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A New Control Instrumentation Laboratory in Engineering Technology

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Experiments developed for a new laboratory for control instrumentation technology are presented. The experiments are designed to cover basic principles, specific measuring devices, implementations of measurement systems, and computer control and data acquisition systems. Several of the experiments are based on practical problems encountered in industry. Emphasis is given to the teaching of basic principles through applications, with the same software and hardware tools as those currently used in industry.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in control instrumentation.
2. The paper describes new equipment useful in courses on process control, transducers and sensors, control systems, control instrumentation.
3. Undergraduate/junior–senior students are involved in the use of the equipment.
4. Introducing concepts of auto-tuning for process regulators is a new approach.
5. The material presented is incorporated in engineering teaching through the description of experiments and equipment, and grading procedures.
6. Johnson, *Process Control Instrumentation Technology* (Wiley, 1993) and Bateson, *Control Systems Technology* (Merrill, 1993) accompany the presented materials.
7. The concepts have been tested in the classroom. The paper describes the conclusions drawn from the experience.
8. Auto-tuners for process control will become very useful in future applications.

INTRODUCTION

THIS PAPER presents the development of a new laboratory for control instrumentation in the Engineering Technology Department, at the California State University, Long Beach. The philosophy for the development of the new laboratory emphasizes applications, since the engineering technology curriculum is heavily oriented towards applications, and is along the following general guidelines, as set forth by the American Society for Engineering Education [1]:

- The students should do experimental work expected of engineering professionals in the discipline.
- laboratory should be a place for the student to learn new and developing subject matter.
- The laboratory courses help a student to gain an understanding of the real world and work as part of a team.
- The laboratory should help a student to develop his/her ability to communicate effectively.

These general principles are applied to a rigorously structured sequence of experiments, which are performed for the semester-long course 'Process Control Instrumentation Technology'. The course meets for 5 hr per week (2 hr lecture, 3 hr laboratory), for 14 weeks. This is the first course in either control instrumentation or in control systems that our students take. Therefore there is a need to cover simultaneously fundamental concepts of measurement systems and fundamental concepts of control systems, through a carefully designed series of laboratory experiments. The experiments are designed with the following objectives in mind:

- Each experiment should be built upon the experience obtained from the previous ones, in a modular fashion.
- The experiments should be general enough to cover fundamental principles, and they should form an integrated program.
- They should reflect current needs of industry and should be based on problems encountered in practice.
- Emphasis should be given on the implementation of systems, rather than design, since the courses are part of an engineering technology curriculum.

The experiments are divided into three major categories, with increasing degree of complexity from category I to category III:

I. General experiments: introducing general tools and methods that will be used through the rest of the course.

II. Transducers and transducing techniques: introducing basic measurement principles and applying the techniques from part I to implement measuring devices.

III. Process measurement and control, data acquisition and computer control: introducing process measurement, process control and computer control concepts through the use of two thermal processes.

DESCRIPTION OF THE COURSE AND LABORATORY EXPERIMENTS

The lecture part of the course covers the following topics in 14 weeks of instruction:

- Introduction to process control
- Analog signal conditioning
- Digital signal conditioning
- Data acquisition
- Temperature sensors
- Mechanical sensors
- Optical sensors
- Actuators and final control elements
- Discontinuous control modes (on/off control)
- Principles of continuous control modes
- Analog controllers
- Digital controllers
- Tuning of proportional plus integral plus derivative (PID) controllers

The laboratory experiments follow the lecture material closely and are designed in such a way as to bridge the gap between theory and industrial practice.

General experiments

The general experiments introduce measurement and instrumentation techniques that are of a general nature and will be used repeatedly throughout the course. Three basic sets of experiments are performed here: Wheatstone bridge experiments, operational amplifier (op-amp) configurations and analog signal conditioning.

