2006-567: VIRTUAL CONTROL WORKSTATION DESIGN USING SIMULINK, SIMMECHANICS, AND THE VIRTUAL REALITY TOOLBOX

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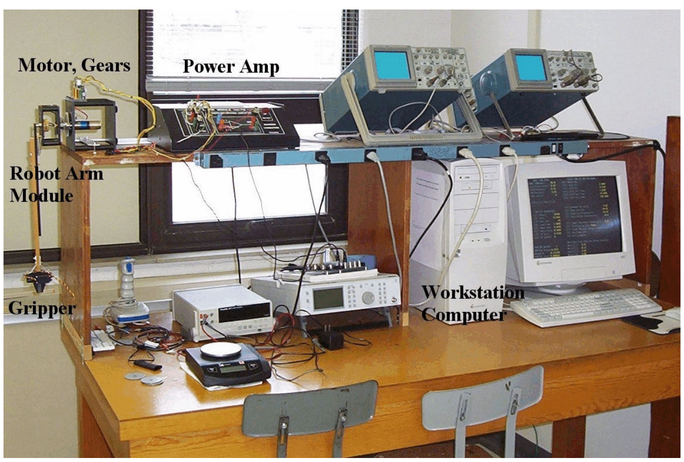
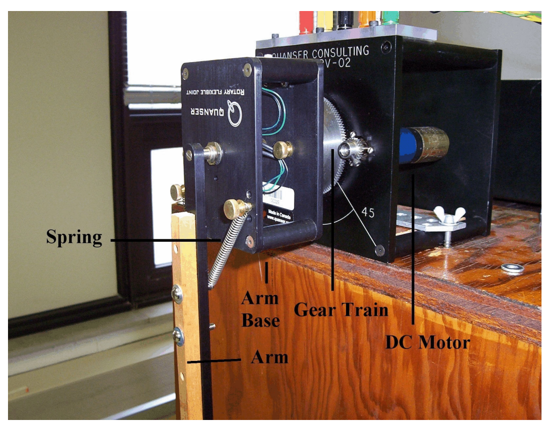
Virtual Control Workstation Design Using Simulink, SimMechanics, and the Virtual Reality Toolbox

Abstract Control workstations are used in education to teach control theory principles as well as a test station for control algorithm development. Two workstations from Quanser Consulting are being used in our electrical and computer engineering program in student projects. Additional workstations have not been purchased for students in the control theory courses because of cost and space constraints. However, incorporating a laboratory feel into these courses would enhance learning and retention. The design and use of a low-cost virtual control workstation in the first undergraduate control theory course will be discussed. The virtual workstation was modeled from the physical electrical and mechanical parameters of a Quanser Consulting electro-mechanical system.

I. Introduction Two control workstations from Quanser Consulting have been used in over a dozen student projects in the Electrical and Computer Engineering (ECE) Department at Bradley University as well as for faculty research [1]. The Quanser Consulting product line is extensive and many of the products have been developed with assistance from the controls community [2]. The virtual workstation was modeled to match the performance characteristics of the physical control workstation shown in Fig. 1. The workstation can be used in three robot arm configurations; level, inverted, and non-inverted; with each resulting in significant differences in static and dynamic properties. Single-loop, multi-loop, feed-forward, and adaptive controllers have been used in past student and faculty projects [3,4].





Expanded View of Arm Mechanism

Figure 1. Quanser-Based Control Workstation.

The virtual control workstation was designed using MATLAB, Simulink, SimMechanics, and the Virtual Reality Toolbox software packages [5]. Simulink provides a graphical user interface for nonlinear model development and simulation [6]. In 2002, the software package SimMechanics was added as an enhancement to the Simulink environment for modeling mechanical systems. In conjunction with the Virtual Reality Toolbox, the Simulink platform can be used to design a virtual control workstation. Initial planning of the workstation design was started in Spring 2004 and was motivated by an externally-funded research project which used the new SimMechanics package for the design of a software testbed for earthmoving equipment [7]. A sabbatical research proposal was developed for the workstation design and was approved in Fall 2004 for the Spring 2006 semester. The primary goal of the sabbatical research period was to complete the virtual control workstation for the first undergraduate control theory course EE431 [8]. In addition, course lecture material and homework problems would be modified to incorporate use of the workstation. An outline of the completed project tasks leading up to and including the first part of the sabbatical period are shown below.

