Development of Educational Materials for Mechatronics

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Abstract: - This paper reports the development of teaching materials for mechatronics in tertiary education. Current industrial societies strongly require many mechatronic engineers, and most technical universities actually provide mechatronic exercises in their courses. On the other hand, it is a little difficult for teachers and students to freely modify and improve the mechatronic materials provided by education industries because the provided materials are finished products. Hence a simple and inexpensive educational system is newly developed to overcome disadvantages of the finished products. In this paper, a desirable system structure is proposed for mechatronics education, and a practical example is shown with the aim of soundly learning control, sensor, actuator, and mechanics.

Key-Words: - Mechatronics, Education, Actuator, Sensing, Control, Pneumatics, Dynamics

1 Introduction

Nowadays convenient mechatronic devices become widespread in our lives, and current industrial societies strongly require many engineers capable of mechatronic design. Most mechanical departments of the technical universities are also resonant with the industrial requirements, and provide mechatronic exercises for students in their courses. In general, the mechatronic exercises are conducted using the mechatronic materials provided by education industries. On the other hand, the provided materials are often finished products, and it is a little difficult for teachers and students to modify and arrange the products for mechatronics education. For this reason, it is rather difficult for students to soundly understand the whole structure or relationship of mechatronic elements in short hours of the exercise. In other words, there is no saying that every student has mastered the fundamental ability to create new mechatronic devices by use of the existing teaching materials.

Hence we mapped out a plan to build up handmade materials for mechatronics in tertiary education. The word ‘mechatronics’ comes from the fusion of mechanics and electronics, and nowadays mechatronics is also regarded as system integration technology including information and communication devices. **Figure 1** shows the typical block diagram of mechatronic device composed of four key elements of a controller, a sensor, an actuator, and a mechanism. The four kinds of technologies have been often separately lectured as control engineering, measurement engineering, actuator engineering, and mechanics, respectively in general technical universities. Because of the isolated lecture, it is considered to be difficult for students to accurately understand mutual relationships of engineering, or to globally grasp the whole system of mechatronic device.

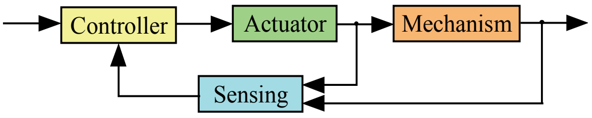


Figure 1. Typical block diagram of mechatronic device

The goals of learning mechatronics design in universities are considered to be mainly defined as follows:

1) To soundly understand each role and position of four key technologies,

2) To properly select and distribute each key technology or creating a desired mechatronic device,

3) To exactly estimate and evaluate the total performance of a desired mechatronic device.

Thus we attempt to develop the universal frame of mechatronics education. Fortunately, some convenient microcomputers are familiarized around the world, which are equipped with graphical user interfaces and many useful signal processing elements. Furthermore, useful CAD software is also provided for control design. The proposed educational system is constructed under the convenient microcomputer and CAD software. The mechatronic devices are newly developed to deeply learn the mechanism and relationship between controllers and sensors. It is also desirable for the developed device to include various kinds of mechanical knowledges and technologies.

First, the basic system of mechatronics education is shown, which is equipped with microcomputer and CAD software for control design. Next, a mechatronic device is proposed, which is inexpensive, safe and suitable for student's exercise. The mechanical device is composed of an acrylic pipe, a ping-pong ball, and a DC motor with a plastic propeller, and aims to stop the ball at the desired position using a range sensor. The ball in the pipe falls down in the gravity field, and is blown up by airflows of the rotational propeller. Understanding the ping-pong motion needs the fundamentals such as mechanics, thermodynamics, and pneumatics. According to the physical modeling process, the ping-pong motion simulator is also made up by CAD software. The actual ping-pong control experiments are compared to the ping-pong motion simulations by CAD, and the degree of agreement is discussed between experiments and simulations. Finally, some future proposals are shown to improve and evaluate the teaching materials.

