Experiential Learning from Teaching a Process Control Course in an ET Program

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Abstract

This paper summarizes experiential learning from teaching a senior level process control course in our Engineering Technology Department. Effective teaching of difficult process control concepts can be accomplished by combining mathematical analysis, numerical methods, and computer simulation experiments. Demonstrating process control concepts through simulation can be achieved using expensive off-the-shelf packages. However, in our case, Microsoft Excel has proven to be an inexpensive, yet powerful, and easy to use tool to simulate the behavior of dynamical systems under open loop or closed loop feedback control. Projects submitted by students illustrate the effectiveness of the approach.

Introduction

Our Control and Instrumentation program provides a number of courses on process control, process modeling and simulation, electrical/electronic systems, computer technologies, and communication systems. One of the senior level process control courses is titled Process Control Systems. The objective of this course is to teach students the scientific and engineering principles underlying process dynamics and control. Students learn how to integrate and apply knowledge of engineering to identify, formulate and solve process control problems. They use modern computational techniques to solve process control problems.

This course covers a wide spectrum of process control concepts. Specifically, it covers the following topics:

1. Introduction to Process Control: Control Objectives and Benefits
5. Introduction for Feedback Control: The Feedback loop and control systems hardware
6. PID Control: Algorithm and tuning for dynamic performance
7. Stability Analysis and Controller Tuning: Principles, Ziegler-Nichols closed-loop, Bode method
9. Practical application of feedback control: Ratio control, Split range control, Override control
10. Enhancements to PID Feedback Control: Cascade and feedforward control

Demonstrating important control concepts for dynamic systems is achieved by using a combination of mathematical analysis, numerical methods, and computer simulation. An example is presented by discussing the concept of PID control with emphasis given on the role simple and inexpensive software tools such as Microsoft Excel can play in helping students master these concepts.

The remaining of the paper is organized as follows. Section II outlines the PID control concepts that students must master. Section III outlines the process to be controlled and its model, the numerical methods required to solve equations describing the dynamic behavior of the controlled process, and the numerical results from integrating the process model in Excel. Section IV provides computer simulation results that demonstrate the PID control concepts. In Section V, a case study from a student final project is presented. It demonstrates how students have been able to utilize Microsoft Excel to simulate the dynamic behavior of a chemical process under PID feedback control. The project entails process modeling, feedback control, and computer simulation of a chemical process. Section VI summarizes the results, followed by bibliography in Section VII.

II. PID Control Concepts

The PID controller has been widely used in the process industries since its introduction in the 1940s. Its widespread use is primarily due to its simple structure which involves three adjustable/tuning parameters.

In mathematical terms, this algorithm is described by the following equation:

\[ u(t) = u_s + K_c \cdot e(t) \quad \text{(Proportional mode)} \]

\[ + K_c \cdot \left( \frac{1}{\tau_i} \right) \cdot \int_0^t e(t) dt \quad \text{(Integral mode)} \]

\[ + K_c \cdot \tau_d \cdot \frac{de(t)}{dt} \quad \text{(Derivative mode)} \]

Or, in the Laplace domain,

\[ G_c(s) = \frac{u(s)}{e(s)} = K_c \cdot \left[ 1 + \frac{1}{\tau_i \cdot s} + \tau_d \cdot s \right] \]

where:
- \( u(t) \) = current control action,
- \( u_s \) = bias term,
- \( K_c \) = proportional gain,
- \( \tau_i \) = integral time,
- \( \tau_d \) = derivative time,
- \( G(s) \) = controller transfer function,
- \( s \) = Laplace operator

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There are several good textbooks\textsuperscript{1,2,3} summarizing the properties of the PID controller. Simply, by focusing on one of these properties, specifically the properties of the controller’s proportional mode, we will show how mathematical analysis can be used to prove these properties and how simulation in Excel can demonstrate them.

