Educational laboratory exercises cover a wide spectrum ranging from programmed and highly structured tasks to discovery-learning-based and unstructured experiences. In structured or direct-instruction-based exercises, students are given lists of materials, step-by-step procedures, and often specific results to calculate. In unstructured or discovery-learning-based exercises, students are given an outline of steps and measurements (guided-inquiry-based instruction) or perhaps no more than a statement of goals (inquiry-based instruction). In the past 20 years, there has been a movement in science teaching—chemistry, biology, and physics—toward inquiry-based instruction, also called discovery learning [1]-[3]. Tinnemans and Chan make a good case for a discovery-learning approach in their artfully titled article: “Step 1: Throw Out the Instructions” [4]. Before we tried instructionless labs, we assumed that the students couldn’t devise their own procedures…. Much to our surprise the students show considerable skill in designing their own labs. [4] Discovery-learning-based instruction has been shown to help develop abstract reasoning [2], enhance two-year retention of concepts, and improve the student’s attitude toward the subject matter [1]. The principal features of discovery learning relative to a directed laboratory procedure are:

- Instead of being given specific instructions, students are provided with a statement of objectives and possibly an outline of steps, but are given no specific procedure to follow.
- There is no one correct procedure, but many possible procedures.
- The methods for analyzing and interpreting data may be broadly presented, but specific steps to carry out or tables to complete are not provided.

The education literature provides many examples of high-quality controls laboratory programs (e.g., [5]-[8]), and in a recent special magazine section on the future of control education, nearly all authors expressed the importance of an emphasis on the practical [9]-[11].

At the University of Wisconsin-Milwaukee (UWM), we have developed a controls laboratory sequence emphasizing discovery learning. The sequence evolved incrementally over several years, during which time it became clear that system identification could be used as a vehicle for discovery learning. In our first efforts, complete models were provided to the students, and multiterm controllers were tested from the outset. Today, students carry out system identification, build a model, “design a controller and assess its performance” in each laboratory exercise. The development is from the simplest possible system model—a dc gain-to a dynamic model and three-term control. The semester culminates in a master-slave servo tracking problem in which students implement control for a servo that must track a progressively more agile target.

The laboratory sequence is used in the electrical engineering program at UWM with the first course in controls. This is an elective course usually taken by electrical engineering majors in their senior year. At the outset of the controls course, students are conversant with many aspects of circuit analysis, including dynamics and differential equations, and have had some exposure to experimental statistics as part of a lecture course in engineering mathematics. The introductory controls course syllabus covers the traditional topics, starting with Laplace transform and modeling and concluding with design using root locus. The laboratory exercises are run in two-hour lab periods, with Lab 4 conducted over two periods.

Organization of the Laboratory Exercises

The five laboratory exercises are outlined in Table 1. For each laboratory exercise, students write a prelaboratory report (the “prelab”), which is assigned the week prior and turned in at the beginning of the laboratory period. The prelab prepares students through a series of pencil-and-
For Labs 1 and 2, the prelabs are rather structured. Students are provided data similar to what they will observe and are walked through the data analysis and interpretation. For Labs 3 through 5, the prelabs are progressively less structured, providing progressively more discovery learning. The fourth prelab calls on students to design the laboratory procedure independently to achieve goals of system identification, control design, and performance assessment. The fifth prelab exercise presents students with an unstructured design challenge. Students work in groups of two or three, and for each exercise a report is written (the "postlab") in which students present findings.

**Motor Servo Apparatus**

The apparatus is a servo unit with a dc motor, a tachometer, and a potentiometer for position sensing. The hardware is shown in Fig. 1, and the electrical layout is illustrated in Fig. 2. The hardware comprises a 1/20 HP dc motor with reduction gear and tachometer, a mechanical bar, which is the motion output of the system, and a potentiometer for position detection. This equipment, plus amplifier, was provided by Quanser Consulting of Hamilton, Ont., Canada (http://www.Quanser.com). Specialized components, such as the blocks and links shown later in Fig. 6, were fabricated at UWM.

### Table 1. Content of laboratory exercises 1 through 5.

<table>
<thead>
<tr>
<th>Lab #</th>
<th>Identification</th>
<th>Controller Design</th>
<th>Measurements</th>
<th>Additional Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DC gain (velocity servo)</td>
<td>Open loop and P-type closed loop</td>
<td>Tests: Steady-state error</td>
<td>Linearization Uncertainty</td>
</tr>
<tr>
<td>2</td>
<td>Lab 1 result used (velocity servo)</td>
<td>Open loop and P-type closed loop</td>
<td>Tests: Transient response Disturbance rejection Parameter variation</td>
<td>Experiment design Uncertainty</td>
</tr>
<tr>
<td>3</td>
<td>Step response, first-order model (velocity servo)</td>
<td>PI by pole placement</td>
<td>Tests: Step response Sinusoid tracking</td>
<td>Modeling accuracy Model order Uncertainty</td>
</tr>
<tr>
<td>4</td>
<td>Step response, frequency response, second-order model (position servo)</td>
<td>PD and PID</td>
<td>Frequency response, tracking error (PD and PID control)</td>
<td>Student-designed identification experiment</td>
</tr>
<tr>
<td>5</td>
<td>Model from frequency response data (position servo)</td>
<td>PID design by root locus</td>
<td>Competitive target tracking</td>
<td>Root locus design Empirical tuning</td>
</tr>
</tbody>
</table>