2 System elements for mechatronics exercise

2.1 Microcomputer and CAD software

NI myRIO^{TM} is adopted as a real-time microcomputer for mechatronics exercise. The microcomputer is equipped with many A/D, D/A, and I/O ports, and it is easy for beginners to graphically program by virtue of GUI of LabVIEW^{TM}. The real-time operating system is also provided for feedback control of mechatronics exercise. Besides, the myRIO is expected to be hardly broken for rough handling because it is enveloped by a hard cover with firm electrical connectors. Matlab/Simulink^{TM} is adopted as CAD software for motion simulation and control design. This software is familiar with many control engineers around the world, which is provided by the MathWorks. The software is widely used to develop actual products in industrial fields.

On the other hand, it is considered to be rather difficult for an alone beginner to complete a mechatronic exercise accompanied with a sensor, an actuator, and a controller, using a motion simulator effectively. Hence, one myRIO and two personal computers are provided to a pair of students. The GUI of LabVIEW is installed in one personal computer, and the CAD software of Matlab/Simulink is installed in the other. The pair of students aims to complete the mechatronic exercise in cooperation with each other.

2.2 Mechanical system for mechatronics exercise

It is educationally desirable for mechatronics exercise to include sensing, actuating, and mechanically designing. Here, we introduce a classical toy called blowing-up pipe shown in **Figure 2**. The toy has a principle that human exhaling pressure blows up a light ball, and the ball stops in air by tuning the breath. Hence a mechanical system similar to the toy is proposed for mechatronics exercise.

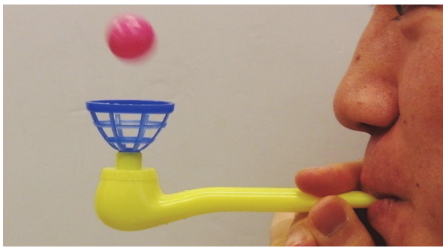


Figure 2. Toy called blowing-up pipe

Figure 3 shows the whole view of the mechanical system for mechatronics exercise. The mechanical system is composed of an acrylic pipe, a ping-pong ball, and a DC motor with a propeller to mimic the toy motion. The rotational flow of the propeller lifts up the ball, and the ball position is measured by a range sensor attached to the outlet of the pipe. The microcomputer myRIO catches the ball position through a range sensor, and produces the control input to the motor driver after filtering noises of the ball position. The final aim of the exercise is to quickly and stably stop the ping-pong ball at the desired position. To realize the aim, there are five educational and technical challenges as follows:

a) Filtering positional signals of a range sensor to remove low frequency drifts and high frequency noises,

b) Generating pseudo velocity by using the difference data of ball positions,

c) Designing a positioning controller with feedback signals of position and velocity,

d) Improving the inlet of propeller flow to effectively draw in air into the pipe,

e) Devising the inlet to change the air flow onto the ball from turbulent to laminar.

Substantial points a), b), and c) are basic elements concerned with signal processing and control, and the following points d) and e) are concerned with pneumatics or fluid engineering. Although Figure 3 shows an example with a rectifier and a hood to attain the points d) and e), these ingenious devices are not provided in front of students in advance. All students must exercise their ingenuities to effectively and smoothly lift up the ball. **Table 1** shows the net prices of mechanical elements. The total price is approximately 100US$, which is mainly occupied by the motor driver. Although we used the commercial product as a motor driver, the total price will become more inexpensive if the motor driver is also made up of some electrical parts by ourselves.

