

The Educational Impact of Modular, Open-ended Controller Design Projects*

MICHAEL REYNOLDS, PETER H. MECKL and BIN YAO

School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088, USA. E-mail: meckl@purdue.edu.

In the fall of 2001 we implemented the first of a series of new controller design projects in our Junior/Senior level controls class in Mechanical Engineering at Purdue University. Our first new project was the design of a controller for the point-to-point motion of a gantry crane. Student teams modeled the gantry crane and developed a controller to meet performance specifications. The equipment was used for different projects in subsequent semesters. At the end of each semester, each group presented their design and students stayed voluntarily and asked questions for several hours. We have been very impressed with the quality of the students' work. We believe that the combination of hands-on equipment, the challenge of the project specifications, and a design competition greatly motivated our students. The purpose of this paper is to describe the changes we have made to our projects and what we have learned from the process.

INTRODUCTION

ME 475 is our Senior level automatic controls course in Mechanical Engineering at Purdue University. The course is built upon learning and applying classical control techniques such as root locus and Nyquist plots. In the laboratory part of the class, students use an analog computer to model differential equations and control a servo table. In past semesters the course would end with a project where students would identify and control a 'black box'. The Black Box was a circuit box programmed with a second-order transfer function. Reviews of the course frequently mentioned disappointment with the old project because it lacked a 'hands-on' quality that Mechanical Engineering students frequently enjoy. The Black Box project also did little to motivate students' interest in controls because it was a very straightforward application of the lecture notes. Some teaching assistants would refer to the old project as a 'glorified homework problem' because the only difference between the project and a typical homework problem was the depth and allotment of points. It was clear that a new project was needed and in the summer of 2000 we set out to design one.

We looked to Quanser Teaching Systems for the equipment used in the project. We purchased four Quanser Linear Experiment modules [1] for use in a lab that has a maximum of twelve students. The modules included a track, one mass with a DC motor and one unpowered mass, a teeter-totter that the track can be placed on, a spring for connecting the masses, a pendulum rod, a power amplifier, an ISA or PCI computer interface board and the Wincon software [2] that interfaces with

SIMULINK. We chose Quanser because they had a reputation for high quality equipment that was modular, allowing for many different experiments with the same set of components. The Quanser systems also had an interface with MATLAB, which allowed students to implement real-time controller designs in SIMULINK with ease.

In our first three semesters we used the Quanser equipment for a gantry crane project, a floating oscillator project and an inverted pendulum project. The modularity allows us to make a new project each semester, avoiding the problem of students finding old solutions. In this paper we detail our first project, the gantry crane, and our latest project, the inverted pendulum. The floating oscillator project was omitted from detailed discussion since all of our findings can be shown from the other two projects.

GANTRY CRANE PROJECT

A gantry crane configuration—one suspended rod attached to a controlled mass on the track, as shown in Figs 1 and 2—was chosen because the dominant system dynamics can be modeled with a fourth-order transfer function [3], something we knew students could handle, which means the modeling and control would go beyond a simple second-order design. (More information on the particular setup can be found at www.quanser.com.) We wanted to give students a challenge without an overbearing amount of complexity and the gantry cranes were a perfect fit for this goal. Part of the challenge that we provided to students was how to deal with practical implementation constraints such as the nonlinear friction that typically arises in real-world applications.

* Accepted 5 September 2003.



Fig. 1. Pictures of the experimental setup.

Nonlinear effects such as stiction and actuator saturation are critical in the operation and control of the system. Gantry cranes also have numerous industrial applications such as construction equipment, milling machines and printers. These applications help to motivate the students in terms of the practical usefulness of the project.

The gantry crane system consists of a 6 V DC motor powered by a linear amplifier. The amplifier is connected to the computer through a PCI board and Wincon software. The Wincon software enables SIMULINK to send control signals to the motor through MATLAB's Real-time Workshop toolbox. The DC motor drives the 0.9 kg cart with a rack and pinion configuration. Pinned to the cart is a 64-cm rod that has a mass of about 0.3 kg. Digital encoders measure the rotation of gears as the cart moves along the track and the angle of the pendulum rod.