For example, we teach the students that a PID controller in proportional only mode has the following properties:

- The closed loop system order remains the same
- The time constant of the closed loop is reduced, thus the system becomes faster
- For non-integrating process, the steady state offset because of a step change in setpoint or disturbance is not zero
- For integrating process, the steady state offset because of a step change in setpoint is zero
- For integrating process, the steady state offset because of a step change in disturbance is not zero

In class, we use detailed mathematical analysis to prove these properties. The analysis is similar to the one mentioned in classical process control textbooks\textsuperscript{3} and is omitted for the sake of brevity.

Even though these properties are proven mathematically, the students learn how to use computer simulations to demonstrate them. This goal is accomplished by integrating the dynamic model of the controlled process, in the form of differential equations, with the equations of the controller and programming all of them in Excel.

For instance, using an integrating process, the students demonstrate the last two properties in using Excel. A step by step process is shown in the next section.

III. Process Control Description and Simulation in Excel

An integrating process is shown in Figure 1. It is a water tank.

\textbf{Figure 1: Schematic of Water Tank Process}
The variables are defined as follows:

- $F_i$: input flowrate (manipulated variable),
- $F_d$: input flowrate (disturbance)
- $F_o$: output flowrate (constant)

Our objective is to simulate how the water tank level $h$ changes with time as $F_i$ and $F_d$ change with time. To accomplish this, we need to solve the differential equations describing the water tank level as a function of $F_i$ and $F_d$.

Using material balances, we derive the differential equation describing this process. The equation is:

$$\frac{dh}{dt} = \frac{1}{A} \cdot F_i + \frac{1}{A} \cdot F_d - \frac{1}{A} \cdot F_o$$

where $A$ is the cross sectional area of the water tank.

Solving this equation as an initial value problem can be accomplished using a number of numerical methods. A simple such method is the Euler method. Typically, we have to find a function $y(t)$ given its derivative (or slope) $f(t, y)$ and an initial value point $(t_i, y_i)$. In our case, we used the following algorithm:

1. **Step 1**: Start from a known initial point $(t_i, y_i)$
2. **Step 2**: Calculate the slope at point $(t_i, y_i)$
   
   \[ \text{slope} = \frac{dy}{dt} \Big|_{t_i} = f(t_i, y_i) \]

3. **Step 3**: Calculate an estimate of the true solution at the next time point $t_i + 1$

   \[ t_{i+1} = t_i + dt \]

   \[ y_{i+1} = y_i + f(t_i, y_i) \cdot h \]

4. **Step 4**: Update "old" with "new" values and go to Step 1 if integration time has not been reached

   \[ t_i = t_{i+1} \]

   \[ y_i = y_{i+1} \]

Implementation of this algorithm is very easily accomplished in Excel. Indeed, the students learn how to solve numerically differential equations in Excel. Although more tedious, this approach helps students better understand how commercial packages may internally work. A simple interface has been developed to allow testing of the process response to input changes. Figure 2 shows the process response (how the level changes with time) when the disturbance (flowrate $F_d$) changes by 0.5 gal/min. As expected, the water tank level behaves like an integrating process.
Figure 2: Process Response to Step Change in $F_d$ of Magnitude 0.5 gal/min.

While programming the integration of the process model in Excel, students have access to all calculated data and can easily check their calculations for correctness. A small section showing the first few steps of the model integration using the Euler method is shown below.

<table>
<thead>
<tr>
<th>Integration Step</th>
<th>Process Time (min)</th>
<th>Input Flowrate (MV)</th>
<th>Input Flowrate (DV)</th>
<th>Output Flowrate (Constant)</th>
<th>Level (old)</th>
<th>Rate of Change for Level</th>
<th>Level (new)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT (min)</td>
<td>Time (min)</td>
<td>$F_i$ (gal/min)</td>
<td>$F_d$ (gal/min)</td>
<td>$F_o$ (gal/min)</td>
<td>$h_{old}$ (ft)</td>
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<td>$h_{new}$ (ft)</td>
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Figure 3: Step by Step Calculations when Integrating the Water Tank Model in Excel
Developing such a simulation requires the students to solve differential equation in Excel, a widely available software tool. Using this simulation, the students study the open loop dynamic behavior of the process behavior under certain scenarios. Understanding process behavior is a requirement for designing effective control systems.