- **Fall 2004:** Start the first phase of the workstation design as an undergraduate senior project [9].
- **Spring 2005:** Develop a new Simulink-based modeling experiment for the Fall 2005 senior laboratory course EE450 [10]. Joysticks were purchased for the new laboratory experiment and the virtual control workstation.
- **Summer 2005:** Modify the workstation developed in the senior project for the Fall 2005 EE431 control theory course's end of the semester design project.
- **Fall 2005:** Evaluate use of Simulink and the workstation in the EE450 and EE431 courses.
- **Spring 2006:** A nonlinear friction subsystem model was developed that includes Coulomb, stiction, and viscous friction effects. Gear backlash was also added to the system model.

In the next section, course and curriculum modifications will be discussed in relation to the virtual workstation use as well as the goals of the revised curriculum. The details of the workstation design will be presented in Section III and use in the first control course in Section IV. Section V will discuss student feedback and assessment and concluding remarks.

II. Course and Curriculum Modifications The laboratory program in our ECE Department consists of a five-semester sequence of required independent laboratory courses which meet once a week. Starting in the junior year, the laboratories are six contact hours which allow for several relatively complex design projects which range from two to six weeks. In the fall semester, the senior laboratory experience consists of three projects or experiments; a first week experiment in the system theory area (EE450), a six-week mini-project design which is a microcontroller-based product design (EE450), and finally the last seven weeks are devoted to the senior capstone project (EE451) [10-12]. See [12] for details of our assessment process for ABET and how the laboratory program prepares students for research-oriented senior projects.

The first-week senior laboratory experiment in EE450 was changed in Fall 2005 from a circuit design and analysis problem to a Simulink modeling problem to prepare students for control workstation use. Simulink is used briefly in the junior system theory courses but the primary focus in these courses are MATLAB and the Signal Processing Toolbox [13]. Two control theory elective courses are offered in the senior year [8,14]. The first course, EE431, consists of classical control and modeling for continuous-time systems and use of the Control System Toolbox [15]. Modeling topics include amplifiers, sensors, DC motors, gear trains, and robot arms. Gain, lag, lead, lag-lead, and PID-type controllers are covered for the root locus and frequency domain design methods. Seventy-five to 90 percent of the senior class take this elective course. The major focus of the second course, EE432, is modeling, analysis, and controller design for sampled-data systems. Simulink is an integral part of lectures and the homework set.

The primary change to the 2005 fall semester control course EE431 was using the virtual workstation in the end of semester design project. The physical and virtual workstations were introduced in the first week of class and three reading assignments (PowerPoint slides) were created for exposure to the workstation. The Blackboard course management system is used to distribute course reading assignments [16]. The second reading assignment used animation results from the virtual workstation to illustrate initial condition responses and how they were affected with and without dynamic braking. The third reading assignment discussed the modeling of the mechanical subsystems using SimMechanics and the Virtual Reality Toolbox.

The goals of the revised curriculum:

- Incorporate a laboratory feel into the control theory courses to enhance learning
- Reduce the learning curve of using Simulink in senior capstone project designs
- Reduce the learning curve of using basic control theory for the EE431 design project
- Reduce the learning curve of using basic control theory for senior projects in the controls area
- Better prepare control students for graduate or industry work in the systems modeling area
- Meet the above goals without more time commitment from students

III. Virtual Workstation Design The first step in the virtual workstation design was the development of the SimMechanics model for the mechanical subsystems shown in Fig. 1. This required measurements of dimensions and masses of the individual components of the robot arm assembly. The inertia of the individual components was determined from a mechanical engineering handbook. It was decided because of time constraints to eliminate the mechanical springs (see expanded view in Fig. 1) and fix the arm to the arm base. The arm is now in a classical pendulum configuration. The arm consists of the base, shaft, and gripper subsystems.

