2006-1328: SHARING LABORATORY RESOURCES ACROSS DEPARTMENTS FOR A CONTROL SYSTEMS CURRICULUM

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Sharing Laboratory Resources Across Departments for a Control Systems Curriculum

Abstract:

As is the case in most curricula, Control Systems is a required course for both Mechanical and Electrical Engineering students at Ohio Northern University (ONU). Students in both majors are given extensive laboratory experience and have access to electives in this area. Students in Electrical Engineering take a two-quarter sequence while Mechanical Engineering students take one course. Both of these sequences introduce students to Programmable Logic Controllers (PLCs) in addition to the traditional course content. This makes students from both departments eligible for two elective courses in the area of control systems offered by the Mechanical Engineering department.

Over the past four years, the instructors for these four courses have collaborated closely to share laboratory and classroom content. The required Control Systems courses in both departments currently share a textbook. In addition, over half of the laboratory exercises in the Mechanical Engineering course are also used in the Electrical Engineering courses, with minor modifications. While this has caused some scheduling and administrative difficulties, it has reduced cost to the College of Engineering and simultaneously increased the quality of the laboratory. Another area of common hardware is that the same PLC devices are used to introduce students to this technology in the required Control Systems courses in both departments. These same PLCs are again used for Applications in Control Systems. This has the economic benefit of sharing equipment costs between the two departments, while at the same time insuring that students taking Applications in Control Systems are already familiar with the hardware they will be using for this elective course.

The paper will detail the collaboration between departments during this four-year period. Details of purchasing as well as administrative and scheduling challenges will be addressed. Faculty and student assessment of the laboratory experience will also be provided. It is hoped that other institutions may benefit from similar collaboration to keep costs down while still providing a significant control systems laboratory experience, something many Mechanical Engineering programs lack.

I. Introduction:

Most undergraduate Mechanical Engineering (ME) programs include a control systems course. At Ohio Northern University, this course has included a weekly laboratory component for many years. Updating this laboratory and providing students with a strong hands-on experience have been recent priorities of the mechanical faculty. At the same time, the Electrical Engineering (EE) program has historically had a required two-course sequence in control systems. The electrical engineering program is part of the Electrical & Computer Engineering and Computer Science Department (ECCS) at Ohio

Northern. Both of these EE control courses have had a required laboratory component with weekly laboratory meetings. The key equipment used in the EE control laboratories was ten years old and the department was seeking to replace this hardware. This older equipment could only implement analog controller and sensor designs, lacking an easy interface for students to practice digital implementation schemes for controller designs and sensors. Thus, with two departments in need of improving their laboratory equipment for control system courses and with these prices continuing to climb, it was thought that collaboration between the two departments would allow for much better-equipped laboratories. This paper will provide an overview of this collaboration over the past four years.

Between the two departments, there are currently five courses in the control systems area, and each includes a laboratory component. The course catalog descriptions for these courses and their expected enrollment by major are stated below. Further encouraging our collaboration is the fact that students from either department can enroll in several of these courses.

- ME 419 – Control Systems (5 credits). Modeling, analysis and design of linear feedback control systems. Laplace transforms, transfer functions and frequency response. Introduction to digital controls and logic. Laboratory work in digital logic design, and performance studies of real systems. Prerequisites for this course include a course in differential equations, an ME computer applications class, and dynamics. This is a required course in the mechanical engineering curriculum. Typical enrollment is 35 students.
- ME 429 – Applications In Control Systems (4 credits). Applications in control systems concentrating on PLCs and ladder logic. Advanced control theory explored. Laboratory work concentrates on PLC applications. The prerequisite is ME 419 or senior standing in electrical or computer engineering. This is an elective course that can be taken by three majors: electrical, computer, and mechanical engineers. Typical enrollment is 16 students.
- ME 449 – Intelligent Systems (4 credits). Interdisciplinary student teams work to control complex, nonlinear systems. Students are introduced to neural networks, fuzzy logic, and genetic algorithms. The course also includes a project involving students at multiple universities. The prerequisite is ME 419 or ECCS 444. This is an elective course for either electrical or mechanical engineers. This course is running for the first time in Spring 2006. The typical enrollment is expected to be about 15 students.
- ECCS 444 and ECCS 445 – Control Systems 1 and 2 (4 credits each). Classical feedback control systems. Mathematical modeling of systems. Design of feedback control systems using root locus, frequency response methods. State space modeling and control system design (state feedback, LQR, and observers). Computer simulation. Integrated laboratory experience. The sequence's prerequisites include one course in signals and systems and a course in energy conversion (motors). This is a two course sequence required in the electrical engineering curriculum. Typical enrollment is 18 students.