Wheatstone bridge measurements. Among the most fundamental measuring techniques are those based on resistance measurements. Changes of the transducer resistance are used to measure such physical variables as temperature, strain, displacement, etc. The transducer whose resistance reflects the physical variable to be measured is set up as one leg of a Wheatstone bridge configuration (Fig. 1). Students are exposed to bridge measurements by either balancing the bridge through a high-resolution decade resistance box or by calculating the unknown resistance R_x from voltage measurements. Resistance R_x is calculated by measuring the voltage ΔV across the bridge, given the values of R_1, R_2, R_3 and voltage V_0 (Fig. 1):

$$\Delta V = \frac{R_2 R_3 - R_1 R_x}{(R_1 + R_3)(R_2 + R_x)} V_0$$

Emphasis is given to the fact that although the experimental results indicate a linear relationship between R_x and ΔV,in the above formula, ΔV is non-linearly related to R_x. The students are asked to provide an explanation of this apparent disagreement between experiment and theory, and this introduces the concept of measurement linearization: the relationship between R_x and ΔV is very close to linear if the true value of R_x is close to its nominal value (the value that balances the bridge). Hence, for values of R_x within its nominal range, a simple linear circuit can be built to give the value of R_x from the measured value of ΔV. However, if R_x exceeds this nominal range, then the linear relationship no longer holds, and the true value of R_x must be calculated from the above nonlinear formula given the measurement ΔV. It is therefore desired that measurements remain in the linear range.

Operational amplifier (op-amp) configurations. This is another fundamental group of experiments, since op-amps are being extensively used throughout the course. The students use the standard 741 op-amp, and they are responsible for designing, implementing and testing simple inverting and non-inverting op-amp circuits, as well as summing, averaging and differential configurations. Special emphasis is placed on the implementation of an instrumentation amplifier. Moreover, the students design and implement a hysteretic configuration with a given hysteresis width, since this will be used later on for on/off control of a thermal process.

Signal conditioning. The students are required to design and implement two signal conditioning modules which will be used later on for data acquisition and process control, as shown in Fig. 2, where the signal conditioner is located between the data acquisition board and the process signals. The data acquisition board is the industry standard

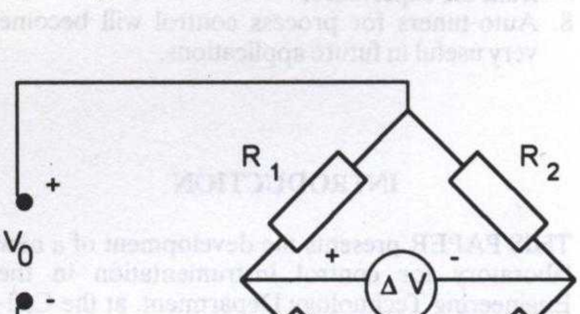

Fig. 1. Wheatstone bridge configuration.

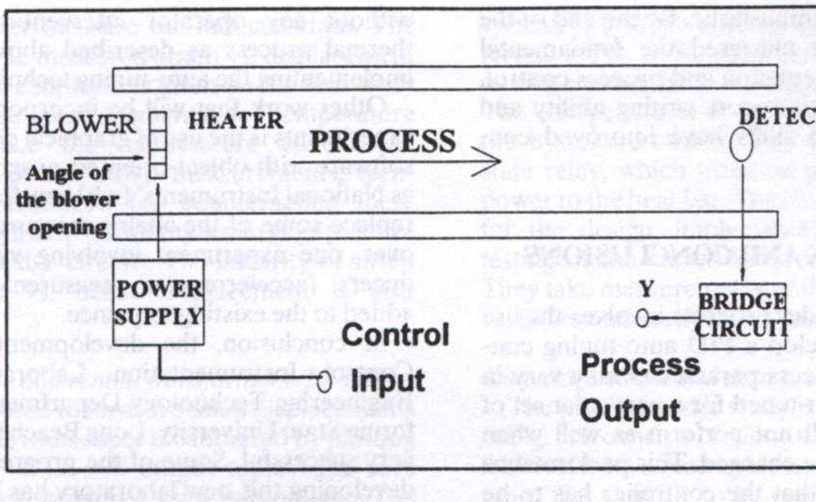

Fig. 2. Thermal control process.

OPTO-22 B6 brain board, with an A/D (analog-to-digital) converter whose voltage inputs are in the [0 V, +5 V] range. The process output is a voltage in the [−5 V, +5 V] range and has to be conditioned to the range of the A/D converter. In a similar fashion, the D/A (digital-to-analog) converter output, which is the [0 V, +5 V] range, has to be conditioned to the [0 V, +10 V] range, which is the range of the system control input. The students use the signal conditioning principles taught in the course to design the modules, and they draw upon their experience from the previous experiments to implement the signal conditioners using op-amps.

