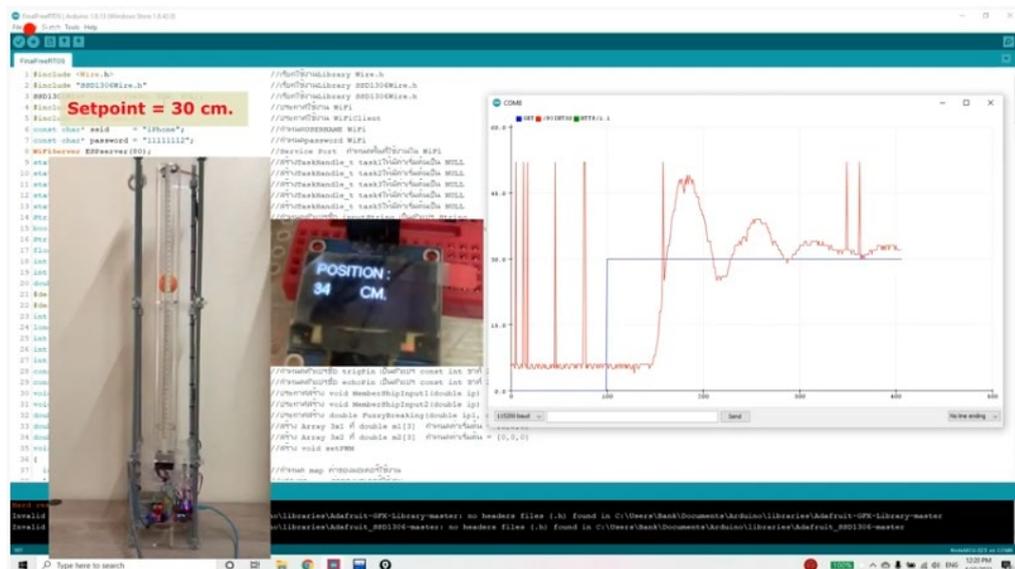


Figure 5. Screen shot of air levitation system.

3.3 Series Elastic Actuator

With increasing of using physical human-robot interaction (pHRI) device such as service robot, orthotic device, collaborative robot, and haptics, it is important for students to gain hands-on experience about designing and control of force-feedback devices. The definition of series elastic actuator (SEA) is the mechanical device that installs an elastic element such as a spring attached with the mechanical energy source output, to improve the performance such as low impedance, passive mechanical energy storage and tolerance to impact loads. Based on spring-displacement, the SEA device can sense the external force without using any force sensor. Figure 6(a) shows the CAD design of reaction-force sensing series elastic actuator. This system represents the working principle of mass-spring system which can apply for orthotic device or haptic interface. The end-effector is driven by 24VDC brushed motor through a ball-nut screw. The position of end-effector is measured by combing the position of moving rod and the deviation of spring displacement.

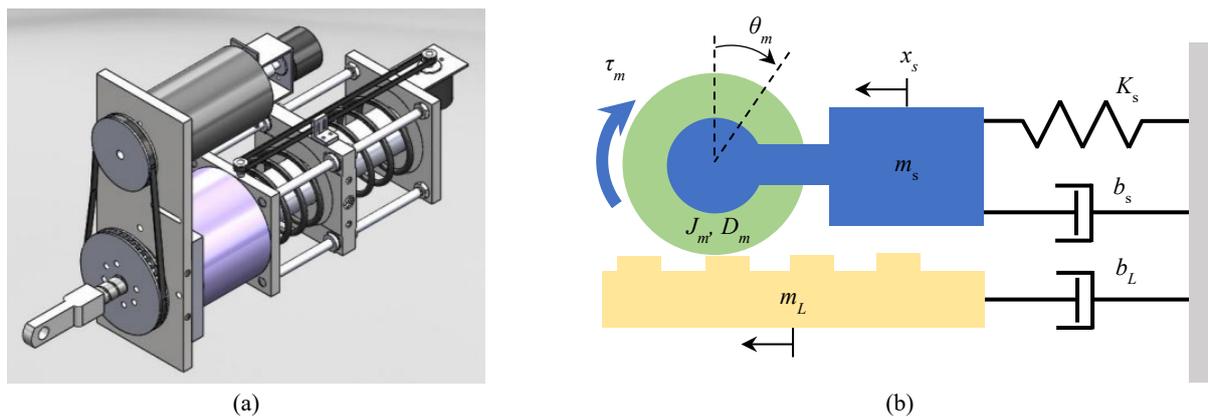


Figure 6. (a) The prototype of SEA, (b) free body diagram.

According to proposed project stage, learning activities should be

- *Stage 1:* Propose the concept of mechanical design, how to design part and assemble, write a free body diagram of this system for deriving the equation of motion as shown in Figure 6(b)
- *Stage 2:* Identifying the component of loop control where one encoder is used to detect the spring displacement. How the motor angular position be converted to the moving rod position by using transmission ratio. How to find the stiffness constant of spring based on Hook's law.
- *Stage 3:* Implement the controller to the embedded system (similar to Air levitation system). To demonstrate the contribute of this work, teacher should guide students how to design the experiment for example the motion control when the load is attached to the end effector. What the reference signal should be suitable for this work?
- *Stage 4:* By doing the experiment, the performance of controller can be observed in real-time. What is the time response graph telling us? What the effect of controller parameter is?

The experiment with SEA prototype was conducted as shows in Figure 7. The dumbbell load is attached for exerting the uniform external force. The reference position of end-effector was set as ramp input signal instead of a step signal. Then the student can notice the motion of dumbbell load and compare the result which is differ from the step response.

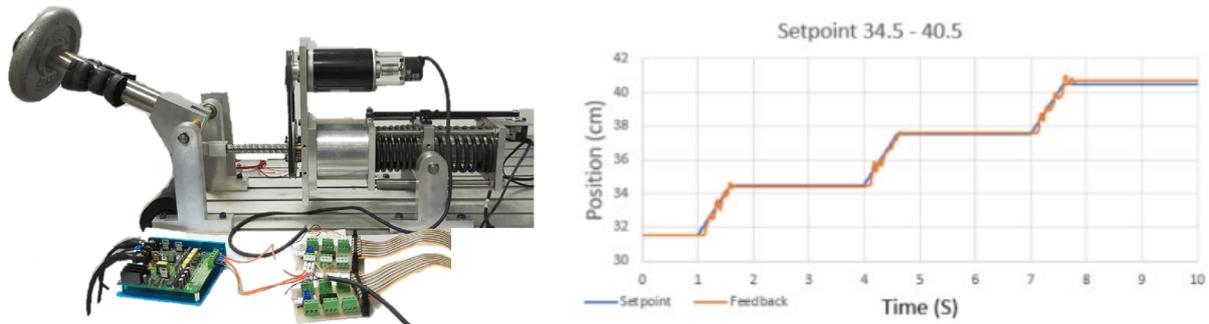


Figure 7. Position control of SEA prototype project under the load and the response.

4. Conclusion

The hands-on activity with project-based plant systems explores the knowledge and experience to the enrolled students. The limitation of feedback control laboratory can be solved by project-based approach. For example, the experiment is based on the learner conditions such as own interesting, low cost and time to conduct the experiment so that more flexible and feasible than the traditional approach. The activities of each topic are divided into four stages: 1) planning and propose topic, 2) identifying the component of control loop, 3) implementing a digital controller based on given template including conducting the experiment and 4) analyzing and evaluating the performance of control. Based on these stage as a pacer, students can follow up their work and are assessed by teacher. Furthermore, the students can discussion their experience with different topics among groups.

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