The goal of the project was to design a controller that would move the endpoint of the gantry rod a distance of 40 cm in the horizontal direction in minimum time. The length of the track is about 90 cm but we chose a much smaller move distance to allow for overshoot and to minimize the probability of the rod swinging out and hitting someone standing near the track. The minimum guideline for the project was to have a 5% settling time, as shown in Fig. 2, of less than 15 s. The steady-state error must be zero with the theoretical design when nonlinear friction is not considered and less than 0.5 cm on the actual implementation. This implementation limit was set due to the effect of static friction, which is large relative to the actuator

signal when the error signal is small. Finally, the overshoot must be less than 25%.

Students submitted a formal report that detailed their modeling, controller design and implementation. We provided them with some SIMULINK diagrams that would get them started with their modeling as well as a block they could use to implement a controller (Fig. 3). The students were encouraged to design their own SIMULINK blocks and even implement control structures that were not covered in class. The information provided to the students was the minimum needed to operate the hardware along with some advice on modeling the gantry crane. We encouraged each team to construct a theoretical model based upon standard linear components first, and then explore other methods of modeling physical systems. Nearly every group developed and synthesized multiple models.

We handed out the project around the middle of the semester and dedicated three weeks of lab time to allow students time to work in their teams. The project was due during the last week of the semester, giving the student groups about 8 weeks to work on the project. We decided to hand out the projects long before they were due so that the student teams had sufficient time to explore solutions and learn other control schemes outside of class. Many students read other control texts and even found related journal articles.

The student teams came up with many excellent designs. The design that won the competition (i.e., had the lowest settling time) combined a highly accurate model with a logical controller design.

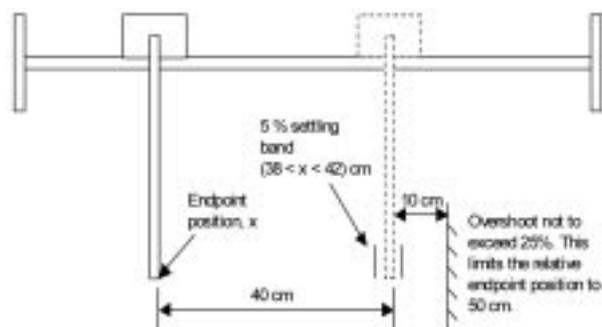


Fig. 2. Gantry project schematic.

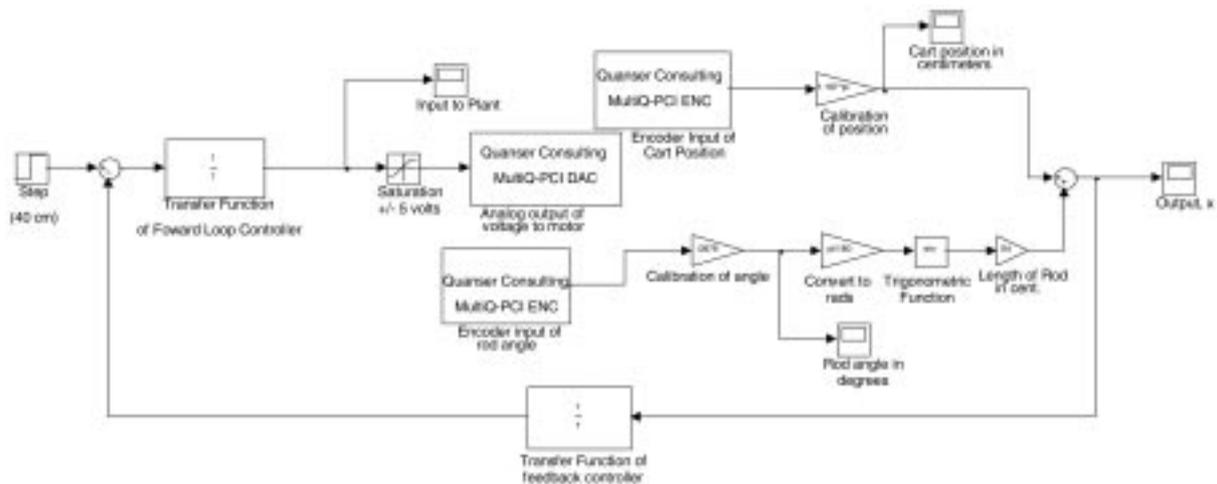


Fig. 3. SIMULINK block diagram of control structure.

