Experiences Using MATLAB/Simulink for Dynamic "Real-time" Process Simulation in an Undergraduate Process Control Course

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1. Introduction

Process simulation technology has evolved dramatically over the past 10 years with the increasing application of object oriented programming. Many packages are available which allow intuitive visualization of process data coupled with a user-friendly graphical interface which allows rapid synthesis of process flowsheets using click-and-drag operations. These packages are common in industry for both process modeling and real-time process control. A significant challenge for instructors is to prepare students to use these tools in their undergraduate chemical engineering curriculum.

In this paper, we describe the use of MATLAB's dynamic simulation engine, Simulink, in an undergraduate process dynamics and control class. Using the graphical user interface (GUI) design tool, dubbed GUIDE by MATLAB, one can create customized interfaces that allow the students to quickly interpret data from the process as well as make modifications to the control operations in an intuitive framework. In effect, it is possible to emulate the interface typically found on an industrial distributed control system (DCS). Using these tools, we have introduced a number of case studies into the undergraduate control curriculum (process control modules (PCM)). In this paper, we concentrate on one of the new case studies: the pulp digester. A continuous digester is one of the strategic processes of pulping operations. In terms of the physical unit, it may be as large as 20ft in diameter and 120ft tall with capacity to hold as much as 1/4 of the daily production in transit. The digester is a multi-phase reactor/separator combination with a moving packed-bed where lignin is removed from wood chips. Various complexities of the process provide a rather rich example for chemical engineering students to exercise the combined application of principles learned in transport, reaction engineering, unit operations, process design, process control and numerical methods.

2. Process Control Modules (PCM)

The Process Control Modules (PCM) are a set of programs written in the MATLAB/SIMULINK environment, for use instruction of an undergraduate course on process dynamics and control. The modules are based on fundamental process models of industrial unit operations (distillation column, biochemical reactor, pulp digester, heated-tube furnace), and incorporate a realistic graphical user interface to emulate an industrial control environment. They were developed to allow educators to strike a proper balance between

theory and practice using a computer-based control laboratory. Such a laboratory can address a variety of issues in process control: modeling, identification, simulation, analysis, and design. The students can deal with realistic problems in the form of benchmark problem modules, and this will not only reinforce the concepts presented in the lecture notes (primarily theory) but will also make the process more interesting.

Such an approach to education will allow for fundamentals to be stressed in the lectures while enabling the interaction with complex, practical process problems via software modules. The software tools that we have chosen for the instructional laboratory are MATLAB (*matrix laboratory*) and SIMULINK (*Dynamic System Simulation Software*). They represent an interactive program for scientific and engineering calculations. MATLAB has become a standard among academic and industrial users alike for use as both an educational tool as well as a research utility. Other software packages for control education include PICLES [1], and ACS [2]; however, these packages do not, in general, adequately handle large practical-scale problems.

The primary distinction of the PCM software package is the ability to incorporate complex dynamical process models with convenient graphical user interfaces (developed in the MATLAB graphics language) in a way to achieve a realistic emulation of an industrial distributed control system operator's console [3,4]. Furthermore, the entire package is based on a commercial software platform (MATLAB) which allows individual instructors to customize, or add to, existing modules. The flexibility of this platform allows for migration to many PC and workstation hardware platforms, and allows for continued use of the PCM package through upper level control elective courses by the addition of specialized MATLAB control toolboxes.

3. MATLAB/Simulink for Real-time Simulation

Simulation parameters

The individual simulation modules employed in PCM consist of c-code subroutines which are integrated to MATLAB/Simulink using a gateway subroutine. A compiled version of the code is ultimately used (a cmex file or c-MATLAB-executable file), so there is no run-time compilation of the unit operation code.

