Design of an Ideal pH Controller

Part 1: Rodrick Alberto
Part 2: Phat Le
Part 3: Rafael Vasquez
Part 4: Jed Durante

Section B00 (M/W), Team B13, Lab 2

Abstract

Process controls are listed as some of the most important equipment to understand in chemical engineering. In this report, pH controls are tested on its controller design using acids and bases and the results were analyzed appropriately. From the analysis, the P controller comes out as the most reliable controller to use for this experiment since it reaches the steady-state pH level the fastest. Additionally, there were no offsets or oscillations that occurred, which resulted in easy detection of the step response curve. This is due to the results being properly adjusted to the tuning of the proposed transfer functions. These results show how individual controllers are determined to be different based upon the inputted parameters. However, in the future, several improvements can be made in the data collection process. For example, tuning is required to find the theoretical values for the individual controllers, which would allow for the direct acquisition of the controller coefficients. Overall, the results that were obtained implied that there can be multiple controllers that are viable; but, there will always be one that is the most efficient controller to use over the other controllers.

1 Introduction

The use of different process controls are essential in the chemical engineering field. Consequently, using a variety of pH controls assists the chemical engineering field in regulating the use of acids and bases in an efficient manner. Process controls often come in various forms, such as the proportional controller (P), proportional-integrated controller (PI), proportional-derivative controller (PD), and proportional-integral-derivative controller (PID). Process controls also operate in a closed-loop system. A closed-loop system is a control system that regulates the feedback coming from the inputs of the process to its relevant setpoints. Each controller acts differently with the input of the experimental data to find the desired pH levels. Controllers mentioned are used in multiple industries, such as pharmaceuticals, biotechnology, and even chemical processing industries.[1] Controllers have feedback controls that adjust the overall tuning of the data collected, which relates to approaching a steady state in flow rates. By using these controllers, any used parameters within systems are calibrated and fitted for its local operating conditions.[2] In terms of using it as a pH control, the controller choice is often unclear due to its nonlinear data samples.[3] Overall, the research of specific process controls has been studied in order to fully understand the individual controllers.

2 Background

Controllers have multiple design aspects that can be changed to fit its required function such as selecting the right controller and tuning. Determining the correct controller to use is a crucial step in control theory. Using the wrong controller can lead to unwanted results and failures of both the process and controller, such as creating a too acidic environment in a pH control process or burning out the controller. Besides determining which controller to use for one's process, tuning of the said controller is another crucial part that allows for the efficient optimization of the controller. However, tuning is also a complicated process that requires careful analysis of data.

Determining the controller type has important considerations. P-only control speeds up the system response, but too much can lead to instabilities. I-only control eliminates offset, but too much can produce overshoot and oscillations. D-only control has a stabilizing effect, but too much can be unstable with noise. Therefore determining which components to avoid and use must be taken into account before implementation to assure that the system works properly. In addition, different tuning methods also play an important role in controller design. Tuning methods such as Ziegler-Nichols (ZN) and Cohen-Coon (CC) focus on guaranteeing a quarter decay ratio system response. However, there are differences within these two tuning methods as ZN has a slower response time, but being less oscillatory. In addition, integral of absolute error (IAE) can all be used to minimize all errors in a uniform fashion. These are just some tuning methods, but there are other methods that might be considered for one's process.

Despite all these possible design choices, the process at which one's system operates dictates one's choice and there will be no one correct option. For instance, pH control is an even more complicated process for control theory than others due to its highly non-linearity nature and high precision needed.[4] Although multiple industries require pH control, not all processes use the same controller or tunings. For instance, in the textile industry pH control is important in dyeing levelness, and the use of a fuzzy-gain scheduled PID controller is widely accepted due to its robustness and self-adaptation.[5] However, pH control of industrial effluent might use a coefficient diagram method PI controller due to its stability and robustness.[6] Determination of which tuning and controller to use for a process ultimately depends on one's process, and there is no definite answer as advantages and disadvantages must be taken into account for that specific process. It is ultimately up to the engineer's discretion on which controller and tuning would be best for their process.

In this experiment, we show how different controllers and tunings lead to drastically different pH responses in the linear region of a buffer solution. In addition, we determined which would be the most optimal controller and tuning for our process after careful analysis of our data.