The SimMechanics model is shown in Fig. 2 which consists of the motor, three set of gears, and the robot arm assembly. Doubling clicking any one of the blocks in Fig. 2 opens a SimMechanics GUI that allows entry of mass, inertia tensor, axis for center of gravity, and coordinates of the mechanical part. Modeling the friction in the mechanical subsystems was the most time-consuming part of the model development. Experimental steady-state data and initial condition and step responses were used to derive the viscous, Coulomb, and stiction friction terms. Although the individual subsystems could have been modeled with friction, an equivalent friction seen by the motor was used to reduce simulation time. The friction model was implemented as an embedded m-file.

Connections from the SimMechanics model to the Virtual Reality Toolbox are made through the interface block "VR Sink". Body sensors are added to the SimMechanics model which allow the mechanical motions (rotations for this system) to be connected to the VR sink. These sensors were omitted in Fig. 2 for clarity. A Virtual Reality view of the motor-gear assembly and the default view for the workstation are shown in Fig. 3. The user can view the assembly from different angles as well as zooming in or out using the VR GUI interface. Ten figures (JPEG and GIF files) were created for the workstation views using Paint Shop Pro [17]. These figures were used in conjunction with the VR Toolbox's GUI interface to design the different views. The

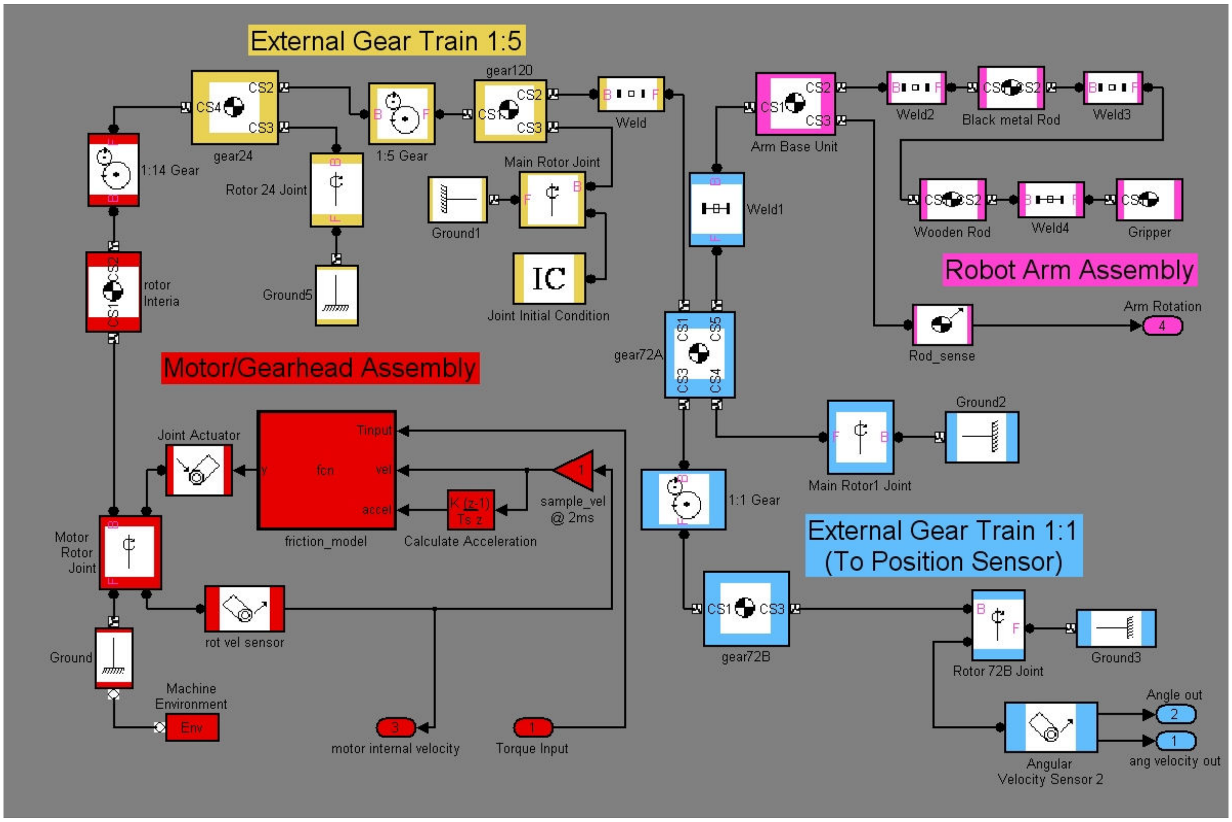


Figure 2. SimMechanics Model of Motor/Gear/Arm Mechanism.

