Laboratory Teaching via the World Wide Web

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Abstract

The engineering controls systems laboratory at UTC has been made available for students to use via the World Wide Web. Students can conduct controls lab experiments from remote sites. This paper describes the hardware and software that is used for this facility, describes the way the course is managed and discusses strengths and "opportunities for improvement" that have been observed in this offering.

The web address for the lab is http://chem.engr.utc.edu.

Hardware and Software

The controls laboratory for several years has been using desktop computers for data acquisition and control of engineering equipment. The students conduct experiments to accomplish system identification and to design feedback controllers for the systems. The data acquisition and control software is written with LabVIEW software. Controller design involves tuning two feedback controllers, a proportional controller and a proportional-integral controller.

The computers are all networked with ethernet and have internet (IP) addresses. A web-server program was developed which allows students to conduct experiments using widely available web browsers. The students conduct the experiments either from computer labs on campus or from home computers via internet providers.

Hardware Stations

Seven different stations for controls systems experiments are available. They are listed in Table 1, below.
Each of these stations is a single-input, single output system. All are inherently stable systems when run in open-loop configuration. That is, if you specify a fixed input value, the system will reach a constant steady-state condition.

Staqtions #1 through #4 and #7 in Table 1 all have variable-voltage, variable-frequency (VVVF) power supplies to vary the speed of 3-phase motors that provide the motive force in the experiments. Each of these VVVF power supplies receive a 0-10 volt control signal from an analog output channel on an A/D board in the control station. The position control station (#5) receives its motive power from a DC-motor that is controlled by a pulse-width modulated (PWM) power supply. The PWM receives a 0-10 volt control signal as just described. The level control station (#6) receives its motive power from a variable speed laboratory pump that is controlled by a 4-20 ma current signal from the control station.

The first 5 stations listed in Table 1 are fast-acting systems. They have response times on the order of 1-second; typically, an experiment can be completed within 10 to 30 seconds. These systems are called the "fast" systems. The last 2 listed control stations have response times on the order of 1-minute; typically, an experiment can be completed on these systems within 10 to 30 minutes. These systems are called the "slow" systems. The significance of this will be brought out below.

Table 1. Experimental Stations available

1	Pressure control by varying the speed of the blower
2	Speed control of a motor-generator set by varying the signal to the motor power supply
3	Voltage control of a motor-generator set by varying the signal to the motor power supply
4	Flow control in a closed flow loop by varying the speed of the pump
5	Position control in a cart-on-a-rail by varying the torque in the motor
6	Level control in a water tank by varying the speed of the water pump
7	Temperature control in a heat exchanger by varying the flow rate of the hot water supply

The pressure control station involves the pressure of air in a manifold that is fed by an air blower that is powered by the 3-phase motor. The air pressure is sensed by a piezo-resistive pressure transducer and a 0-10 volt signal is sent to the control station. The manifold feeds three outlet ducts, either of two of which can be closed by control of the computer to provide different loads on the blower.

The speed and the voltage control stations involve a self-excited DC-generator that is driven by the 3-phase, 5-hp motor. In the "speed" mode, the speed is detected by a chopper wheel and photocell on the drive shaft. The frequency of the pulse train signal out of the photocell is converted into a 0-10 volt signal and then sent to the control station. In the "voltage" mode, the voltage out of the generator (0-85 volts) is converted by a voltage divider into a 0-10 volt signal and then sent to the control station. The electrical power output of the generator can be connected to either one or both of 2 banks of resistance load. The loads are sets of eight 300 watt, 120 volt light bulbs.

The flow control station involves the flow of water in a line that is fed by water pump that is powered by the 3-phase motor. The water flow rate is measured by a Micro-Motion coriolis-force mass flow meter. The output signal is in the form of a 4-20 ma current signal which is sent to the control station. The manifold feeds two other lines, either or both of which can be closed by control of the computer to provide different loads on the pump.