Exposure to programmable logic control occurs in both ME 419 and ECCS 444. The interested student (from either major) can then pursue this topic in more detail in ME 429. Similarly, students interested in continuing their knowledge in control could also elect to take ME 449.

A. Equipment purchases:

The electrical engineering control systems laboratory contains six workstations equipped with basic hardware, including oscilloscopes, function generators, power supplies, and PCs. In 2003, the mechanical control lab was moved to a new space as part of a major building renovation. Over the past four years, the two departments have purchased the following equipment. The department fiscally responsible for each purchase is listed in parentheses, with that department then being responsible for possible repair, upgrade, and replacement costs.

- 8 PCs for the new ME control lab (ME)
- 8 IAC Workstations for the new ME control lab (ME)
- 8 industrial NEMA-23 servomotors with encoders and tachometers (ECCS)
- 8 digital amplifiers (ME)
- 4 High-torque gearheads (ECCS)
- 9 Direct Logic PLCs[1] (6 ME and 3 ECCS)
- 6 Quanser rotary systems[2] (each system includes data acquisition hardware and software, a power supply, and sensors) (5 ECCS and 1 ME)
- 5 Quanser rotary system attachments (3 flexible joint and 2 ball-beam balancer stations) (ECCS)
- Quanser 3 DOF Helicopter[3] (ME)
- Quanser linear inverted pendulum[4] (ME)
- Temperature control modules (ME)
- Fluid level/temperature/pH modules (ME)
- Network concurrent Matlab license (College of Engineering)
- Individual group Matlab license (ECCS)

In general, students work in groups of two, and there are multiple sections of the lab. The goal is to have eight of each major piece of equipment so that there can be sixteen students per section. Some equipment (such as the helicopter) is used for demonstrations, or by students outside of the normal lab time, so only one setup is needed.

A Quanser rotary system station (rotary plant hardware with multiple sensors, power supply, data acquisition board and real-time software interface) . We selected Quanser's product due to its flexible laboratory experiments and ease of user interface. Both EE and ME students can graphically design their real-time controllers in Matlab's Simulink environment, avoiding the issues of writing lines of code, compiling code, etc. Quanser's product line also includes additional apparatuses that specifically relate to EE and ME students, such as their flexible joint, ball and beam, and helicopter experiments.

Each PLC station consists of the main microprocessor with several optional input and output modules to control a variety of sensors. We chose to purchase the AutomationDirect DL405 family of products Ladder logic programming can be done via the handheld unit or via the graphical user interface software. Again, both ME and EE student backgrounds are accommodated.

This sharing of equipment purchases has resulted in several major advantages. First, and most obviously, both departments have realized cost savings by sharing equipment. For example, ECCS chose to purchase three PLCs, while ME purchased six PLCs, resulting in each department having access to nine PLCs without the cost of purchasing eight setups. While it would be unfair to suppliers to publish exact costs for each item above, the total cost is over $125,000, so each Department has saved on the order of $60,000. Second, the authors have been able to provide their laboratories with more equipment than they would have been able to individually, since no equipment has been duplicated. By carefully selecting the Quanser family of products, we have been able to collect a good selection of apparatuses that function on the base rotary plant setup that meet both department needs for educational laboratory hardware. Finally, this collaboration at the laboratory level has also led to increased collaboration in teaching between the two departments.

B. Administrative Challenges:

This collaboration would not have been possible without the support of various administrators. These include strong encouragement for collaboration from the Dean, as well as support from the two department chairs. This support has allowed the collaboration to be successful despite various administrative challenges:

- Ownership: To date, the individual departments still retain ownership of the equipment that they have purchased. However, thanks to the willing cooperation of the department chairs and the three faculty involved, this ownership is in effect transparent. Equipment is stored and used based on functionality, not department. For instance, all of the PLCs and related equipment are stored together in the Mechanical Engineering area, whereas all of the Quanser equipment is stored in the Electrical Engineering area.

