M1598.000200: Actuation and Sensing Mechanisms in Robotics Systems

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Lab #4: Force Control of a Pneumatic Muscles using a Custom-Built Strain Gauge Load Cell

So far, you have built an artificial muscle, have characterized its dynamics, implemented an open loop controller, and built a force feedback sensor. In Lab#4, you will use the skills acquired to develop and implement a closed loop controller, especially PID (Proportional-Integral-Differential) Controller, for a pneumatic artificial muscle. You will use the custom-built strain gauge load cell to measure force and close the loop. The block diagram of the controller can be observed in figure 1. Use this as a guideline to build your controller.

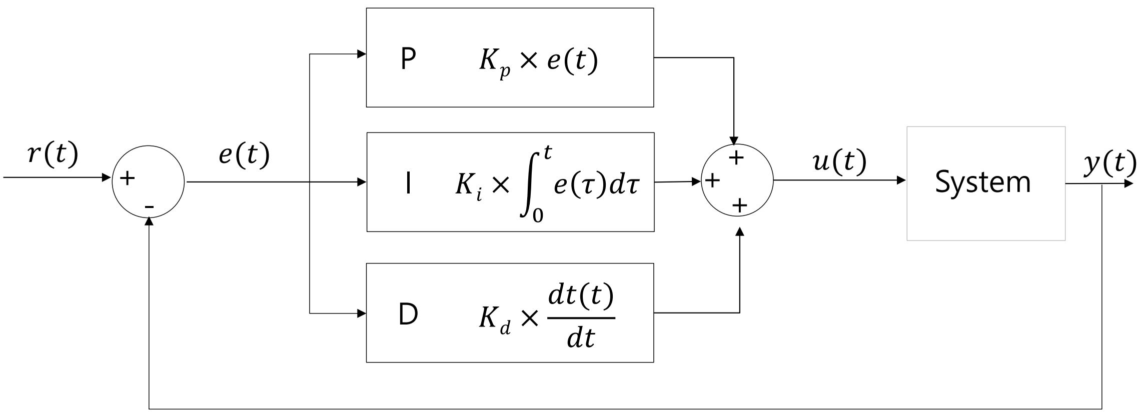

Figure 1. Closed loop control schematic for PID control.

Materials

- 1 x Pneumatic Muscle (from *Lab #1*)
- 1 x Pneumatic PWM control circuit (from *Lab #2*)
- 1 x Custom-Built Strain Gauge Load Cell with amplifier circuit (from *Lab #3*)
- 1 x Testing Machine (Instron)
- Pressure Rregulator (SMC 2030 212 cl) : Controller
- 1 x Laptop for data acquisition

Experiments

The setup will consist of a muscle and the force sensor bracket in the configuration shown in figure 2. The entire setup will be provided by the TA.

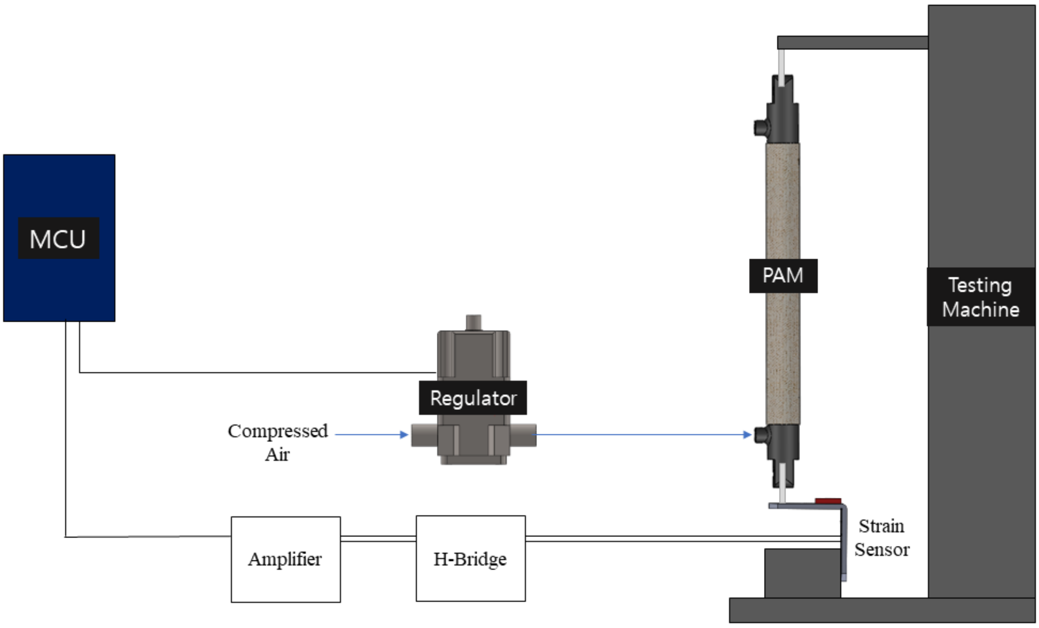

Figure 2. System setting for PID closed loop control of the pneumatic artificial muscle.

