

Innovations in Undergraduate Control System Instructional Laboratory

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Abstract

With the growth of microcomputer capabilities, control engineering has witnessed a significant shift towards digital implementation of digital controllers. Many modern industrial and commercial control systems employ digital computers. With the use of digital computers in the loop, one can readily generate C code from graphical simulation tools such as Simulink block diagrams for real-time controller implementation. This has provided the impetus for establishment of a real-time instructional control laboratory at Milwaukee School of Engineering. In this paper the development of this innovative integrated real-time control system laboratory will be described. Next modeling, simulation, controller design and implementation of a few typical laboratory experiments and projects of different complexity are presented. This paper also reports on Simulink modeling of the nonlinear inverted pendulum with some research results for different swing-up controllers.

Introduction

With the great advances in microelectronics and high-performance data acquisition and control boards, the control of modern industrial and commercial systems with a digital computer is becoming more common. To bridge the gap between academics and industry it is essential to supplement the teaching of control system courses by developing and incorporating into the curriculum a real-time control system laboratory that will allow students to design, implement, and test their own control systems. For a control education laboratory to work effectively and efficiently it should be based on well established systems that provide a variety of experiments that span the spectrum of topics from classical control to optimal, digital, robust, and nonlinear control. If such a system is in place then it becomes feasible for the research professor to concentrate on "build your own" experiments. Or, more appropriately, it gives graduate students an opportunity to build their own open-ended exploratory experiments.

The Electrical Engineering and Computer Science Department at the Milwaukee School of Engineering has recently established a modern real-time control system laboratory. This laboratory was developed to enhance the quality of undergraduate education in control systems and to reinforce the concepts that are covered in the lectures. This real-time control laboratory also opens up research activities for graduate student projects. The undergraduate experiments give students the opportunity to tie theoretical classroom concepts with practical hands-on experiments.

The objective is to provide undergraduate students with computer-based control and introduce them to concepts such as client-server environment, visual instrumentation, automatic code generation, and the modern techniques needed for the design and implementation of automatic control systems. In addition, the use of the Matlab/Simulink combination for analysis and design of modern control systems and the implementation of physical control systems has allowed coverage of topics in undergraduate curriculum that traditionally are considered advanced topics.

The remainder of this paper describes the equipment and software installed in the laboratory, provides an overview of the experiments in the introductory junior-level controls course with details on the rate feedback experiment, and provides an overview of the projects in the senior-level controls course with details on the inverted pendulum project. Both courses are taught on an 11 week quarter system. The laboratory has 10 fully equipped stations with two students working at a station as a team for a capacity of 20 students per section. In the required introductory junior-level course, a two hour per week laboratory session is conducted in addition to three 50 minute lecture sessions per week. In the elective senior-level course, there are three 50 minute lecture sessions per week and no scheduled laboratory sessions. Students work on two different projects throughout the quarter. At MSOE, there are no graduate teaching assistants and the course instructor delivers lectures and directly supervises laboratory sessions. This provides a tight coupling between the lectures and the laboratories. The controls courses as taught at MSOE would require significant modification if the course instructor did not directly supervise the laboratory sessions and if section sizes were much greater than 20 students. More detailed information about these projects and the laboratory manual used in the first course can be found at

http://www.msoe.edu/~saadat/control_system_instructional_lab.htm

Equipment and Software

The laboratory is equipped with state-of-the-art computer aided control equipment for analog and digital control systems simulation, analysis, design, and implementation. A conceptual layout of the equipment is shown in Figure 1. The analysis and design of control systems is carried out via MATLAB and Control System Toolbox, which provide students with immediate access to an extensive range of analysis and design tools. The graphical simulation tool Simulink is used for modeling, design and simulation together with Real-Time Workshop to generate C code from Simulink models for control of servo systems in real time. Finally, Quanser's WinCon software invokes a C compiler to create the executable control code; downloads the executable code to a client controller computer; provides data transfer between Simulink and the servo system; enables on-the-fly controller tuning; and plots data in real-time. The WinCon software consists of two programs: WinCon client and WinCon server. The WinCon client is installed on the control host computer, and WinCon server is installed on the student's laptop. The student's laptop also contains MATLAB, Simulink and the Real-Time Workshop software.