Transducers and transducing techniques

The experiments on transducers introduce measuring principles and specific measuring devices. The following types of transducers are investigated:

- Thermal transducers (thermistors and thermocouples)
- Strain gages
- Linear variable differential transformers
- Light sensors

Each transducer measures the variables of interest generated by an underlying physical process, such as a heat bar for thermal measurements or a small flexible beam for strain measurements. Detailed descriptions of each individual experiment are presented in Appendix A.

Process measurement and control, data acquisition and computer control

The experiments in this section integrate the knowledge the students have obtained from all the previous experiments and the course lectures. Two thermal processes are used to introduce the concepts of on/off control, data acquisition and continuous computer control: a slow thermal process is used for experiments on discontinuous control modes (on/off control), whereas a fast thermal process is used for experiments on data acquisition and computer control (implementation of continuous control modes). Moreover, the fast thermal process is used to introduce the concept of regulator tuning for process control. Detailed descriptions of these experiments along with graphs and block diagrams are presented in Appendix B.

STUDENT RESPONSE AND GRADING PROCEDURES

The class is divided into small groups of three or four students each. Each group works independently, for approximately 3 hr per laboratory session. For the general experiments of category I all groups work on the same experiment in parallel. For categories II and III, however, every group works on a different experiment during a given laboratory session. During the next laboratory session, each group will give a very brief report on the difficulties they encountered in their experiment, for the benefit of the groups that have not performed this experiment yet.

One person from each group is responsible for turning in a technical report, on behalf of the group, within one week after the experiment is completed. The students are required to turn in reports of high professional quality, and use technical communication skills effectively, as if they were reporting to their peers and supervisors in an industrial setting. The report writer is assigned on a rotating basis, so that everybody in a group will have a chance to work on two or three technical reports by the end of the semester. To provide additional motivation to a report writer, he or she gets a 'bonus grade' of 10% extra for writing the report. If, in addition, the report writer turns in a perfect report, then the whole group gets a 20% extra grade. Penalties are applied for late reports, as well as for sloppy or poorly performed and poorly documented experiments.

The response of the students to this arrangement has been extremely enthusiastic. By the end of the semester, they have mastered the fundamental principles of instrumentation and process control, and, in addition, their report writing ability and their communication skills have improved considerably.

FUTURE WORK AND CONCLUSIONS

Work currently under progress involves the use of GENESIS to develop a PID auto-tuning controller. Since the process parameters may vary in time, a PID controller tuned for a particular set of parameter values will not perform as well when these parameters have changed. This performance degradation implies that the controller has to be retuned from time to time. Given that an industrial plant may contain hundreds of such controllers which need periodic retuning, it is desirable that the tuning process be automated. Moreover, it is also desirable that the amplitude of the resulting oscillations during tuning be kept under control. Both of the above objectives are met by employing a PID auto-tuner such as the one described in Åström and Hägglund [5]. The auto tuner collects information about the process as soon as the command to start auto-tuning is given. Then, based on the information collected, it calculates the critical period and gain and adjusts its proportional, integral and derivative gains automatically, without any operator intervention. The same thermal process as described above is used for implementing the auto-tuning technique.

Other work that will be incorporated in future experiments is the use of graphical data acquisition software with object-oriented programming, such as National Instruments' LabView for Windows, to replace some of the analog measurements. Moreover, one experiment involving vibration transducers (accelerometer measurements) will be added to the existing sequence.

In conclusion, the development of the new Control Instrumentation Laboratory, in the Engineering Technology Department, at the California State University, Long Beach has so far been very successful. Some of the progress achieved in developing this new laboratory has been reported in Chassiakos and Wang [6] and in Chassiakos et al. [7]. The laboratory experiments are designed to cover basic principles, specific measuring devices, measurement systems implementations and computer control and data acquisition systems. Some of the experiments are based on application needs taken directly from local industry. and it is believed that students will benefit enormously if they are taught basic principles through practical applications, with the same software and hardware tools as those currently used in industry.