- Scheduling: ONU is on a quarter schedule. In the fall quarter under the current schedule, only the Electrical Engineering courses are in session. As such, there are no fall quarter scheduling issues. The winter quarter is currently the greatest scheduling challenge, as there are four courses (three control courses plus an EE communication systems course) sharing the two laboratory areas, with a total of 20 laboratory hours during the week. The PLC labs are run in the Mechanical Engineering area, while the remaining laboratories are run in the Electrical Engineering area. This has required the scheduling of courses and laboratories much earlier than usual to ensure that all of the lab sections can be accommodated. While this obstacle has been overcome, it has resulted in some inconveniences. These include one professor having three lab sections in the same day, and it has required some 8am and 4pm laboratory times. Only one course in the controls area is being taught in the spring, so scheduling is again not an issue. Both the departments are in the process of implementing curriculum reform, so it is expected that scheduling will continue to be an issue.

- Human Resources: The secretary of the ECCS Department and the Electronics Technician (who reports to ECCS) have both been involved in this collaboration. While they play support roles in the College of Engineering, their willingness to do work outside of their traditional job description has been very instrumental in the success of the collaboration.

II. Course-level collaboration:

The two faculty responsible for ECCS 444-445 and ME 419 have taken the notion of collaborating on equipment purchases to the next level, and begun coordinating on the course level. Since students from either major can then elect to take ME 449, we have tried to make sure the topics taught in the ME and EE required core courses support this elective. Each year, we sit down to choose one text that will be used in these core courses, which helps with the university bookstore overhead costs. Unfortunately, neither faculty is completely satisfied with the undergraduate control textbook selection. We have tried two popular control texts, and have yet to find the ideal reference. Our ideal textbook would not rely too much on either an ME or EE background, yet would include examples relative to both. The texts incorporate Matlab exercises well, but they typically lack coverage of laboratory issues relevant to each chapter. Nonlinear topics such as saturation, precision, deadband, noise propagation, etc. are not mentioned in the undergraduate texts.

Due to the relatively small university setting, the students in both ME and EE typically know each other. Under the current catalog, EE senior students take ECCS 444 in the quarter before senior ME students take ME 419. Thus, the faculty have taken steps to ensure that independent learning occurs, and have varied the labs somewhat between department offerings. On a positive note, having the capability to develop and critique laboratory experiments with another colleague familiar with the course topics and equipment has been very beneficial.

A. Outstanding issues:

The biggest question that remains unresolved is whether or not both majors could be served with one control systems course. Obviously, control systems is a field applicable to both disciplines. However, the background of the students varies significantly in these curricula. Before taking the ECCS 444-445 sequence, the electrical engineering students have completed a course in signals and systems and are familiar with the time domain, frequency domain, and Laplace transforms. They are also comfortable with standard electrical test equipment. Meanwhile, the mechanical students have strength in understanding the physical modeling of systems due to their knowledge of gear ratios, friction, inertia, torque, etc. However, they have not had a signals and systems course.

In addition to the prerequisite disparity, the departments' expectations of coverage vary. For instance, the EE students are exposed to the topic of state space modeling and control design techniques for four weeks, which is not part of the ME curriculum. Finally, there is the problem of lecture size. ME 419 typically enrolls 35 students, while ECCS 444 enrolls 18 students. At this university, lecturing to a class of 50+ students is not typical, and identifying an open classroom of that size would be difficult. Thus, it is challenging to resolve the two curricula control systems contents into one course.

However, the notion of combining both departments' basic control course laboratory experiments into one may be more feasible. As mentioned before, since the students know each other well, we already style the labs differently to ensure independent student learning. With the ongoing curriculum reform, it may be more feasible to have a common lab for ME 419 and ECCS 444 topics if these courses were offered in the same quarter. Then, one set of labs would serve both curricula and allow more flexibility for student and faculty scheduling. This would have the added benefit of allowing students to work in cross-disciplinary groups in the lab.

B. Assessment:

As was stated earlier, the main goal for the EE control systems area was to upgrade the lab hardware. The DC motor and controller boards were 10 years old, and the students were anxious to implement data acquisition systems and real-time computer control methods. The PLCs were aging also, with only four of the original five setups fully functioning. This equipment had served the department well, and we wanted to replace it with sturdy, flexible equipment that would benefit as many students as possible. The laboratory experiments for the new equipment are very similar to the original experiments in objectives and topics; thus, a formal assessment of the laboratory components has not been completed. However, with the new PLCs and Quanser setups, the EE student course evaluations often contain statements such as:

> Our labs helped a lot and it was nice to have real-world practice in our labs. The PLC labs were very useful and I learned a lot from this lab. (2003 EE 444)
>
> The laboratories were useful and interesting--the Quanser system is intuitive. We can concentrate more on the control system than becoming familiar with the equipment. (2004 ECCS 445)

Currently, there are no upper level electives in the ECCS department covering control engineering topics. EE majors have had scheduling conflicts with ME 429 for the past three years, and thus have not been able to enroll in this course; this has been resolved with the new curriculum that is in effect next year. The other possible elective for EE students in the area of control is ME 449, which is running for the first time this spring and a few EE majors have enrolled in this course. Thus, at this time, it is difficult to conclude any quantitative effects of the new lab hardware with regards to EE majors.