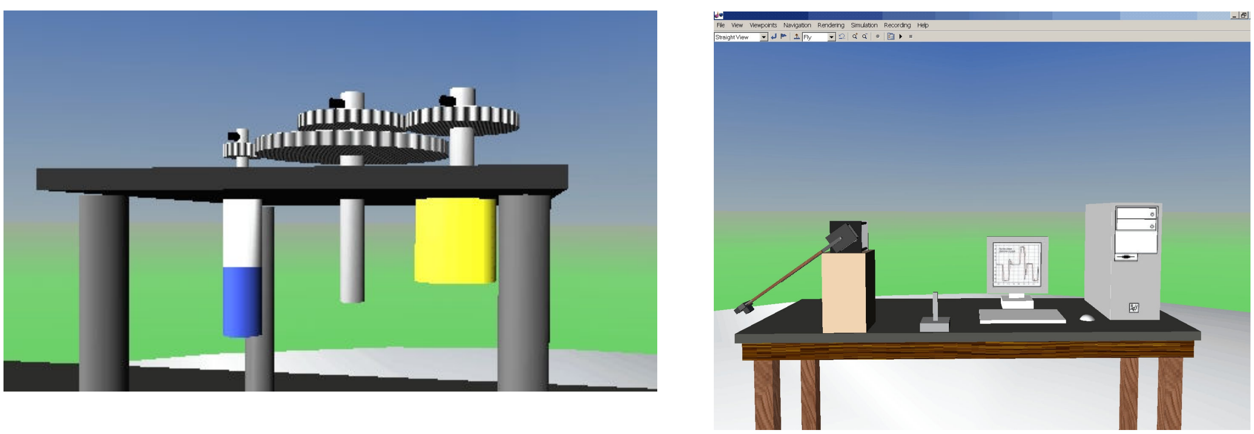


Figure 3. VR Toolbox Views: Motor-Gears and Workstation Default.

VR Toolbox GUI uses V-Realm Builder by Ligos Corporation which provides the environment for creating 3-D visual simulations.

The Simulink diagram of the electromechanical control system is shown in Fig. 4. The system is arranged in a unity-feedback configuration. The feedback gain can be selected to be one (closed-

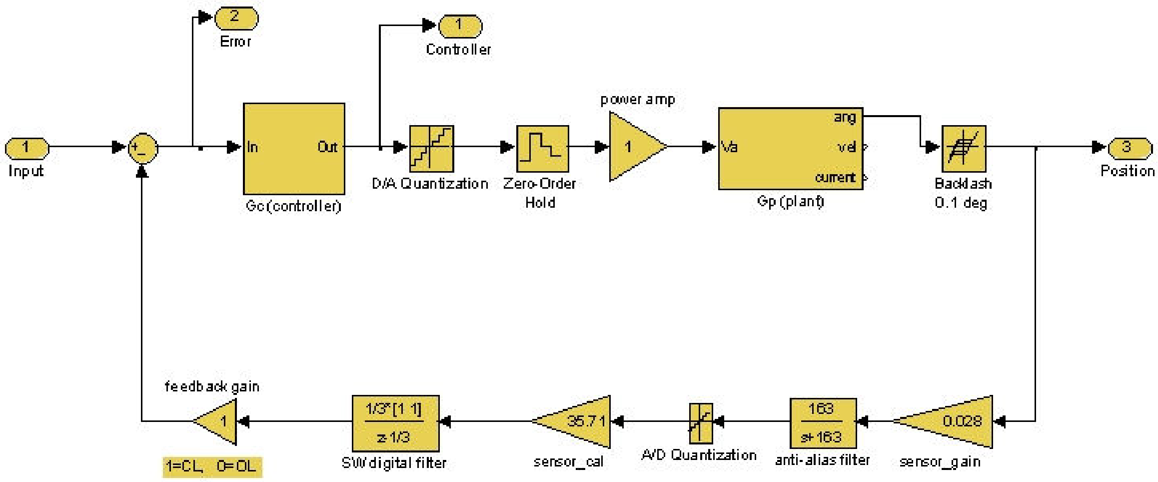


Figure 4. High-level Simulink Model of Control System.

