Development of low-cost logic-gates based on the pneumatic system using an automatic controller for education in engineering physics

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Abstract. To comply international accreditation requirement in program study of engineering physics for undergraduate students, Telkom University, we initiated student center learning (SCL) to achieve course learning outcomes (CLO) through Automatic Control course. We developed automatic controller for low-cost logic-gates based on the pneumatic. The pneumatic was derived analytically using a well-known second-order physical system and its parameters were characterized using simple experiments. The mass of piston and spring, friction coefficient, and spring constant in the pneumatic system are 8 g, 10.2, and 411 N m⁻¹. We simulated open and closed loop system based on proportional-derivative (PD; \( K_p=100 \) and \( K_d=15 \)) using Matlab and implemented it to stabilize the system. The pressure pump \( P \), a setting point, and \( K_p \), \( K_i \), and \( K_d \) are 35 psi, 4 cm, 3.1, 124.6 s⁻¹, and 0.02 s. We, then, used the pneumatic system to build prototypes based on logic gates cases. Case 1 is a miniature elevator using AND gates. A pneumatic-based vertical carrier was used to implement NAND gates in the case 2. OR gates pneumatic-based was used to implement pressing machine (case 3). Case 4 and 5 are a sorting system using NOR gates and automatically stamped cake using 3-Input AND gates respectively.

1. Introduction
To compete a program study in the regional and/or worldwide, nowadays, the national and international standard is a must-to requirement [1]. A national accreditation agency for higher education (BAN-PT) is an agency who take responsibility for a national standard and ensure that all the program study in Indonesia must obey these rules. However, not so many program studies have the international accreditation. One of the international accreditation is Indonesian Accreditation Board for Engineering Education (IABEE). The program study of engineering physics at Telkom University has declared to participate in this program and partially implemented it in the last a year. We modified the curriculum into student-centred learning (SCL) [2] and focus on the course learning outcomes (CLO) for each subject.
In this semester, we selected several subjects to be involved in this program. One of the subjects is an automatic control. We evaluated the existing curriculum, previous results, and tried to modify to ensure that CLO was fulfilled. A project-based class was selected as a pilot project to boost the achievement of CLO. Education for engineering students needs the comprehensive and technical knowledge of science as well as practical skills [3]. We, then, chose a pneumatic system [4, 5] and logic gates as cases. Students should identify the physical system, to obtain the equation, to determine the parameters, and to simulate the results. After that, they should develop some logic gates based on the pneumatic system using an automatic controller.

Our group designed and developed logic-gates based on the pneumatic system as low-cost as possible for engineering course. Because this is a project-based class in an automatic-control course, then, we built five versions of a pneumatic system as well as case studies. Each version was fully examined, and some data are only shown in a typical data for a pneumatic system, open and closed loop simulation, and/or the comparison data between simulation and measurement. Hopefully, the method is one of the best approaching to implement SCL and to achieve CLO. Moreover, this third-year course can be a baseline to enter research activities in the last year program for the undergraduate students.

2. Model and simulation

The physical system of a pneumatic was analysed as shown in Figure 1. The system composed of a piston with a piston mass ($M_p$), a spring with a mass of spring ($M_s$) and spring constant ($k$), a coefficient of friction ($b$), and a stick and load mass ($M_l$). The external force was introduced to the system using an external pump with a constant pressure ($P$) and cross-sectional area of the pipe ($A$). Assumed that the atmospheric pressure is insignificantly affecting to the system. Based on Newton’s law, a well-known second-order physical system was derived as in the following equation [6]:

$$\sum F = ma$$  \hspace{1cm} (1)

$$PA - F_{friction} - F_{spring} = (M_p + M_s + M_l)a.$$  \hspace{1cm} (2)

A friction force ($F_{friction}$) and spring force ($F_{spring}$) are forces due to a friction between the piston and the house and due to the presence of spring itself respectively. The sum of piston, spring, and load mass are in the range of 8-24 g. We, then, conducted simple experiments to determine a friction coefficient ($b$) and a spring constant ($k$). Several known masses are attached to a springless pneumatic system alternately to measure a friction coefficient. These known masses were also used and applied to the pneumatic system without a house to measure a spring constant. The interval data of friction coefficients and spring constants are 0.35-4 and 7-1103 N m$^{-1}$ respectively. Noted that we used two types of spring, therefore, there are two different of a mass of spring as well as constant spring. Some oils were also attached to the house to minimize the effect of a friction.