3 Theory

Controller decision and tuning are based off fitting the open loop step test data to different proposed process transfer functions such as

$$G_P = \frac{K_P}{s} \tag{1}$$

$$G_P = \frac{K_P}{s(\tau_P s + 1)} \tag{2}$$

$$G_P = K_P \tag{3}$$

$$G_P = \frac{K_P}{\tau_P s + 1} \tag{4}$$

$$G_P = \frac{K_P e^{-\theta_P s}}{\tau_P s + 1} \tag{5}$$

where K_P is the process gain, τ_P is the process time constant, and θ_P is the process time delay. K_P is

$$K_P = \frac{\Delta PV}{\Delta CO} \tag{6}$$

where ΔPV is defined as the the steady state change in measured process variable and ΔCO is the steady state change in the controller. The process gain describes how the process variable changes when the controller output changes. τ_P is

$$\tau_P = \frac{t_{2/3} - t_{1/3}}{0.7} \tag{7}$$

where $t_{2/3}$ is the time it takes for the process to reach two-thirds of the final steady state value, and $t_{1/3}$ is the time it takes for the process to reach one-third of the final steady state value. The time constant measure how long it takes for the process to get to about 63% of the way to steady state conditions. θ_P is

$$\theta_P = t_{1/3} - 0.4\tau_P \tag{8}$$

and is the time delay when the process variable responds to a change when a controller output signal is issued.

Using direct synthesis of the closed loop system

$$\frac{Y(s)}{Y_{SP}(s)} = \frac{G_C G_P}{1 + G_C G_P} = G_d = \frac{1}{\tau_C s + 1} \tag{9}$$

and the aforementioned proposed transfer functions, controller settings were determined by fitting the derived equations to an ideal PID controller

$$G_C = K_C(1 + \frac{1}{\tau_I s} + \tau_D s) \tag{10}$$

where K_C corresponds to the P mode, τ_I corresponds to the I mode, and τ_D corresponds to the D mode. Thus, the proposed transfer function in Eq. (1) results in a P only controller

$$G_C = \frac{1}{K_P \tau_C} \tag{11}$$

where $K_C = 1/K_P\tau_C$, $\tau_I = \infty$, and $\tau_D = 0$. The proposed transfer function in Eq. (2) results in a PD controller

$$G_C = \frac{1}{K_P \tau_C}(\tau_P s + 1) \tag{12}$$

where $K_C = 1/K_P\tau_C$, $\tau_I = \infty$, and $\tau_D = \tau_P$. The proposed transfer function in Eq. (3) results in a I controller

$$G_C = \frac{1}{K_P \tau_C s} \tag{13}$$

where $K_C = 1/K_P\tau_C$, $\tau_I = \tau_C$, and $\tau_D = 0$. The proposed transfer function in Eq. (4) results in a PI controller

$$G_C = \frac{\tau_P}{K_P \tau_C}(1 + \frac{1}{\tau_P s}) \tag{14}$$

where $K_C = \tau_P/K_P\tau_C$, $\tau_I = \tau_P$, and $\tau_D = 0$. The proposed transfer function in Eq. (5) results in a PID controller

$$G_C = \frac{\tau_P}{K_P(\tau_C + \theta_P)}(1 + \frac{1}{\tau_P s})(\frac{1 + \frac{\theta_P}{2}s}{1 + \tau_P s}) \tag{15}$$

where $K_C = \tau_P/K_P\tau_C + \theta_P$, $\tau_I = \tau_P$, and $\tau_D = \theta/2$.

These controllers can then be further tuned with IAE tuning methods for set point changes where

$$K_C = \frac{a_1}{K_P}\left(\frac{\theta_P}{\tau_P}\right)^{b_1} \tag{16}$$

$$\tau_I = \frac{\tau_P}{a_2 + b_2(\theta_P/\tau_P)} \tag{17}$$

$$\tau_D = a_3\tau_P\left(\frac{\theta_P}{\tau_P}\right)^{b_3} \tag{18}$$

where $a_1 = 1.086$, $b_1 = -0.869$, $a_2 = 0.740$, $b_2 = -0.130$, $a_3 = 0.348$, and $b_3 = 0.914$.

4 Methods

The experiment used around 150 mL of phosphate buffer solution (PBS) where acids and bases were mixed into the solution using a stir plate. Peristaltic pumps were used as the distributors of acid and base liquids for the PBS. The stir plate was kept at a relatively high mixing rate with no heat being applied to the mixture. A pH probe was then used to detect the pH level in order to find both the titration curve and the buffer region. The buffer region is important data to collect due to the region being the most linear range to work in. The pH probe was also used to record the regulated set point of pH levels for the experiment. Virtual instruments (VIs) from the LabVIEW application assisted with the overall control of acids and bases. VIs were also used to reenact the experimental data with parameters to create individual controllers.