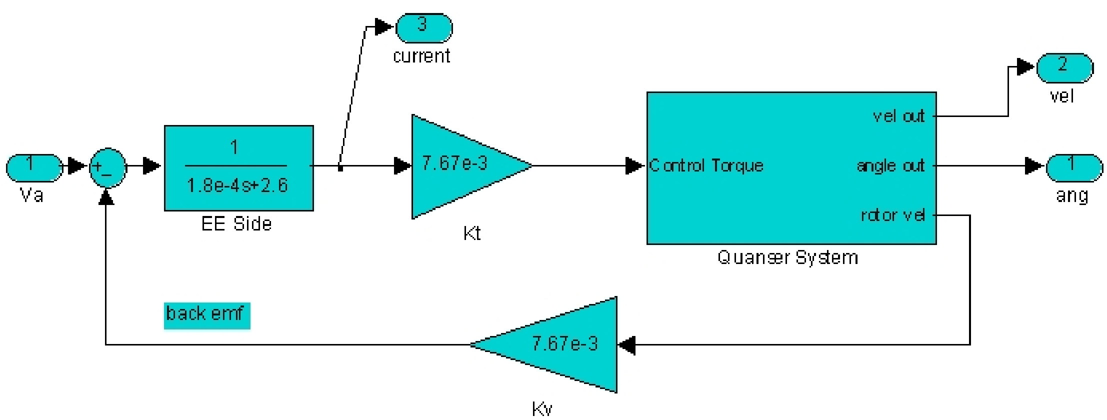


Figure 5. Exploded View of Plant Gp in Fig. 4.

loop) or zero (open-loop). Subsystem Gc represents the controller transfer function, the power amp is modeled with unity gain, and Gp is the plant (Quanser's electromechanical system). Models are also included for the other elements of the physical workstation (A/D and D/A converters, sensor, etc.) An exploded view of the plant Gp is shown in Fig. 5 where the Quanser System subsystem is the SimMechanics model shown in Fig. 2. The electrical properties of the motor (armature inductance, resistance) and the torque and back-emf constants are also shown.

An additional GUI window was created for the virtual workstation to allow user entry of controller configurations (open-loop or closed-loop), selection of proportional controller gain (slide pot or manual entry), and selection of command signals (external joystick control or internal step commands). The view of the computer screen as seen by the control student is shown in Fig. 6 and consists of four windows. The workstation is started by running a m-file that