The level control station involves the level of water in one of two tanks that are supplied by the variable-speed laboratory pump. The choice of which tank to use is made by a 3-way valve under computer control. The two tanks have different cross-sectional areas, so their time constants are different. The pressure is sensed by a piezo-resistive pressure transducer that measures the hydrostatic pressure at the bottom of the tank. The output signal is in the form of a 0-10 volt signal which is sent to the control station.

The temperature control station involves the temperature of water in a reservoir that contains two heat-transfer coils. One coil has hot water flowing at a variable rate, under computer control. The hot water is heated locally with a domestic water heater; the hot water flows in a closed recycle loop. The other coil has (utility) cooling water flowing at a one of three rates, under computer control; the cold water is once-through, and then sent to the drain. The different cooling water flow rates provide different loads for the heating system. The temperature in the reservoir is measured with a
100-ohm, platinum RTD that is connected to an RTD-voltage signal conditioner module. The output signal is in the form of a 0-10 volt signal which is sent to the control station. The temperatures of the inlets and outlets of the hot and cold water are also measured. The flow rates of the hot and cold water are measured by paddle wheel flow-meters; their output signal is in the form of 4-20 ma current signals which are sent to the control station.

Pictures of all the equipment is available on the Web site.More complete descriptions of these have been given before (Henry [1] and Henry [2]).

Software

The systems are operated by client programs using the LabVIEW software on desktop computers at each control station. The software operates the equipment under the conditions of parameters as chosen by the (Web-User) operators.

Table 2. Experiments available. System identification (1-5) and controller design (6 & 7)

	Name	Application
1	Constant input	Developing the steady-state operating curve for the system
2	Step input	Finding the first-order plus dead-time (FOPDT) parameters
3	Sine input	Developing the Bode plot
4	Pulse input	Refining the FOPDT parameters
5	Custom input	Design your own input function. Ramp, sawtooth, triangle, for examples.
6	Proportional feedback	Verifying controller design. Determining region of stability, quarter decay, offset, etc.
7	Proportional-integral feedback	Verifying controller design. Determining region of stability, quarter decay, offset, etc.

Web Environment

All stations are available for experimentation via the World Wide Web. Experiments run via the Web can be run in the "batch" mode or live interactively with a newly developed Java applet interface. The connection paths for running a batch-mode experiment are diagrammed in Figure 1, below.

In the lab at UTC, a computer is acting as a Web server and a "lab" server. Using the Microsoft Internet Server, it communicates with the Web user as a standard Web server by receiving requests for pages and returning them to the Web user.

When a request for an experiment is sent by a Web user, it goes to a different, custom-written (LabVIEW) server. This server is at port 8080 on that same machine, rather than the standard Web port of 80. The Lab-Server receives the information necessary to complete an experiment and parses that information. This server then returns a first response page to the Web user. This first response page tells the Web user that the experiment has been started or has been queued, if the equipment is busy.

Then the Lab-Server builds and saves to the file server several HTML pages that will contain the output from the experiment when the experiment is completed. It also writes on the file server a file that contains the information necessary for the lab station computer (Lab-Client) to run an experiment. This file is given the name of the targeted Lab-Client.

The Lab-Client machine, when seeing an appropriatly named file show up on the file server, reads the file and conducts the experiment that is defined therein. It also deletes the file, indicating to the Lab-Server that another experiment can be sent its way. The Lab-Clients take action that differs depending on whether they are "fast" or "slow" systems.

"Fast" Stations

The "fast" station are most amenable for running experiments in the batch mode. With the slower speeds some people experience on the Internet, a 10-second experiment can be completed while the first response page is being transmitted. The Lab-Client collects the data for an experiment and writes the complete data file when the experiment has completed. This is the fastest way for these experiments to be conducted.

The Lab-Server waits for the data file to be written (the Lab-Server told the Lab-Client what the name of the data file was to be and where it was to be stored). When the Lab-Server sees the results file, it reads the file, constructs the appropriate results graphs and saves the graph images as jpeg files on the file server. The Web user's browser will automatically call for the results pages to be downloaded at the appropriate time (this is called client pull).

