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THE EDUCATIONAL IMPACT OF A GANTRY CRANE PROJECT IN AN UNDERGRADUATE CONTROLS CLASS

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ABSTRACT

In the fall of 2001 we implemented a new controller design project in our Junior/Senior level controls class in Mechanical Engineering at Purdue University. The old project, which involved the identification and control of a "black box", failed to challenge and motivate students. Our new project is the design of a controller for the point-to-point motion of a gantry crane system. Student teams modeled the gantry crane and developed a controller to meet several performance specifications. The designs were implemented in Simulink with MATLAB's Real-Time Workshop. A competition served to further motivate the students. In the end we were very impressed with the great effort the students gave and the quality of their designs. Each group presented their design and most students stayed and asked questions for several hours.

INTRODUCTION

ME 475 is our Junior/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 2nd 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 straight forward 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 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 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.

A gantry crane configuration (one suspended rod attached to a controlled mass on the track) was chosen because the dominant system dynamics can be modeled with a 4th order transfer function [1], something we knew students could handle, yet the modeling and control would go beyond a simple 2nd order design (More information on the particular setup can be found at www.quanser.com). Since our course deals only with SISO design, we wanted a system which could be successfully controlled without needing to use multiple inputs or outputs, something which could also be done with the gantry cranes. 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 non-linear friction that typically arises in real-world applications. Non-linear 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. Figure 1 shows two pictures of the gantry crane used in our project.

The gantry crane system consists of a 6 volt DC motor powered by a linear amplifier. The amplifier is connected to the computer through an 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 long 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.

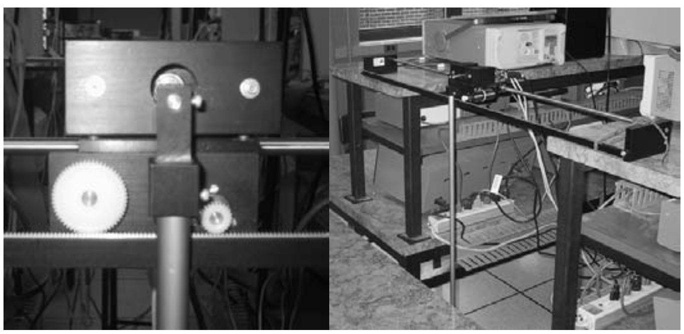

Figure 1: Pictures of the experimental setup.

PROJECT DEFINITION

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 Figure 2, less than 15 seconds. The steady-state error must be zero with the theoretical design when non-linear 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 were encouraged to go beyond just meeting the minimum specifications through a contest. Each of the teams of three students competed against each other for percentage points added to their final course average. Points were generously given to the team with the best performance so that students could get an 'A' for the course even if their grades in the rest of the class were only average. This served to further motivate those who might not have been motivated before. And the contest built an excitement about the project that spread throughout the undergraduate population. The contest also sparked creativity in the students because each team was looking for an "edge", something that would make their design give better performance. We believe that the competition was a factor in the great interest the students took in the project. The competition was judged by weighting the settling time and overshoot along with a presentation score.

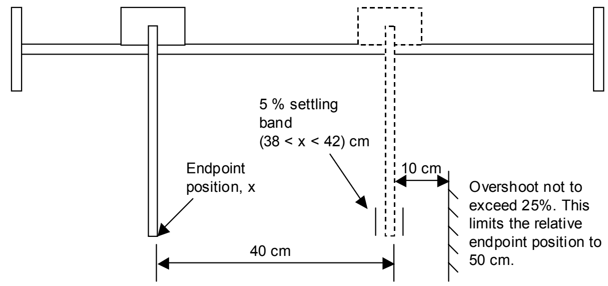

Figure 2: Project Schematic.

Students submitted a formal report which 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 (Figure 3). The students were encouraged to design their own Simulink blocks and even implement control structures that were not covered in the 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 our 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!

A WINNING DESIGN

The student teams came up with many excellent designs. The design that won the contest combined a highly accurate model with a logical controller design. 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 non-linearities