5 Results and Discussion

The results shown are the setpoint response curves to P, PI, PD and PID controllers. K_C, τ_I, and τ_D were varied to produced different results.

Using a PID controller shows, in Fig. 1, extreme oscillatory step response, both negative and positive. K_C was kept constant while τ_D and τ_I were changed. As the ratio of τ_I to τ_D was large, the step response was extreme and unstable. A ratio of τ_I to τ_D closer to one had

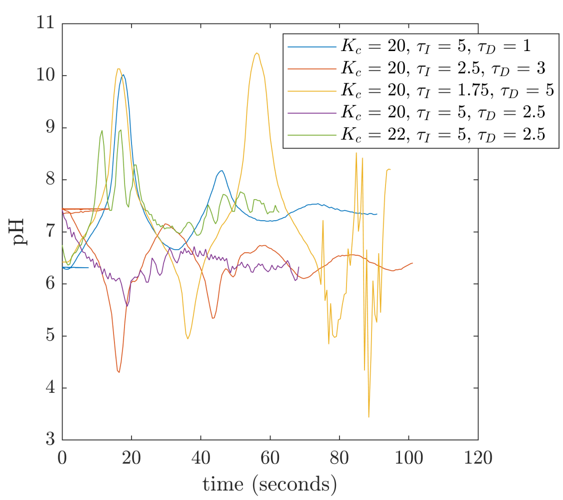

Figure 1: This figure shows five PID controllers with different settings. The most common trend amongst them is they are oscillatory.

smaller oscillations and steady state was reached only after a long period of time. For a P-only controller, the data shows an exceptional step response, especially when $K_C = 20$ where the controller response is only 50 seconds. Shown in Fig. 2, when $K_C = 23$, the response has an initial overshoot; however it reaches steady state quickly with no significant oscillations afterwards. In Fig. 3 the step response of a PI controller demonstrates an extremely large oscillations that does not reach steady state. This indicates that a PI controller is not a suitable controller for a pH controller.

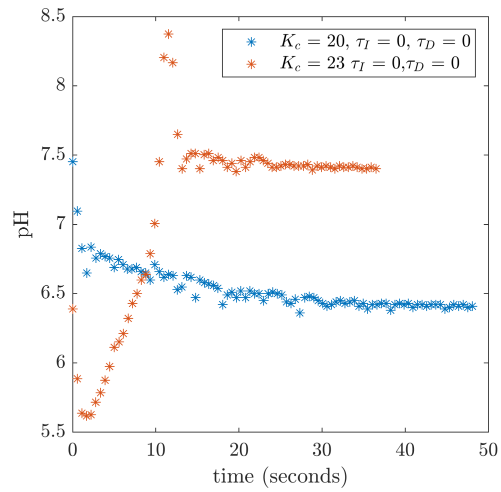

Figure 2: This figure shows two P-only controllers which steady responses. The P-only controller in orange overshoots but reaches steady state faster than the blue P-only controller.

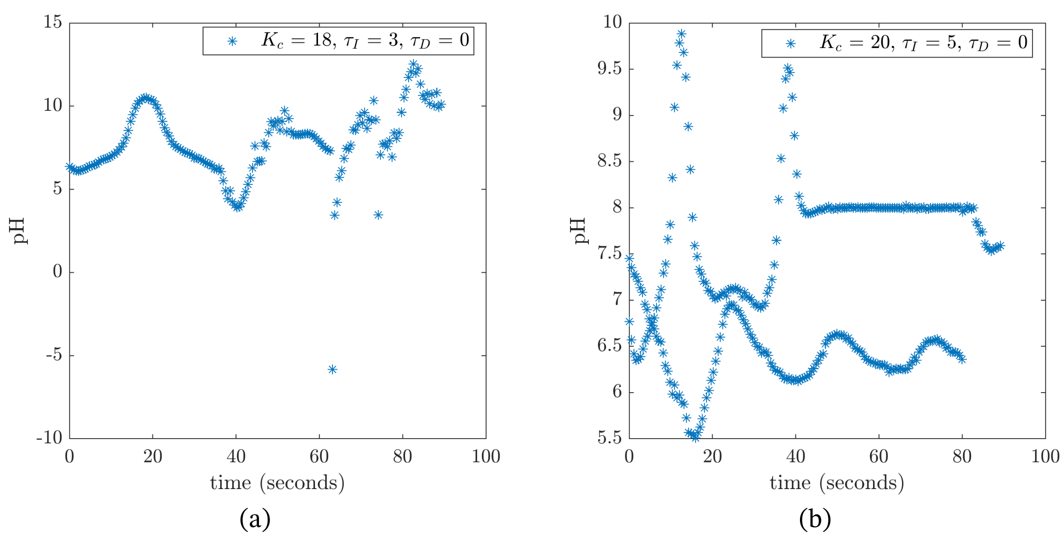

Figure 3: These two are PI controller response curves. Both response curves did not reach steady state and were unstable.