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APPENDIX A: DESCRIPTION OF EXPERIMENTS ON TRANSDUCERS AND TRANSDUCING TECHNIQUES

This appendix presents a detailed description of the experiments introduced in the section on transducers. There are four main categories of experiments, covering thermal transducers, strain gages, linear variable differential transformers and light sensors.

Thermal transducers

A heat bar is used as the underlying process. One end of the bar contains a heating element which is being heated, while heat propagates toward the other end along the length of the bar. Measurements along the length of the bar are taken by a mercury thermometer, a thermistor and a thermocouple. The thermocouple tables are explained and utilized for converting the voltage measurements to temperature. The linearity of thermocouples versus the non-linear properties of thermistors is emphasized.

Strain gages

A small flexible cantilever beam is used as the underlying physical medium. The cantilever undergoes bending by displacing its free end. The free end displacement is measured by a micrometer, whereas a pair of strain gages located on each side of the cantilever measure the inducedstrain. The students plot the measured strain vs. displacement of the free end. Emphasis is given on the sensitivity of strain gage measurements to temperature variations. Since the temperature effects can severely corrupt the strain measurements, techniques are introduced for counteracting these effects (use of an active/dummy strain gage pair in a Wheatstone bridge circuit). The linearity of strain measurements vs. beam displacement is also pointed out.

Linear variable differential transformers (LVDT)

A LVDT is used to measure small displacements of the core. The transducer is calibrated by plotting the amplitude of its AC output against the core displacement as measured by a micrometer. The linearity of the measurements is emphasized. Moreover, the students build a phase-sensitive demodulating circuit (differential rectifier), which converts the AC output of the transducer to positive or negative DC voltage. The reason for preferring the DC voltage output is that it is not only easier to measure, but it can be used as a direct input to a signal processing unit or to a control system. Again the linearity of the DC measurements with respect to core displacement is pointed out.

Light sensors

Measurements involving a photovoltaic cell and a phototransistor are made. An ordinary tungsten filament lamp is used as the light source, and measurements are performed to verify the inverse square law of illumination vs. distance from the source. Moreover, color filters are used and measurements are performed to examine how the response of photoelectric transducers varies with the wavelength of incident light.

APPENDIX B: DESCRIPTION OF EXPERIMENTS ON PROCESS CONTROL, DATA ACQUISITION AND COMPUTER CONTROL

This appendix presents a detailed description of the experiments introduced in the section on process control, data acquisition and computer control. Moreover, a method for automatically tuning PID regulators for process control is described and implemented. The experiments presented cover principles of on/off control, data acquisition and data processing, and process computer control.

On/off control

The same heat bar as was used for temperature measurements in the section on transducers is utilized to introduce on/off control principles. The temperature of the bar at a specified point must be controlled. The students have to design and implement a thermistor-based measurement system, as well as an on/off switch with a given hysteresis width. A Wheatstone bridge is set up, containing the thermistor as the unknown resistance. The voltage output of the bridge is used as input to the hysteretic switch. This switch drives a solid state relay, which turns on and off the main AC power to the heat bar. The students are responsible for the design, implementation, calibration and testing of the closed loop on/off control system. They take measurements of the closed loop system variables and verify its correct operation.

Data acquisition and data processing

The process under study is shown schematically in Fig. 3. It consists of a long tube, through which air is blown from a blower located at the left end of the tube. The variable to be regulated is air temperature, which is measured by a thermistor located at the right end of the tube. Heat is supplied to the air by a heater located next to the blower. The control input is a voltage which, when applied, will change the temperature of the heating element, and that in turn affects air temperature. Students have to implement the block diagram of Fig. 2 for open-loop data acquisition. Moreover the same block diagram will be used later on for continuous closed-loop computer control of the process. Students use an i486-based personal computer, an OPTO-22 B6 data acquisition board, and the industry standard process control software GENESIS [2], to interface with the hardware. The required signal conditioning module has already been built during one of the general experiments (see above). Students are responsible for connecting it to the process and the data acquisition board, and for verifying its correct operation. Moreover, they are responsible for using GENESIS to obtain open loop step responses of the system, for different set points and different settings of the process parameters. The response curves are displayed on-line and they are also saved for later processing. The open loop data are later processed by a graphics package or a spreadsheet (e.g. Lotus 1–2–3), and are incorporated into the laboratory report. From the open loop step response data, estimates of the system's time constant and transportation lag are obtained.