The integration engine suite in MATLAB is impressive. There are first through fifth order fixed step integrators (including the traditional Euler and Runge-Kutta), as well as up to fifth order variable-step integrators (including Adams and several stiff system integrators). While the expert user can fine-tune the tolerances and step-sizes to suit a particular problem, the students that run the PCM modules merely execute the settings that have been provided by the instructor. In effect, they are running a pseudo-real-time simulation, since we never allow them to turn the simulation off until the lab session is completed. The "pseudo" qualification denotes the fact that the integrator will not execute a uniformly synchronized run over time, but will run somewhat slower during the transient following large changes in the input variables, and somewhat faster during steady-state execution. For educational purposes, these effects are inconsequential, and the students experience a realistic real-time interface to the process.

Some of the units are intentionally "throttled" using tight tolerances and small integration step sizes, to prevent excessively fast simulations. From an educational perspective, this is important as it allows the students to think about process changes as they occur. If the simulations executed in a matter of seconds, the exercise would reduce to a simply textbook-like analysis problem that is conducted off-line, and the active learning opportunity is lost.

Graphical User Interface (GUI)

MATLAB affords nice flexibility for customization of the graphical user interface (GUI). An example of such customization is the PCMplot utility, which allows users to load historical data generated by the simulation, regress a low order approximate model, and validate the result. Customizable features include pull-down menus, clickable buttons, and incorporation of standard MATLAB plotting utilities (*e.g*., real-time data plotting). An illustrative example of these features will be discussed in section 5.

4. Continuous Pulp Digester Module

The Kamyr digester is a two phase continuous tubular reactor which uses the kraft process to convert wood chips to pulp through reaction with a heated causticizing solution known as white liquor. The digester consists of several zones in which the flow of white liquor is either: (i) co-current or (ii) counter-current with respect to the chip flow (see Figure 1). The Kappa# is a measure of the residual lignin, the glue-like substance binding cellulose fibers together, in the pulp and is a direct indicator of the pulp quality. The control objective is to minimize the variations of the Kappa# in the presence of measured and unmeasured disturbances. Advantages for its successful control include increasing product quality, minimizing utility usage and reducing downstream processing.