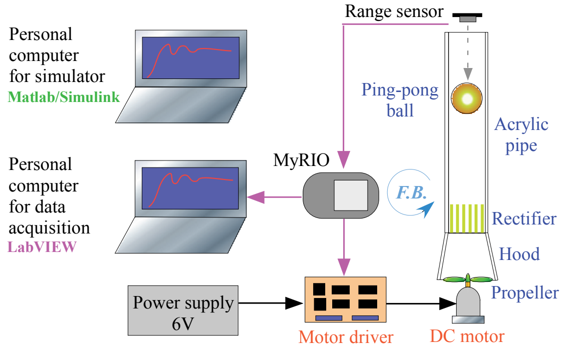


Figure 3. Mechanical system for mechatronics exercise

Table 1 PRICE OF MECHANICAL ELEMENTS

Elements	Price (US$)
1) Ping-pong ball (φ40mm, mass 2.7g)	0.5
2) Acrylic pipe (inner φ43mm, t=2mm, h=500mm)	5
3) Propeller (outer φ60mm)	0.5
4) DC motor (Sprint Dash MOTOR: TAMIYA)	3
5) Range sensor (GP2Y0A21YK:SHARP)	3
6) Motor driver (iMD03-CL: iXs Research)	60
7) Pipe stand	20
8) Pipe clamp	7
9) Miniature vice for capturing a motor	4

3 Dynamic modelling of a floating ping-pong ball

3.1 Electrical model of driver and motor

The propeller attached to the motor axis is rotated by the motor torque, and the output torque is generated from the motor driver driven by PWM (Pulse Width Modulation) function prepared in the myRIO. Although it is well known that DC motor has inductance effect, the transfer function from input voltage v to angular velocity ω is allowed to be a first-order system when the inductance parameter is negligibly small. The transfer function $G_m(s)$ is described as follows:

$$G_m(s) = \frac{K}{Ts+1}, \quad \omega = G_m(s)v. \tag{1}$$

Here, Symbols K and T denote the direct gain and time constant, respectively. Furthermore, when the motor driver is assumed to have a high bandwidth of response, the input voltage v is allowed to be proportional to the output u of PWM as follows:

$$v = K_A u, \tag{2}$$

where Symbol K_A denotes the amplifier constant. These unknown parameters $K \cdot K_A$ and T are estimated by measuring the motor driver system as described later. Additionally, the dead zone is also measured between the angular velocity ω and the duty ratio μ of PWM's input.

3.2 Dynamics of ping-pong ball and pipe

The motion of the ping-pong ball is caused by the weight itself and the difference of pressure between the upper air and the below air in the pipe. Here, the upper air is assumed to have an atmospheric pressure because the upper area of the pipe is open outside. When Symbols m, g, A, P_0, and P denotes the mass of ball, the gravitational acceleration, the pressurized area of ball, the atmospheric pressure, and the air pressure of below air, respectively, the motion equation of the ball is as follows:

$$m\frac{d^2x}{dt^2} = -mg + A\left(P - P_0\right). \tag{3}$$

Here, the x-directional position of the ball is set along the opposite direction of the gravity, and Symbol t denotes time. On the other hand, the below air sandwiched between the ball's bottom and the propeller's surface changes its air pressure P by the airflow of the propeller. Furthermore, the air pressure confined in the pipe is also influenced by leakage flows between the pipe and the ball or propeller. The following symbols are defined to formulate the pressure equation of the below air in the pipe:

P_L : Difference of pressure between P and P_0 $(P_L \equiv P - P_0)$,
Q : Airflow of propeller into pipe,
Q_B : Leakage flow between ball and pipe,
Q_P : Leakage flow between propeller and pipe,
K_b : Bulk modulus of air.

Here, although the airflow Q of the propeller usually becomes swirling flow, the flow is assumed to be laminar flow by adding some rectifier at the inlet of the pipe.

Assuming that the below air in the pipe is under an adiabatic condition, the following pressure equation is obtained:

$$\frac{dP_L}{dt} = \frac{K_b}{V(x)}\left(Q - A\frac{dx}{dt} - Q_B(P_L) - Q_P(P_L)\right). \qquad (4)$$

Here, Symbol $V(x)$ denotes the volume of below air in the pipe, dependent on the ball position x. Leakage flows Q_B and Q_P are determined as functions dependent on variable P_L. **Figure 4** shows the schematic model of below air in the pipe. Symbol V_0 in Figure 4 denotes the initial volume of below air in the pipe under condition x=0.