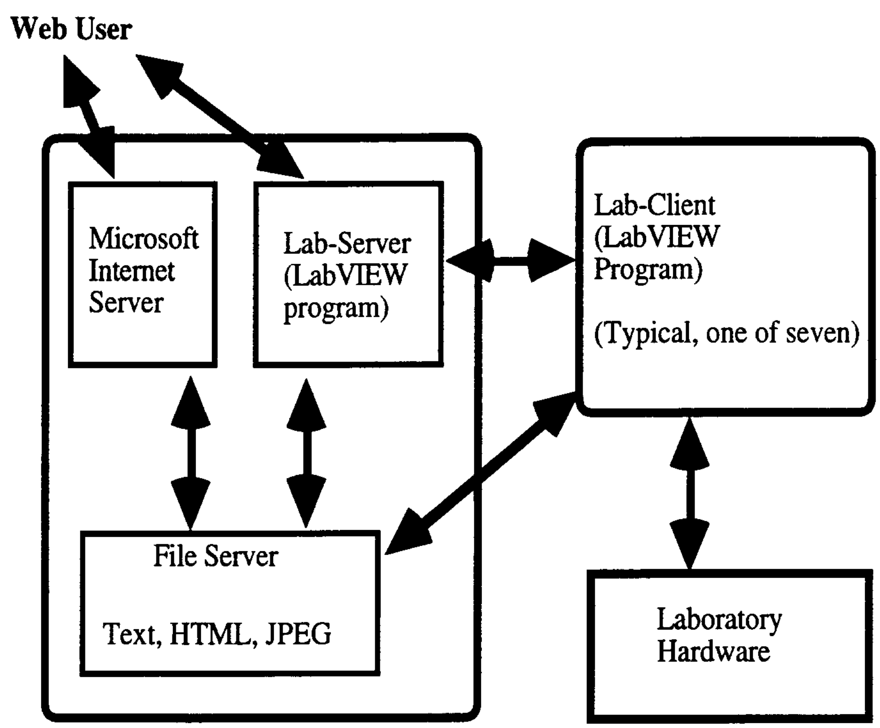

Figure 1. Connection diagram of laboratory units

"Slow" Stations

The "slow" station are not so amenable for running experiments in the batch mode. Some of these experiments can last for tens of minutes, if not longer. For these systems, the Lab-Client collects the data for an experiment and writes the data to a data file while the experiment is being conducted.

The Lab-Server again waits for the data file to begin to be written (the Lab-Server again told the Lab-Client what the name of the data file was to be and where it was to be stored). When the Lab-Server sees the results file, it reads the file, constructs the appropriate results graphs and saves the graph images as jpeg files on the file server. The Lab-Server continues to periodically read the data file, construct the graphs and post the jpeg files while the experiment continues and until it completes. The Web user's browser will automatically call for the results pages to be downloaded at the appropriate time. To the Web user, it appears that the graphs are being updated in real time. There is, of course, the normal Web-delay, so it is not actually "real" time.

Java Applet Development (Real Time Experiments)

For the "slow" systems, a Java interface has been developed that allows very close to "real" time operation of the equipment via the Web. With this application, there is as little as 1 second's delay between an operating command being issued at a Web user's computer and the execution of the command by the Lab-Client. This Java applet allows the user to send control commands to the laboratory and observe (in real time) the response of the system.

In the event of more than one user trying this, the Lab-Client obeys the commands of the first-to-come user and allows subsequent users only to observe. When the controlling user quits, another user becomes the "controlling" user.

Experiments

Seven different experiments can be run on each of the laboratory stations. The software runs an experiment, collects the data and writes the data on a computer hard disk at the end of the experiment. The Lab-Server computer draws a time-response graph of the data and posts the graph on the Web. The file of results data and the graph are available to the Web user. The various experiments consist of the seven listed in Table 2, below.