The modeling was based upon a lumped linear system whose parameters were adjusted to match the experimental response data. The theoretical model had to be modified because of nonlinearities like stiction and the rod angle. The mean squared error between the actual and theoretical response was minimized through an efficient parameter variation scheme. The winning team also developed an input-shaper [4] to suppress the initial backward movement of the endpoint, typical of non-minimum phase systems such as the gantry, and to minimize residual vibration. Designing an input-shaper is another example of the type of creativity shown by many of the student groups. The response of the physical system is given in Fig. 4. The endpoint of the rod came within 5% of the final position in only 2.25s. There was no overshoot and the steady-state error was about 0.2 cm. Those interested in viewing the winning design in more depth can download the final report of the winning team at <http://widget.ecn.purdue.edu/~me475/gantry.html>.

INVERTED PENDULUM PROJECT

Our third student project was the stabilization of an inverted pendulum [5]. The configuration and equipment are the same as the gantry crane, but in this case, both rod angle and cart position must be controlled simultaneously for the rod to be balanced vertically without having a large range of cart travel during the transient. Because our course deals only with single-input, single output (SISO) design, we were concerned the students would be incapable of stabilizing the inverted pendulum within the given limited travel range of the cart in the laboratory set-up. Since many SISO designs can keep the pendulum upright for a finite time, we made the minimum specification to keep the cart within 30 cm of its center position (an arbitrary point near the center of the track) for 30 s (Fig. 5). Before giving the project we confirmed that this is a reasonable goal for every student group to attain.

As with the gantry crane project, we handed out

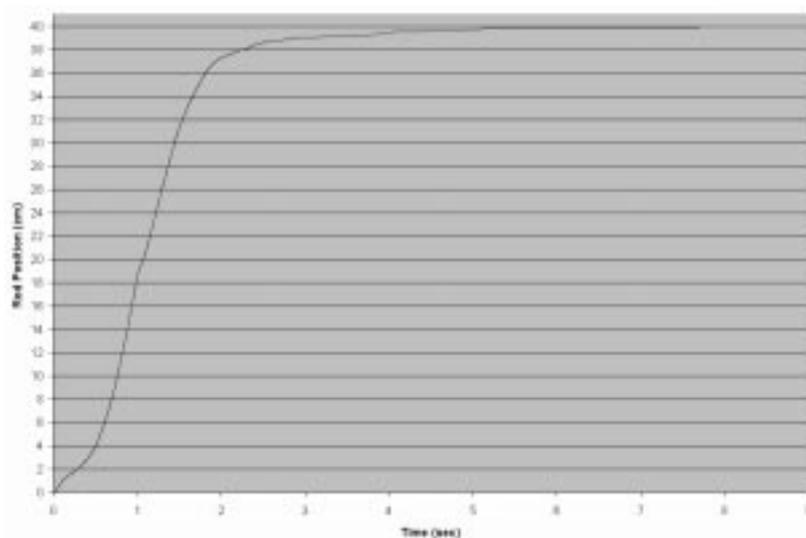


Fig. 4. Horizontal endpoint position of the rod versus time.

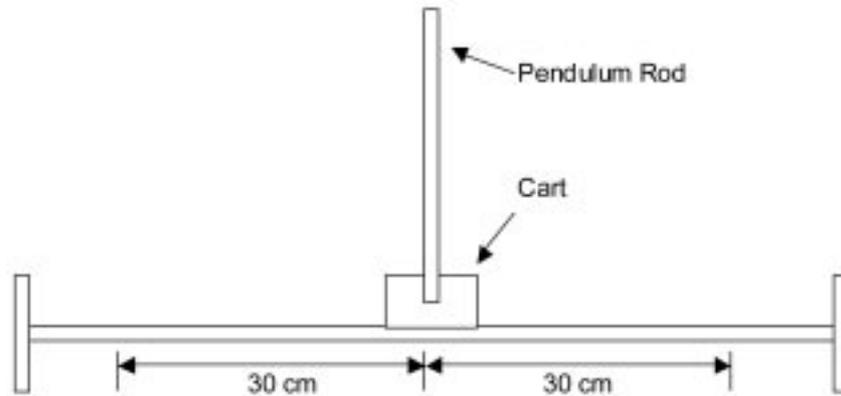


Fig. 5. Inverted pendulum project schematic.