![Figure 2. Electrical layout of the motor servo used in all five laboratory exercises.](image-url)
The controller comprise Keithley MetraByte (http://www.keithley.com) DAS 1602 A/D and D/A cards and a custom C-language controller that implements a menu-driven system for selecting events and controllers, capturing data, and so on. The C-language controller (available by contacting us) was written in-house at a time when it was still difficult to exceed the 64K low-memory limit of Microsoft DOS.

The real-time performance has been tested at up to 2000 [samples/s] in MS-DOS (we actually run at 200 samples/s), although we see 0.5 s pauses in the real-time service in Microsoft Windows 95 and 98. Thus, the control computers are booted in MS-DOS for real-time work. If this project were reimplemented today, we would use real-time LINUX and the MATLAB A/D and real-time toolboxes from MathWorks. In addition to implementation advantages, this would allow the student greater freedom in implementing control and gathering and analyzing data directly in MATLAB and would eliminate the need to learn the special menu interface of the servo software.

The laboratory development was supported by a Wisconsin Laboratory Modification grant, as well as by hardware gifts from Keithley MetraByte and Hewlett Packard. The servo portion of the apparatus, including power amplifier and servo motor, but excluding computer and A/D board, cost approximately $3500 per station.

Detailed Description of the Exercises

Instructional Materials

Students are provided a 30-page document, "User Guide to the Servo System," which has a tutorial section on configuring and calibrating the hardware and software of the servo and a reference guide to the 56 commands of the menu-driven servo software (breakdown: 18 commands for configuration, 15 for data analysis, and 23 for testing). A typical tutorial element is the Hardware Checklist (shown left). The tutorials are direct-instruction materials, as evidenced by the step-by-step character of the Hardware Checklist.

The other written material comprises the laboratory exercises, ranging from 3 to 14 pages in length, with the shorter length corresponding to greater reliance on discovery learning. The first laboratory handouts have a considerable amount of tutorial material and direction, as shown in the example from the Lab 1 Handout.

As described below, by the time the students arrive at Lab 4, they will be designing their own experiments. The following steps come from the Lab 4 guide:

**Step 4.** Design an experiment to identify the second-order, volts-position transfer function of the SRV-02 using frequency response and the MATLAB routine invfreqs.

**Step 5.** Design an experiment to determine the Bode plot of the closed-loop error transfer function $E(s)/R(s)$, from very low frequency to two times the -3 dB point of the closed-loop system. Test the controllers specified in Table 2.

By the time Lab 4 is assigned, the format for the laboratory report is quite open:

Think of your laboratory report as a project report that you are writing as a consultant-subcontractor to a company with a major prime contract. Your report should be concise, and yet sufficiently complete to be useful. It should include:

- A short abstract.
A description of the measurement setup that is sufficiently complete for the measurements to be reproduced.

- Measured data and a description of the process by which it was analyzed.
- The results, including uncertainty.
- Interpretation of the results.

Completeness obviously conflicts with conciseness. Two suggestions: Don’t repeat, and do use illustrations.

Labs 1 and 2: Zeroth-Order Modeling and Control

The objective of each lab is that students carry out nontrivial design with a complete system. This objective is approached in Lab 1 by starting with the simplest possible system model (a dc gain) and the simplest possible controllers: open-loop (offset and proportional terms) and P-type closed-loop control, designed to meet a loop-gain specification. Nonetheless, the exercise involves system identification, controller design, and measuring and contrasting controller performance.

To prepare the student, Prelabs 1 and 2 must introduce several topics:

Prelab 1 Topics
1) Introduction to the servo hardware and software.
2) Determining dc gain and designing open-loop control.
3) Designing P-type, closed-loop control for specified loop gain.
4) Designing P-type, closed-loop control with feedforward.
5) Determining measures of the system response: steady-state error.
6) Uncertainty estimation for measured values.

Prelab 2 Topics
1) Developing and manipulating transfer functions.
2) Designing P-type closed-loop control for specified loop gain.
3) Determining measures of the system response:
   - Rise time,
   - Steady-state error, and
   - Amplitude of a sinusoidal response.
4) Uncertainty estimation for computed values.