Process computer control

This experiment involves the same thermal process as the one used for data acquisition and processing. Students have already implemented the block diagram of Fig. 2. Now they use GENESIS to implement a closed-loop control scheme. GENESIS has a graphical, object-oriented user interface, which allows software implementation of proportional (P), proportional plus integral (PI) or proportional plus integral plus derivative (PID) controllers. The students are asked to implement a PID controller, by using the PID control block from GENESIS. They observe the effects of changing the controller gains, and the effects of using proportional only vs. proportional plus

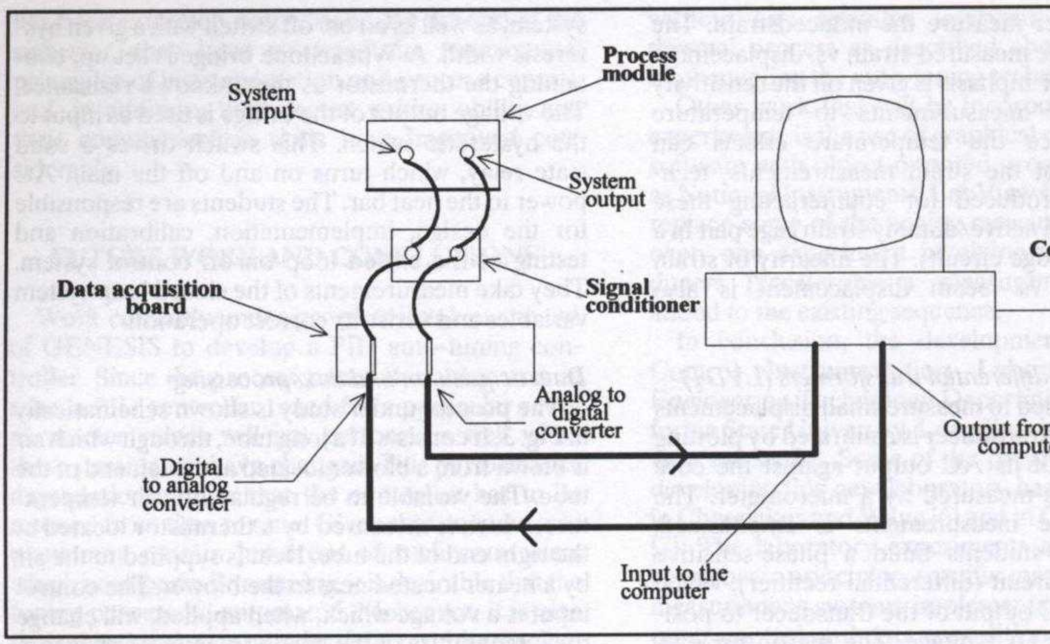

Fig. 3. Block diagram of the temperature control system.

integral versus PID control. The fact that a steady-state error will occur if the controller does not have integral action is pointed out. Moreover, they are asked to come up with a set of PID gains that will provide acceptable system response to a step input, and at this point, after they realize that this is not a trivial matter, the concept of tuning the PID regulator is introduced. The transfer function of a PID controller $G_c(s)$ is typically given as:

$$G_c(s) = K\left(1 + \frac{1}{T_i s} = T_d s\right)$$

where K, T_i and T_d are the proportional gain, the integral time and derivative time, respectively. Tuning of a PID regulator (i.e. choosing the values of K, T_i and T_d) is usually performed by the popular Ziegler–Nichols method [3].