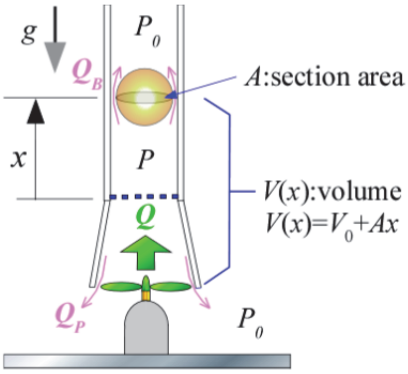


Figure 4. Schematic model of below air in pipe

When the airflow of the propeller into the pipe is assumed to be proportional to the angular velocity of the DC motor, the relationship of Q and ω is as follow:

$$Q = \alpha\omega, \qquad (5)$$

where Symbol α denotes the flow coefficient from the angular velocity to the airflow, and its value is estimated by measuring the airflow as described later. By integrating Equations (1) ~ (5), the block diagram of the dynamical equation of a floating ping-pong ball is obtained as shown in **Figure 5**.

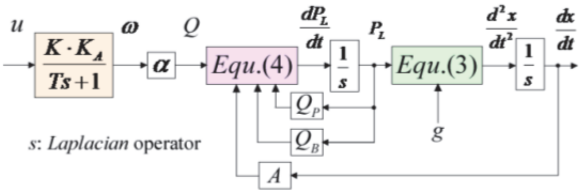


Figure 5. Block diagram of dynamical model

3.3 Parameter estimation by measurement

Some parameters in Equations (1) ~ (5) are unknown, and they must be estimated by direct measurements. First, the direct current gain $K \cdot K_A$ is estimated by measurement results from the input u to the output ω. Here, the input u is generated from the duty ratio μ of PWM's output. Hence, the product gain $K_{\mu\omega}$ from the duty ratio μ to the output ω is estimated from measuring the output ω by using a digital tachometer. The angular velocity ω is also measured under the condition keeping the propeller attached to the motor axis. **Figure 6** shows the measurement result between the duty ratio μ and the angular velocity ω. As shown in Figure 6, the propeller does not rotate at the duty ratio smaller than 10 [%], and the angular velocity saturates at the duty ratio more than 80 [%]. The incremental ratio $K_{\mu\omega}$ between the duty ratio μ and the angular velocity ω is approximately 18.2 [rad/(s%)], and the velocity at the duty ratio smaller than 10 [%] is regarded as zero [rad/s], and that more than 80 [%] is approximated as 1500 [rad/s] of maximum constant.

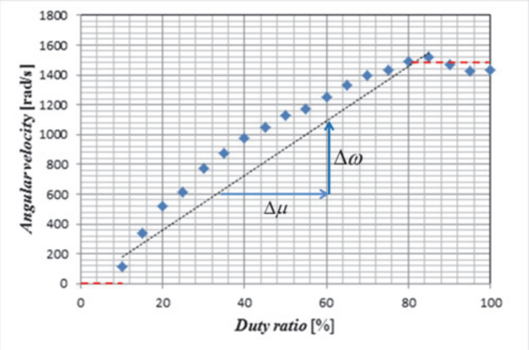


Figure 6. Relationship between duty ratio and angular velocity

Next, time constant T in Equation (1) is estimated by using two same DC motors. Here, one is used as a driving motor and the other is used as an electrical generator. The output axis of the driving motor is connected to the axis of the generator, and the time response of the generator's voltage v_e is measured under the input of duty ratio μ. **Figure 7** shows an example of step response at 50 [%] of duty ratio. Time constant T is estimated about 0.38 [s] as shown in Figure 7, and its estimated value is rather large because the propeller is considered to be attached to the output axis of the motor.

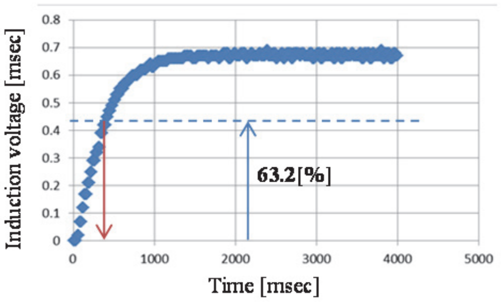


Figure 7. Time response of induction voltage

The flow coefficient α is also estimated from the relationship between the duty ratio μ and airflow Q. The airflow Q was measured by an airflow meter, changing the duty ratio μ, and their relationship was similar to the relationship shown in Figure 6. This result verifies the assumption of proportional relationship between the angular velocity ω and airflow Q in Equation (5). From the measurement results, the flow coefficient α is estimated 1.9×10^{-6} [m^3/rad]. The leakage flow Q_B is assumed to be proportional to the difference pressure P_L, because the change of P_L is considered to be small enough in the system. Under this assumption, the relationship between Q_B and P_L is as follows:

$$Q_B = \beta P_L, \tag{6}$$

where Symbol β denotes the coefficient of leakage flow. Here, the coefficient β was measured according to the following idea as shown in **Figure 8**.

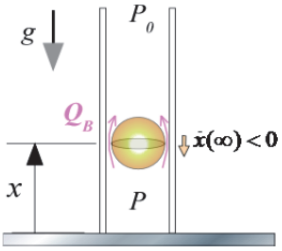


Figure 8. Measurement of leakage flow between ball and pipe

When a ping-pong ball freely falls in a vertical pipe keeping the below inlet of the pipe close, the ball velocity converges to a constant value. In other words, the left terms of Equations (3) and (4) become equivalent to zeros when time passes enough. In this case, the following relationship is obtained as the resolution of Equations (3) and (4) under conditions $Q=0$ and $Q_P=0$:

$$\beta = -\frac{A^2}{mg}\dot{x}(\infty). \tag{7}$$

Here Symbol $\dot{x}(\infty)$ denotes the velocity of ping-pong ball when time passes enough. The coefficient β is estimated from the design parameters A and m, and velocity $\dot{x}(\infty)$, based on Equation (7). The velocity $\dot{x}(\infty)$ is measured from the time difference of ball position by using a high-speed camera. On the other hand, it is difficult to determine the leakage flow Q_P in Equation (4) because it depends on the setting position of the propeller in the hood. The leakage flow Q_P is left as a tuned parameter between experiments and simulations. Table 2 shows parameters of the floating ping-pong ball system obtained by measurements.

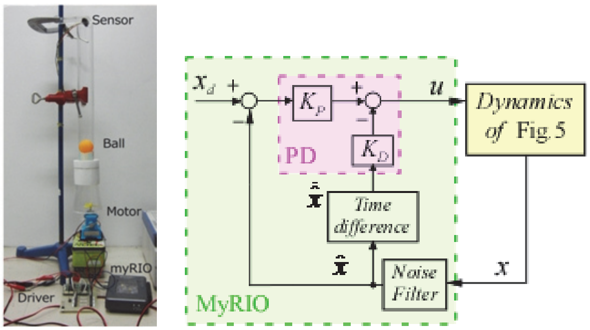
TABLE 2 PARAMETERS OF PING-PONG BALL FLOATING SYSTEM

Item	Symbol	Value	method
Mass of ping-pong ball	m [kg]	2.7×10^{-3}	direct measurement
Section area of ping-pong ball	A [m^2]	1.2×10^{-3}	direct measurement
Initial volume of pipe under ping-pong b	V_0 [m^3]	3.9×10^{-4}	designed value
Bulk modulas of air	K_b [Pa]	1.69×10^{5}	nominal data
Product gain from PWM to angular veloc	$K_{\mu\omega}$ [rad/(s%)]	18.2	estimation from data
Time constant	T [s]	0.38	estimation from data
Transfer constant	α [m^3/rad]	1.9×10^{-6}	estimation from data
Coefficient of leakage flow	β [m^{4}s/kg]	1.4×10^{-5}	estimation from data

4 Experiment and Simulation

4.1 Positioning experiment of a ping-pong ball

Figure 9-(a) shows the overview of the mechatronic system for exercise. The basic and simple PD-control is applied to positioning a ping-pong ball. The microcomputer myRIO processes position data acquired from a range sensor at 1 [msec.] in real time. The high frequency noises of time sequential data are eliminated by a simple low pass filter, and the pseudo velocity $\dot{\hat{x}}$ is also generated from the filtering data by using the difference between current and past data. **Figure 9**-(b) shows the schematic of the simple PD-controller.