Lab 1 Activities: The Basics

Lab 1 introduces the basics of sensing, actuation, and open- and closed-loop control. The first system identification consists of applying several values of constant voltage and measuring the corresponding velocity. A model comprising dc gain and offset is developed by linearizing about a specified operating point. This model is used to design a two-term open-loop controller with unity gain and a P-type closed-loop controller providing a loop gain of ten. The structure of the open-loop controller is seen in Fig. 3, and the structure of the closed-loop controller is shown in Fig. 4. By applying these controllers separately and combining them for closed-loop with feedforward control, students measure steady-state error during velocity regulation.

Lab 2 Activities: Student-Designed Laboratory Procedure

Lab 2 introduces performance measures and the performance improvements that motivate feedback control. Students investigate the correlation between loop gain and rise time.
time, steady-state error and peak motor command, as well as sensitivity to parameter variation and torque disturbance. Parameter variation is introduced by increasing the series armature resistance of the servo motor from 6.4 to 16.4 \( \Omega \). A disturbance torque is introduced by laying the motor servo on its side, as shown in Fig. 5.

With Lab 2, students design their laboratory procedure. To assist them, the following five elements of an experiment design are provided, with several pages of accompanying explanation:

1. Consideration of what results are sought, how the results will be determined, and how their uncertainty will be determined.
2. How the apparatus will be configured, tested, and calibrated (including choice of reference input, controller, controller parameters, etc.).
3. The range of inputs to be tested, i.e., what should be the smallest amplitude input and the largest, the lowest frequency and the highest, etc.
4. How many data points to collect (this requires consideration of how the results and uncertainty will be calculated).
5. A general notion of anticipated results, so that you can verify that the experiment is working correctly while you are running it.

In the first iteration of these exercises, position control of the motor servo was used. This posed two challenges: 1) with position control of the motor servo, the simplest meaningful model is already a dynamic model; and 2) tracking a position trajectory often involves velocity zero crossings, where friction has its greatest effect.

Both of these limitations are addressed by servoing velocity. The simplest model becomes a dc gain with units of radians per second per volt, and velocity profiles can be used that do not include zero crossings, reducing the impact of friction. Labs 1 and 2 are done while the lecture component progresses through modeling and block diagram analysis, and thus students have not yet seen dynamic compensator design. Working with the simple dc gain model facilitates discovery learning: students are able to do system identification, controller design, and performance assessment without recourse to a prepackaged model or controller design.

Lab 3: First-Order Model Identification
Lab 3 introduces dynamic modeling and compensation. As with the first lab, the third lab exercise opens with a focus on system identification. Model complexity and performance objectives are extended by moving to a first-order plant model and PI-type control. The topic of model complexity as a designer choice is introduced.

In the laboratory, the first-order model is identified from open-loop, step-response characteristics of rise time and transient amplitude. These measurements are distinct from those of Lab 1, where the system is identified using steady-state velocity. Series-PI compensation leads to a second-order system with two controller parameters. Pole-placement design is used. The limits of the first-order model are explored. The controller structure is that of Fig. 4.

In Prelab 3, the students are tasked to design three identification experiments: two directed toward plant transfer functions and the third toward error transfer functions. They must draw on their experience in identifying one- and two-pa-
ramer models for the plant, as well as operating the servo hardware and software. Their experiment designs as distinct from their results in the laboratory are critically graded with respect to items 1-5 of an experiment design, listed above.

**Lab 5: Staying on Target**

In the fifth and final lab, students are tasked to design a high-bandwidth PID position-controller for the motor servo. Students bring to bear on this task root-locus design techniques, as well as simulation using signals similar to those being tracked. The apparatus comprises two motor servo units (Fig. 6). The instructor controls the first unit—the target—with the plastic block. The student controls the second.

The apparatus is shown schematically in Figs. 7 and 8. As seen in Fig. 7, the output shafts of two SRV-02 motor servo units are connected by a wire link. The link slides in a groove in the block on the target unit and rotates in a bushing on the tracker unit. As the target moves, the tracker must follow to keep the wire in the groove. The block and groove are 2 cm wide, allowing ±1 cm of motion error before the wire will fall out. The motion command to the target progressively increases in speed. The students’ task is to keep the tracker on the target (the wire in the groove) as long as possible; performance is measured with a stopwatch. As shown in Fig. 8, the reference signal to the students’ controller is the detected position of the target.