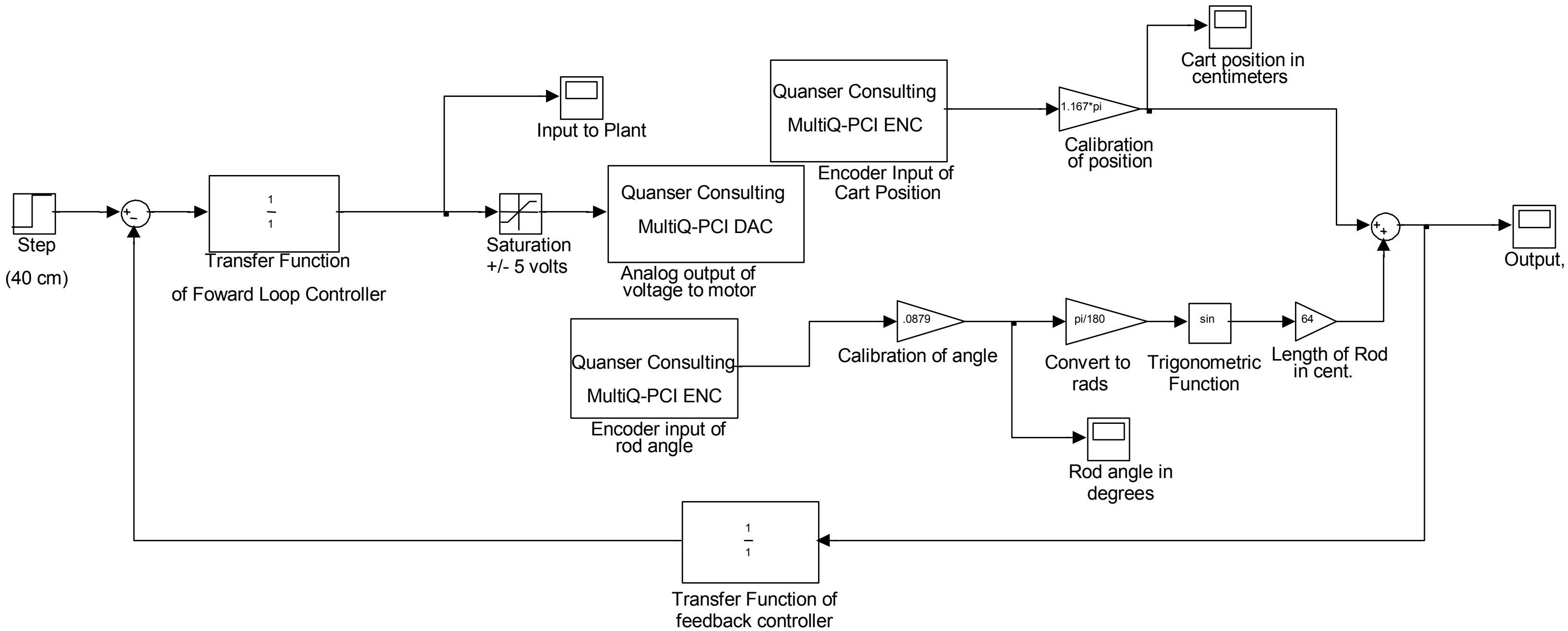

Figure 3: Simulink block diagram of control structure.

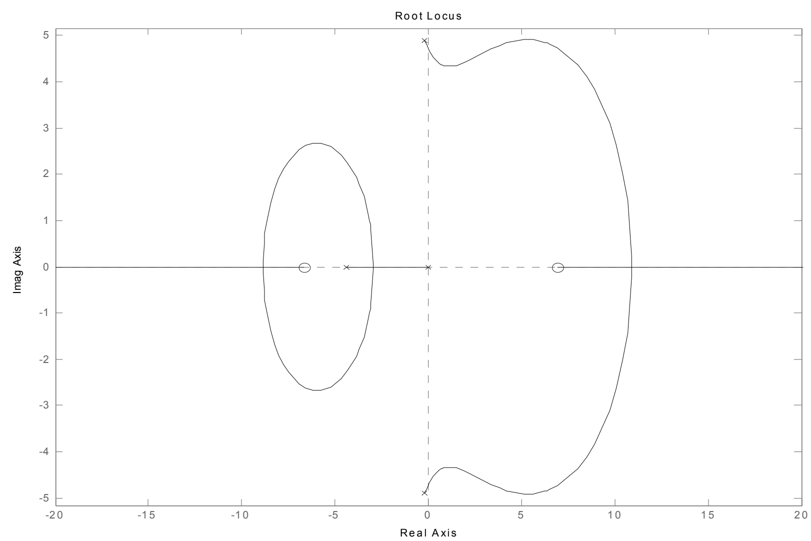

Figure 4: Root locus of the uncompensated system.

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 final transfer function model (between the horizontal endpoint position of the rod, x, and the input voltage, u) had a mean squared error of 0.0063 when the 2 volt step responses were compared. The resulting model was 4th order with a right half plane (RHP) zero as expected:

$$\frac{X(s)}{U(s)}=\frac{-0.01577s^2+0.004815s+0.7244}{0.03927s^4+0.1867s^3+1.002s^2+4.14s} \tag{1}$$

The root locus of the uncompensated system is plotted in Figure 4. It is clear that a feasible controller needs to move the RHP loci into the stable region and as far left as possible. Like several other groups, the winning design effectively cancelled the nearly unstable complex poles with their controller. The winning team identified that the oscillation from these roots would be severely detrimental to fast settling times. Coming up with the most effective cancellation is a big reason why the design gave the best performance.

The cancellation did manipulate the root locus to stabilize the system by concentrating the root locus to the left half plane, but modifications were still required to satisfy the desired transient and steady state responses. First two poles had to be added so that the system would remain a type one system and the controller strictly proper. Both roots were added on the negative real axis at -100 as a first guess. The performance specs were then translated into a desired phase margin and crossover frequency. This was done by using the 'rltool' command in MATLAB and adjusting the gain until the desired values were achieved to optimize the designed controller. Figure 5 shows the resulting pole locations due to the optimized gain along with the corresponding bode plot that shows the phase margin close to 70º and crossover frequency close to 2 rad/sec, both close to the desired values established earlier.