The Ziegler–Nichols tuning rules require the knowledge of two parameters: the critical gain K_u and the critical period T_u. To obtain information about these, a proportional regulator is connected to the system. The proportional gain is increased gradually from a minimum value, and the corresponding output responses are observed. When a sinusoidal output is obtained, the value of the proportional gain is the critical gain K_u and the period of the resulting oscillations is the critical period T_u. As soon as these values are determined, the gains for the PID controller are set according to the Ziegler–Nichols rules [4] as:

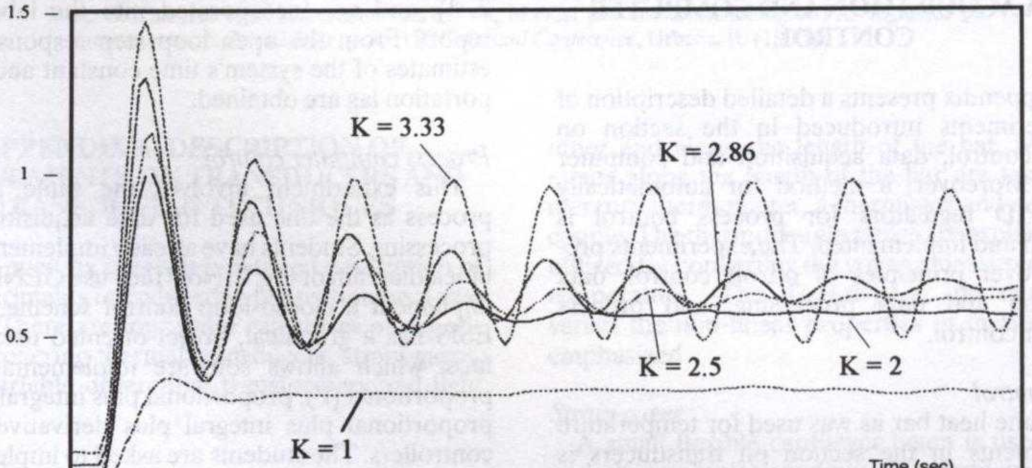

Fig. 4. Ziegler–Nichols tuning of the thermal process.

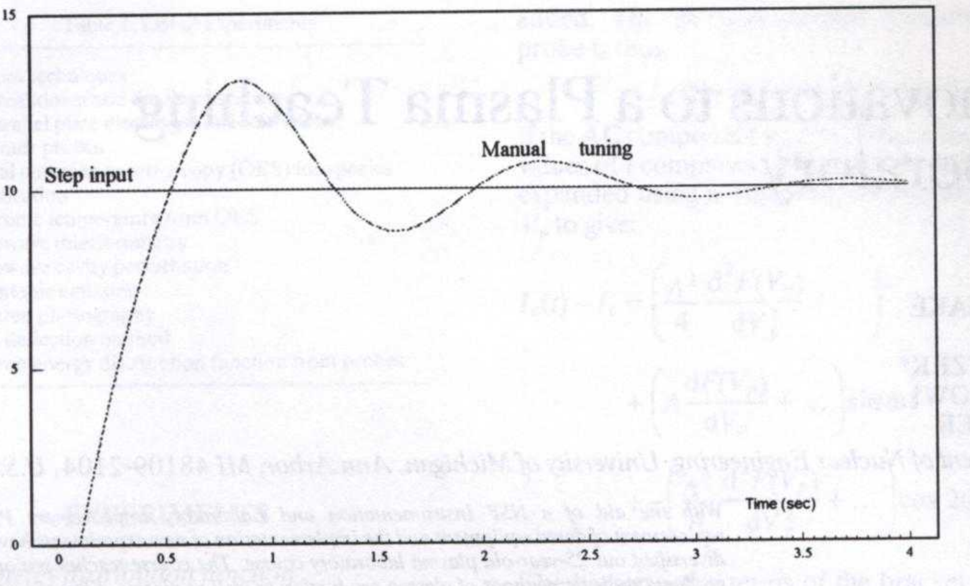

Fig. 5. Step response of the thermal process after the PID controller is tuned.

$$K = 0.6K_u; \quad T_i = T_u/2; \quad T_d = T_u/8$$

The students, having gained familiarity with the GENESIS control blocks and the underlying control concepts, use the PID block to tune the controller. By setting the PID controller to proportional mode only, the proportional gain K is slowly increased until a sinusoidal output is obtained. Typical system responses are shown in Fig. 4 for different values of K. In this example, it is seen that a sinusoidal output is obtained when $K_u = 3.33$ and $T_u = 1.6$ s. After these critical values have been determined, the PID controller gains are set according to the Ziegler–Nichols rules. A typical step response of the system after the controller has been tuned is shown in Fig. 5.

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