DESIGN OF A MINICRANE FOR EDUCATION AND RESEARCH

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Abstract: A miniature bridge crane was designed to serve as an educational tool in the classroom and as a research testbed. The minicrane is a two-axis gantry robot that is approximately 1 m^3. A Siemens PLC was programmed with real-time, anti-swing algorithms, as well as a playback mode to run pre-computed trajectories. The swing-angle of the suspended payload was measured with a digital camera. The device was built at Georgia Tech and shipped to Georgia Tech Lorraine in France where it was used in two controls courses. With this setup, students gain first hand experience in driving a gantry robot, tuning controller gains, using optical sensors, and programming a PLC. The courses also taught advanced vibration control algorithms, which the students designed and tested on the minicrane.

1. INTRODUCTION

Every component of the mechanical engineering curriculum poses challenges to both the educator and the student. Often the challenge for the educator is how to make theories, methods, equations, and proofs take on a meaningful representation to an audience that is often overworked, somewhat disinterested, and lacking in practical experience. A very worthwhile, but often difficult, approach for the educator is to give the students a hands-on experience with the subject matter. The system dynamics and controls curriculum contains a fair amount of complicated theory that is non intuitive for most students. Stability proofs via Routh and Nyquist methods are classic examples. It is also a discipline that generally lacks hands-on training. Laboratory courses in this area are usually relegated to the advanced graduate level. This lack of hands-on exposure is particularly troubling because an increasing percentage of mechanical engineers are required to work with computer controlled machines whose control system is paramount to the success of the product.

One challenge in teaching system dynamics and controls is finding a representative system that is both simple enough to demonstrate basic concepts, yet complex enough to also benefit from more advanced analysis and controls techniques. A bridge crane, like the one sketched in Figure 1, is an excellent testbed this discipline. Simple control methods can be implemented on this system because its dominant dynamics consist of a single, pendulum mode. However, the system has other effects, such as actuator time constants, double pendulum effects, and payload dynamics that can make precise analysis and control very challenging.

With the above issues in mind, the investigators designed and built a miniature bridge crane. The device needed to be easy to work with, easy to

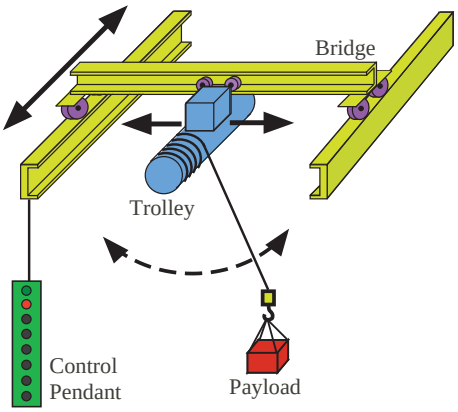

Fig. 1. Overhead Bridge Crane.

transport, yet also capable of performing the variety of controls experiments needed to teach undergraduate and graduate courses. This device was shipped from the US to France where it was used in the Georgia Tech Lorraine (GTL) curriculum. Laboratory assignments were developed that covered basic concepts, such as PI control and ramp generators, along with advanced concepts, such as input shaping and trajectory tracking. More importantly, the labs were designed to give the students the same "hands-on" experience that a professional controls engineer gets working in the field. These included tasks such as tuning gains, programming the PLC, and recording response data for analysis.

The rest of the paper is organized as follows: Section 2 reviews input shaping, one of the basic concepts taught in the Georgia Tech curriculum. Section 3 reviews previous developments in the Georgia Tech controls curriculum. Section 4 follows with the design of the minicrane. It reviews the mechanical and electrical components, and discusses how input shaping is implemented. Section 5 describes the laboratories that were designed for the course and Section 6 discusses the results. Finally, Section 7 gives the conclusions.

2. INPUT SHAPING REVIEW

One of the vibration control concepts taught at Georgia Tech is input shaping. To understand how input shaping works, consider the example of applying an impulse to a flexible system. The dashed line in Figure 2 shows the response to an impulse A_1. Figure 2 also shows a delayed impulse, A_2 and the delayed response. The total response would be the sum of the individual responses. However, notice that the impulses have been timed so that the total vibration is zero after the second impulse. This is how input shaping eliminates vibration in flexible systems.