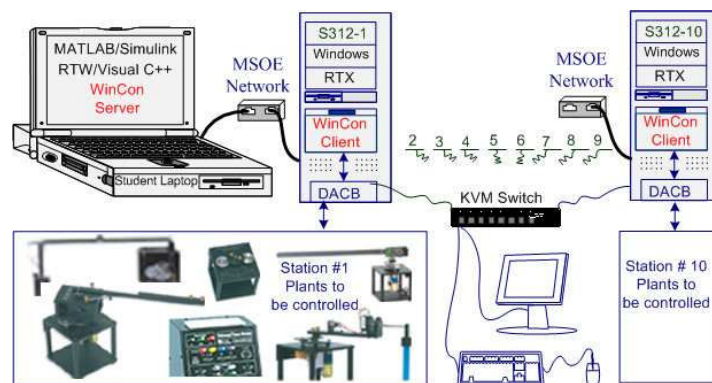


Figure 1. Real-Time Control System Laboratory

Ten Allen Bradley industrial micro PC's provide the WinCon client controllers. Each PC contains the Quanser ISA MultiQ-2E Data Acquisition and Control Board enabling real-time processing and storage of multi-channel analog input and output data. Each station is equipped with a Quanser UPM1503-24V Power Module and SRV02-ET Servomotor that includes encoder, tachometer and potentiometer. Several modular mechatronics components provide the capability for design and

control of systems with a wide variety of plant dynamics for several experiments of different degrees of difficulty. Also at each station there is an Agilent 54600 oscilloscope, HP 33120A Function Generator, HP E3631A Power Supply, and an HP 34401A multimeter, all connected to a General Purpose Interface Bus (GPIB).

The students perform all their design work on their laptops. They connect their laptops to the host computer via an Ethernet cable. WinCon server enables students to connect to the desired workstation over the internet and generate the real-time code on their laptops. The real-time code is downloaded automatically to the host computer. The control is executed on the host computer and data is streamed to the laptop for on-the fly controller tuning and real-time plotting.

Laboratory Experiments

An innovative approach is to integrate the real-time control laboratory in the first control system core course where some laboratory sessions can be used for instruction as well as hands-on experience of lab work. The experiments are designed in a manner which allows a reinforcement of the concepts that are covered in the lecture. The developed modular experiments and laboratory manual allow the student to become familiar with the commonly used devices such as sensors, transducers, signal conditioning circuits, microprocessor interface, controller design, implementation and test on the real-time hardware.

In the first session students learn the basics of the software and hardware used for implementation of control systems. The second session is devoted to operational amplifiers; A/D-D/A converters; and emulation and implementation of typical compensators. The next two sessions focus on modeling, an orderly approach to digital simulations, and investigation of the effect of damping on the system response. Case studies include the third-order Butterworth filter, a mechanical system, a moving coil actuator, a simple pendulum, a nonlinear system and the inverted pendulum.

In the six remaining sessions students perform the following experiments:

- Position Control I (Rate Feedback)
- Velocity Control I (Velocity Feedback)
- Position Control II (PD Controller)
- Position Control III (Phase-lead Controller)
- Ball and Beam Project

For each experiment students develop the system model, design the controller based on reasonable performance criteria, and simulate their control system in Simulink. Next, students construct an implementation diagram, build and download it to one of the client workstations, and establish if the control system meets the design specifications. One of the above experiments, Position Control I (Rate Feedback), is briefly presented here.

Position Control I (Rate Feedback)

Position control systems are used extensively in industrial applications such as robotics and drive control. Modern position control systems are achieved with precision using incremental encoder sensors. In this experiment students design and implement a position control system for low frequency square wave input. The objectives of this project are:

- To obtain the servo plant model
- To design a position control system such that the output angle tracks a commanded position using position and velocity feedback and determine the feedback gains to achieve the given time-domain specifications
- Build the compensated servo plant in Simulink and simulate offline to obtain the response to a square wave input and verify the design

- Build the WinCon application, implement and test the system on the real-time hardware
- A schematic layout of the servomotor is shown in Figure 2.

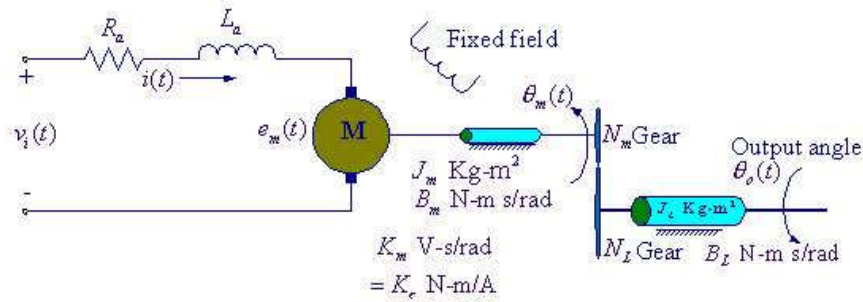


Figure 2. Servo plant schematic

From the detailed equations describing the electrical and mechanical systems the block diagram representation is obtained as shown in Figure 3.