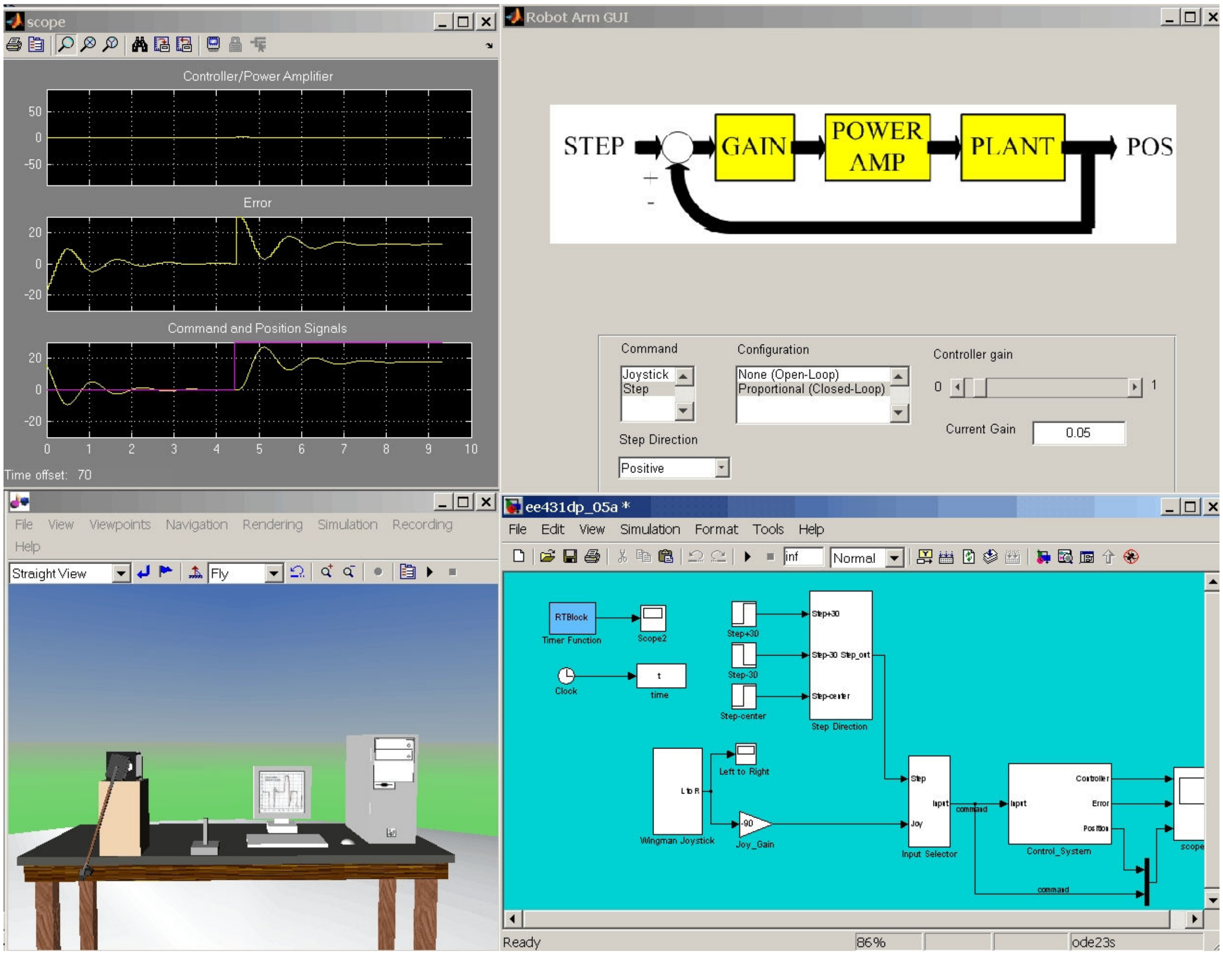


Figure 6. Virtual Workstation Full Screen.

opens the four windows and updates the Simulink model parameters based on user entry into the Robot Arm GUI in the top right-hand corner in Fig. 6. Step inputs (positive, negative, or zero degrees) or an external joystick can be selected for the command signal.

The high-level Simulink model of the system is shown in the bottom right-hand corner in Fig. 6. A scope window is shown in the upper left-hand corner with three subwindows for the controller (power amp) output, the error signal, and the command and actual robot arm positions. The VR window is shown in the bottom left-hand corner. The movement of the arm is surprisedly close to what is observed with the physical system if the controller gain is reasonable (stable system). If a high gain is used to create an unstable system in the physical workstation, the result is a spinning of the arm which creates an unsafe condition if a student’s hand or arm is nearby. The virtual station also shows a spinning arm with high gain but is much more pleasant to observe. Designing the virtual model to run in real-time and obtaining a good match between the physical and virtual workstation responses were critical goals of the project design. A comparison of the performance characteristics is shown in Table I.

Table I. Comparison of Virtual and Physical Workstation Parameters.