Real systems cannot be moved around with impulses, so we need to convert the properties of

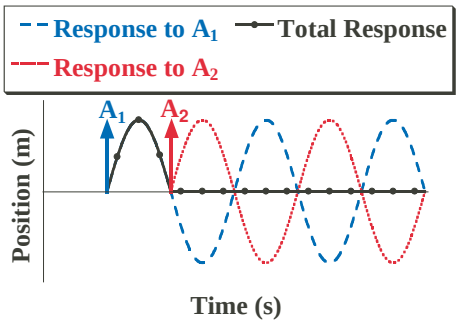

Fig. 2. System response to Impulses.

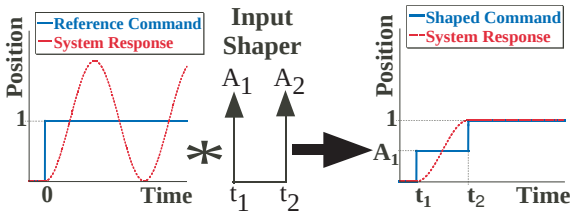

Fig. 3. Input shaping a Generic Command.

the zero-vibration impulse sequence given in Figure 2 into a usable command. This can be done by simply convolving the impulse sequence with any desired command. The convolution product is then used as the reference command for the system. If the impulse sequence, also known as an input shaper, causes no vibration, then the convolution product will also cause no vibration (**?**; **?**). This command generation process, called input shaping, is demonstrated in Figure 3. The figure shows the original command, a step, and the shaped command, which is a two-step staircase. Figure 3 also shows the system response. The step response vibrates as expected. However the response to the input shaped command has zero residual vibration. The only penalty is an increase in the rise time of the system.

3. PREVIOUS DEVELOPMENTS

During the past 6 years Georgia Tech has integrated bridge crane dynamics and controls into both the undergraduate and graduate mechanical engineering curriculum. The curriculum is composed of: 1) a series of examples and problems that lead the students through the development of a bridge crane dynamic model and an oscillation control method, 2) a computer simulation of a bridge crane with a graphical user interface (GUI) that allows the students to drive the crane through cluttered work environments, 3) a 10 ton bridge crane that the students can use to test oscillation control algorithms that they develop.

The examples and homework problems are introduced over a five-week period in the undergraduate System Dynamics and Controls course

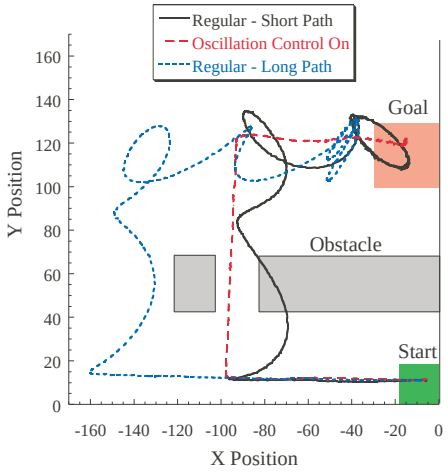

Fig. 4. Student Data Driving Through an Obstacle Field.

(ME3015). The curriculum starts with a pendulum attached to a moving base, adds actuator dynamics, explores the effects of various input signals, and then presents the input-shaping oscillation control algorithm. Variations of the more complex examples and problems are used in a graduate course, Advanced Control System Design and Implementation (ME6404).

The GUI-based bridge-crane simulation offers an overhead view of the crane workspace (**?**). Using a simulated control pendant, students move the crane through an obstacle-filled workspace. The dynamic response is scaled to a large bridge crane at the Savannah River Technology Center (**?**) and its motion is observable in real time. Without oscillation control, the payload swings freely underneath the trolley as the crane is moved, stopped, turned, etc. Students have a difficult time traversing the workspace without colliding into obstacles. With oscillation control enabled, the students quickly learn how to safely traverse the obstacle field.

The oscillation control algorithm presented in ME3015 and ME6404 was implemented on a large gantry crane located at Georgia Tech. After completing their assignments using the GUI crane simulation, the undergraduates are allowed to drive the real crane both with and without input shaping enabled. Their efforts are videotaped by an overhead camera. Figure 4 shows three such cases. Two of the cases are under regular control and large payload oscillations are evident. The solid line shows that when the student attempted to take the short route to the goal location, the payload collided with the large obstacle. (The obstacles are made of lightweight material, so they are easily knocked out of the way.) The dashed line shows a case when the oscillation control is enabled and the student can easily traverse the short path.