Test 1: Sensor Calibration

- Two Pins on the Arduino (MCU) board will be used for inflation and release control respectively. In addition, the A0 port will be used for the *Custom-Built Strain Gauge Load Cell* built in the previous lab. The Ads1115 chip has 16-bit resolution for reading analog inputs from 0-5 V. This means you will have unit values from 0-1023 for reading the sensor. This needs to be calibrated so the output can be translated in newton [N] dimension.
- Apply the linear regression to calibrate the custom built strain gauge load cell. Find the sensitivity constant (slope) and the initial bias (offset). The calibration curve will be the mapping between the control input and the sensor value.

$$P_{in} = c_1 V_{load\ cell} + c_2$$

After the calibration is done, apply the PID control loop using the pressure regulator as the controller. The control input at time t, u(t) will be generated by the pressure regulator, which is the pressure applied to the PAM. The feedback loop is constructed based on the error (ϵ) between the target force and the observed force ($\hat{F}$). The force level is estimated from the load cell voltage value $V(t)$, as well as the testing machine measurement.

$$\epsilon(t) = \hat{F}(\hat{V}(t)) - F(V(t))$$

The time step is defined according to the clock activated in the micro-controller board. The time step (dt) used in the experiment is 100 ms. Then, the PID error can be derived.

$$\dot{\epsilon(t)} = \frac{\epsilon(t+dt) - \epsilon(t)}{dt}, \qquad \int_{\tau}^{\tau+dt} \epsilon\, d\tau = \frac{1}{2}(\epsilon(\tau+dt) + \epsilon(\tau))$$

By setting each gain values of PID, the total feedback can be expressed as below.

$$e(t) = K_p\,\epsilon(t) + K_I \sum_{\tau=0}^{t} \int_{\tau}^{\tau+dt} \epsilon\, d\tau + K_D \dot{\epsilon(t)}$$

Using the error equation, build the PID control loop in the micro controller board and start the gain tunning, which best follows the target force.

Test 2: Constant Force Control

>> P (Proportional) Control
Use a K_P to adjust the rate at which your controller increases your duty cycle. Run the code with following parameters;

a. Tune the K_p gains
b. Set the desired force you want to measure.

>>PD (Proportional-Integral) Control
Use a K_P and K_D to adjust the rate at which your controller increases your duty cycle. Run the code with following parameters;

c. Maintain the K_p gain which is set previously.
d. Tune the K_I gains.
e. Set the desired force you want to measure.

>>PID (Proportional-Integral-Differential) Control

- Use a 'K_p' (proportional gain), 'K_I' (Integral gain), and 'K_d' (Differential gain) to adjust the rate at which your controller increases your duty cycle. Run the code with following parameters;
    a. Maintain the K_P and K_D gains which are set previously.
    b. Tune the K_I gains.
    c. Set the desired force you want to measure.
- You can conduct with different parameters if you want.

Test 3: Force Profile Control
There will be given predesigned force curve which varies by time t. Check the designed PID controller can successfully follow the force profile.

$$F_{ref}(t) = 15 \sin\left(\frac{\pi}{150} t\right) + 50 \ \ [N]$$

<u>Results</u>

1. (10 pt.) Plot the result from the Test1 and provide the calibration mapping.
$$P_{in} = c_1 V_{load\ cell} + c_2$$
2. (30 pt.) Provide step response plots for various gain parameters (P,PD,PID cases) and desired constant forces.
    a. Each plot should be in Force (N) vs. Time (sec).
    b. Each plot should show a target force level, a response signal measured by the strain-gauge force sensor.

3. (10 pt.) Plot the given force profile and the controlled force. Provide the error of the controlled signal and discuss whether the gains are correctly set.

Discussion

1. (10 pt.) Report and discuss the rise time, settling time, steady state error, and transient-response characteristics for all cases in Test 2. Discuss the differences between the three cases.
2. (10 pt.) Can the characteristics of the actuator be observed based on the step responses (F-t curves we obtained)?
3. (10 pt.) What advantages does closed-loop control provide over open-loop control? Are there any drawbacks?
4. (10 pt.) What elements can be added or substituted to the controller to improve it? How do these elements help the controller? (Hint: bang-bang controller, Lead-lag compensator, dynamics of the system, nonlinear control methods)
5. (10 pt.) Are there scenarios in which a linear controller would not work for this type of artificial muscle? Would the system go unstable?

References for answering the questions

- Knospe, Carl. "PID control." IEEE Control Systems Magazine 26.1 (2006): 30-31.
- Chen, W-H., et al. "Nonlinear PID predictive controller." IEE Proceedings-Control Theory and Applications 146.6 (1999): 603-611.
- Thanh, TU Diep Cong, and Kyoung Kwan Ahn. "Nonlinear PID control to improve the control performance of 2 axes pneumatic artificial muscle manipulator using neural network." Mechatronics 16.9 (2006): 577-587.