pH Control Strategy Testing in a Bioreactor

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Abstract
A 5-L bioreactor was set up with an impeller, cooling and heating coils, probes for measuring pH, temperature and dissolved oxygen concentration. The reactor instrumentation was interfaced with a computer via data acquisition hardware. LabVIEW, a graphical programming language was used in all measurement and control programs. The reactor temperature control could be achieved by a conventional proportional-integral (PI) controller. In contrast controlling pH was difficult due to a considerable variation in the slope of the titration curve. A simple PI loop resulted in aggressive pH control actions, causing excessive base addition and likely demise of the microorganisms. In this work synthetic waste water was used for testing control schemes. The Generic Model Control (GMC) and gain-scheduling adaptive control strategies were investigated and compared with a PI control scheme. In these strategies, the rate change of pH was assumed to be a function of residence time, base addition, and pH, allowing the continuous calculation of base added against the pH measured. Some experimental and simulated results are presented for comparison.

Keywords: Bioreactor, Proportional Integral controllers, Generic Model Control

Introduction
Biological processes are carried out by living organisms such as bacteria, fungi, algae or mammalian cells to achieve diverse outcomes ranging from an extremely complex process such as biological wastewater treatment to less complicated such as biomass production. In all of these processes the main objective is to maximize the cell growth while maintaining the biological activities of the microorganisms. To achieve this target, the four key parameters pH, Dissolved Oxygen (DO) concentration, temperature and exit gas compositions such as CO₂, NH₄, or NO₃ compositions, should be closely monitored and controlled. A control strategy design has been developed for a biological nutrient removal system in a waste water treatment process (Vu et al. 2014). In that design 6 control loops have been formed but temperature, pH and ammonium concentration are monitored but not controlled since the number of process variables (PV) is less than the number of manipulated variables (MV).

In this work further investigations on temperature and pH measurement and control are conducted through simulations and implementations in a 5-L bioreactor to allow future implementations of non-linear and multi-input-output control.

Methods, Materials, and Equipment
For any control strategy design it is more beneficial if the new design can be tested in a bench scale set-up first then further tested in a pilot plant set-up. Two main biological processes involved in the removal of the main contaminants in waste water are nitrification and denitrification. The conditions, which favour the nitrification reaction are (i) Dissolved Oxygen (DO) level above 2 g/L, (ii) maximum reaction temperature below 30°C and (iii) a pH level within 6.8 to 7.4. A control strategy has previously been designed to control the DO levels. However in this work the developed control
scheme could not be tested because the available organism did not demonstrate a significant oxygen requirement and the DO level remained relatively constant during the test. Control program testing of temperature and pH is discussed below.

Methods
The reactor temperature control could be achieved by a conventional PI controller. The controller gain and integral time can be calculated in situ following the Ziegler-Nichols tuning method (Ogunnaike B and Ray W 1994).

Conventional feedback control was investigated in the bioreactor pH control. As pH control was difficult due to large variations in process dynamics, a simplified differential equation shown in Equation (1) was used to describe the rate of change of pH of an acid effluent fed to a stirred tank having volume V(litre, L) (Astrom K 1995, Shinkey F 1996).

\[ \frac{d(pH)}{dt} = \frac{1}{\tau} \left[ \frac{1}{\text{Ln10}} + \frac{u}{10^{-pH} \text{Ln10}} \right] \quad (1) \]

In Equation (1) pH is the pH of the outlet stream or inside the reactor; u is the flowrate of acid (positive) or base (negative) added to the tank to adjust the pH; and \( \tau \) is the time constant or residence time of the waste water in the tank:

\[ \tau = \frac{V}{F} \quad \text{Flowrate of acid effluent (litre/unit time)} \]

Equation (1) can be used in scheduled adaptive control of the reactor pH. Since the residence time \( \tau \) is dependent on the effluent flowrate \( F \), the controller gain \( K_c \) and integral time \( \tau_i \) can be selected for different values of \( F \). The design task can be performed off-line. Values of controller gain \( K_c \) and integral time \( \tau_i \) according to different values of \( F \) can be tabulated in a look-up table to be included in the control program. When the effluent flowrate is changed, the controller parameters can be automatically updated. This adaptive control design is only suitable for large full scale reactors with significant possible changes in effluent flowrates. The design would not show any significant difference if the control design was applied to a 5-L bioreactor.