There are several features of the continuous digester that pose challenging control problems, thus making this an ideal exercise for classroom study:
- the main control variable, Kappa#, is sampled infrequently and there can be long time delays associated with its measurement;
- the digester is subject to unmeasured variations in the biological feedstock (composition, moisture, and density) and white liquor compositions;
- there are significant time delays between the manipulated variable action and their observed effects in the primary and secondary measurements;
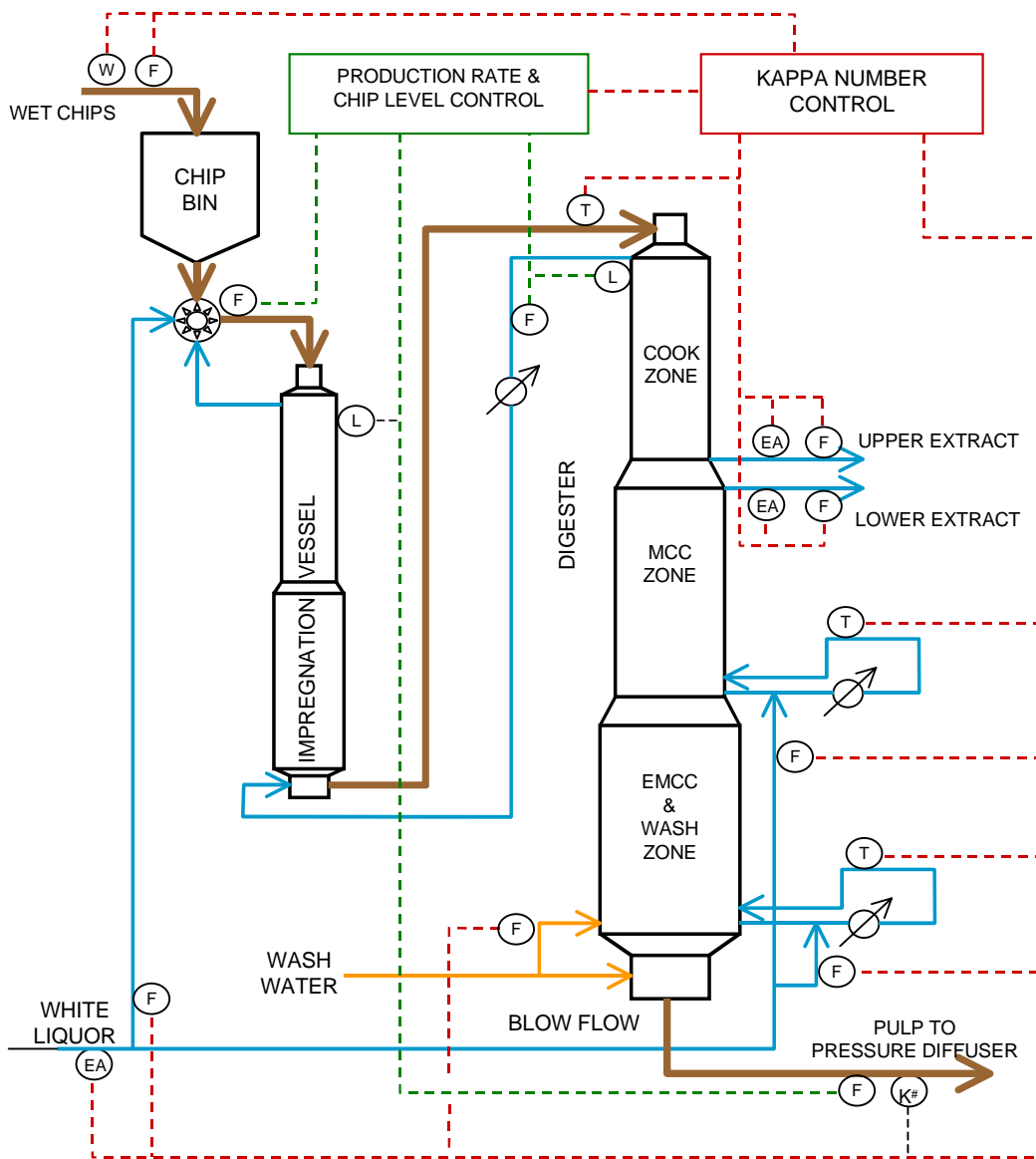- the digester exhibits nonlinear behavior, particularly in the lower Kappa# range.

Figure 1: Continuous Digester Schematic

The development of fundamental digester models for control studies is a non-trivial and time-consuming task. For this reason, several digester benchmark problems (DBP) have been developed to provide a common comparison base for continuous digester control studies [5,6]. These DBPs are simplified process models which captures the major dynamic characteristics of digester behavior. In the DBP employed in this study [6], the continuous digester is modeled with two vessels, an impregnation vessel and a reaction vessel (shown in Figure 1). The impregnation vessel is modeled as a mixing section followed by pure time delay in which the white liquor is diluted by the wood chip moisture. The reaction vessel is modeled with three zones; a co-current cook zone, a counter-current modified continuous cook (mcc) zone and an extended modified continuous cook (emcc) zone. It is assumed that there are two phases, a solid phase consisting of five components and a liquor phase consisting of six components and that the two phase are in thermal equilibrium. The reactor

zones are described by mass and energy balances of the following form (the interested reader is referred to the original paper for complete details):

$$\frac{\partial \rho_{Si}}{\partial t} = -v_S \frac{\partial \rho_{Si}}{\partial z} + R_{Si} \qquad i = 1,...,5$$

$$\frac{\partial \rho_{Lj}}{\partial t} = \mu v_L \frac{\partial \rho_{Lj}}{\partial z} + R_{Lj} \qquad j = 1,...,4$$

$$(1+\alpha)\frac{\partial T}{\partial t} = -v_S(1 \pm \alpha \frac{v_L}{v_S})\frac{\partial T}{\partial z}$$

where the signs reflect the co-current and counter-current sections, respectively. There are three primary zones, in which these ten equations are applied. In the implementation for PCM, a lumped approximation of order 50/zone was used to yield a set of ordinary differential equations of dimension 1500. This points out two of the complex features that underly all of the unit operations employed in PCM: (i) high dynamic order, and (ii) complex nonlinear behavior.