The biggest effect that this collaboration has had is in the new laboratory experiences available from ME seniors. This change began to be implemented for the 2002-3 academic year. Unfortunately, no clear indication of a sustained improvement can be shown at this time based on student self-assessment of learning outcomes. Figure 1 below shows the average students response to the survey shown in Figure 2. Note that Outcome 8 was added after the 2001-2 year. However, student performance in classroom, homework, and laboratory exercises has indicated better knowledge of the material than before this laboratory was implemented. It is felt that there are two major reasons for the lack of improvement in self-scored student outcomes. Perhaps the clearest reason is that an additional topic is being covered, meaning that all of the other material is covered more quickly. The other reason is that a hands-on laboratory often makes the students realize what they do not know. They are suddenly forced to deal with systems that are non-linear, and results that do not match the textbook. This is difficult for them, but actually means they have a better understanding of the material.

As evidence of this, results from a second survey are also included. This survey relates specifically to the laboratory portion of the course as it relates to course outcomes. A copy of the survey is included as Figure 3. Figure 4 shows the average response to these questions over the past three years. A few things are worth noting. First, the average response to all questions is generally positive (please note the scale for these questions has a maximum of four, an effort to force students to avoid neutral responses). Secondly, this has been stable over the three years that this laboratory has been offered. As such, the authors' view based on student performance that these laboratories have enhanced learning seems to be borne out when looking at this laboratory-specific survey. It must be noted here that the 2002-2003 data on these two surveys was previously reported by the authors in the Proceedings of the 2004 ASEE Annual Conference and Exposition.[5]

C. Applicability outside of our school:

The sharing of control systems laboratory resources can be achieved at other universities. Ohio Northern is not the first university to realize shared control laboratory resources across multidisciplines. In 2005, the University of Illinois reported on their past decade of endeavors to establish a common laboratory resource for their College of Engineering.[6] Similar to ONU, cost was a driving force for the collaboration in order to maintain state-of-the-art facilities. Another benefit was the reduction of faculty loads due to the hiring of a lab manager to maintain the equipment and design new experiments in this single lab. However, unlike ONU, this lab services 700 undergraduates annually and is funded at the College of Engineering level.

When considering the likelihood for success, one factor to consider is the size of the university. For instance, at this university all engineering majors are taught in the same physical building. Another factor to consider is the supportiveness of administration and staff. Ideally, administration should be more than cooperative due to potential cost savings. Possibly the most important factor for success is a good working relationship between the faculty sharing the laboratory space and/or equipment. Faculty with flexible attitudes toward scheduling and sharing of resources are essential for the survival of this collaboration effort.

Along with the above factors leading to success, one should examine whether such an effort is practical for the university. One consideration is how laboratory learning provides a different learning experience from a simulated software environment. Also, if one department is operating without a lab already, collaborating with the other department may be the only way to implement a lab without outside funding, as startup costs for equipment such as oscilloscopes, function generators, power supplies, etc. tend to be high. Finally, deciding on a text which facilitates the shared laboratory environment may be a deciding factor. In the authors' opinion, a good cross-disciplinary textbook with an integrated lab component is lacking for undergraduate control systems.

III. Conclusion:

The Controls Systems Curriculum in Mechanical Engineering and Electrical Engineering at Ohio Northern University has greatly benefited from recent collaboration. The laboratory equipment has been updated and expanded significantly, giving students valuable exposure to modern equipment. Administrative support and a strong relationship among faculty have overcome the challenges of scheduling and ownership. To date, the courses and the physical laboratory spaces remain distinct for a variety of reasons. The expanded lab opportunities have led to improved student learning and better achievement of course outcomes.

This type of collaboration can be applied at other universities. It is certainly easier at smaller universities, where the departments share a building. This collaboration has worked because it was initiated at the faculty level, but was supported by administration. This type of collaboration could allow mechanical engineering departments that do not currently have a laboratory component in their control systems class to give their students laboratory experience without the cost and space requirements associated with starting a new laboratory.