System Parameter	Virtual Workstation	Physical Workstation
Open-loop DC gain (deg/volt) from 0 to ± 90 degrees	43 (max), 28 (min)	43 (max), 24 (min)
Proportional gain Kp for instability	0.45 @ 30 deg, 1.0 @ 88 deg	0.52 @ 30 deg, 1.2 @ 88 deg
Limit cycle first evidence of instability	Yes	Yes
Steady-state position errors for Kp=0.01 to 0.9. This varies the arm position from approx. 20 to 90 degrees	70.3 to 2.3 degrees, worse case variation with physical system is 7.0 degrees @ Kp=0.06	71.3 to 2.8 degrees
Backlash at output gear that drives arm	0.5 degrees	1.7 degrees
Initial condition (90 deg) response (no motor current)	Time until ± 2 deg from equilibrium= 4.40 sec, undershoot= -59.1 deg	Time until ± 2 deg from equilibrium= 4.45 sec, undershoot= -62.0 deg
Initial condition (90 deg) response (brake mode, motor current non-zero)	Time until ± 2 deg from equilibrium= 0.86 sec, no undershoot	Time until ± 2 deg from equilibrium= 0.98 sec, no undershoot
Closed-loop step responses: Kp =0.03 for 0% overshoot Kp= 0.067 for 25% overshoot Kp = 0.1 for 40% overshoot Note: O.S.=overshoot, tp=time to first peak, Ts=settling time	O.S.=0% , tp=0.59 sec, Ts=0.59 sec, Final position=14.81 deg O.S. =30.8%, tp=0.46 sec, Ts=0.78 sec, Final position=19.0 deg O.S.=35.4%, tp=0.38 sec, Ts=0.99 sec, Final position=22.65 deg	O.S.=0.5% , tp=0.60sec, Ts=0.51 sec, Final position=13.86 deg O.S. =24.9%, tp=0.45 sec, Ts=0.76 sec, Final position=19.59 deg O.S.=40.0%, tp=0.38 sec, Ts=0.91 sec, Final position=21.85 deg
Motor current required to overcome static friction (stiction)	59ma, drops to 38ma when velocity is non-zero	58ma (typical), drops to 40ma when velocity is non-zero
Motor current versus motor applied voltage without arm (1 to 6V)	72 to 319ma	75 to 200ma
Output gear velocity versus applied voltage without arm (1 to 6V)	14.4 to 91.9 RPM	11.7 to 93.2 RPM
Simulation and real-time parameters: VR display has 7 viewpoints. All external gear and arm rotations can be observed. Simulation time is 1.7 times slower than physical system. Examples: A simulation time of 60 seconds corresponds to 35.3 seconds real-time. The effective VR display refresh time is 17ms.	Joystick, VR display, and robot arm angle sampled at 10ms rate. Sim-Mechanics model sampled at 5ms rate. Toshiba Satellite Pro 6100 Labtop Computer, Pentium IV 1.8GHz, 512MB RAM	Control cycle time = 10ms 200 MHz Pentium-based computer, Quanser Consulting Data Acquisition Board (MultiQ-3 ™)

IV. Workstation Use in Control Theory Course The virtual workstation was used in the end of semester design project in Fall 2005 for the EE431 course. The format of the design project is similar each year in regard to controller type (proportional), control specification (phase margin), and comparison of simulation and theoretical results. A linear model is provided for the plant which is changed each year. The plant's transfer function has been based on experimental system identification of the Quanser robot arm system in either the inverted or non-inverted arm configuration. Several lectures in the course cover the detailed modeling of the robot arm system.

The physical system is 6^{th} order, in addition to the nonlinear characteristics due to the force of gravity, stiction and Coulomb friction, and gear backlash. A second-order transfer function with time delay provides a reasonable match with experimental results. The 2005 three-page handout provided to the students can be obtained from the EE431 web site [8]. Two weeks are allowed for the design.

The first part of the design project requires a root locus design to calculate the proportional gain for a phase margin (PM) specification. The time delay term is ignored. All work is shown on paper although the Control System Toolbox can be used to verify the design [15]. The parameters from a closed-loop step response are compared to predicted values using second order design equations. In the second part of the project, the closed-loop step response is evaluated with the controller gain found in Part 1 but with time delay included. The students will observe the degradation of system performance when time delay is included. Part 3 of the project is independent of Parts 1 and 2. A frequency domain method is used to determine the proportional gain for the PM specification. Time delay can be accounted for in the frequency domain and therefore this is the better design method for this system. All design work is on paper but can be verified with the Control System Toolbox. The closed-loop step and frequency responses are evaluated and compared to predicted values.