(a) Overview (b) Simple PD-controller

Figure 9. Positioning system of ping-pong ball

Under the above control design, the gain parameters K_P and K_D were tuned observing the positioning response of the ping-pong ball by trial and error. **Figure 10** shows the experimental result at 0.25 [m] of the desired position x_d when the gain parameters K_P and K_D were set to 10 [/m] and 10[s/m], respectively. Although low frequency vibrations are still left, the position of the ping-pong ball is staying in the neighborhood of 0.22 [m]. The offset of 0.03 [m] is not able to be removed by the simple PD-controller because this system has essentially leakage flows from the pipe to opened air. Removing the positioning offset requires some additional control compensators. Additionally, the position shorter than 0.1 [m] is not measured because of the limitation of the range sensor as shown in Figure 10.

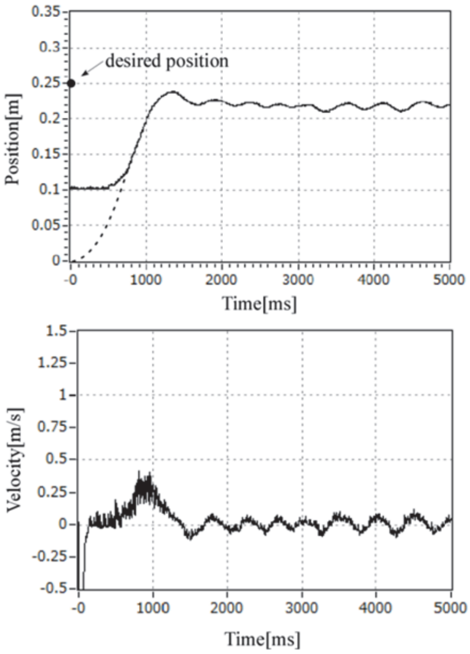


Figure 10. Experimental result of positioning control of ping-pong ball (x_d=0.25 [m], K_P=10 [/m], K_D=10 [s/m].)

4.2 Positioning simulation of a ping-pong ball

The ping-pong ball simulator is built up based on the dynamical model shown in Figure 5 by using Matlab/Simulink. In addition to setting parameters on Table II, the electrical properties of DC motor and PWM are also programmed in the simulation model as shown in Section 3.3. The measurable region of the range sensor is considered as mentioned in experimental results, and the leakage flow Q_P between the propeller and hood is set to three times of Q_B.

Figure 11 shows the simulation result when setting the gain parameters K_P and K_D to same values at the experiment.

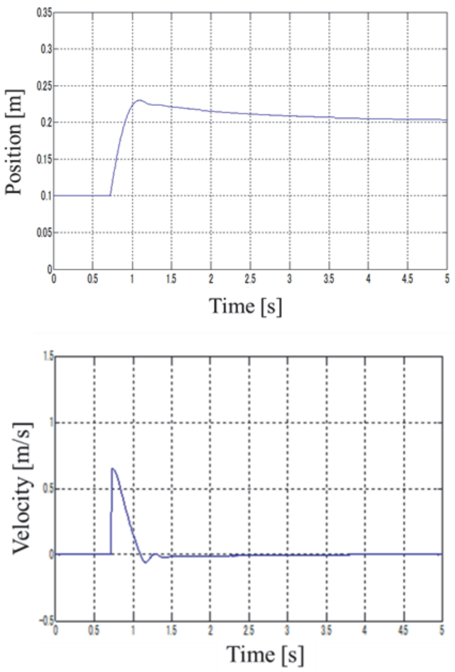


Figure 11. Simulation result of positioning control of ping-pong ball (x_d=0.25 [m], K_P=10 [/m], K_D=10 [s/m].)

The simulation result in Figure 11 is globally similar to the experimental result in Figure 10. However, residual vibrations are actually observed in the experimental result as shown in Figure 10. The difference between the experiment and simulation is considered to be caused by the following reasons:

a) Approximating the DC motor property as Equation (1) by neglecting the coil inductance of DC motor,

b) Neglecting the transfer delay from the angular velocity ω to the airflow Q in Equation (5),

c) Neglecting the rotational motion of a ping-pong ball.