System Dynamics or System Identification

The "constant input" experiment is the simplest. The control station (Lab-Client) supplies a constant value input signal to the hardware equipment and collects the data for the time specified by the user. In the case of pressure, flow, voltage, speed and level stations, where the Web user may specify different load-parameters, the computer sends signals to take the load-changing action.

Figure 2 shows the results of an experiment on the pressurecontrol system for a constant input signal of 50%, one of the exhaust ducts closed and an experiment lasting 10 seconds. The pressure (on the y-axis) is plotted versus time (on the x-axis). The first few seconds are when the blower is starting up from an "off" condition. Notice the signal at "steady-state" (from about 3 to 10 seconds) has noise, also. We ask our students to quantify that.

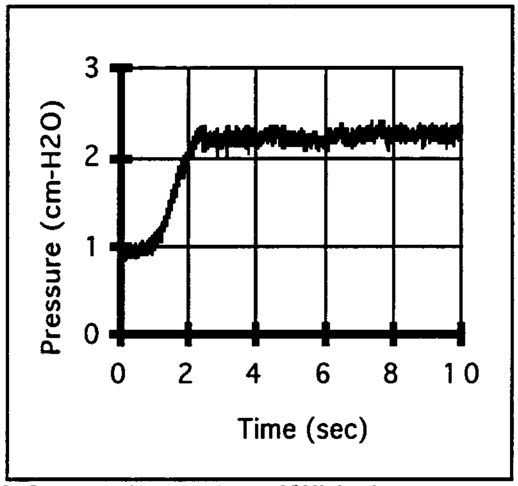

Figure 2. Response of constant input of 50% for the pressure system

From a series of these experiments, the user can construct a steady-state operating curve for the system. We ask our students to do that. By the way, there are 1,951 data points in the graph of Figure 2. This indicates a sampling frequency of the data acquisition system of about 195 Hz.

The "step input" experiment provides a step change in the input signal. The control station (Lab-Client) initially supplies a constant value input signal to the hardware equipment and then instantaneously changes the input by an amount and at the time specified by the user. As mentioned above, different load-parameters are handled by the computer. Figure 3 shows a portion

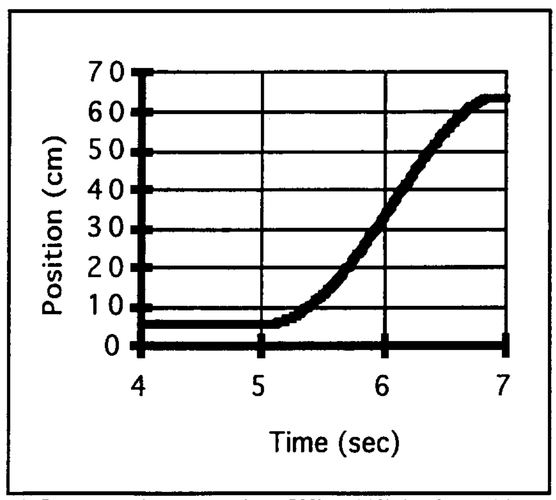

Figure 3 Response of step input from 50% to 90% for the position system

of the results of an experiment on the position control system for an initial input signal of 50%, a step increase of 40% at 5 seconds and an experiment lasting 10 seconds. The position (on the y-axis) is plotted versus time (on the x-axis). From this type of experiment, students are asked to find the empirical first-order-plus-dead-time parameters for the system. By the way, there are 215 data points in the graph of Figure 3. This indicates a sampling frequency of the data acquisition system of about 72 Hz. The computer at this position station is slower than the one on the pressure station.