A new Part 4 was added in 2005 to use the virtual workstation. With the gain obtained in Part 3, the closed-loop step response from the virtual workstation is compared with results obtained in Part 3. It is suggested to the students to use the workstation before starting the project to find the range of the proportional controller gain for a stable response. The intent is to reduce simple mathematical mistakes in the design process.

V. Project Assessment and Concluding Remarks The goals of the revised curriculum were discussed in Section II. Because there is no common ground between senior capstone projects, it is difficult to draw conclusions that are sufficiently broad to drive or assess a curriculum change. Also, the capstone project advising is distributed to all faculty members so student evaluation is not consistent. The seven-week senior laboratory course EE450 has been our best tool for assessment because it has two common projects graded by one instructor [12].

The goal to reduce the learning curve of Simulink in senior capstone project designs was tested by designing a six-week design project for the Fall 2005 EE450 course that required system modeling using Simulink. This microcontroller-based design project is changed each year and typically requires an average of seventy hours for each student. The Simulink work of several students was better (more model sophistication) than what has been demonstrated for the one and half semesters for the senior capstone project. All of the Simulink modeling work received above average scores. All student comments regarding Simulink were positive. In previous years, the modeling component of the six-week design project consisted of PSPICE circuit simulations. Integration of Simulink into the senior laboratory also proved beneficial to the EE431 control theory students. Approximately 20 percent of the 2005 class used Simulink to double-check homework answers even though it was not required. Prior to 2005, less than 5 percent used Simulink to check answers and most years it was not used.

The other curriculum goals shown in Section II will require at least two more academic years to fully evaluate. The first use of the virtual workstation in EE431 showed no significant differences in quality of work of the design project. The original plan was to introduce the workstation in Fall 2006 in conjunction with a redesigned homework set to use the system throughout the course. Several factors of the design project prevent its use as the only assessment tool for the virtual workstation. First, the project is optional. An average of six hours is required for the project although there is a wide range for the class (3 to 20 hours). Intermediate answers from the design project can be checked with the instructor in order to minimize the design time. Students who have not completed the majority of the homework set (26 assignments) have found that the design project is impossible. These students have represented 10-25 percent of the class over the last ten years. Although the design project grade is not a direct part of the course grade, the material is part of the last in-class test as well as the final exam, so there is a strong incentive to complete the work. Several students complained that the virtual system requires the work to be performed in our laboratory which is a disadvantage because of their time constraints at the end of the semester. In past years, the students were able to perform all work at home since they have the student versions of the Control System Toolbox and MATLAB.

Based on the positive comments from students regarding Simulink as a design and analysis tool it will be continued to be used as the first experiment in EE450. Simulink will be recommended to EE431 students as a tool for verifying homework answers. The EE431 homework assignments will be modified for the 2006 class to include the parameters of the Quanser workstation subsystems instead of generic amplifier, motor, and gear train models. All of the design assignments (four) will be redesigned to use the virtual workstation. Several analysis assignments can also be modified for workstation use. In order to expand use of the virtual workstation, the transistor modeling part of the course will be deleted (two lectures and two homework assignments). Deletion of two homework assignments will allow an earlier date for the end of semester design project. Past design project and homework performance from 1993-2005 has been maintained and will be useful in assessing future improvements due to the virtual workstation.

The issue of requiring the students to use the virtual workstation in our laboratory has been addressed. The SimMechanics model can be compiled into stand-alone code that can be used on any computer that has MATLAB and Simulink. For our system, the Real-Time Workshop was used to convert the SimMechanics subsystem model into a S-Function block [18]. The S-Function is a computer language description of the subsystem (m-file, C-language, etc.) The S-Function block for the mechanical system can be used without the SimMechanics package. An additional benefit of the stand-alone code is a significantly decreased simulation time of the overall model.

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