Equation (1) can be better used in Generic Model Control (GMC) of the reactor pH (Ogunnaike B and Ray W 1994). This control scheme has a control model shown in Equation (2), where \( \varepsilon \) is the difference between pH measurement and pH setpoint, \( \varepsilon = \text{pH}_{\text{setpoint}} - \text{pH}_{\text{measured}} \).

\[ \frac{d(pH)}{dt} = k_1 \varepsilon + k_2 \int \varepsilon \, dt \quad (2) \]

From (1) and (2), \( u \) can be isolated as follows.

\[ u = \left[ (k_1 \varepsilon + k_2 \int \varepsilon \, dt) \text{Ln10} - 1 \right] 10^{-pH} \quad (3) \]

The GMC scheme was compared with the PI scheme in pH control simulations as shown in Figure 1. The experimental implementation of temperature and pH control in the reactor will be presented and discussed in the Result Section. Figure 1 shows the performances of the PI and GMC controllers for a pH setpoint change from 3 to 7 at a fixed effluent flowrate at 0.2 L/min. The PI controller
performs very aggressively. The controller action \( u \) obtained from GMC shown in Figure 1.B is more reasonable, thus would cause less movement the control valve.

Figure 1. Comparison of PI Controller and GMC Performances for a Setpoint Step Change in pH from pH 3 to pH 7, Fixed Effluent Flowrate at 0.2 L/min (A: pH; B: \( u \)).

Figure 2 compares the performances of PI and GMC controllers for a step change in the effluent flowrate from 0.2 to 0.1 L/min at a fixed pH of 6. GMC does not provide any change in \( u \) or it does not require any addition of base or acid to the reactor. As a result the output pH would exhibit an offset of 0.002. Meanwhile the pH response from the PI controller varies within the pH range from 5.992 to 6 and addition of base varies within the range from -0.0003 to 0. This small range of addition of base can be negligible because it would be difficult to get any pump to accurately work within this range.

Figure 2. Comparison of PI Controller and GMC Performances for a Disturbance Step Change in Effluent Flowrate from 0.2 to 0.1 L/min, Fixed pH at pH 6 (A: pH; B: \( u \)).

Equipment and Material
The bioreactor at Murdoch is an automated, custom-built 5L reactor, interfaced with a computer via an Analog Device 68 data acquisition system. Heater power, agitation rate, aeration rate and pump speeds for nutrient and titrant additions can be controlled via LabVIEW software, and the reactor returns online readings of pH, dissolved oxygen and temperature. Also interfaced with the control computer are two digital mass balances for measuring inflow of nutrient and titrant, and a gas
analyser for determining reactor exit gas composition. The bioreactor can be configured for either batch, fed-batch or continuous culture modes.

A full test run of the bioreactor sterilisation and control programs was performed using *Lactobacillus casei* grown from Yakult fermented milk in a tomato juice-based broth. Lactic acid bacteria was chosen due to its propensity to rapidly acidify culture media, allowing thorough testing of the pH controller.

**Results and Discussion**

Testing of the temperature controller was conducted to check the performance of the PI controller with the designed parameters for a temperature change in the reactor from the ambient temperature to 37°C. The controller tuning in situ and the control response are shown in Figures 3 and 4, which demonstrate a good response with very little overshoot and oscillation.

![Figure 3. Temperature PI Controller Design in Situ. (Controller gain and integral time were changed at 60 minutes after that oscillations settled).](image)

![Figure 4. Temperature Response of the Designed PI Controller for a Step Setpoint Change from Ambient Temperature to 37°C.](image)
Acid-base titration is open loop unstable and the current bioreactor set-up is only capable of unidirectional pH adjustment. That is only adding base to increase pH. If the effluent pH is over the setpoint, there is no control action until the pH drops to meet the setpoint. This scenario can be changed in the future by adding a switch and an acid line to the system. In the current situation it is desired to have zero controller output when the pH is at the setpoint to prevent any overshoot and potential destabilisation of the system. Integral action by the controller is therefore unsuitable for this application. As the bioreactor vessel is relatively small, base additions to the vessel often result in a rapid initial jump in pH followed by a decline as the titrant is neutralised by acid.
oscillatory effects do not represent the final pH of the system and the use of a derivative component in the controller would heighten the controller response to these. As a result a proportional-only controller was therefore chosen for pH control as shown in Figure 5 above.

Figure 6 shows the pH response of the P controller for a disturbance change and setpoint change in the effluent pH. Compared with the simulation result in Figure 1, the responses are very similar to those obtained from the GMC scheme. Simulations and experimentations with different control strategies have yielded some important modifications to the equipment and software that would improve the robustness and effective performance of pH control.

Conclusions
This part of the project involved further simulations, implementations and testing of temperature and pH control of the effluent in a lab-scale bioreactor. The temperature control could be well achieved with the in situ designed PI controller. The PI controller performed well in both temperature setpoint tracking and disturbance rejection. For pH control the P-only controller performed better than PI because the integral term resulted in overshoots but the pH response of the P controller exhibited a pH offset of ± 0.15. In simulations the GMC strategy showed similar control actions as those of a P controller but the pH response looked better. The GMC scheme will be tested in the future after some modifications to the equipment and software are finished.

References