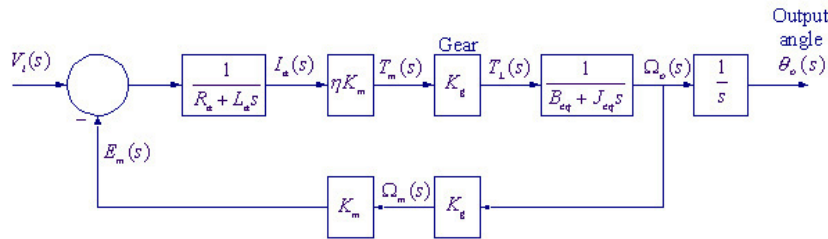


Figure 3. Servo plant block diagram

In the pre-laboratory assignment the student begins the design cycle by obtaining the transfer function model, controller design, simulation and preparation of the implementation diagram as follows. The servo plant transfer function neglects the armature circuit inductance

$$\frac{\theta_o(s)}{V_i(s)} = \frac{a_m}{s(s + b_m)} \quad (1)$$

In equation (1), parameters a_m and b_m are

$$a_m = \frac{\eta K_m K_g}{R_a J_{eq}}, \quad b_m = \frac{B_{eq}}{J_{eq}} + \frac{\eta K_m^2 K_g^2}{R_a J_{eq}} \quad (2)$$

Position Control Design

The compensated block diagram with position and rate feedback given by

$$V_i(s) = K_P[\theta_i(s) - \theta_o(s)] - K_D \Omega_o(s) \quad (3)$$

is shown in Figure 4.

The closed-loop compensated transfer function is

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{K_P a_m}{s^2 + (K_D a_m + b_m)s + K_P a_m} \quad (4)$$

The controller gains, K_P and K_D , are determined for a given input $\theta_i(t)$ (e.g., a square wave of amplitude 20° and a frequency of 1 Hz) and reasonable design specifications such as

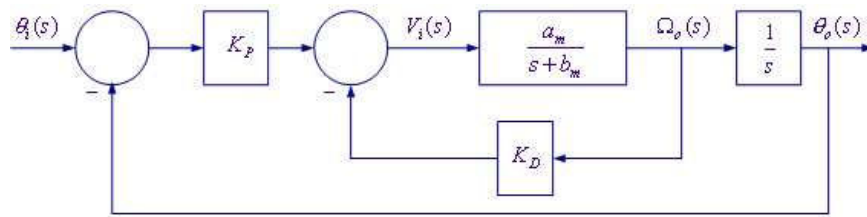


Figure 4. Position Control using position and rate feedback.

- Step response damping ratio of $\zeta = 0.707$
- Peak time of $t_p = 0.05$ second.

A Simulink diagram is constructed and the simulated response is obtained. When the student finishes testing their model in Simulink, the model is prepared for implementation on the real-time hardware. This means the plant model has to be replaced by the I/O components that form the interface to the real plant.

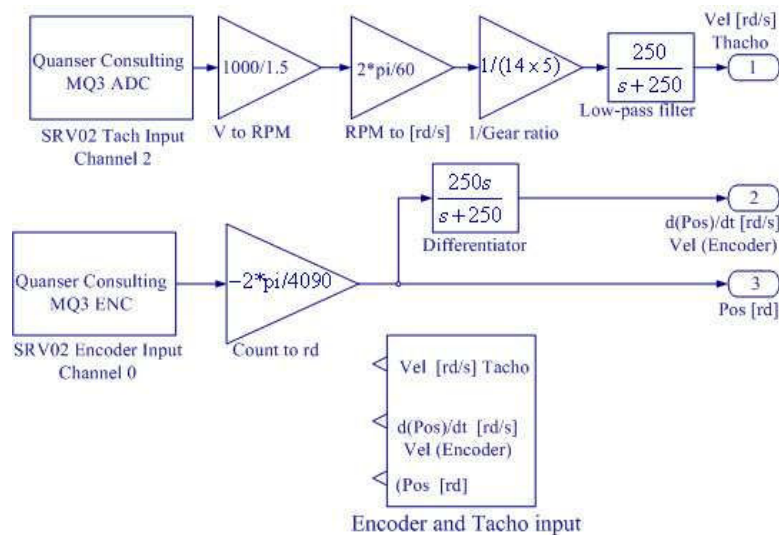
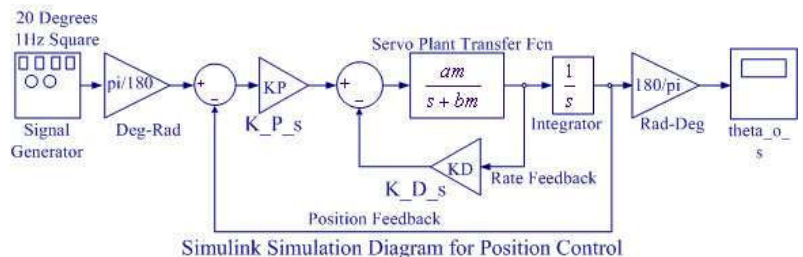