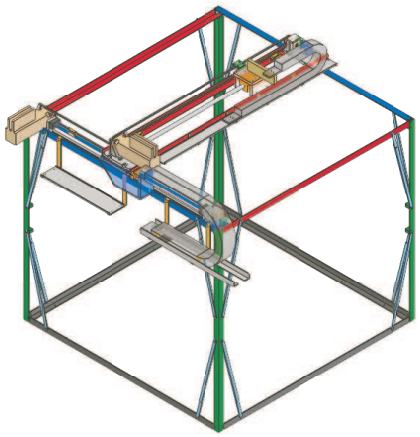

Fig. 5. Bridge Minicrane.

As a part of the graduate course, students are required to design and implement different oscillation controllers for the crane. This gives them first hand experience with developing a realistic controller. It also exposes them to actual working versions of advanced controls techniques and the challenges involved with implementation.

The crane is also used in a senior-level experimental methods course, ME4055. Teams of students run the crane through various tests and videotape the payload response. They extract the position data from the video and perform data reduction. Each team of students designs their own series of experiments, on topics such as obstacle avoidance, trajectory tracking, payload dynamics, and hoisting effects.

4. BRIDGE MINICRANE DESIGN

4.1 Mechanical Design

Students at the main Georgia Tech campus in Atlanta can use the 10-ton crane to conduct their experiments, but those at GTL cannot. Therefore, a miniature bridge crane was built and transported to France. This small crane has all the functionality of the large crane. A sketch of the minicrane is shown in Figure 5. Its size is approximately 1 m^3. It is capable of movement in both x and y directions. It is driven by two Siemens AC, synchronous servo motors. These move the trolley and bridge axes via two timing belts. A Siemens digital camera is also attached to the trolley pointed at the payload support cable. As the payload swings, the camera can measure the angular displacement of the cable. The minicrane was designed to be light and compact to make it easy to transport. Almost all of the structural elements are lightweight aluminum and made as thin and small as possible without degrading the structural integrity. In addition, the structure was designed to be easily disassembled and collapsed

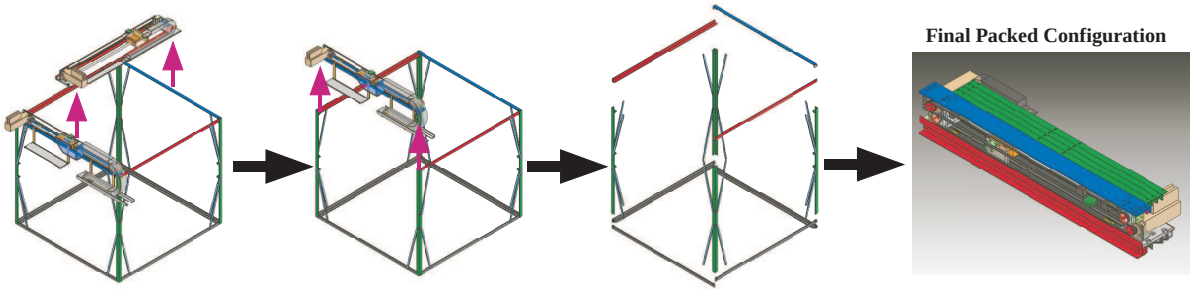

Fig. 6. Bridge Minicrane Dissassembly.

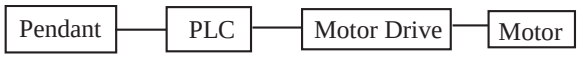

Fig. 7. Signal Flow through Major Components.

to fit into a compact travelling box. The collapsed configuration is shown in Figure 6. All of the disassembly can be performed with a single tool.

4.2 Electrical Overview

Figure 7 shows the electrical layout of the minicrane. The control pendant has four directional buttons to drive the crane and two buttons to change the controller mode. The pendant signal is sent to a Siemens PLC, the PLC applies the desired algorithm, and generates a series of velocity setpoints for the motors. The user also has the option to run a trajectory stored in a setpoint buffer. The velocity setpoints are then interpreted by the drives which, in turn, send the power signal to the motors. The drives contain a ramp generator and PI controller that uses feedback from the motor encoders. Table 1 lists all of the Siemens equipment used in the minicrane.