the project description in the middle of the semester and gave the students three weeks of lab time to work exclusively on the project. We also provided them SIMULINK information and a block diagram similar to Fig. 3. The student teams again impressed us with their abilities to stabilize the pendulum. Every student team was able to meet the minimum specification and most teams were able to create a stable upright pendulum. Some teams were able to stabilize the inverted pendulum without controlling the cart motion because there was enough friction between the cart and the track to keep the cart from moving outside of the specified range. So while technically being unstable, the design was functionally stable. Only one team used a MIMO state-space design, and this team won the competition by being able to keep the cart closer to its starting point than any other team. This makes sense because only through a state-space design would there be any control of the position of the cart. Those interested in viewing the final report of the winning team can download it at <http://widget.ecn.purdue.edu/~me475/pendulum.html>.

As with the gantry project, the information we provided the students was minimal and consisted in basic operation of the equipment and some advice on where to begin. We felt this was necessary in order to preserve the open-endedness of the projects. By leaving these projects open-ended we were able to achieve two important pedagogical benefits: first, the students were able to use their own creativity in their designs and, second, in the end the class was able to compare and contrast different methods and ideas together. It was this process at the end of the semester that was so exciting: students teaching each other what they had discovered. And students were motivated to listen by the effort they had given in the project. They wanted to know other ideas because they became personally invested in the project. We know they wanted to learn because attendance at the student presentations was not mandatory and was in the evening during a very busy final week of the semester. And yet every

semester we had at least two thirds of the class in attendance.

EDUCATIONAL IMPACT AND ASSESSMENT

We found that student groups were very motivated during this process, even though they worked countless hours together. They gained first-hand knowledge of practical implementation issues and the open-endedness of the controller design process. The challenges of modeling and controlling a real system with nonlinearities such as stiction, motor saturation, and the crane swing caused the students to go beyond a simple application of course material and seek out new information. Students consulted journal articles, other texts and other professors. While they found helpful information they did not find easy answers. Student teams developed novel approaches that went far beyond the scope of the course.

We believe there were three key aspects of the projects that motivated students beyond their work on projects of the past. The first aspect was the hands-on nature of the project. In each of these new projects students could easily see the quality and impact of their controller. They wanted to get good performance and worked very hard to understand the system.

The second aspect of the new projects that motivated students was the challenge that the project presented. We asked them to do things for which we never provided clear instructions or procedures [6]. There were only guidelines and advice, which served to point them in the right direction. This approach, often called 'Discovery Learning', has been implemented in other control courses [7]. This paper shows not only another implementation of discovery learning, but documents its success. The projects that we used previously in ME 475, as well as most other projects in the curriculum, don't seem to take this 'leap' by asking students to go beyond what they have been taught. Students not only had to

Table 1. Survey results: 21 students took the survey, the number of responses in each category is given

| Statement | Strongly Agree | Agree | Unsure | Disagree | Strongly Disagree |
|--|----------------|-------|--------|----------|-------------------|
| The I.P. project presented me with a challenge that forced me to go beyond a simple application of the text. | 8 | 11 | 2 | | |
| I became more excited about controls because of this project. | 5 | 11 | 4 | 1 | |
| The competition motivated my team to work harder. | 5 | 10 | 1 | 4 | 1 |
| I enjoyed the 'hands on' nature of this project. | 10 | 10 | 1 | | |
| Overall I was very satisfied with the I.P. project. | 5 | 12 | 4 | | |

figure out how to achieve the desired performance specifications, they also had to develop their own experiments in order to model the system. This type of open-ended procedure has also been successful in measurement and instrumentation courses [8]. While some students were frustrated, nearly all of them stepped up to the challenge and began to seek out knowledge because they wanted to.