Figure 5. Interfaces to the SRV02 Feedback Signals

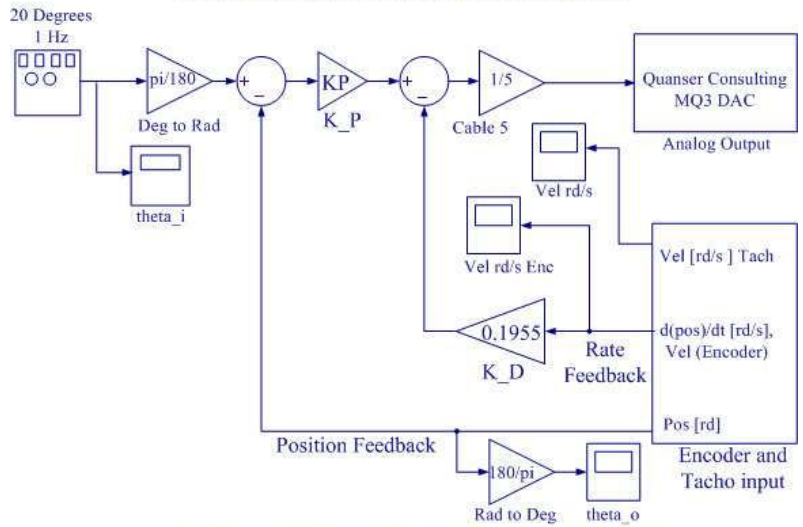
Before coming to the laboratory students complete the implementation diagram. Using the Simulink library and WinLib, a subsystem containing the interface to the SRV02 to access the tachometer and the encoder signals is created as shown in Figure 5. The WinLib is a library of Quanser DACB drivers containing many blocks such as analog input (ADC), analog output (DAC) and encoder input which are accessible from Simulink library. The encoder is used to provide the digital phase information. This signal is differentiated to produce a velocity signal using a low-pass band-limited differentiator such as $\frac{250s}{s+250}$. To obtain simulated and real-time results simultaneously, the implementation model is added to the previously constructed Simulink model as shown in Figure 6.

Using the set of leads, universal power module (UPM), SRV-02 DC-motor, and the connecting board of the MultiQ3 data acquisition board, the wiring diagram is completed as shown in Figure 7.

Real-time plots of plant position variables are obtained on the student laptops as shown in Figure 8. Notice both simulated and real-time results. The controller gains K_P and K_D can be fine-tuned "on the fly" (i.e. while the controller is running in real-time).



Simulink Simulation Diagram for Position Control



Simulink Implementation Diagram for Position Control

Figure 6. Simulation and Implementation diagram for position control



Figure 7. Wiring diagram for servo motor position control system

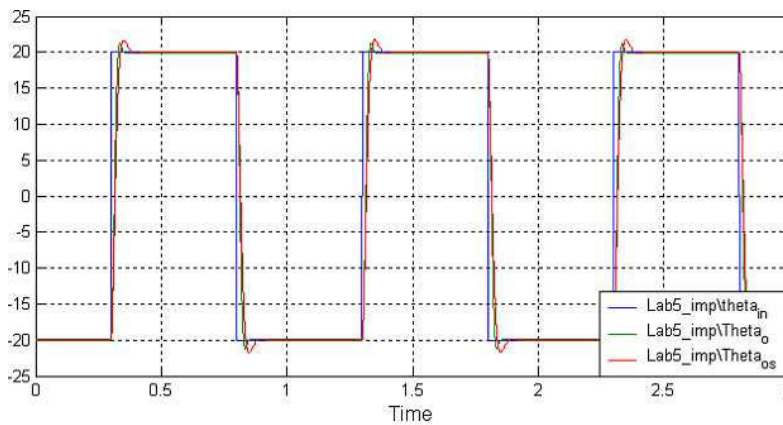


Figure 8. Real-time plots

Advanced Projects

The objectives of these projects are to give students in the senior-level controls course exposure to state-of-the-art in modern control system design. Practical applications include Inverted Pendulum, Flexible Link, and Flexible Joint projects utilizing state-space feedback design by pole placement or Linear Quadratic Regulator (LQR) design. Some projects involve z-domain modeling including design and implementation of discrete-time controllers. Students are assigned two projects, which vary from year to year.

- Flexible Link Project
- Flexible Joint Project
- Rotary Inverted Pendulum Project
- Position or Velocity Control Project (z-domain modeling and discrete-time controller)

The Rotary Inverted Pendulum Project is briefly presented here.

Rotary Inverted Pendulum

The control of an inverted pendulum is a well-known and a challenging problem that serves as a popular benchmark in modern control system studies. A schematic picture of the rotary inverted pendulum of length l and mass m supported by a pivot arm is shown in Figure 9.

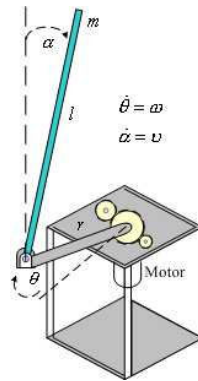


Figure 9. Simplified Inverted Pendulum schematic

The arm must move in the horizontal plane in such a way as to keep the pendulum in an upright position. This is similar to the classic pendulum mounted on a cart which must move in such a way as to keep the pendulum in an upright position. An inverted pendulum is an inherently unstable system. Force must be properly applied to keep the pendulum in an upright position. The problem of balancing an unstable system occurs in practice in the areas of missile stabilization, control of a space rocket during takeoff, and control of robots. The purpose of this project is to design hybrid controllers for balancing the rotary inverted pendulum in the vertical-upright position.