Table 1. Siemens Components Used

Name	Model No.
PLC 314C-2 DP	6ES7314-6CF00-0AB0
Compact Servomotor	1FK7022-5AK71-1AA0
Masterdrive MC Compact Plus	6SE7011-5EP50
Simatic Camera VS 723-2	1P 6GF1 723-1AA

4.3 Input Shaping Implementation

The input shaping algorithm starts by creating a buffer for the command - a vector variable of a finite length. This buffer is used to store the command values for each time step. A graphical representation of such a buffer is shown in the upper right-hand corner of Figure 8. The upper left-hand portion of the figure shows the unshaped initial command in the digital domain. This baseline command could be created in real time, for example by reading a joystick position or the states of the operator pendant buttons. In order to fill the buffer with the input-shaped command, the algorithm acquires the baseline command each time through the control loop. Then, the algorithm multiplies the baseline command at that instant by the amplitude of the first impulse in the input shaper. This value is added to the current time location in the shaped-command buffer. The amplitude of the second impulse is then multiplied by the baseline command. However, this value is not sent directly out to the control loop. Rather, it is added to the future buffer slot that corresponds to the time location of the impulse. This real-time process will build up the shaped command as demonstrated in the bottom of Figure 8. The figure indicates the state of the algorithm at the first time step and at the eighth time step. To avoid having the index exceed the size of the buffer, a circular buffer is used where the index goes back to the beginning when it reaches the end of the buffer.

5. USE OF MINICRANE IN EDUCATION

5.1 Overview

The minicrane was used in two controls courses at Georgia Tech Lorraine. The graduate students performed 6 labs using the minicrane that were intended to reinforce many of the concepts they learned in lecture. Figure 9 shows a block diagram that summarizes how the minicrane was configured for these labs. Notice that the students had

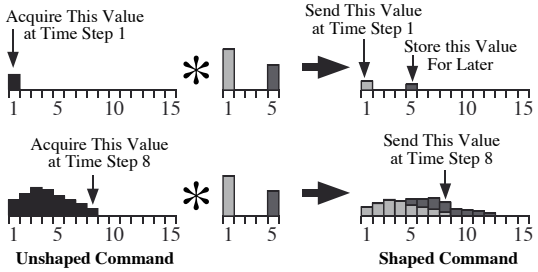

Fig. 8. Real-Time input shaping.

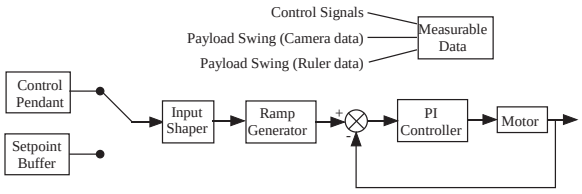

Fig. 9. Block Diagram.

access to four main blocks in the control architecture: the PI controller, the ramp generator, the trajectory buffer, and the input shaper. In addition, the students measured the payload swing either manually, with a ruler, or electronically using the digital camera. They could also measure any of the control and/or feedback signals in the control loop.

The overall goal of the labs was to teach the students how each of the control blocks effected the trolley and payload response. There was a special effort to familiarize them with the input shaper and how it benefited the response.

5.2 Lab Descriptions

Lab 1 *Goals:*

- Get students acquainted with the equipment.
- Observe how the rise and fall times of the drive effect the motor response.
- Observe how the rise and fall times of the drive effect payload swing.

Procedure: A simple point-to-point move is preprogrammed into the PLC. The students use a drive parameterization program to adjust the rise and fall times. These parameters effect how quickly the drive responds to the PLC commands during the point-to-point motion. The students measure the motor response with encoders and by visually observing the response. The students also manually measure the effect of changing the rise time on the payload response using a ruler.

Results: Increasing the rise time causes a sluggish motor response. However, this makes the payload oscillate less.

Lab 2 *Goals:*

- Tune the PI controller gains to achieve small trajectory tracking error.
- Tune the PI controller gains to achieve small payload oscillation.

Procedure: The students manually adjust the proportional and integral gains in the drive. The students measure the effects on the motor response and the payload response.

Results: Increasing the PI gains will improve tracking error. However if the gains are set too high the system goes unstable. The students also realize that choosing lower PI gains reduces payload oscillation because it causes a sluggish system response.