The controller was then implemented on the physical system and the gains were increased to account for some of the unmodeled friction in the system. The control signal also had to be checked to make sure it stayed below the saturation voltage of the motor and above the voltage required to overcome stiction. This narrow window of motor voltage proved to be a challenge to many designs because it is difficult to account for a priori. But through careful analysis of the control signal, many groups overcame this limitation. The final controller had two open-loop poles and two zeros:

$$G_{controller}=25\frac{s^2+.41s+23.86}{s^2+198.5s+9850.14} \tag{2}$$

The above controller was cascaded with the plant in the forward path and implemented in Simulink via Wincon. The input trajectory was shaped to suppress the initial backward movement of the endpoint, typical of non-minimum phase systems such as the gantry, and to minimize residual vibration. The team theorized that by providing a small amount of actuation at the beginning of the command signal this non-minimum phase behavior would be reduced. The design of 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 Figure 6. The endpoint of the rod came within 5% of the final position in only 2.25 seconds. 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://expert.cc.purdue.edu/~reynoldm/gantry.html.

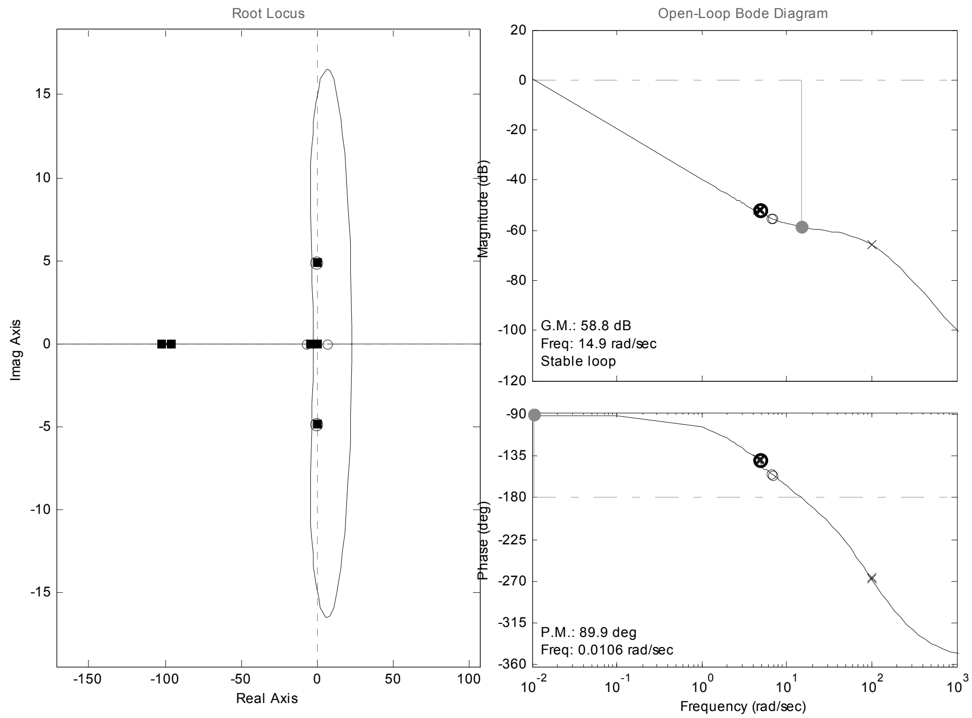

Figure 5: Root Locus and bode plot of the compensated system.

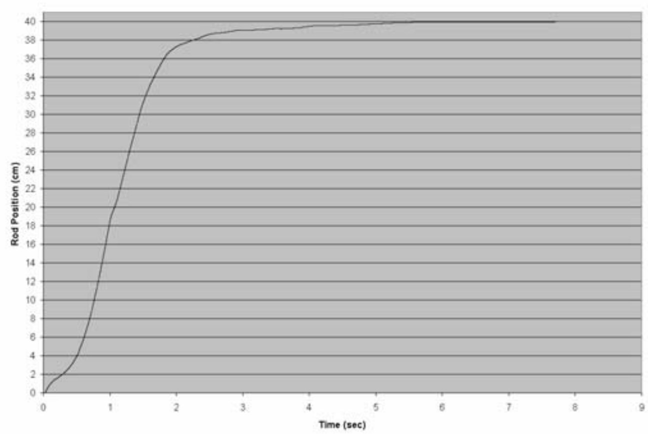

Figure 6: Horizontal endpoint position of the rod versus time.

OVERALL RESULTS OF THE GANTRY PROJECT

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 non-linearities 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.

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. Most students at the final presentation session stayed for the entire time even though it was a busy week for them and they were not required to be there. Together we discussed various control strategies for several hours of the evening and the students asked excellent questions. Students gained an appreciation of 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. The excitement has spread to the undergraduate population in general and the course, which is an elective, has tripled enrollment in the spring semester.

CONCLUSIONS AND FUTURE WORK

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 sometime. The gantry crane setup provided an excellent challenge to our students while not being overbearingly difficult. Most student groups developed novel designs that went beyond a simple application of their notes.

ACKNOWLEDGEMENTS

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