Nonlinear Model

The pivot arm of radius r rotates in a horizontal plane by the servomotor. One encoder is used to measure the angular position and velocity of the servomotor and another encoder is used to measure the pendulum angle and velocity. The governing differential equations of the system are as follows

$$(J_{eq} + mr^2)\dot{\omega} - \frac{1}{2}mLr \cos \alpha \dot{v} + \frac{1}{2}mLr \sin \alpha v^2 + B_{eq}\omega = T_L \quad (5)$$

$$\frac{1}{3}mL^2\dot{v} - \frac{1}{2}mLr \cos \alpha \dot{\omega} - \frac{1}{2}mgL \sin \alpha = 0 \quad (6)$$

or

$$\alpha\dot{\omega} - b \cos \alpha \dot{v} + b \sin \alpha v^2 + B_{eq}\omega = K_1 v_i(t) - K_2 \omega \quad (7)$$

$$c\dot{v} - b \cos \alpha \dot{\omega} - d \sin \alpha = 0 \quad (8)$$

where

$$\alpha = J_{eq} + mr^2, \quad b = \frac{1}{2}mLr, \quad c = \frac{1}{3}mL^2, \quad d = \frac{1}{2}mgL \quad (9)$$

The following nonlinear differential equations are derived

$$\dot{\omega} = \frac{1}{f(u)} [db \cos \alpha \sin \alpha - (cp)\omega - (cb \sin \alpha)v^2 + (cK_1)v_i(t)] \quad (10)$$

$$\dot{v} = \frac{1}{f(u)} [ad \sin \alpha - (pb \cos \alpha)\omega - (b^2 \cos \alpha \sin \alpha)v^2 + (bK_1 \cos \alpha)v_i(t)] \quad (11)$$

where

$$p = B_{eq} + K_2 \quad \text{and} \quad f(u) = ac - b^2 \cos^2 \alpha \quad (12)$$

The servomotor viscous friction has been included, but the friction between the pendulum and the rotating arm has been neglected. Nonlinearity also arises due to the Coulomb friction which gives rise to limit cycles. The Coulomb friction compensation can be considered by amending the control law with a step function.

Linearized Model

To be able to design linear regulator state feedback, the model must be linearized. Equations (10) and (11) are linearized about the equilibrium state of the system for small α (i.e., when the Inverted Pendulum is near its equilibrium point). For small α , $\sin \alpha \cong \alpha$, $\cos \alpha \cong 1$, and $f(u) \cong e = ac - b^2$. Also, for small α , v^2 is negligible, and the following linearized equations are obtained

$$\dot{\omega} = \frac{bd}{e}\alpha - \frac{pc}{e}\omega + \frac{cK_1}{e}v_i(t) \quad (13)$$

$$\dot{v} = \frac{ad}{e}\alpha - \frac{pb}{e}\omega + \frac{bK_1}{e}v_i(t) \quad (14)$$

By combining equations (13) and (14) with $\dot{\theta} = \omega$, $\dot{\alpha} = v$, the following linear state space model of the inverted pendulum is obtained

$$\begin{bmatrix} \dot{\theta} \\ \dot{\alpha} \\ \dot{\omega} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{bd}{e} & -\frac{pc}{e} & 0 \\ 0 & \frac{ad}{e} & -\frac{pb}{e} & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \frac{cK_1}{e} \\ \frac{bK_1}{e} \end{bmatrix} v_i(t) \quad (15)$$

The uncompensated step response has a root at origin and a real root in the right half plane, corresponding to a non minimum system with an unbounded response.

The simulation diagrams for the nonlinear differential equations (10) and (11) and the linearized state equation (15) with their combined subsystems are constructed as shown in Figure 10. A simulation of both the nonlinear and linearized models for a small perturbation input verifies the linearization as shown in Figure 11. From this observation a threshold angle α_{th} , for which the linear model is in close agreement with the nonlinear response, is approximately 25° to 30° . This information is used for the state feedback controller design.