Lab 3 *Goals:*

- Program a simple input shaper into the PLC.
- Compare shaped and unshaped payload swing for various move distances.
- Compare shaped and unshaped payload swing for various payload heights.

Tasks: The students design a simple input shaper for the baseline pendulum length and enter it into the PLC. The students compare the payload swing for a point-to-point motion with and without input shaping. The experiment is repeated for various move distances and cable lengths. The results form a sensitivity analysis of the shaper.

Results: Input shaping reduces the payload swing in all cases. However, for some move distances the unshaped motion also creates "natural input shaping" that causes low levels of swing. In addition, changing the payload length degrades input shaping performance because it changes the system natural frequency.

Lab 4 *Goals:*

- Create and test a robust shaper, a fast shaper, and a multimode shaper.
- Understand the strengths and weaknesses of each shaper.

Tasks: The students create each of the above shapers using the known system parameters and the concepts they learned in lecture. The system response is measured using a digital camera that automatically calculates the swing angle every 100 ms. For the robust shaper, the students measure the payload swing for various pendulum lengths and compare the results to the previous lab. For the fast shaper, the students measure the response time and also measure the swing for one and two-mode payloads. For the multimode shaper, the students perform an FFT analysis on the two-mode payload that yields the system natural frequencies. Then, they design a multimode shaper using a combination of the single-mode shapers and test it on the two-mode system.

Results: The students experimentally confirm the speed and robustness of the shapers they designed. In the process they realize that robust shapers are slow and fast shapers excite high frequency modes. They also learn how multimode shapers can be constructed from simple one-mode shapers.

Lab 5 *Goals:*

- Simulate how to use input shaping in an industrial, warehouse environment.

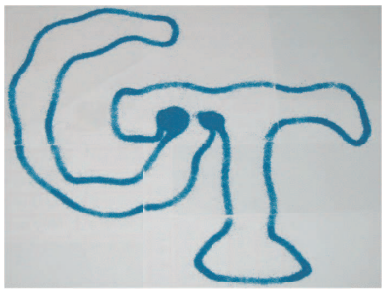

Fig. 10. Sample Student Project: Using Sand to Spell out "GT".

Tasks: Generate an input shaped trajectory to move a payload through a cluttered workspace. The same trajectory must be used for two different multi-mode payloads. The trajectories are generated in Matlab, downloaded to the PLC, and then run on the minicrane using a real obstacle field. The trajectories are evaluated on time and number of obstacle collisions.

Results: The students use many of the concepts learned in previous labs to find the right compromise between robustness and speed.

Lab 6
The last lab required the students to design their own, unique control experiments. This forces the students to use concepts outside of the bounds of what was taught in class. They must not only understand the ideas, but synthesize new ones. For example, one group used input shaping to eliminate multimode vibration for hoisting beams that can rotate. Another group used the crane to write "GT" in sand, as shown in Figure 10.

5.3 Undergraduate Laboratory Course

A second, undergraduate laboratory course was also taught at Georgia Tech Lorraine. The goal of the course is to teach basic laboratory procedures and writing methods. In this course the students were given the minicrane as their lab device, as well as several options for projects they could work on. The students chose a project that involved testing a new input shaper designed to compensate for nonlinearities. Note that this is not a "mock" research project, the students were dealing with a project that is on the cutting edge of input shaping research. In their project the students:

- Programmed the digital camera to measure the payload position.
- Estimated the error of their sensors.
- Ran several experimental trials.
- Analyzed the data to determine the effectiveness of the new shaper.
- Wrote a formal lab report and gave a presentation detailing their work at an automation conference.

6. RESULTS

Educational achievements of this project include:

- Developed a system to mimic the control and operation of industrial cranes.
- Students learned how tuning standard control parameters effects system response.
- Students programmed control algorithms.
- Students understood the strengths and weaknesses of the different oscillation control algorithms.
- Students performed tests to accurately measure the vibration characteristics of various input shapers.
- Students completed group projects that demonstrated their own control algorithms at an automation and drives conference.

7. CONCLUSIONS

This paper described the bridge crane dynamics and control curriculum developed at Georgia Tech Lorraine. Central to this effort was the construction of a portable bridge crane. Labs were designed to give the students a unique learning experience that went beyond the normal bounds of classroom learning. With this curriculum the students were faced with problems where the results were a real-life machine response that they could see and measure. This gave the students a deeper understanding for the control algorithms they were using and how they affect the system.