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Bibliography

1. Automation Direct Programmable Logic Hardware: Direct Logic 405, 2006 [Online]. Available: http://web1.automationdirect.com/adc/Shopping/Catalog/PLC_Hardware/DirectLogic_405
2. Quanser – Rotary Control Challenges, 2006 [Online]. Available: http://www.quanser.com/english/html/challenges/fs_chall_rotary_flash.htm

3. Quanser – Specialty Challenges, 2006 [Online]. Available: http://www.quanser.com/english/html/products/fs_product_challenge.asp?lang_code=english&pcat_code=exp-spe&prod_code=S1-3dofheli&tmpl=1
4. Quanser – Linear Control Challenges, 2006 [Online]. Available: http://www.quanser.com/english/html/challenges/fs_chall_linear_flash.htm
5. John-David Yoder, Juliet Hurtig, and Michael Rider, "Providing Hands-on Experiences in a Mechanical Engineering Controls Systems Course", Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition.
6. Andrew G. Alleyne, Daniel J. Block, Sean P. Meyn, William R. Perkins, and Mark W. Spong, "An Interdisciplinary, Interdepartmental Control Systems Laboratory", *IEEE Control Systems Magazine*, vol. 25, no. 1, February 2005.

ME 419 Course Objectives

Use the following scale:
5 – Strongly Agree 4 – Agree 3- Neutral 2 – Disagree 1 – Strongly Disagree

Upon completion of this course, the student will be able to:

1. Draw and simplify block diagrams.
2. Use Laplace Transforms to solve differential equations.
3. Model real-world systems using Laplace Transforms, block diagrams, and Matlab.
4. Design digital control systems using digital logic or PLC programming.
5. Analyze control systems based on steady-state error, disturbance rejection, feedback, transient response, and stability.
6. Design a controller, selecting appropriate gains for a specified response.
7. Use the root-locus method.
8. Use frequency-response methods (NOTE: This outcome was not included in the 2001-2002 academic year)

Figure 1: ME 419 Course Objectives

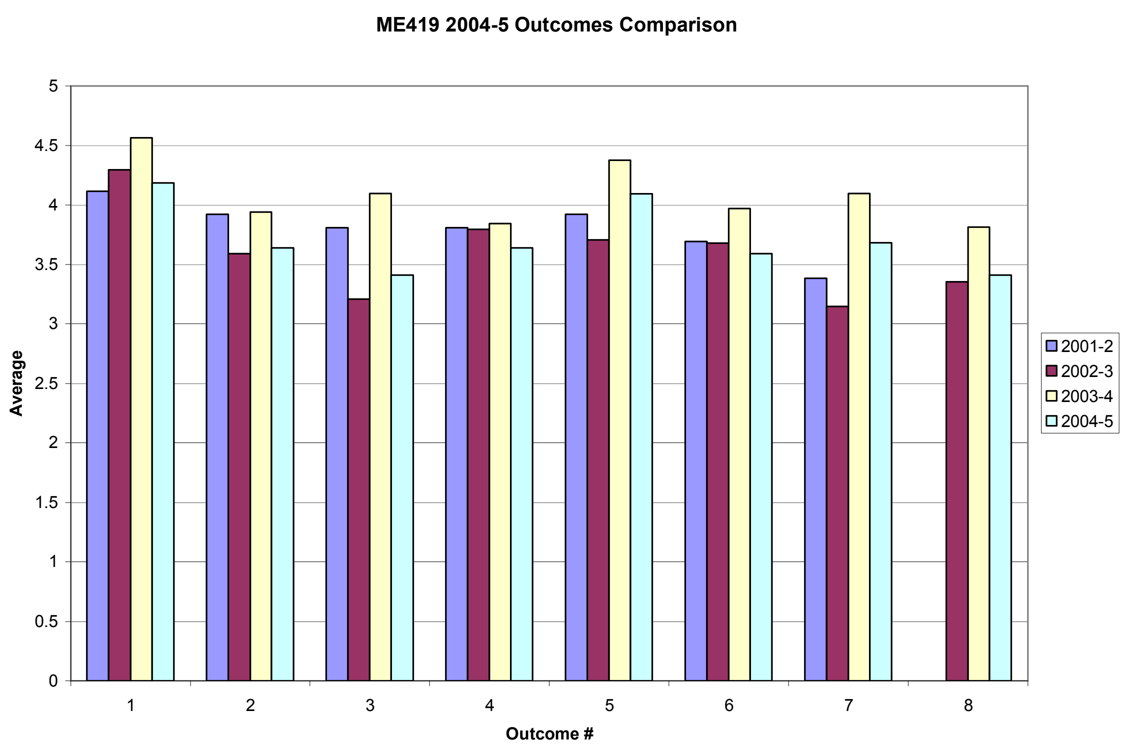

Figure 2: Student self-assessment to the ME 419 course objectives.