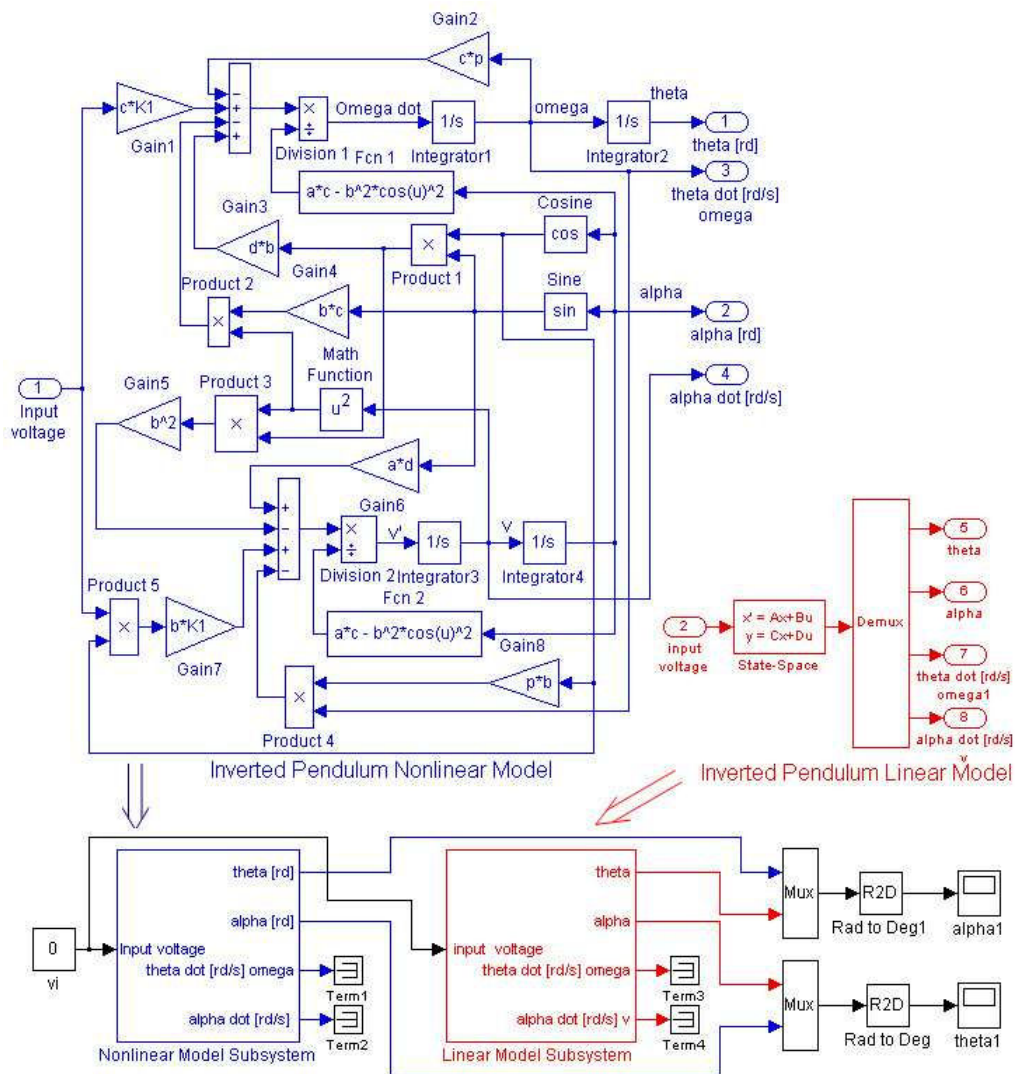


Figure 10. Nonlinear, Linear and the combined Simulink Models

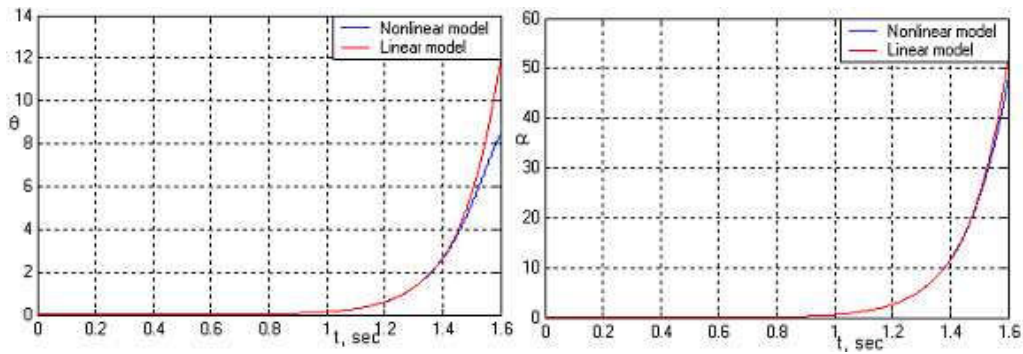


Figure 11. Linear and nonlinear models comparison for θ and α

Control Strategy

The controller consists of three parts: a *swing-up controller*, a *catch controller* and a *state feedback stabilizing controller*. Initially, the pendulum is in the downward position and the swing-up controller is used to bring it close to the top position. Once it is sufficiently close to the top equilibrium position, it is caught and switched to the state feedback stabilization controller.

Manual Mode

For this mode, the pendulum is raised manually by hand towards the upright position (no swing up controller) until it is captured by the catch-controller which turns on the state feedback stabilizing controller. A manual switch is provided to allow the experiment to be performed with manual swing-up or self-erecting mode, using an appropriate swing-up controller.