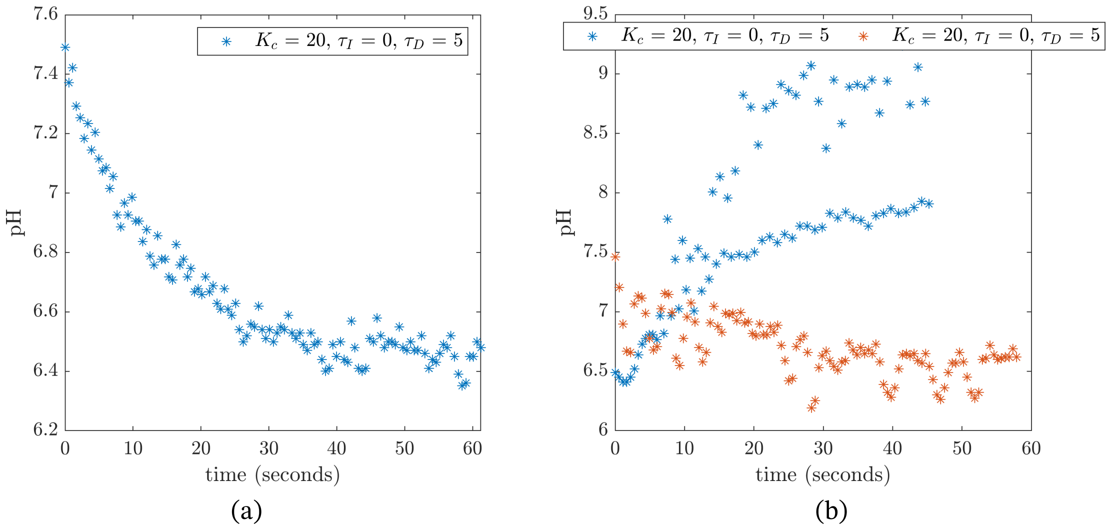

Figure 4: These figures show PD controller response curves. For the step up response curve, there was excessive oscillations and the response curve did not reach steady state. Step down response curves had little to no oscillations.

With a PD controller, the results show a response with little to no oscillation; however, when the step response was positive, the response was highly oscillatory whereas when the response was negative, the response had little to no oscillations. Both step responses were done with the same setting as shown in Fig. 4. When $K_C = 18$ and $\tau_I = 8$s, the step response curve does not reach steady state indicating that at these setting the controller is unstable. When $K_C = 20$ and $\tau_I = 5$s the step response is also unstable.

As a result, the most stable and effective controller is the P-only controller because the step responses are stable and non-oscillatory. A P-only controller is appropriate because, within the buffer region, the change in pH in linear so the process transfer function that models the pH behavior within the buffer region should be a linear model.

The issue present in the results is the fact that the theoretical models used to lead to the experimental results are not present. There was issue in determining a theoretical closed loop transfer function, which did not allow for the proper selective testing of a control transfer function. There was also a misinterpretation of how the experiment was supposed to be done. The error was in the thought that, when the buffer region was determined, a step response was supposed to be done on the buffer solution and afterwards, use the data and a proposed process transfer function to determine a controller transfer function. However, what was supposed to be done instead while in the lab was to determine the coefficients of the proposed process transfer function and then determine the controller transfer function. Afterwards, a theoretical closed loop transfer function was supposed to be determined and tested with different setting to produce the most effective step response.

Another source of error was the inability to properly model the step response data to certain proposed process transfer function such as Eq. (12). Because the proposed transfer function could not be modeled there was no way to verify the if that proposed transfer function was valid. As a result, the theoretical controller setting could not be determined because they were based on coefficients of the proposed process transfer function which resulted in the inability to use tuning methods.