The following section outlines results when the water tank process is under proportional only control. The objective is to demonstrate the properties of the PID controller when proportional only control is used.

IV. PID Control in Excel

Under feedback control, we would like to study the dynamic response of the water tank level when the process disturbance, $F_d$, changes and/or the desired water tank level setpoint changes. The controller will adjust the manipulated variable, $F_i$, to control the tank level. Studying the behavior of the water tank level under these scenarios will help us demonstrate the properties of the proportional mode of the PID controller using Excel.

To accomplish this, the process model and the controller equation are solved simultaneously. A simple graphical interface was developed in Excel that shows the controller tuning parameters, setpoint and/or disturbance changes, and the process response. Figure 4 shows the results when only the water tank level setpoint changes in a stepwise manner. As we can see, the controller is able to move the process from one setpoint value to another with no steady state offset. This clearly demonstrates one of the properties of the proportional mode of the controller which says that a proportional controller eliminates steady state offset for integrating processes when the setpoint changes in a stepwise manner.

Figure 4: A proportional controller eliminates steady state offset for an integrating process for step changes in the setpoint.
Using the same simulation, the students can demonstrate another property of the proportional controller. This property says that the controller cannot eliminate steady state offset when a disturbance changes in a stepwise manner. Indeed, Figure 5 demonstrate this property.

Figure 5: Steady state offset when a disturbance changes in a stepwise manner

As we can see in Figure 5, the controller cannot maintain the process at the desired setpoint. There is a steady state offset, as the mathematical analysis proved this property. Furthermore, by increasing the controller gain, students can demonstrate that this offset is reduced. Figure 6 shows this result.

Figure 6: Steady state offset reduction due to increased controller gain
In summarizing the results so far, students can be taught difficult process control concepts by combining mathematical analysis, numerical methods, and computer simulation. Microsoft Excel provides an easy to use and inexpensive programming environment and platform for students to experiment with process control concepts. It is easy to be used and this is demonstrated in the next section which outlines a student project submitted as part of this course on process control.

V. Test Case: Modeling and PID Control of a Chemical Reaction Process - A Student Project.

To evaluate how well the students mastered the different process control concepts, they were tasked with conducting a project relevant to the material of the course. This particular student project involved modeling of a chemical process, solving the process model, and controlling the process using a proportional-integral-derivative (PID) controller. The student used Microsoft Excel to simulate the process model and create a comprehensive HMI (Human Machine Interface) for the model and the associated controller.

The following synopsis of the project demonstrates the process modeling skills that were acquired through this course and the adaptation of software, such as Excel, that provided the means to model, simulate and control the process at desired conditions.

a. The Chemical Process

The process under consideration is shown in Figure 7. Reactants A and B are fed to a series of three equal size, constant density, and well mixed reactors. The objective is to control the concentration of reactant A at the exit of the third reactor. This is achieved by manipulating the flow rate of pure A component by adjusting the recycle valve position.

![Figure 7: Schematic of controlled process with PI control on recycle stream](image-url)
Such a reaction process is of the type \( A + B \rightarrow C + D \). The reaction of ethyl acetate with sodium hydroxide to form sodium acetate and ethyl alcohol falls into such type of reaction.