Feedback Stabilizing Controller Design

For the compensated closed-loop system a state feedback controller $u(t) = -Kx(t)$ is designed so that the compensated closed-loop has a desired pair of dominant second-order poles with a time constant of $\tau = 0.1$ sec and a damping ratio of $\zeta = 0.8$. The remaining poles have real parts corresponding to sufficiently damped modes (time constants $\tau_3 = 0.05$ sec and $\tau_4 = 0.008$ sec) so that the system mimics a second-order response. The gain matrix K is found such that the characteristic equation for the controlled system is identical to the desired characteristic equation.

Swing-up Controller Design with Positive Feedback and Adaptive Rate Gain

The linearized model is found to be accurate when the pendulum angle α is within a small range, $\pm 30^\circ$. Therefore, the state feedback stabilization controller is accurate when the pendulum is within this region. A Swing-up controller is designed to swing the pendulum to the upright position from the stable "at rest" position. This controller is responsible for the swinging up the pendulum to a position in which the stabilization mode can take over. First, the servomotor is placed under position control then an algorithm is prescribed for the driving force.

Servomotor rate feedback and position feedback are designed for a step response damping ratio $\zeta = 0.8$ and peak time $t_p = 0.115$ sec.

Various schemes can be devised to prescribe a driving force for a suitable trajectory in a controlled manner such that energy is gradually added to the system to bring the pendulum to the inverted "catch" position. Students are asked to develop and implement different swing-up controllers and select the controller that can bring up the pendulum smoothly with the least number of swings. The nonlinear Simulink model developed is particularly useful for swing-up controller design. In this paper one of the swing-up controllers is described where the desired position is determined by the following control law

$$\theta_i(t) = P\alpha + Dv + Y \max[e^{a(\alpha_{min}+2\pi)}, e^{-a\alpha_{max}}] \quad (16)$$

This feedback based on the pendulum angle and its velocity creates a trajectory with growing amplitude. An adaptive rate gain that changes with the states of the pendulum is designed. The strategy is to detect the pendulum maximum and minimum swings α_{max} , α_{min} and adjust the gain exponentially to bring the pendulum up smoothly. A Simulink implementation of the control in (16) is shown in Figure 12.

The system is simulated and values for P , D , a , and Y are adjusted for a satisfactory swing-up. These parameters may need to be fine tuned when running the embedded system. The simulation results for the swing-up controller are shown in Figure 13.

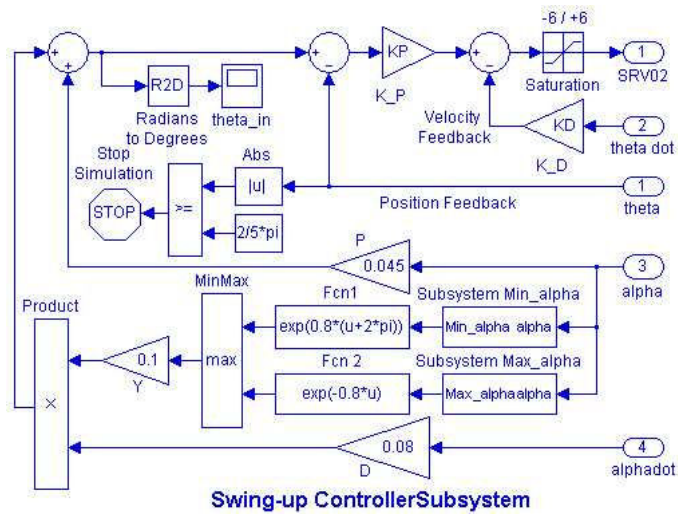


Figure 12. Simulink diagram for Swing-up controller design

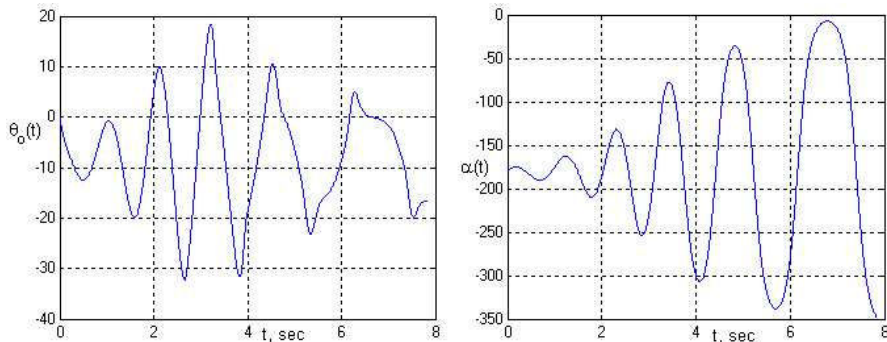


Figure 13. Swing-up Controller Response

Catch Controller

The Catch Controller Subsystem is shown in Figure 14. Its purpose is to track the pendulum angle α and facilitate switching between the swing-up and stabilization modes. This controller is to be enabled when α is within $\pm 5^\circ$ and for as long as $|\alpha| < 25^\circ$. The completed implementation diagram including the state feedback control, the swing-up control, and the catch control is shown in Figure 15.