Laplace transform is used to get a transfer function. The initial condition of the system at $t = 0$ is assumed to equal to zero for the position, velocity, and acceleration. Based on equation (2), the open loop transfer function is as follow:

$$G_p(s) = \frac{1}{ms^2 + bs + k}$$  \hspace{1cm} (3)

with $m$, $b$, and $k$ are total mass, friction coefficient, and spring constant respectively. Those data were varied depend on the version which is built by each group of students. A parallel PD and/or PID-controller was designed using equation (4):

$$G_c(s) = K_p \left( \frac{\tau_d s^2 + \tau_i s + 1}{\tau_i s} \right)$$  \hspace{1cm} (4)

with $\tau_i$ and $\tau_d$ are time integration and differentiation, and $K_p$ are proportional amplifier. A block diagram of the system was shown in Figure 2. We assumed that a feedback, a sensor ($H(s)$), in this system is equal to the one. The closed loop transfer function of this system is:
\[ C(s) = \frac{G_p(s)}{1 - G_c(s)G_p(s)} \left[ \frac{E}{s} - G_c(s)R(s) \right] \]  

(5)

**Figure 1.** The physical system of a pneumatic with a piston mass \( M_p \), a spring mass \( M_s \), spring constant \( k \), a coefficient of friction \( b \), and a stick and load mass \( M_l \). A constant pressure \( P \) was applied to the system.

**Figure 2.** A block diagram of the system. The setting point, error signal, control signal, and output signal are labelled as \( R(s) \), \( E(s) \), \( U(s) \), and \( C(s) \) in domain-s.

A well-known second-order physical system [5] was used and natural frequency \( (\omega_n) \) and damping factor \( (\zeta) \) were determined using equation (3) and (4). We, then, used PD controller to simulate open and closed loop system using Matlab (Figure 3). The values for \( K_p \) and \( K_d \) are 100 and 15. Noted that \( K_d \) is a differential amplifier and it was calculated through \( K_pT_d \). It is clearly seen that the open loop system could not achieve the setting point. A better response of PD-controller has a rise time of 0.002 s, maximum overshoot of 5.1% at 0.009 s, and a settling time of 0.04 s. We also tried PID-controller with parameters were varied starting from 0.5-29.7 \((K_p)\), 4-124.6 \((K_i)\), and 0.02-36 \((K_d)\). In the next section, we discussed the implementation of PID-controller in the pneumatic system and used it in the case of logic gates.
3. Result and discussion

We built five versions of pneumatic system, however, we only showed one result. The specifications of the spring are a diameter of 25 mm, a thickness of 1.5 mm, and a turn number of 15. A total mass of piston ($M_p$), a spring ($M_s$), and a stick and load are 8 g. A spring constant ($k$) and a coefficient of friction ($b$) are 411 N m$^{-1}$ and 10.2. We applied a pressure pump of 35 psi through a pipe with a cross-sectional area of $12.6 \times 10^{-6}$ m$^2$. An analytical approach and tuning for PID-controller was performed [7]. One of PID parameters are 3.1 ($K_p$), 124.6 s$^{-1}$ ($K_i$), and 0.02 s ($K_d$).

Figure 4 (a) shows the output signal ($c(t)$) between measurement and simulation data. During the rise time, the simulation data was faster than measurement data. It seems that a friction force and the atmospheric pressure, as well as a flow rate of a pump, affected the measurement. In the real system, a final point could not be achieved well. Both those data have the settling time of around 15 s.

When the setting point was changed to 5 cm, we faced the problem. The actual point could not follow the control signal. Therefore, the error signal is still 100% until a sudden decrease of the signal at the 18th second (Figure 4 (b)). This problem can be solved after we are increasing the pressure pump.
Figure 4. (a) The data comparison of an output signal (c(t)) between measurement and simulation for the setting point of 4 cm and (b) an error data point is at 5 cm setting point. All the conditions are on 35 psi pressure pump, $K_p=3.1$, $K_i=124.6$ s$^{-1}$, and $K_d=0.02$ s. Blue line-dot and red line are measurement and simulation data respectively.

We, then, used the pneumatic system to build prototypes based on logic-gates cases (Figure 5). Case 1 is a miniature elevator using AND gates. A pneumatic-based vertical carrier was used to implement NAND gates in the case 2. OR gates pneumatic-based was used to implement pressing machine (case 3). Case 4 and 5 are a sorting system using NOR gates and automatically stamped cake using 3-Input AND gates respectively.

Figure 5. The prototypes based on a pneumatic system for the case of: (a) a miniature elevator (AND gates), (b) a vertical carrier (NAND gates), (c) pressing machine (OR gates), (d) a sorting system (NOR gates), and (e) automatically stamped cake (3-Input AND gates)

4. Conclusion
We performed student-based class for developing five versions of a pneumatic system using logic gates. We made a simple model for the physical system of pneumatic and conduct simple experiments to determining parameters such as load mass (8-24 g), friction coefficients (0.35-4), and spring constants (7-1103 N m$^{-1}$). A simulation data was generated using $K_p=100$ and $K_d=15$ to achieve a rise time of 0.002 s, maximum overshoot of 5.1% at 0.009 s, and a settling time of 0.04 s. A setting point of 4 and 5 cm was analysed in the real system. The setting point of 4 cm could not achieve exactly due to friction forces, the atmospheric pressure, and pump flow rate. Meanwhile, there is a problem for 5
cm set point due to lack of pressure pump. In part of the student-centred learning (SCL) and the course learning outcomes (CLO), finally, the students can use any engineering tools (soft and hard ware), analyse the system, and implement a model and simulation into a real system.

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