6 Conclusions

In conclusion, various pH controllers were used to compare its experimental values with each other. From plotting the controllers through closed-loop systems, there seems to be some controllers that created the desired results while other controllers were completely rejected. When plotting the experimental data, the P-only controller proved to be the best since the graph demonstrated both no offset and no oscillations. Aside from the P-only controller, the PD controller showed results similar to the P-only controller. However, the P-only controller still remains the better controller due to the fact that the P-only controller reached steady-state at around 10 seconds faster compared to PD controller. As for the other controllers tested, such as PID, too many oscillations occurred, which resulted in making the controller unsuitable. The experimental values found would have been compared to the theoretical values, but the theoretical transfer function was not found; thus tuning functions were never applied. For future lab experiments, more time and preparation is needed to find the theoretical coefficients in order to compare with the experimental values. Overall, the results that were obtained led to the conclusion that P-only is the best characterization of the controller. However, more must be done in the future, such as what was suggested previously.

Bibliography

(1) Valarmathi, K.; Devaraj, D.; Radhakrishnan, T. Adaptive Enhanced Genetic Algorithm-Based Proportional Integral Controller Tuning for Ph Process. *Instrumentation Science Technology* **2007**, *35*, 619–635.

(2) Chen., C.; Chang, F. Design and Analysis of Neural/Fuzzy Variable Structural PID Control Systems. *IEE Proceedings - Control Theory and Applications* **1996**, *143*, 200–208.

(3) Yu, W. Multiple Recurrent Neural Networks for Stable Adaptive Control. *Neurocomputing* **2006**, *70*, 430–444.

(4) Kumnmar, A. et al. Nonlinear PI controller for pH process. *Chemical Engineering Communications* **2004**, *191*, 241–261.

(5) Huang, C.; Yu, W. Applying a fuzzy gain-scheduled PID controller to dyebath pH. *Textile Research Journal* **2001**, *71*, 1074–1078.

(6) Meenakshipriya, B. et al. pH Control of industrial effluent using CDM based PI controllers. *Indian Journal of Chemical Technology* **2015**, *22*, 141–147.

Appendix

1. Adaptive Enhanced Genetic Algorithm-Based Proportional Integral Controller Tuning for pH Process

   - Author(s): Valarmathi, K.; Devaraj, D.; Radhakrishnan, T. K.
   - Year published: 2007
   - Journal name: Instrumentation Science & Technology
   - 1-3 major accomplishments of this paper:

     (a) Justifies how pH process controls are essential in multiple chemistry industries

     (b) Used Enhanced Genetic Algorithm (GA) to optimized tuning parameters of controllers

2. Design and Analysis of Neural/Fuzzy Variable Structural PID Control Systems

   - Author(s): Chen, C.L.; Chang, F.Y.
   - Year published: 1996
   - Journal name: IEE Proceedings - Control Theory and Applications
   - 1-3 major accomplishments of this paper:

     (a) Able to compute multiple process control systems while having high nonlinear data sets

     (b) Provides a comparison of controllers related and see how all of them are applicable to the nonlinear systems

3. Multiple Recurrent Neural Networks for Stable Adaptive Control

   - Author(s): Yu, W.
   - Year published: 2006
   - Journal name: Neurocomputing

- 1-3 major accomplishments of this paper:
    (a) Used and tested multiple controllers on a pH neutralization process
    (b) Provides distinct evidence with controllers, i.e. PID controller, that can be applicable for future lab experiments

4. Nonlinear PI controller for pH process
    - Author(s): Kumnmar, A.A.; Chidambaram, M.; Rao V.S.R.; Pickhardt R.
    - Year published: 2004
    - Journal name: Chemical Engineering Communications
    - 1-3 major accomplishments of this paper:
        (a) Explains why pH control is a difficult process to handle due to its non-linearity and high precision.
        (b) Provides evidence on how a PI controller using a Wiener model may be a suitable choice to use.

5. Applying a fuzzy gain-scheduled PID controller to dyebath pH
    - Author(s): Huang, CC; Yu, WH
    - Year published: 2001
    - Journal name: Textile Research Journal
    - 1-3 major accomplishments of this paper:
        (a) Describes how pH control is an important aspect for the textile industry.
        (b) Suggest the use of a fuzzy gain-scheduled PID controller for its self-adaptation and robustness.

6. pH Control of industrial effluent using CDM based PI controllers
    - Author(s): Meenakshipriya, B; Saravanan, K; Krishnamurthy, K; Kanthabhabha, P

- Year published: 2015
- Journal name: Indian Journal of Chemical Technology
- 1-3 major accomplishments of this paper:
  (a) Compares the different tuning methods for a PI controller in a pH neutralization system of industrial effluent.
  (b) Suggests that a internal model control based PI controller would be the best due to its stability and robustness.