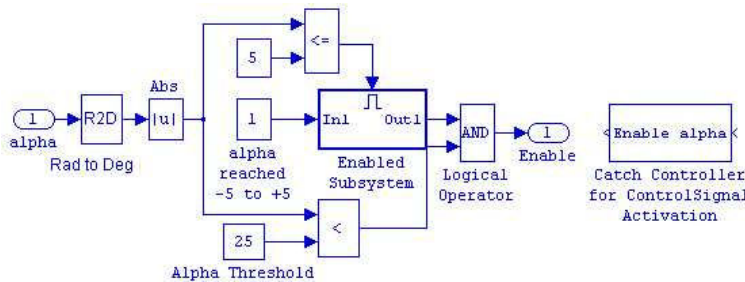


Figure 14. Catch Controller for control signal activation

The steady state response of the real-time system is shown in Figure 16. The inverted pendulum system allows the user to add disturbances by tapping on the tip of the pendulum. The controller maintains stability unless the disturbance causes the angle to exceed 25 degrees in either direction.

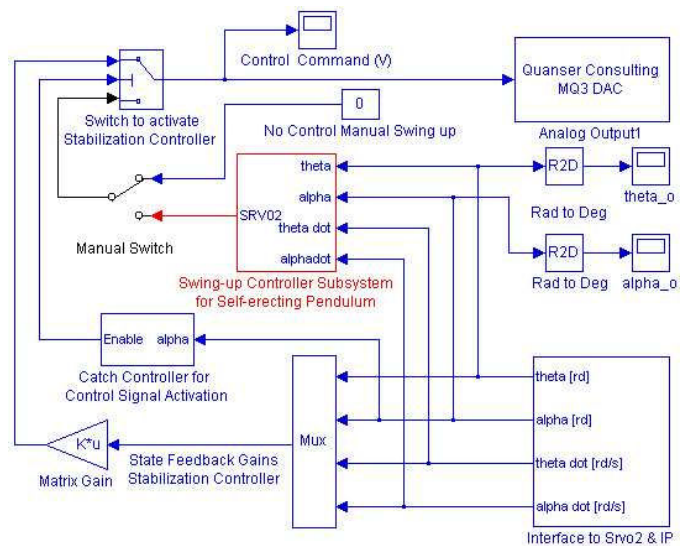


Figure 15. Implementation diagram for the Rotary Inverted Pendulum

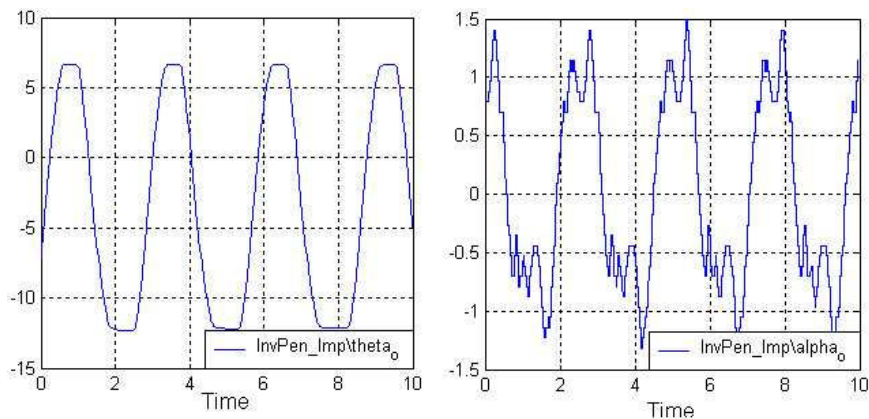


Figure 16. Steady-state response of real-time inverted pendulum system

Conclusion

This paper has described the integration of a real-time control system laboratory with a beginning undergraduate control systems course and a senior-level control systems course. The integrated software/hardware combination gives students an early exposure to computer-based control and facilitates a single unified environment for modeling, simulation and all the steps of the control development process.

MATLAB, Simulink, and Real-Time Workshop together with Quanser WinCon allow students to work under easy-to-use, intuitive Windows interfaces. Students are able to generate real-time code and implement their models within seconds on the Quanser real-time hardware. Real-time plots are obtained easily and quickly allowing students to observe how a control system behaves in real time. They can observe the effect of parameter changes and controller gains on their system's behavior - either interactively or automated via scripted m-files. Students can experiment with various control strategies and different scenarios and find out the consequences, thus obtaining confirmation of their theoretical learning and acquiring a better understanding of the complex interactions taking place inside a specific real-time control system.

The experiments are designed in a manner which allows a reinforcement of the concepts that are covered in the lecture beginning with the basics of the software and hardware used for implementation of control systems, operational amplifiers, A/D-D/A converters, emulation and implementation of typical compensators and an orderly approach to digital simulations. Beyond the software and hardware basics, experiments of different degrees of difficulty that span the spectrum of topics from classical control to optimal, digital, robust, and nonlinear control are introduced. The inclusion of this laboratory has added a new dimension to the teaching of control system courses at MSOE and has been well received by the students.

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