5. Educational Control Exercises

The previously described unit operation has been incorporated into the Process Control Modules, and the corresponding flowsheet is given in Figure 2. The process variables of interest for this educational implementation are a subset of the total simulation variables, and are summarized in Table 1. From the flowsheet, the students can execute the simulation and change process variables (*e.g.*, introduce a load disturbance). In a closed-loop flowsheet, the students could access and change (in real-time) the controller tuning parameters.

Process Outputs	Manipulated Inputs	Disturbance Variables
Kappa #	Upper Extract Flowrate	Chip Flowrate
Upper Liquor EA	Cook Zone Temperature	Chip Moisture
Lower Liquor EA	MCC Temperature	
Lower Na_2S Concentration	MCC Trim Flowrate	

Table 1: PCM Digester Module Process Variable Summary

Using the GUI tools described earlier, a process monitor window was developed, as shown in Figure 3. Key features of this monitor include:
- Individual real-time graphs of four key process variables
- "Pointer" button to enable readout of process variable values
- "Save" button to archive data for analysis (*e.g.*, regression)
- A toggle switch to allow students to move between the flowsheet (simulation) windows and the process monitor windows.
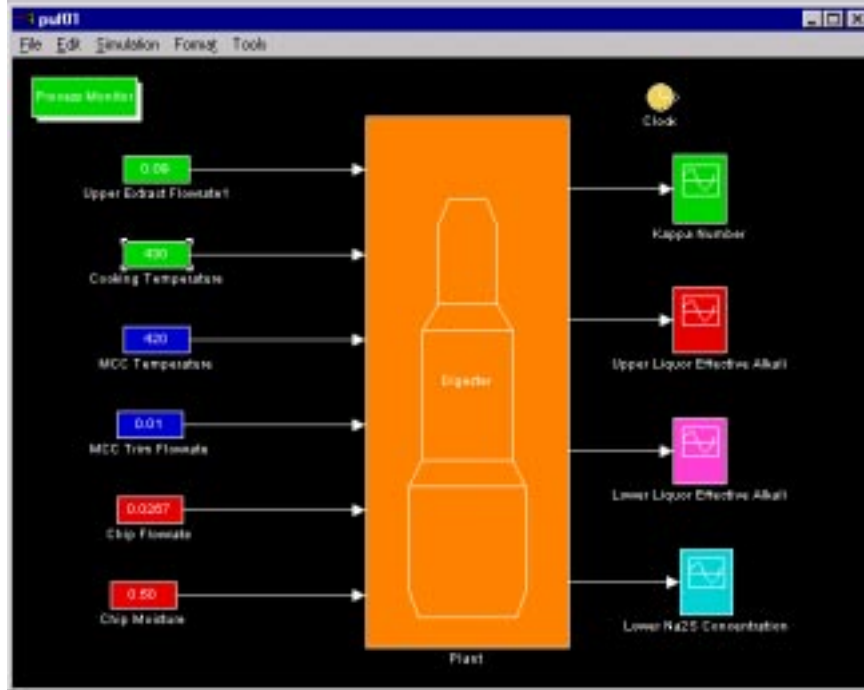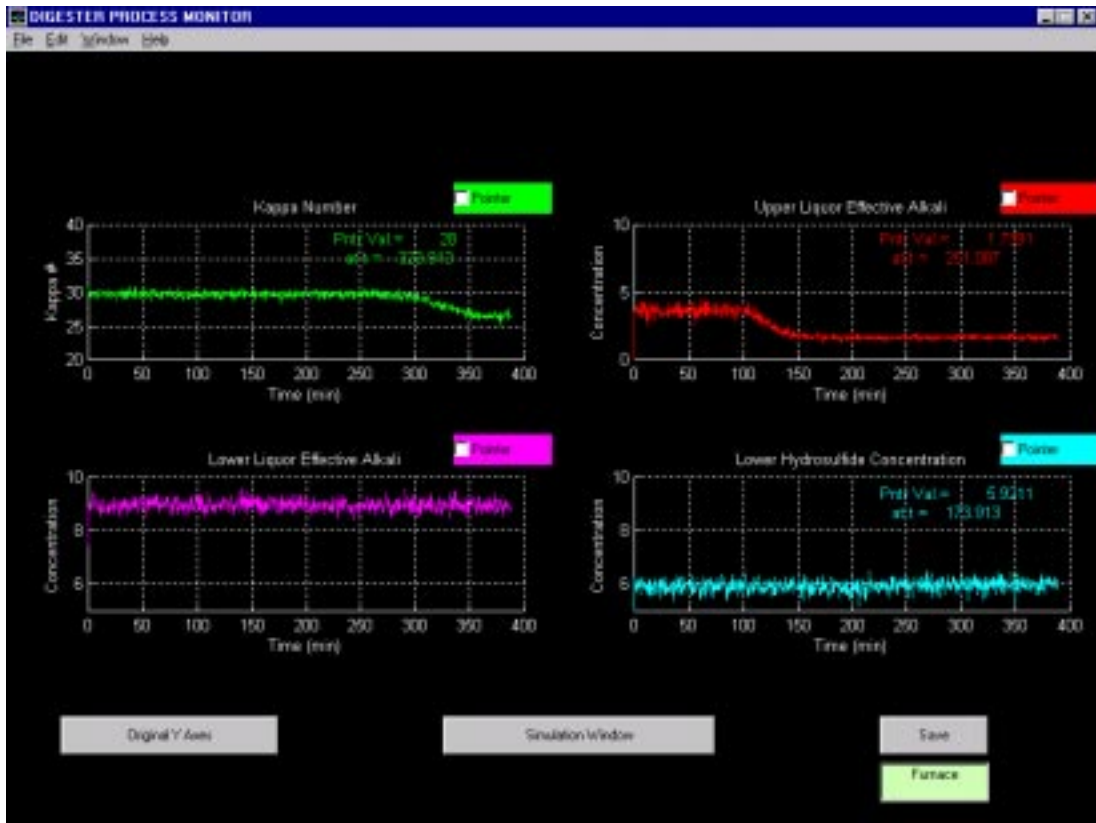
Figure 2: Digester Flowsheet Window