Table 1 shows process data [5] used to simulate the process. It includes data regarding reactor size, feed rates, and concentrations.

| Table 1: Process Data |
|-----------------------|---------------------|
| **Initial Concentration of Component A after mixing with Component B, \( (C_{A0}) \)** | 0.0567 mol/L |
| **Initial Concentration of Component B, \( (C_{B0}) \)** | 0.10 mol/L |
| **Throughput of Component B, \( (F) \)** | 5000 L/min |
| **Reactor Tank Volume (V)** | 2000 L |
| **Reaction Rate Constant, \( (k) \)** | 36.2 L/mol*min |
| **Recycle Analyzer Delay Time, (td)** | 10 min |
| **Concentration of Component A at the exit of the 3rd Reactor, \( (C_{A3}) \)** | 0.0086 mol/L |

b. **The Procedure**

Initially, a detailed mathematical model of the process was developed using material balances. This model was integrated using the Euler method in Excel. It served the purpose of a real chemical process.

To design the PI controller, transfer functions relating the controlled variable (3rd reactor outlet concentration of A), manipulated variable (recycle valve position), and disturbance (concentration of B component) were developed. The transfer function models were all approximated with first order plus dead-time models.

For this particular process, these simplified models are:

a) Process transfer function:

\[ G_p(s) = \frac{C_{A3}(s)}{V(s)} = \frac{K_p}{s+a} = \frac{0.0269 \cdot e^{-10.3269s}}{s+3.059} \]

b) Disturbance transfer function:

\[ G_d(s) = \frac{C_{A3}(s)}{F_B(s)} = \frac{K_d}{s+p} = \frac{3.059 \cdot e^{-10.3269s}}{s+3.059} \]
Using the previous process transfer function given by equation , a PI controller was designed using the Cohen-Coon method. Table 2 shows the tuning parameters obtained using the Cohen-Coon method and the ones finally implemented after some “fine tuning” of the controller.

### Table 2: PI controller tuning parameters

<table>
<thead>
<tr>
<th>Transfer Function: ( G_p(s) = \frac{0.0088e^{-10.3269s}}{3269s+1} )</th>
<th>K = 0.0088</th>
<th>( \tau = 0.3269 )</th>
<th>( \tau_d = 10.3269 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Tuning</td>
<td>Calculated</td>
<td>Actual (used)</td>
<td></td>
</tr>
<tr>
<td>( K_c = \frac{1}{K} \cdot \frac{\tau}{\tau_d} \cdot \left( 0.9 + \frac{\tau_d}{12 \cdot \tau} \right) )</td>
<td>( K_c = 12.7 )</td>
<td>( K_c = 20 )</td>
<td></td>
</tr>
<tr>
<td>( \tau_i = \tau_d \cdot \left( \frac{30 + 3 \cdot \frac{\tau_d}{\tau}}{9 + 20 \cdot \frac{\tau_d}{\tau}} \right) )</td>
<td>( \tau_i = 2.01 )</td>
<td>( \tau_i = 3 )</td>
<td></td>
</tr>
</tbody>
</table>

c. Simulation Results

The detailed mathematical model of the process and the PI controller were simultaneously solved in Excel. Figure 8 shows the first few calculations while Figure 9 shows the controller’s ability to achieve a desired 3rd reactor outlet concentration for component A. Indeed the controller achieves the desired concentration of 0.0086 mol/L and proves one of the properties of a PI controller which says that a PI controller eliminates the steady state offset for step changes in the setpoint.
VI. Conclusion

This paper summarized experiences from teaching a senior level process control course in an Engineering Technology program. Effective teaching of difficult process control concepts was accomplished by combining mathematical analysis, numerical methods, and computer simulation experiments. Microsoft Excel proved to be an inexpensive, yet powerful, and easy to use tool to simulate the behavior of dynamical systems under open loop or closed loop feedback control. Final projects submitted by students illustrate the effectiveness of the approach.

VII. Bibliography

Biographical Information

Dr. TZOUANAS is an Assistant Professor of Control and Instrumentation in the Engineering Technology Department at the University of Houston-Downtown. His teaching and research interests focus on process control systems, process modeling and simulation, artificial intelligence and expert systems. His professional experience includes management and technical positions with chemicals, refining, and consulting companies. He is a member of AIChE.

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