The "sine input" experiment provides a sinusoidal variation in the input signal. As mentioned above, different load-parameters are handled by the computer. Figure 4 shows the results of an experiment on the flow control system for a sinusoid input function with amplitude of 30%, centered about 60%, a frequency of 0.2 Hz and an experiment lasting 10 seconds. The flow rate (on the y-axis) is plotted versus time (on the x-axis). From this type of experiment, students are asked to find the empirical amplitude ratio and phase shift for this frequency. By the way, there are 632 data points in the graph of Figure 4. This indicates a sampling frequency of the data acquisition system of about 63 Hz. This relative slowness is due to the fact that the computer at this flow station is doing some averaging of the flow readings.

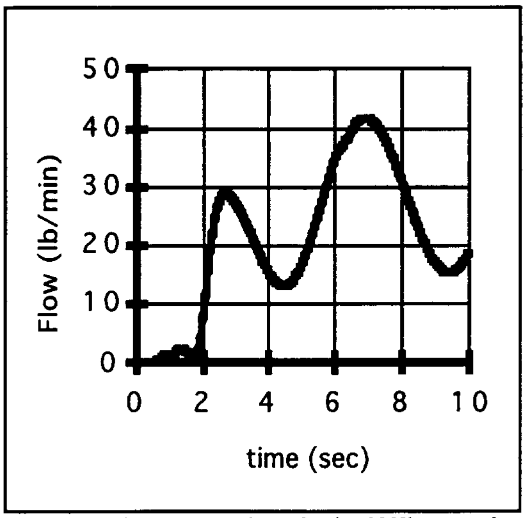

Figure 4 Response of sine input with amplitude of 30% centered at 60% for the flow system

These results can also be plotted as the output versus the input and produce a Lissajous plot. This is shown in Figure 5. The start-up transients are responsible for the spurious part of the curve in the lower right corner. By conducting experiments at a number of different frequencies, the students can construct a Bode plot. We have our students do that. From the Bode plot they determine the empirical system order, the ultimate frequency and the ultimate controller gain.

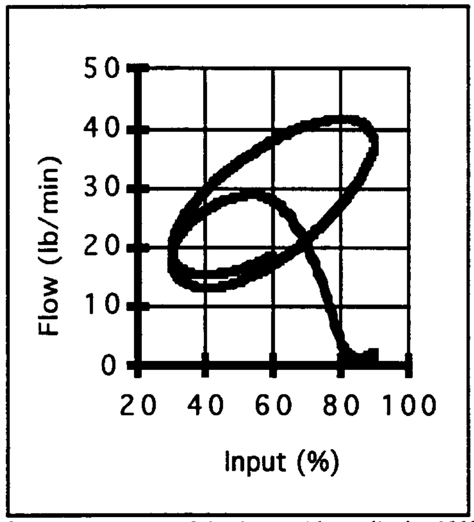

Figure 5. Lissajous response of sine input with amplitude of 30% centered at 60% for the flow system

The "pulse input" experiment provides a step change in the input signal and then a return to the initial value of the input signal. The control station (Lab-Client) initially supplies a constant value input signal to the hardware equipment and then instantaneously changes the input by an amount and at the time specified by the user. As mentioned above, different load-parameters are handled by the computer. Figure 6 shows the results of an experiment on the voltage control system for an initial input signal of 40%, a step increase of 40% at 4 seconds followed by a step down (of -40%) at 7 seconds and an experiment lasting 10 seconds. The voltage (on the y-axis) is plotted versus time (on the x-axis). Notice that the self-excited DC-generator exhibits considerable hysteresis in this experiment.

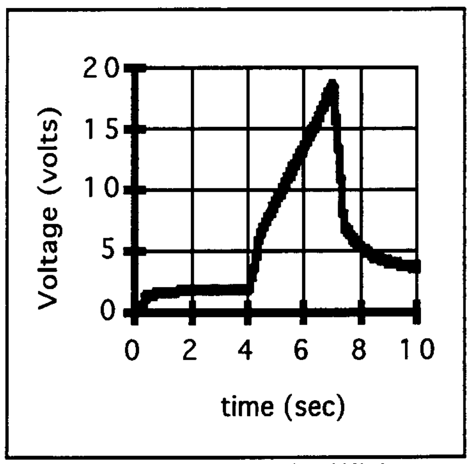

Figure 6. Response of pulse input from 40% to 80% & return to 40% for the voltage system

From this type of experiment, students can again find the empirical first-order-plus-dead-time parameters for the system. Additionally, with Fourier transform methods, the entire Bode plot can be constructed from this one experiment. By the way, this system has a sampling frequency of the data acquisition system of about 195 Hz.