The third part of our new projects that motivated students was the contest. We offered an automatic 'A' for the entire course as first prize for the group with the best performance. This created an opportunity for students who had not done as well on the midterm or homework to still get an 'A'. This also created a healthy drive among the groups to outdo each other. Word would get around about a particular group's performance and other groups would work even harder to improve. We also offered percentage bonuses towards the cumulative score for the members of the second and third place teams. The effect of the design competition was to establish two different 'hurdles' for students to attempt. The first hurdle was the minimum performance guidelines, something we felt every student could do and something they should do for satisfactory completion of the project. The second hurdle was the competition itself, a voluntary hurdle that would push the brighter students, who might have stopped

working after meeting the minimum specifications, to formulate better controllers. We believe the competition to be a unique contribution that works well with discovery learning environments.

The project created an environment where students synergized learned control theory, design and imagination. 'The project served to bring together a lot of different topics discussed in class and tie them together the way that a real-life control system design project would. This made the class more enjoyable because it demonstrated the purpose and usefulness of the topics that were taught in the course,' said student Jason Brown. There was great excitement, the magnitude of which we had never seen before among undergraduates, when the student groups presented their final designs to one another. Each group wanted to learn what controller design other teams had chosen and how they developed it. Students gained an appreciation for the complexity of the controller design process when stringent performance requirements are to be met, which serves to motivate them for graduate study in advanced control techniques.

Table 1 shows the results of the survey we gave the students at the end of the inverted pendulum project. The survey was completed by 21 of the 26 students in the class that semester. We were pleased that 17 of the 21 respondents indicated they were very satisfied with the inverted pendu-

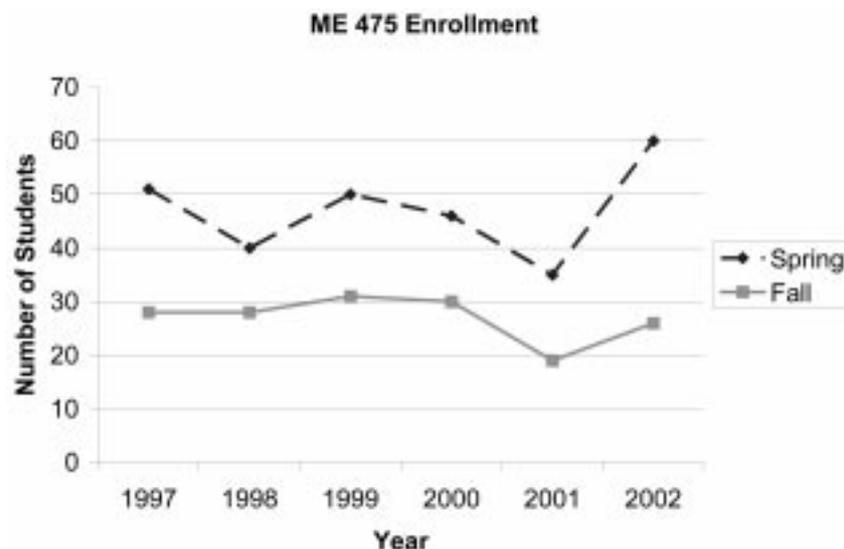


Fig. 6. Enrollment data for ME 475, 1997–2002.

lum project. We also feel confident in our previous statements about what motivated the students: 71 percent indicated agreement or strong agreement with the statement 'The competition motivated my team to work harder' and all but one respondent enjoyed the hands-on nature of the project. Perhaps the most encouraging result was that 16 of 21 respondents felt more excited about controls because of the project.

We have also noticed an increase in enrollment since the projects began in fall 2001. Figure 6 shows the enrollment trends for four years prior to the new projects and the two semesters after the first gantry crane project. The spring and fall semesters are shown separately since our course, which is an elective, generally has more students in the spring semester. Before the new projects we had been seeing a slow decline in enrollment but the trend has been reversed. We feel confident in attributing this reversal to the new projects since a number of students have told us that they heard and saw the new projects and they took the class because of them.