Each student group achieves two performance results: 1) the performance of their first controller, designed as part of the prelab using the model identified with data from Lab 4 and root locus and simulation techniques; and 2) the performance of a controller tuned during the laboratory session. Student performance is often remarkable. A reasonably tuned controller by the authors will track the target for 100 s. The students’ initial controllers typically stay on target for 30 s; and the hand-tuned controllers can hold-lock for 300 s or more. The students find Lab 5 an exciting experience, which they approach with a lot of energy.

In part to balance the extensive reporting required in Lab 4 and in part to reduce the workload at the end of the semester, the reporting requirement is modest:

Write a short report (1 page maximum, not including figures) describing the most important aspects of how you arrived at your controller design.

**In-Class Experience**

Our experience with discovery learning has been entirely favorable, with 93% of students during the past five semesters completing all of the laboratory reports and 72% earning marks for their laboratory work that maintained or improved their course grade. The students remark in course evaluations that the laboratory is considerable work and is confusing. But it is to be expected that a discovery-learning experience will often be both more work and more confusing than a direct-instruction experience.

Like Tinnesand and Chan [4], we find that the students show considerable skill in designing their own labs. Indeed, the greatest challenge we experience in implementing the discovery-learning laboratory is not with the student, the student’s workload, or the self-designed laboratory procedures, but with the demands of understanding and pedagogical skill placed on the laboratory instructor, most often a teaching assistant at UWM. Continuous interaction with the students is required, and for perhaps one-third of the student groups, adjustments need to be made in their laboratory designs. Problems need to be recognized as they arise,
and the problem-solving experience is, of course, part of the
learning experience. But the student is not expected to re-
solve all problems without the assistance of the instructor,
and the instructor must regularly interact with each of the
students, observing efforts that have gone off track and pro-
viding input that helps resolve problems while maintaining
the opportunity for discovery learning. These are forma-
dable demands to place on a graduate student, and it is best to
have a professor in at least one of the laboratory sections
and to have close coordination between the professor and
the teaching assistants.

Our experience has been that laboratory procedures de-
veloped by the students are more similar than different.
Variations that exist lie in the dimensions of number and dis-
tribution of data collected and the design of the statistical
analysis (for example, in choosing which measurements to
take several times to estimate variability). The software sys-
 tem allows a range of controllers to be realized and parame-
ters such as sample rate to be varied; but it is important to
minimize complexity, so the students are not making
choices along the dimensions of, for example, controller
structure or sample rate.

An important indirect benefit that we find is the opportu-
nity to tie developments in lecture to experiences the stu-
dents have had in the lab (see also [10] and [11]). As one
student put it in the course evaluation: "Lab application and
discussion drives it home."

Conclusions

A sequence of laboratories is presented that have been de-
signed to maximize student involvement in the design as
well as execution of the laboratory exercises. The first lab
begins with the simplest possible model, a dc gain, and stu-
dents explore fundamental ideas of sensing, actuation, and
feedback. With the second lab, student-designed experi-
ments are introduced. By the end of the sequence, students
independently design and implement system identification,
controller design, and performance assessment for high-
performance tracking with a motor servo.

The education literature establishes the potential for dis-
covery learning to increase learning outcomes in laboratory
teaching. This poses a challenge for controls, because even
a simple control system is nonetheless a system. Its design
can touch on many issues, including a possibly complex sys-
tem model; implementation issues, possibly including com-
puter programming; nonlinearities, including friction and
saturation; and instrumentation. For discovery learning, the
situation must be simple enough that the student can work
without precise instructions. We have chosen to emphasize
discovery learning at the expense of some details: System
modeling starts with the simplest possible model; the equip-
ment configuration and controller are provided; and stu-
dents do no real-time programming; at the outset students
are guided toward experimental conditions that avoid
nonlinearities, and the needed instrumentation is built into
the servo software package. With these elements, and some
guidance from the instructor when needed, students dis-
cover the means to carry out system identification, control-
er design, and performance assessment.

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Brian Armstrong graduated from MIT in 1980 with a B.Sc. in
physics and mechanical engineering. He completed his M.Sc.
and Ph.D. in electrical engineering at Stanford in 1984 and
1988. After a post-doctoral position at INRIA in Rennes,
France, he joined the Department of Electrical Engineering at
the University of Wisconsin-Milwaukee. He was also a visiting
professor at the Universidade Estadual de Campinas, Brazil,
and in 1997 he spent a sabbatical year at the Telecommunica-
ations Laboratory of Mitsubishi Electric, Rennes, France.

Ronald Perez is an Associate Professor of mechanical engi-
neering at the University of Wisconsin-Milwaukee. He re-
ceived his Ph.D. in mechanical engineering from Purdue
University in 1990. His research interests include mecha-
tronics, control theory and applications, robotics, intelli-
gent control, neural networks, and fuzzy logic. He has
authored or coauthored over 50 journal articles, conference
publications, and monographs and has been organizer and
chairman of many technical sessions.