Figure 3: Digester Process Monitor Window

In a typical offering of the senior-level course, Chemical Process Dynamics and Control (CHEG 401), at the University of Delaware, we would include the following specific exercises:

- Steady-state modeling of the process gains between the inputs (both manipulated and disturbance) and the process outputs.
- Dynamic modeling of process behavior using first-order-plus-deadtime models.
- Validation of dynamic models using PCMplot utility.
- Single-loop PID design and controller tuning using Cohen-Coon, Ziegler Nichols, and Relay methods.
- Smith Predictor design to handle significant deadtime in Kappa# variable.
- Single-loop internal model control (IMC) design.
- Decoupling design to remove interactions for single-loops.
- Model predictive control design for digester, taking into account process constraints and multivariable interactions.

The management of these modules in a one semester course offering is accomplished by weekly (2 hour) lab assignments which typically address one of the previously enumerated exercises. The students can run the exercises in the University laboratory, or at home with the Student Edition of MATLAB/Simulink.

6. Acknowledgments

7. How to Learn More About PCM and the Digester Benchmark Problem

Interested educators are referred to the Web-page for the Process Control Modules at:
http://www.che.udel.edu/pcm

Interested researchers and educators should contact fkayihan_ietek@msn.com for more information about the IETek Digester Benchmark.

8. References

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9.   Biographical Information

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