CONCLUSIONS

We were very pleased with the changes that we made with the project in ME 475. The new equipment and competition created an environment

where students vigorously pursued learning and applying control systems knowledge. With the various types of experiments that we can develop with the Quanser system, we can create a different project each semester for quite some time. We would recommend that the instructor of any controls course consider presenting their students the challenge of an open-ended, hands-on project with practical issues such as hardware limitations and nonlinearities. This is not only our recommendation, but was the recommendation of a panel of control educators at the National Science Foundation/IEEE Control Systems Society Workshop on New Directions in Control Engineering Education [9]. Our educational goals were exceeded far beyond what we expected because students took personal ownership of their projects and were motivated by all the aforementioned factors. Student creativity was achieved, and used as a teaching tool when student groups presented their work to each other. Student surveys and enrollment data confirm the excitement students have about our new projects.

Acknowledgements—The authors would like to thank Mike Logan, Marty Mlynarik and Tami Tracy for their work in setting up the hardware and software used for the project. We would also like to thank Prof. Jim Jones for his advice and direction on the paper. Finally, thanks go to students Jason Brown and Ashwin Kumar for providing insight on their experiences in working on the project.

REFERENCES

1. *Systems & Procedures*, Quanser Consulting (2000).
2. *Wincon 3.1 Manual*, Quanser Consulting (2000).
3. H. Butler, G. Honderd and J. Van Amerongen, Model reference adaptive control of a gantry crane scale model, *IEEE Contr. Syst. Mag.*, **11**, 1991, pp. 57–62.
4. N. Singer and W. Seering, Preshaping command inputs to reduce system vibration, *J. Dyn. Syst. T. ASME*, **112**, pp. 76–82 (1990).
5. J. Petric and Z. Situm, Inverted pendulum driven by pneumatics, *Int. J. Eng. Educ.*, **19**(4) 2003, pp. 597–602.
6. M. Tinnesand and A. Chan, Step 1: Throw out the instructions, *Sci. Teach.*, **54**, 1987, pp. 43–45.
7. B. Armstrong and R. Perez, Controls laboratory program with an accent on discovery learning, *IEEE Contr. Syst. Mag.*, **21**, 2001, pp. 14–20.
8. L. K. Saunders, A novel structure for measurement and instrumentation courses, *P. IMECE*, 2002.
9. P. Antsaklis, T. Basar, R. DeCarlo, N. H. McClamroch, M. Spong and S. Yurkovich, Report on the NSF/CSS workshop on new directions in control engineering education, *IEEE Contr. Syst. Mag.*, **19**, 1999, pp. 53–58.

Michael Reynolds is an Assistant Professor of Engineering at the University of Arkansas—Fort Smith and a Ph.D. Candidate in Mechanical Engineering at Purdue University. Michael received his B.S. in Mechanical Engineering from Marquette University in 1996 and his M.S.M.E. from Purdue University in 1999. His research focuses on developing and benchmarking time-optimal commands for flexible systems.

Peter H. Meckl is an Associate Professor of Mechanical Engineering at Purdue University. Dr. Meckl obtained his Ph.D. in Mechanical Engineering from MIT in 1988. He joined the faculty in the School of Mechanical Engineering at Purdue University in 1988. Dr. Meckl's research interests are primarily in dynamics and control of machines, with emphasis on vibration reduction and motion control. His teaching responsibilities include undergraduate courses in systems modeling, measurement systems, and control, and graduate courses in advanced control design and microprocessor control. Dr. Meckl was selected as an NEC

Faculty Fellow from 1990 to 1992. He received the Ruth and Joel Spira Award for outstanding teaching in 2000.

Bin Yao is an Associate Professor of Mechanical Engineering at Purdue University. Dr. Yao earned his Ph.D in Mechanical Engineering from the University of California in 1996. Dr. Yao's research interests include Adaptive Control, Robust Control, Robotics and Nonlinear Control. His teaching responsibilities include undergraduate modeling and controls courses and graduate courses in Adaptive Control and Nonlinear Control. Dr. Yao received a National Science Foundation CAREER award in 1998.