ME 419
Laboratory Evaluation

Use the following scale
4 – Strongly Agree 3 – Agree 2 – Disagree 1 – Strongly Disagree

___ 1) Using the DIGIACS helped my understanding of **digital logic**.

___ 2) Using LOGICWORKS helped my understanding of **digital logic**.

___ 3) The 'water level' lab helped my understanding of **PLCs**.

___ 4) Using the speed control systems in the upstairs lab helped my understanding of **block diagrams.**

___ 5) Using the speed control systems in the upstairs lab helped my understanding of **proportional gain**.

___ 6) Using the speed control systems in the upstairs lab helped my understanding of **disturbances**.

___ 7) Using the speed control systems in the upstairs lab helped my understanding of **feedback**.

___ 8) Using the speed control systems in the upstairs lab helped my understanding of **first order systems**.

___ 9) Using the speed control systems in the upstairs lab helped my understanding of **frequency response**.

___ 10) I am comfortable using Matlab or Simulink to model systems.

___ 11) I am comfortable using Matlab or Simulink to design a controller by varying gains and observing the response.

___ 12) Implementing a proportional controller in Labview helped my understanding of control systems.

___ 13) Implementing a PID controller in Labview helped my understanding of control systems.

I learned the most from the lab that: ____

I learned the least from the lab that: ____

Figure 3: ME 419 Laboratory Survey.

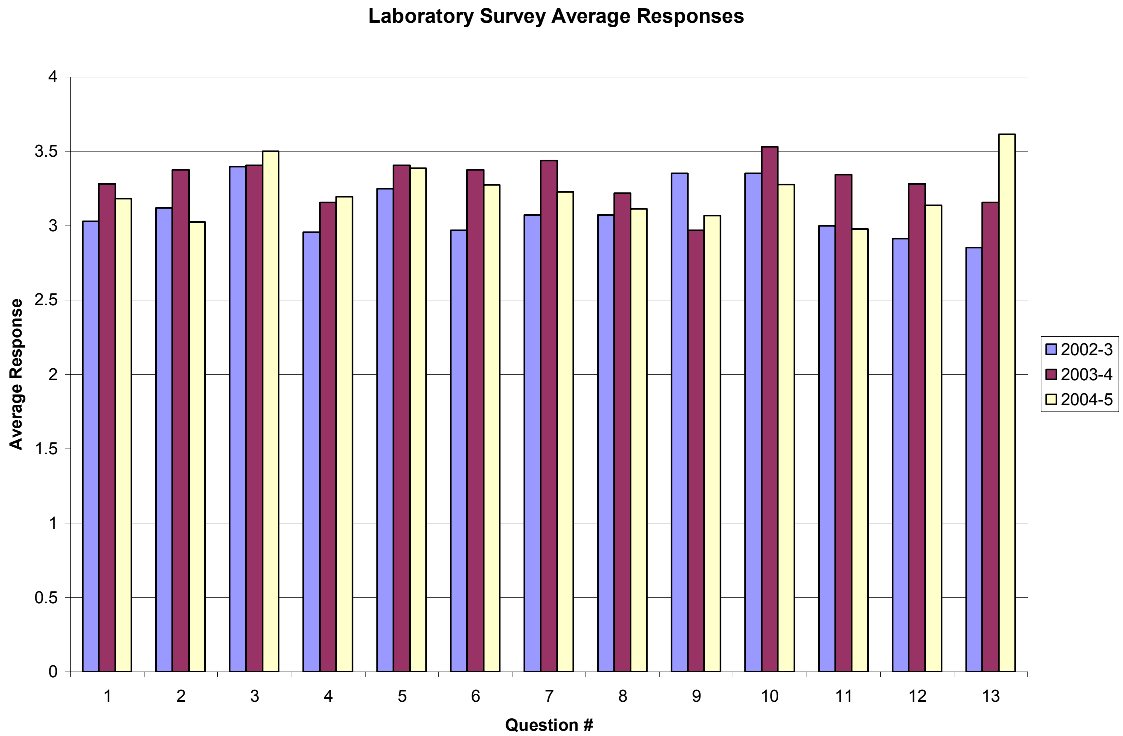

Figure 4: Student responses over the past three years to the laboratory survey.