Here, for example, by adding a first-order system with 40 [msec.] of time constant between the input u and the output Q in Figure 5, the simulation result in **Figure 12** is obtained. It is confirmed that the simulation result also has residual vibrations because of the added first-order system.

4.3 Discussion of experiment and simulation

It is a little difficult to completely stop the floating ball only by applying the PD control. In addition to the PD control, some advanced control will be necessary to remove residual vibrations in future. It is also important to program the dynamical property inducing the vibration in the simulator in order to have a good agreement with experiments. It is necessary to find out where the time delay is caused and to properly formulate the essential dynamics.

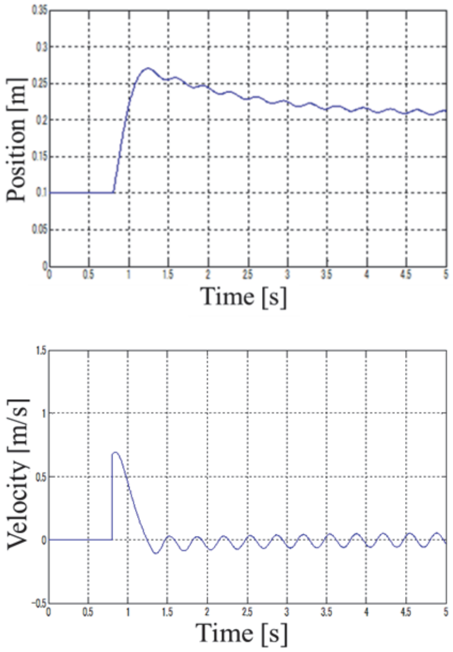


Figure 12. Simulation result of positioning control of ping-pong ball (x_d=0.25 [m], K_P=10 [/m], K_D=10 [s/m], adding a first order system with 40 [msec] of time constant)

5 Conclusion

This paper reported the development of educational materials for mechatronics. As an example of mechatronics exercise, we built up a positioning system of a ping-pong ball using a propeller and a DC motor. The main results are as follows:

(1) A teaching material is newly proposed for mechatronics exercise in tertiary education, which is made of safe, familiar, and inexpensive products. The material is positioned as mechatronic device that automated a toy called blowing-up pipe.

(2) The blowing-up system of a ping-pong ball requires to control the ball position by using a microcomputer and a range sensor. In addition to learning how to use a microcomputer called myRIO, creating pseudo velocities and noise reduction filters from position data is educationally suitable for the exercise of signal processing.

(3) Positioning a ping-pong ball is conducted by PD control of the ball position. Students practically learn how to tune the PD gains, observing the ball motion. Moreover, they understand that the system finally has a positional offset because of air leakage by use of only PD gains.

(4) Improvement of positioning performance needs to understand the system dynamics. The simulator of blowing-up system is provided for students to learn the approach through model-based-design. They confirm not only parameter studying by simulation but also fundamentals such as mechanics, thermodynamics, and pneumatics through modeling the mechatronic system.

(5) Smoothly sending air from a propeller into a pipe is important to mechanically improve the inlet of the pipe. It is educationally expected that students naturally think of pneumatic elements such as hoods and rectifiers, and make up these by using familiar goods.

Recently, we informally provided the above exercise material for some groups of students, and observed their reactions for the teaching material. As the result, we noticed the following points:

a) Students need a little time for mastering how to use the graphically programming LabVIEW,

b) Students are not rather interested in the fundamentals such as mechanics, thermodynamics, and pneumatics,

c) Some students became absorbed in improving the inlet of the pipe, more deeply than in tuning the control gains.

Although there were above some problems, the handmade material for mechatronics exercise had a good reputation from many students. After this, we will apply this teaching material to the current exercise in our engineering course. After applying to the exercise, we also need to collect questionnaires about the exercise from students, and the provided teaching contents must be reconfirmed or improved. Furthermore, we will need to continue developing new materials for mechatronics exercise, keeping the system concept constructed by both the convenient microcomputer and useful CAD.

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