The "custom input" experiment provides a chance for the Web user to design any input waveform for an experiment. The waveform is entered as a table of time-input data pairs. The control station interpolates linearly between data points. The control station (Lab-Client) supplies an input signal to the hardware equipment that follows the time-input data table specified by the user. As mentioned above, different load-parameters are handled by the computer. Figure 7 shows the results of an experiment on the speed control system for an initial input signal that goes from 0% to 50% (linearly) over 4 seconds, stays at 50% for 3 seconds, then increases (linearly) to 100% over the next 3 seconds. If the experiment is longer than the waveform specification, the waveform is repeated with the period specified by the waveform data specification. This experiment lasted 20 seconds. The speed (on the y-axis) is plotted versus time (on the x-axis).

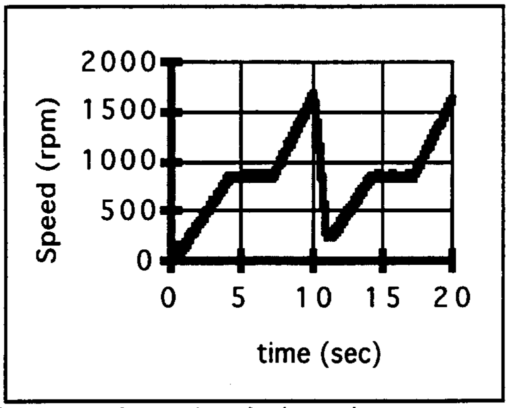

Figure 7. Response of custom input for the speed system

The most useful experiments that can be done with the custom specifications are ramp or a sawtooth waves. Notice in Figure 7, the speed system is able to pretty well keep up with the input signal changes except at the step change that occurs at a time of 10 seconds. By the way, this system has a sampling frequency of the data acquisition system of about 195 Hz.

Controller Design

The "proportional feedback input" experiment provides a chance for the Web user to design a proportional feedback controller. The control station (Lab-Client) supplies an input signal to the hardware equipment that is equal to the "error" (the difference between the set-point and the output signal) multiplied by the controller gain. A "bias" as specified by the user is added to the input signal. As mentioned above, different load-parameters are handled by the computer. Figure 8 shows a portion of the results of an experiment on the pressure control system for a set point of 3 cm-H2O that changes to 4 cm-H2O at 5 seconds. The controller gain is 5 %/cm-H2O. The pressure (on the y-axis) is plotted versus time (on the x-axis).

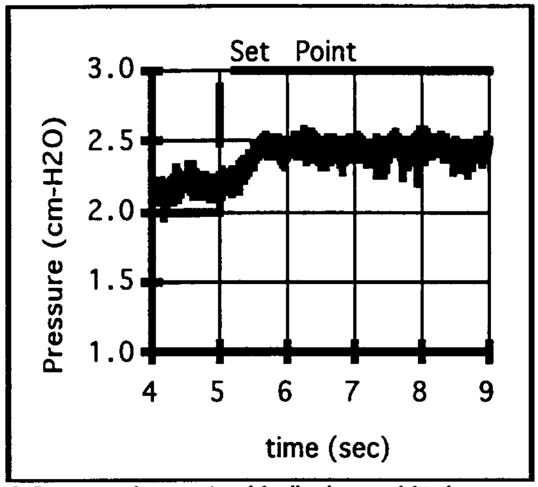

Figure 8 Response of proportional feedback control for the pressure system

Notice the offset of about 0.5 cm-H2O in this experiment. This offset is one of the characteristics of a proportional control system.

The "proportional-integral feedback input" experiment provides a chance for the Web user to design a proportional-integral feedback controller. The control station (Lab-Client) supplies an input signal to the hardware equipment that is equal to the "error" plus the integral of the error (divided by the integral time constant) multiplied by the controller gain. As mentioned above, different load-parameters are handled by the computer. Figure 9 shows a portion of the results of an experiment on the pressure control system for a set point of 3 cm-H2O that changes to 4 cm-H2O at 5 seconds. The controller gain is 5 %/cm-H2O and the integral time constant is 0.2 seconds. The pressure (on the y-axis) is plotted versus time (on the x-axis).

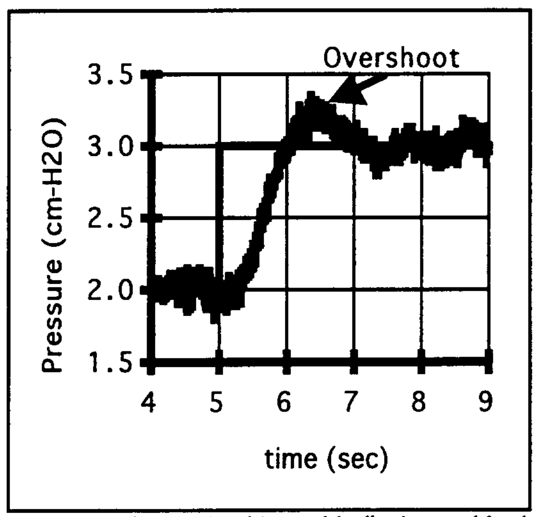

Figure 9 Response of proportional-integral feedback control for the pressure system

Notice the overshoot followed by the virtual elimination of offset in this experiment.

Modeling

The lab course invloves modeling of the system. We have the students construct first-order-plus-dead-time models of the physical systems. The modeling is done with Excel. They model the step response, the sine response, the Bode plot, the root locus plots and the responses to step changes in set points for feedback controllers.

These Excel models are avaiable on the Web site. The students use their experimentally determined parameters to apply the models.

Course Management

Beginning in the Spring, 1996, semester, we have offered a "Web"-based class. The equipment was available via the Web for 24 hours a day, 7 days a week. This class is managed by-in-large without "face-to-face" meetings. Laboratory information and assignments are provided on the Web server. The experiments, the analysis of the data, the controller design and the reporting were done at times chosen by the students. Discussion among students is available via a listserv. Students' reports are submitted via e-mail. This year (1997-1998) 6 students have chosen this method of completing the laboratory; the regular hands-on students number about 30.

Faculty Workload Equivalent

The amount of work that went into putting this (existing) laboratory on the web was about half the amount of work of developing the lab originally from scratch. The previously prepared lab manual had to be significantly revised for applicability to the Web user. The Web site took significant preparation time, largely due to the newness of the medium for the developer.

Strengths and Challenges

Sharing resources is one strong point of this ability to teach system dynamics and controls laboratory via the internet. The investment in equipment at UTC can be shared by other engineering schools. Previously, we have actively used the equipment for about 6 hours a week for about 20 weeks per year. This is a very small utilization fraction (about 0.014) of the available hours in a year. Providing learning opportunities for students with scheduling conflicts is another strong point of this ability to teach engineering laboratory via the Web.

When first installed, the main weaknesses were equipment or communication bugs. Nearly all of these have been worked out. With NSF support, all stations in the controls lab have been upgraded. They now have Windows NT 4.0 operating system with Pentium Pro Intel processors. All computers are on uninterruptible power supplies, so even across brief power outages, the lab remains up and available.

The main challenges being experienced now are the common challenges of distance education. These challenges include student motivation and record keeping.

Future

UTC is committed to continuing to develop and expand this Web-available laboratory. Extending the experiments to include unit operations labs is under development.

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